Report No. FHWA-SC-18-01

Laboratory Performance of Liquid Anti-Stripping Agents in Asphalt Mixtures used in South Carolina

FINAL REPORT

Sponsoring Agency:
South Carolina Department of Transportation

In Cooperation with:
U.S. Department of Transportation
Federal Highway Administration

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February 15, 2018

Technical Report Documentation Page

1. Report No. FHWA-SC-18-01	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Laboratory Performance of Liquid Anti-Stripping Agents in Asphalt Mixtures used in SC		5. Report Date February 15, 2018 6. Performing Organization Code
7. Author(s) Serji Amirkhanian, Ph.D., Feipeng Xiao, P.E., Ph.D. and Mary Corley		8. Performing Organization Report No. TCTC 18-01
9. Performing Organization Name and Address Tri-County Technical College P.O. Box 58, 7900 U.S. Hwy. 76, Pendleton, SC 29670		10. Work Unit No. (TRAIS) 11. Contract or Grant No. SPR 726
12. Sponsoring Agency Name and Address South Carolina Department of Transportation 1406 Shop Rd., Columbia, SC 29201		13. Type of Report and Period Covered Mar. 2016 – Feb. 2018 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Stripping is a phenomenon involving the loss of adhesion or bond between the asphalt binder and the aggregate in an asphalt mixture. In general, stripping results from the presence of water combined with the adhesive relationship of the aggregate and the asphalt binder. Most State Highway Agencies (SHAs) require the use of an anti-strip additive to control moisture damage. Anti-strip additives could be divided into two broad categories: (a) hydrated lime Ca(OH)2 and (b) liquid anti-strip additives (ASAs). Although the SCDOT has been utilizing hydrated lime for many years in their hot mix asphalt (HMA) mixtures, there are many new liquid ASAs in the market that are proven to be effective in minimizing the moisture susceptibility of HMA mixtures. This research project investigates the effects of various liquid ASAs and hydrated lime on several high-traffic volume mixture types used in South Carolina. In addition, various dosage rates for the liquid ASAs included in this project are examined to determine recommended dosage rates.

17. Key Words Liquid Anti-Stripping Agent; Asphalt; Pavements	18. Distribution Statement No restrictions.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. Of Pages 138	22. Price

Form DOT F 1700.7 (8–72) Reproduction of completed page authorized

Acknowledgements

The authors wish to extend their appreciation to the South Carolina Department of Transportation (SCDOT) and the Federal Highway Administration (FHWA) for sponsoring this research project. The assistance of Messrs. Zwanka, Swygert, Selkinghaus, Hawkins, Gunter and Waites of SCDOT and Mr. Garling of FHWA was instrumental in the completion of this project.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the presented data. The contents do not reflect the official views of Tri-County Technical College, SCDOT, or FHWA. This report does not constitute a standard, specification, or regulation.

Executive Summary

Overview

Stripping is a phenomenon involving the loss of adhesion or bond between the asphalt binder and the aggregate in an asphalt mixture. In general, stripping results from the presence of water combined with the loss of adhesion between the aggregate and the asphalt binder under repeated traffic loading. Most State Highway Agencies (SHAs) require the use of an anti-strip additive to control moisture damage.

The bond between the aggregate and the binder should last the entire life of the pavement. Several mechanisms, such as infiltration of water; hydraulic scouring due to tire pressure and pore pressure within the pavement structure; film rupture; and spontaneous emulsification can break the bond between the aggregate and the asphalt binder. Stripping usually begins at the bottom of the pavement layer and travels upwards gradually. In many cases, the gradual loss of strength over the years causes various types of surface defect manifestations like rutting, corrugations, shoving, raveling, cracking, etc., which makes the identification of stripping in the pavement very difficult.

The main objectives of this proposed research project were to a) evaluate the use of liquid anti-strip additives (ASAs) and hydrated lime in high-volume PG 64-22 asphalt mixtures typically used in various parts of the state; and b) provide recommendations regarding dosage rate of the liquid ASAs in various mixtures. A secondary objective included comparison of the laboratory performance of liquid ASA mixtures to that of mixtures containing hydrated lime with respect to moisture susceptibility.

Literature Review

Researchers identified six contributing mechanisms that might produce moisture damage: detachment, displacement, spontaneous emulsification, pore pressure-induced damage, hydraulic scour, and the effects of the environment on the aggregate-asphalt system (Taylor and Khosla 1983, Kiggundu and Roberts 1988, Terrel and Al-Swailmi 1994). However, it is apparent that moisture damage is usually not limited to one mechanism but is the result of a combination of many processes. From a chemical standpoint, the literature is clear that although neither asphalt nor aggregate has a net charge, components of both have non-uniform charge distributions, and both behave as if they have charges that attract the opposite charge of the other material.

Results

Mix designs were performed according to SCDOT specifications utilizing one PG 64-22 asphalt binder source, six aggregate sources, six reclaimed asphalt pavement (RAP) sources corresponding to the six aggregate sources, and one hydrated lime source. The mixtures containing hydrated lime were considered the control mixtures; thus, the same gradation and optimum binder content in each hydrated lime mixture was used with the five liquid ASA sources. Two dosage rates [0.7% and either 0.5% or 0.07% by weight of the binder] for each liquid ASA were utilized for comparison purposes. The lower dosage rate in each case was recommended by the respective liquid ASA supplier. In general, it was found that the dry and wet ITS values of mixtures containing aggregates A and E were lower than the ITS values from the other aggregate sources. Additionally, all of the wet ITS values were much higher than the minimum SCDOT requirement for moisture susceptibility of 448 kPa (65 psi).

Conclusions

1. Both liquid ASAs and hydrated lime could improve the moisture sensitivity of HMA. In addition, those ASAs also had influence on pavement behaviors such as rutting, fatigue, raveling and so forth.
2. The wet ITS values of all mixtures tested in this study were greater than 65 psi (448 kPa) regardless of aggregate source, ASA type, and mixture type, which met the minimum wet ITS requirements for mix design per SCDOT 2007 Standard Specifications.
3. There were statistically-significant differences between the wet ITS values of mixtures made with various liquid ASA sources when used with aggregate sources E and A but not with the other aggregate sources. The wet ITS values of aggregate sources A and E and/or 0.07% liquid ASA source V were much lower than the corresponding dry ITS values.
4. All mixtures containing hydrated lime produced TSR values that were greater than 85%, regardless of mix type and aggregate source.
5. When aggregates A and E were utilized with some liquid ASA sources, the TSR values were found to be less than 85%.
6. The dosage rate of liquid ASAs affected the moisture susceptibility of mixtures in some cases. For instance, in some cases, the liquid ASA was not as effective at a lower dosage rate compared to the higher dosage rate tested in this research project. Thus, the SCDOT's currently-recommended dosage rate of 0.7% (by weight of base binder) was necessary for some liquid ASAs to be effective.
7. It is recommended that SCDOT consider specifying the use of liquid ASAs in Surface Type B mixtures as well as in Intermediate Type A and Intermediate Type B mixtures on a case-by-case basis at the mix design stage based on the results of ITS values, TSR values, and boiling test results of the specific aggregate and ASA sources.

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Chapter 1: Introduction

Stripping is a phenomenon involving the loss of adhesion or bond between the asphalt binder and the aggregate in an asphalt mixture. In general, stripping results from the presence of water combined with the adhesive relationship of the aggregate and the asphalt binder. Most State Highway Agencies (SHAs) require the use of an anti-strip additive to control moisture damage. For instance, SCDOT requires an anti-strip additive in all asphalt pavement mixtures in order to improve the performance of the pavements.

The bond between the aggregate surface and the binder is considered by many researchers to be one of the most important factors influencing the structural integrity of a flexible pavement. The bond between the aggregate and the binder should last the entire life of the pavement. Several mechanisms, such as infiltration of water; hydraulic scouring due to tire pressure and pore pressure within the pavement structure; film rupture; and spontaneous emulsification can break the bond between the aggregate and the asphalt binder (Busching et al. 1986, Kim and Amirkhanian 1991). This phenomenon of breaking the bond between the aggregate and the binder is known as stripping. Stripping usually begins at the bottom of the pavement layer and travels upwards gradually. In many cases, the gradual loss of strength over the years causes various types of surface defect manifestations like rutting, corrugations, shoving, raveling, cracking, etc. (Roberts et al. 1996), which makes the identification of stripping very difficult. In addition, it often takes many years for the surface indicators to show up. To prevent moisture susceptibility, proper mix design and compaction in the field are essential.

There are many ways to prevent stripping in a pavement; however, the use of anti-stripping additives (ASAs) is the most common (Huang 1993, Lu and Harvey 2006, Putman and Amirkhanian 2006, Xiao and Amirkhanian 2009, Gandhi et al. 2009). One of the most commonly-used ASAs in the United States is hydrated lime (Little and Epps 2001). Other ASAs include liquids like amines, di-amines, liquid polymers, and solids like Portland cement, fly-ash, flue dust, etc. Many contractors prefer liquid ASAs since they are relatively easy to use (Kennedy and Ping 1991 and Lu and Harvey 2006). However, many SHAs prefer hydrated lime due to its excellent performance over many years and the ease of validating the use of the material. The SCDOT has been using hydrated lime as its primary ASA for many years, but it currently does allow the use of some other ASAs in selected mixture types.

Many SHAs use an approved qualified list for many of the products used within each state. This is an important step since some ASAs are aggregate- and/or asphalt binder-specific; thus, they may not be effective in all mixes, and in some cases, they could even be detrimental. Thus, a proper study of the mix should be done by systematically testing the mix for moisture susceptibility using several laboratory tests such as indirect tension testing (ITS) and the boiling test. ITS tests for moisture susceptibility are generally conducted on mixes with 7 ± 1 percent air voids (Hunter and Ksaibati 2005).

The mechanisms through which these ASAs work are different from each other. The liquid ASAs work by reducing the surface tension between the aggregate surface and the asphalt binder. The adhesion of the binder to the aggregate surface is enhanced when surface tension is reduced, which is why these materials are called surfactants (Putman and Amirkhanian 2006).

There are many factors and issues that affect moisture damage in a typical hot mix asphalt (HMA) mixtures including:

- Aggregate type,
- Binder type,
- Binder grade (PG 64-22 vs PG 76-22),
- Gradation of the aggregate,
- Air voids of the field mix,
- Traffic level,
- Environmental issues (e.g., rain, freeze-thaw cycles, etc.),
- Additives used, and
- Effective, or lack of effective, pavement drainage system.

Usually aggregates are identified as being the main cause of stripping; however, it is important to mention that moisture damage tends to be highly dependent on the characteristics of aggregate and binder interactions. An aggregate source mixed with one binder source might exhibit major signs of stripping; however, combined with another binder source, it may produce an acceptable performance. This makes identifying and preventing moisture damage in many asphalt mixtures difficult and complicated.

In many cases, moisture damage can occur early and be severe, which reduces the life of a flexible pavement and causes a major cost to the state agency. In some cases, state agencies will mill a stripped pavement and place an overlay; however, this might not be the correct solution since moisture damage often occurs from the bottom of the pavement upward, compromising the entire pavement structure. One of the most effective ways in preventing moisture damage in pavements is ensuring the proper design and construction of an effective drainage system. In addition, it is very important to have a preservation program to maintain the drainage system through the life of the pavement. Since it is not possible to prevent HMA pavements from being exposed to water, anti-strip additives are often used in helping to improve the performance of the mixtures.

As in many other states around the country, hydrated lime has been used successfully in South Carolina as an ASA for many years and has a proven track record for increasing asphalt mixture resistance to moisture susceptibility. Over the past several decades, manufacturers of liquid ASAs have improved the performance of the products as well as the temperature stability during the asphalt mixing process. For the last decade or so, the utilization of liquid ASAs has gained popularity due to advancements in available liquid ASAs as well as their relatively low cost and ease of application. Thus, it is important to investigate the performance of these improved liquid ASAs in various typical SCDOT mid- to high-traffic volume mixtures made with PG 64-22 asphalt binders to determine the compatibility of liquid ASAs with these mixtures.

Many research projects have indicated that a stripped pavement will not fail unless the pavement structure has pronounced flexibility, and the damage will be minimal if stripping is restricted to the coarse aggregate. However, several researchers have concluded that if there is evidence of fine aggregate stripping, severe damage will result. The main reason for this conclusion is because the fine aggregate constitutes the basic matrix of the mixture. In many cases, researchers have concluded that if a stripped asphaltic mixture is exposed to a dry environment, the stripping process is reversed and the mixture will heal itself; however, the failure of a stripped pavement due to traffic is not reversible.

1.1 Summary

Anti-strip additives could be divided into two broad categories: (a) hydrated lime Ca(OH)2 and (b) liquid anti-stripping additives (ASAs). Hydrated lime is quicklime that has been hydrated with water and finally pulverized. It is important to note that when producing hot mix asphalt (HMA) mixtures, only hydrated lime should be used and not agricultural lime, which is powdered calcium carbonate. Agricultural lime is not effective as an anti-strip agent. There are various effective methods of adding hydrated lime to HMA at the plant. Many state departments of transportation (DOTs) specify a lime solution to be sprayed on the aggregate. Some contractors “marinate” aggregate stockpiles in a lime slurry. In many states, the hydrated lime is added to the aggregate on the cold feed belt. Research has shown that it is more effective if the aggregate is coated with the hydrated lime prior to mixing with the asphalt binder. There are many different types of liquid ASAs available on the market. Most of these liquid ASAs are surfactants. In some states, liquid ASAs are added to the asphalt binder at the terminal prior to delivery to the hot mix plant. In other states, properly-equipped contractors are allowed to add liquid ASA to the HMA during mixing.

Although the SCDOT has been utilizing hydrated lime for many years in their HMA mixtures, there are many new liquid ASAs in the market that are proven to be effective in minimizing the moisture susceptibility of HMA mixtures. Therefore, the SCDOT has chosen to investigate the effects of various liquid ASAs and hydrated lime on several high-traffic volume mixture types typically used in South Carolina. In addition, various dosage rates for the liquid ASAs included in this project are examined to determine recommended dosage rates.

Chapter 2: Scope of the Research Project

2.1 Research Objectives

There were several objectives of this study. The main objectives of this proposed research project were to a) evaluate the use of liquid anti-strip additives (ASAs) in high-volume PG 64-22 asphalt mixtures typically used in various parts of the state; and b) determine the recommended dosage rate of the liquid ASAs in various mixtures. A secondary objective included a comparison of the laboratory performance of these liquid ASA mixtures to the laboratory performance of mixtures containing hydrated lime with respect to moisture susceptibility.

The following sections describe the details of each of the objectives of this project.

2.2 Evaluation of Liquid ASAs in High-Volume Mixtures

The first main objective was to determine the moisture susceptibility of laboratory-prepared PG 64-22 mixtures containing liquid ASAs used in mixture types designated for high-traffic volume pavements in South Carolina. Based on recommendations from the South Carolina Department of Transportation (SCDOT) Steering Committee, the following materials were evaluated for this portion of the project: one PG 64-22 asphalt binder source (Associated Asphalt Inman), five aggregate sources, five reclaimed asphalt pavement (RAP) sources corresponding to the five aggregate sources (% RAP from existing mix designs used), and five liquid ASAs (MeadWestVaco Evotherm 3G (M1-J1) and MorLife 5000; ArrMaz 7700 and LOF6500 with CecaBase 945; and a Zydex product). All mixtures contained a typical amount of RAP used in SCDOT mixtures (% RAP from each respective job mix formula) and were tested for performance properties. The specific tasks for this portion of the research project included the following:

1. Conducting an extensive literature review on the topic of anti-strip additives used in high-traffic volume PG 64-22 asphalt mixtures;
2. Conducting gyratory mix designs (or using existing applicable mix designs provided by SCDOT) for each aggregate source containing hydrated lime and the typical percentages of RAP used in the field;
3. Determining the optimum asphalt binder content and volumetric properties (air voids, VMA, VFA, dust/asphalt ratio, etc.) of each mixture; and
4. Investigating the effects of various liquid ASAs on the moisture susceptibility of various mixtures made at optimum asphalt binder content through the performance of indirect tensile strength (ITS) and boil test procedures (SC-T-70 and SC-T-69, respectively).

Input was sought from the Steering Committee to determine which material sources and performance characteristics would be used in this portion of the study. The testing tasks for this portion of the project were performed concurrently with the literature review.

2.3 Optimization of Dosage Rate for Liquid ASAs

The second main objective of this project was to determine recommended dosage rates for the selected liquid ASAs tested in this research project. All mixtures contained a typical amount of RAP used in SCDOT mixtures (% RAP from each respective job mix formula). The specific tasks for this portion of the research project included the following:

1. Conducting an extensive literature review on the dosage rate of various liquid ASAs used throughout the country;
2. Utilizing the existing dosage rate specified by SCDOT for liquid ASAs to evaluate the moisture susceptibility of all mixtures;
3. Utilizing the manufacturer's recommended dosage rate for liquid ASAs to evaluate the moisture susceptibility of all mixtures;
4. Comparing the results obtained from tasks 2 and 3; and
5. Developing recommendations for SCDOT regarding the minimum dosage rates for various liquid ASAs to be used in PG 64-22 mixtures.

Input was sought from the Steering Committee to determine which material sources would be used in this portion of the study. The testing tasks for this portion of the project were performed concurrently with the literature review.

2.4 Comparison of Mixtures Containing Hydrated Lime to Liquid ASAs

A secondary objective of this project was to evaluate the performance characteristics of liquid ASAs in PG 64-22 high-volume mixtures compared to the performance of mixes containing hydrated lime with respect to moisture susceptibility. The following materials were evaluated for this portion of the project: one PG 64-22 asphalt binder source, five aggregate sources, five reclaimed asphalt pavement (RAP) sources corresponding to the five aggregate sources (% RAP from existing mix designs used), one hydrated lime source, and five liquid ASAs (MeadWestVaco Evotherm 3G (M1-J1) and MorLife 5000; ArrMaz 7700 and LOF6500 with CecaBase 945; and a Zydex product). The specific tasks for this portion of the research project included the following:

1. Conducting an extensive literature review on the use of hydrated lime in asphalt pavement layers;
2. Utilizing existing mix designs containing hydrated lime provided by SCDOT officials and conducting additional mix designs for any mix designs that were not available for the selected aggregate sources; and
3. Comparing the moisture susceptibility results of mixtures made with various liquid ASAs to mixtures made with hydrated lime through the performance of indirect tensile strength (ITS) and boil test procedures (SC-T-70 and SC-T-69, respectively).

Input was sought from the Steering Committee to determine which mix designs would be utilized for this portion of the research project. The testing tasks for this portion of the project were performed concurrently with the literature review.

2.5 Organization of the Report

The first chapter of this report contains the introduction. Chapter 2 describes the objectives of the project and organization of this report. The literature review of this subject matter is included in Chapter 3. Chapter 4 contains the experimental design and the materials used. The data and results of the research have been summarized in Chapter 5. Chapter 6 contains the summary, conclusions and the recommendations for this research project.

Chapter 3: Literature Review

A comprehensive literature review was conducted to investigate the concept and mechanism of stripping in asphaltic concrete mixtures.

3.1 Background: Moisture Susceptibility of Asphalt Mixtures

Moisture damage, caused by a loss of bond between the asphalt binder, or the mastic, and the aggregate under traffic loading, can cause a decrease of strength and durability in asphalt mixtures. Moisture damage is relatively prone to causing the separation and removal of asphalt binder from the aggregate surface, thus leading to stripping in the asphalt pavement and ultimately causing premature failure. Stripping can progress from either the top or bottom of an asphalt pavement layer. The common cause in all cases of stripping is the presence of water. The potential for asphalt pavement moisture damage can be controlled or reduced through material selection; utilization of mixture designs that include a high asphalt film thickness; inclusion of anti-stripping additives; and proper pavement design, construction, compaction, and drainage.

Researchers identified six contributing mechanisms that might produce moisture damage: detachment, displacement, spontaneous emulsification, pore pressure-induced damage, hydraulic scour, and the effects of the environment on the aggregate-asphalt system (Taylor and Khosla 1983, Kiggundu and Roberts 1988, Terrel and Al-Swailmi 1994). However, it is apparent that moisture damage is usually not limited to one mechanism but is the result of a combination of many processes. From a chemical standpoint, the literature is clear that although neither asphalt nor aggregate has a net charge, components of both have non-uniform charge distributions, and both behave as if they have charges that attract the opposite charge of the other material (Curtis et al., 1992, Robertson, 2000, Little et al. 1999).

Moisture susceptibility is a complex phenomenon dependent upon the mechanisms of asphalt binder and aggregate. The nature of these mechanisms and their interaction makes it difficult to predict with certainty the characteristics of various factors in determining moisture susceptibility. In general, moisture susceptibility is increased by any factor that increases moisture content in the asphalt pavement, decreases the adhesion of asphalt binder to the aggregate surface or physically scours the asphalt binder.

There are many treatments to improve the moisture sensitivity of asphalt mixtures. These treatments can be simply grouped into those that are added to the binder and those that are added to the aggregate. The most common chemicals used to reduce moisture sensitivity are alkyl amines, which are generally added to the binder, and hydrated lime, which is added to the aggregates. The results indicate that both liquid anti-stripping additives (ASAs) and hydrated lime can decrease the moisture sensitivity of asphalt mixtures. In addition, those ASAs can also influence pavement behaviors such as rutting, fatigue, raveling and so forth (Pickering et al. 1992, Aschenbrener and Far 1994, Khosla, et al. 2000, Tohme et al. 2004, Sebaaly et al. 2007).

3.2 Background: Anti-Stripping Additives in Asphalt Mixtures

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

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

With the advent of new liquid ASAs in the market, which are both low cost and relatively easy to use, the utilization of liquid ASAs is gaining popularity. The mechanism through which liquid ASAs work is by reducing the surface tension between the aggregate and the asphalt binder. When surface tension is reduced, it promotes increased adhesion of the binder to the aggregate. For this reason, liquid ASAs are also called surfactants.

Liquid ASAs are normally added in doses between 0.5 and 1.5% by weight of the binder (as recommended by the manufacturer). The liquid ASA may be added either to the aggregate or to the heated binder. Both of these procedures have certain disadvantages. If added directly to the aggregate, uniform coating of all of the aggregates is not ensured due to such a small quantity of the ASA. If added to the heated binder, care should be taken to ensure that the liquid ASA is heat stable and will not disintegrate at such high temperatures.

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

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

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

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

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

A study by Arr-Maz (Lavin) indicated that all liquid ASA mixtures and hydrated lime mixtures met the TSR criteria except for a Missouri dolomite mixture with amidoamine at the 0.25 and 0.5 percent dosage level. Also the results showed that the optimum dosage of these liquid ASAs was 0.25 percent by weight of the asphalt cement.

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

1. In the case of thermal cracking, both hydrated lime and liquid additives improved the fracture temperature of the HMA mixtures from all five sources. However, the lime-treated mixtures showed significantly higher fracture stresses for all sources. This

indicates that if thermal cracking occurs, the lime-treated mixtures will have significantly fewer cracks per mile than the non-treated and liquid-treated mixtures. Fewer cracks per mile translates directly into lower maintenance cost and time for repair.

2. Lime either maintained or improved the fatigue resistance of four out of the five types of HMA mixtures. On the other hand, the impact of the liquid additives on the fatigue resistance of the HMA mixtures was source-dependent and very inconsistent. In most cases, the liquid additive resulted in a significant change in the slope of the fatigue curve of the mix indicating an unbalanced impact on the low- and high-strain regions. This behavior contributed to the poor performance of the liquid-treated mixtures in the MEPDG fully mechanistic structural design.
3. Lime either maintained or improved the rutting resistance of the HMA mixtures from all five sources. The impact of liquid additives on the rutting resistance of the HMA mixtures was source dependent; for the non-moisture sensitive mixtures from Alabama and Illinois, the liquid additives reduced their rutting resistance compared to the non-treated mixtures.
4. The life cycle cost data for new construction projects revealed that the use of lime in HMA mixtures resulted in significant savings, which in some cases were more than 45%. The use of liquid additives in HMA mixtures may result in additional cost, which in some cases could be as high as 50%. The data generated on the four mixtures from Alabama, California, Illinois, and South Carolina show that lime is highly compatible with asphalt binders and will generally result in life cycle cost savings in the order of 13-34%.

The study completed by Sathanathan (2010) indicated that the cost analysis data revealed the following:

1. The use of lime additives in HMA mixtures resulted in significant savings, in some cases more than 45%.
2. The use of liquid additives in HMA mixtures may result in additional cost, in some cases as high as 50%.
3. The data generated on the four mixtures from Alabama, California, Illinois, and South Carolina show that lime is highly compatible with the use of neat asphalt binders and resulted in savings on the order of 13-34%.
4. The data generated on the mixtures from Texas show that the lime is highly compatible with the use of polymer-modified binders and can result in savings on the order of 40-45%, which is significantly higher than the savings that could be realized with the use of liquid additives.
5. The data showed that the use of hydrated lime additives always improved the performance of the HMA pavement to a magnitude that always far outweighed its cost. On the other hand, the use of liquid additives did not always improve the pavement performance to the magnitude that it would offset its cost.
6. The cost analysis data showed that the use of lime in HMA mixtures that do not require improvement in their mix design TSR can still result in significant savings, such as in the cases of the mixtures from Alabama and Illinois. On the other hand, the

use of liquid ASAs in HMA mixtures that do not require improvement in their mix design TSR can result in significant cost increases, such as in the cases of the mixtures from Alabama and Illinois.

Liquid ASAs have been shown to generally satisfy the demands if proper care is given to their selection and application. Many tests showed that the use of liquid ASAs is less cost-effective on low-volume and dry-environment pavements. The ITS test has proved to be a potentially valuable tool for district-level labs because it does not need complex equipment or a strict environment (Sebaaly et al. 2007, Putman and Amirkhanian 2006).

Chapter 4: Experimental Design, Materials, and Testing

For cases in which an applicable mix design was available from SCDOT, those existing mix designs were used. For all other cases, a gyratory mix design was performed. Mix designs were performed according to SCDOT specifications utilizing one PG 64-22 asphalt binder source, five aggregate sources, five reclaimed asphalt pavement (RAP) sources corresponding to the five aggregate sources (% RAP from existing mix designs used), and one hydrated lime source. The mixtures containing hydrated lime were considered the control mixtures; thus, the same gradation and optimum binder content in each hydrated lime mixture was used with the five liquid anti-stripping additive (ASA) sources. All material sources and contents were selected based upon input from the Steering Committee. The detailed information is shown in Figure 4-1.

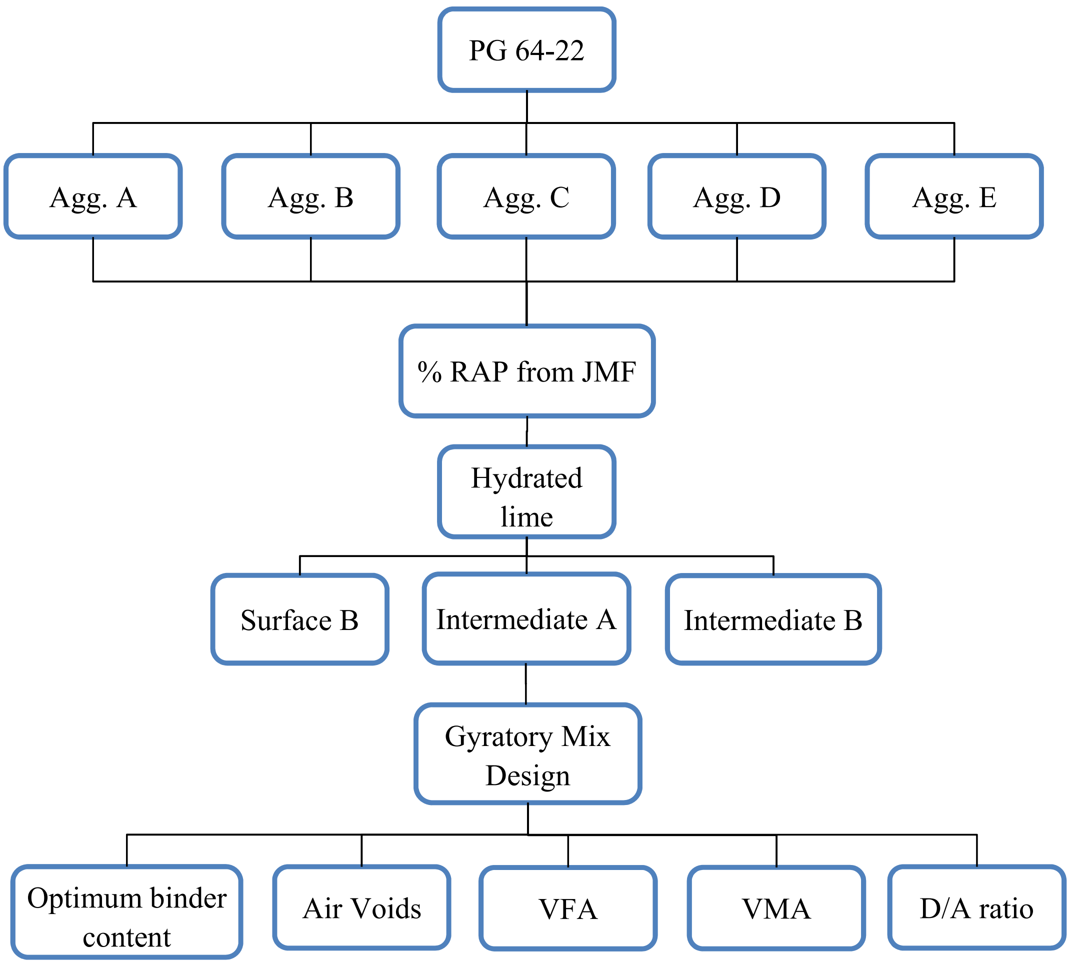


Figure 4-1 Gyratory Mix Design of Various Aggregate Sources and Surface Types

4.1 Liquid ASAs: Performance Testing

The moisture characteristics of various mixtures were investigated in this study. The main test methods used were indirect tensile strength (ITS) test and boiling water test according to the specifications set by SC-T-70 (Laboratory Determination of Moisture Susceptibility based on Retained Strength of Asphalt Concrete Mixture) and SC-T-69 (Method of Determining the Effectiveness of Anti-Stripping Additives in Hot Asphalt Mixtures), respectively. The detailed information is shown in Figure 4-2.

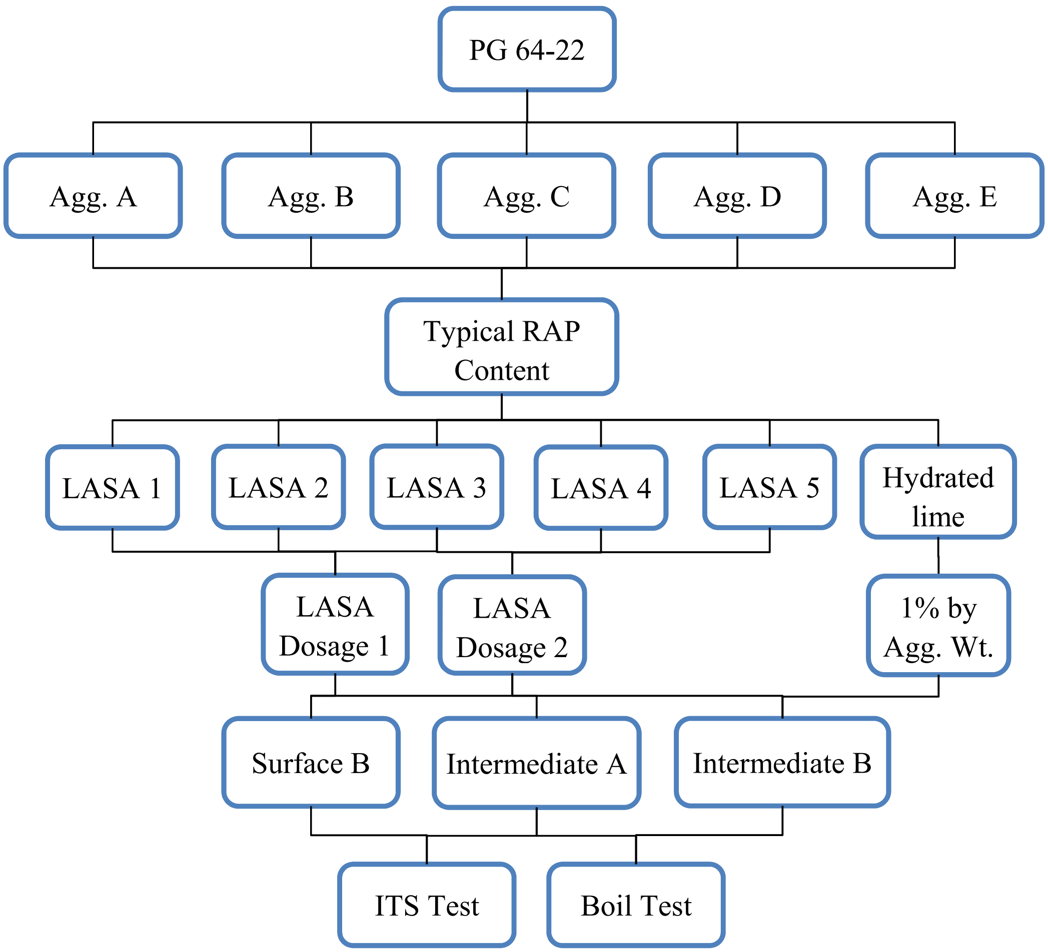


Figure 4-2 Moisture Susceptibility Testing of Various Aggregate Sources, ASAs, Mixture Types, and Liquid ASA Dosage Concentrations

4.2 Aggregate Sources and Properties

To achieve the objectives of this research, the Steering Committee recommended the selection of five different aggregate sources throughout South Carolina. In addition, the researchers added one more aggregate source to this study. Thus, a total of six aggregate sources, referred to as aggregate sources A through F in this report, were utilized to conduct this research work. The aggregate sources selected are all typically utilized for producing asphalt mixtures in South Carolina and are from various regions around the state. The characteristics and physical properties of these aggregate sources satisfy the requirements of the SCDOT specifications. Figure 4-3 shows the geographic locations of these aggregate quarries in South Carolina.

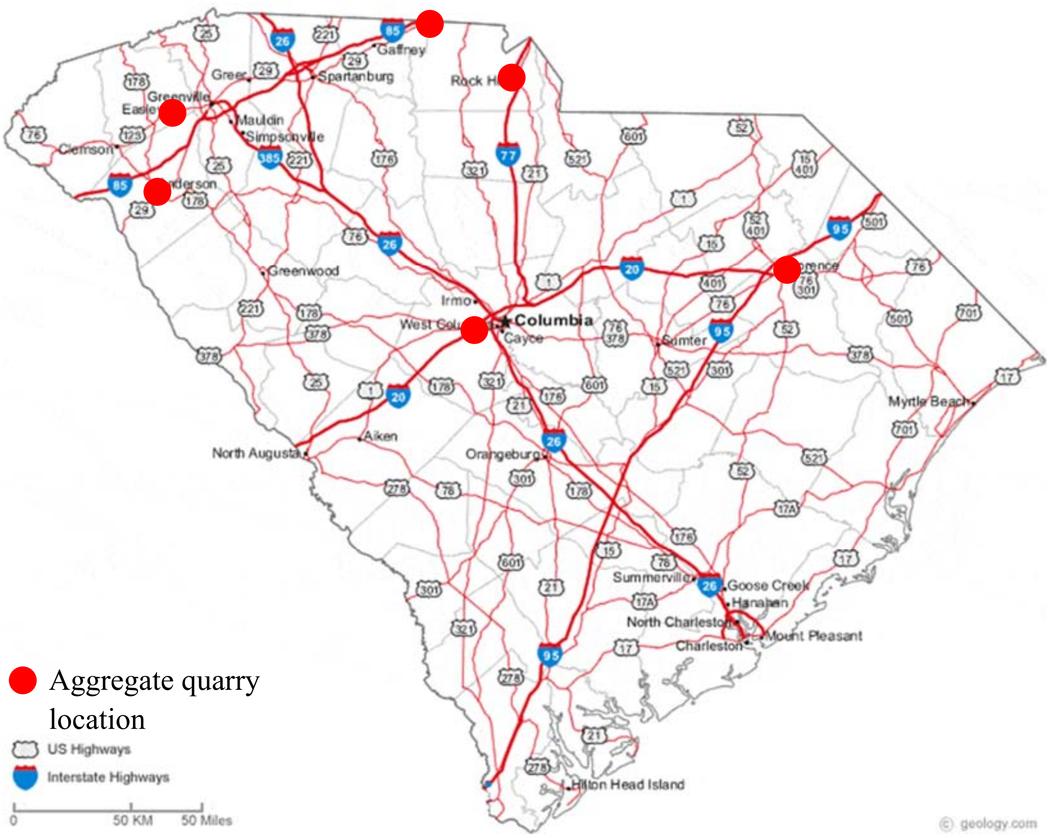


Figure 4-3 Geographical Locations of Various Aggregate Quarries in South Carolina

The basic physical and engineering properties of these aggregate sources are shown in Table 4-1. For coarse aggregate size fractions, the properties shown include Los Angeles (LA) abrasion loss percentage, percent absorption, various specific gravities, soundness loss percentage, and sand equivalency. For fine aggregate size fractions, the properties shown include fineness modulus, percent absorption, bulk specific gravity at saturated surface dry (SSD) condition, and soundness loss percentage.

Table 4-1 Physical Properties of Coarse and Fine Aggregates Utilized in This Study

Coarse Aggregate	LA Abrasion Loss (%)	Absorption (%)	Specific Gravity			Soundness % Loss at 5 Cycles			Sand Equivalent
			Dry (Bulk)	SSD (Bulk)	Apparent	1 to 3/4	3/4 to 3/8	3/8 to #4	
A	51.6	0.64	2.770	2.790	2.820	0.4	0.3	0.6	81
B	33.7	0.68	2.590	2.610	2.640	0.7	1.3	1.6	70
C	24.7	0.44	2.610	2.620	2.640	0.2	1.6	0.8	64
D	47.7	0.68	2.752	2.770	2.800	0.5	0.4	0.6	57
E	54.7	0.76	2.630	2.650	2.680	0.8	0.6	0.6	71
F	29.6	0.57	2.680	2.700	2.700	0.6	1.4	0.5	56

Fine Aggregate	Fineness Modulus	Absorption (%)	SSD (Bulk)	Soundness % Loss
A	2.23	0.50	2.775	4.5
B	2.60	0.90	2.630	1.0
C	2.84	0.30	2.640	0.6
D	2.94	0.40	2.640	0.6
E	2.60	0.10	2.681	2.1
F	2.63	0.80	2.704	1.3

Notes: A-F ~ aggregate source; LA ~ Los Angles; SSD ~ Saturated surface dry

As can be seen in Table 4-1, these aggregate sources generally have different physical properties that can affect the performance of asphalt mixtures.

4.3 Asphalt Binder

For this research project, the following SCDOT mixture types were used: Surface Type B, Intermediate Type A and Intermediate Type B. Based on recommendations from the Steering Committee, PG 64-22 from the Associated Asphalt Inman terminal was utilized to produce the asphalt mixtures in this study because it is a typical binder source used for non-interstate pavements in SC. The rheological properties of the PG 64-22 binder from this study are shown in Table 4-2.

4.4 Anti-Stripping Additives

Six anti-stripping additives (ASAs) were used in this research project based on the recommendations from the project's Steering Committee. Hydrated lime is the ASA typically used to prevent moisture susceptibility in South Carolina's mixtures. Liquid ASAs have not typically been used in SCDOT's mixtures in many parts of the state. However, the five liquid ASAs selected for this project have been used around the country, and some have been utilized in South Carolina in lower-volume pavements. The basic physical and chemical properties of these ASAs are shown in Table 4-3.

4.5 Sample Preparation and Testing

To control the moisture-induced damage of some asphalt pavements, ASAs are added to improve the bond strength between asphalt binder and aggregate. In this study, some existing job mix formulas (JMFs) were followed to prepare the mixtures in the lab. These JMFs, provided and approved by the Steering Committee, are currently utilized in various asphalt plants around South Carolina to produce the field mixtures. All aggregate and RAP sources used in this project were obtained from the respective quarries and asphalt plants from each JMF.

As recommended by the manufacturers, all liquid ASAs were mixed with asphalt binders at a proper temperature (typical mixing temperature of 310 °F – 315 °F) for 3 – 5 minutes to achieve a homogenous state before being blended with the aggregates. Two dosage rates of each liquid ASA were utilized to produce the asphalt mixtures (Table 4-4). The current dosage rate from SCDOT's specifications (0.7% by binder weight) was used as one dosage rate for all liquid ASA sources. The recommended dosage rate from each liquid ASA supplier was then utilized as the second dosage rate for each source.

The heated aggregate materials were blended with asphalt binder containing the appropriate liquid ASA to fabricate both the indirect tensile strength (ITS) samples and boiling test samples according to specifications set forth by SCDOT.

Table 4-2 Rheological Properties of PG 64-22 Binder

Binder type	Source	Aging states						
		Unaged	Unaged		RTFO	PAV		
		Viscosity (135°C)	Fail temp.	G*/sinδ (64°C)	G*/sinδ (64°C)	G*sinδ (25°C)	Stiffness (-12°C)	m-value (-12°C)
		(cP)	(°C)	(kPa)	(kPa)	(kPa)	(MPa)	
PG 64-22	Venezuela	645	68.8	2.03	4.94	1429	103	0.376

Table 4-3 Physical and Chemical Properties of Anti-Stripping Additives

Properties	Liquid ASA I	Lime	Liquid ASA II	Liquid ASA III	Liquid ASA IV	Liquid ASA V
Ingredients	Fatty amidoamine	Calcium Hydroxide $Ca(OH)_2$	Modified Fatty amidoamine	Alkylamines; Alkanol amines; Alkylene amines	Fatty amine derivatives	hydroxyalkyl-alkoxy-alkysilyl Benzyl Alcohol Ethylene Glycol
Physical state	Liquid	Powder	Liquid	Liquid	Viscous Liquid	Liquid
Color	Dark brown	White	Brown	Brown	Amber. (Dark)	Pale yellow
Odor	Mild	Odourless	Ammonia like odor	Flishy	Fishy, Amine-like	-
Molecular weight	-	-		-	-	-
Specific Gravity	0.96-0.98	2.3-2.6		-	1.03-1.08	1.015-1.03
Vapor density	>1	-	>1	4.6 (Air = 1)	-	-
Bulk density	-	-	0.94-0.99	1.09	-	-
Ph values	-	-	Alkaline	11.9	10-12	10% solution in water neutral
Boiling Point	-	2850C (CaO)	>150C	255C	>200C	-
Flashpoint	>300F	-	-	Closed cup: 165C	>204C	>80C
Viscosity	300 cps (100F)	-	-		127 cps (77F)	1-50 cps
Solubility in water	Slight	Negligible 0.185-0.070%	-	-	0.02 g/l	Water dispersible

Notes: ASA ~ anti-stripping additive; I-V ~ ASA type

Table 4-4 Dosage Rates of ASAs in Asphalt Mixtures

	ASA (% by weight of the binder)					
	I	Lime	II	III	IV	V
Dosage 1	0.5	1.0*	0.5	0.4	0.5	0.07
Dosage 2	0.7	1.0*	0.7	0.7	0.7	0.7

Notes: * ~ percentage of total aggregate

The ITS and boiling test samples were prepared based on the Superpave mix designs provided by the Steering Committee that had been completed by asphalt contractors and approved by SCDOT. For the Surface Type B mixtures, the gradations of the various mixtures made from aggregate sources A-F are shown in Table 4-5 and Figure 4-4 Gradations of Various Surface Type B Mixtures. It can be noted that the gradations of all of the Surface Type B mixtures met SCDOT specifications. Many of the mixtures made and tested in this research project had similar gradations; therefore, this may have reduced the effect of aggregate gradation on the ITS and boiling test results.

Table 4-5 Superpave Mix Design Gradations of Various Surface Type B Mixtures

Surface Type B		12.5 mm 1/2"	9.5 mm 3/8"	4.75 mm #4	2.36 mm #8	0.60 mm #30	0.150 mm #100	0.075 mm #200
	Upper range	100.0	100.0	75.0	56.0	36.0	18.0	8.0
	Lower range	97.0	76.0	52.0	36.0	16.0	5.0	2.0
Agg. A	100	99.0	92.0	65.0	49.0	31.0	11.0	6.0
Agg. B	100	99.0	88.0	66.0	48.0	24.0	9.0	4.0
Agg. C	100	98.0	93.0	68.0	50.0	27.0	10.0	4.0
Agg. D	100	98.0	91.0	63.0	47.0	23.0	8.0	4.0
Agg. E	100	99.0	93.0	60.0	42.0	27.0	10.0	4.0
Agg. F	100	99.0	94.0	70.0	51.0	27.0	9.0	5.0

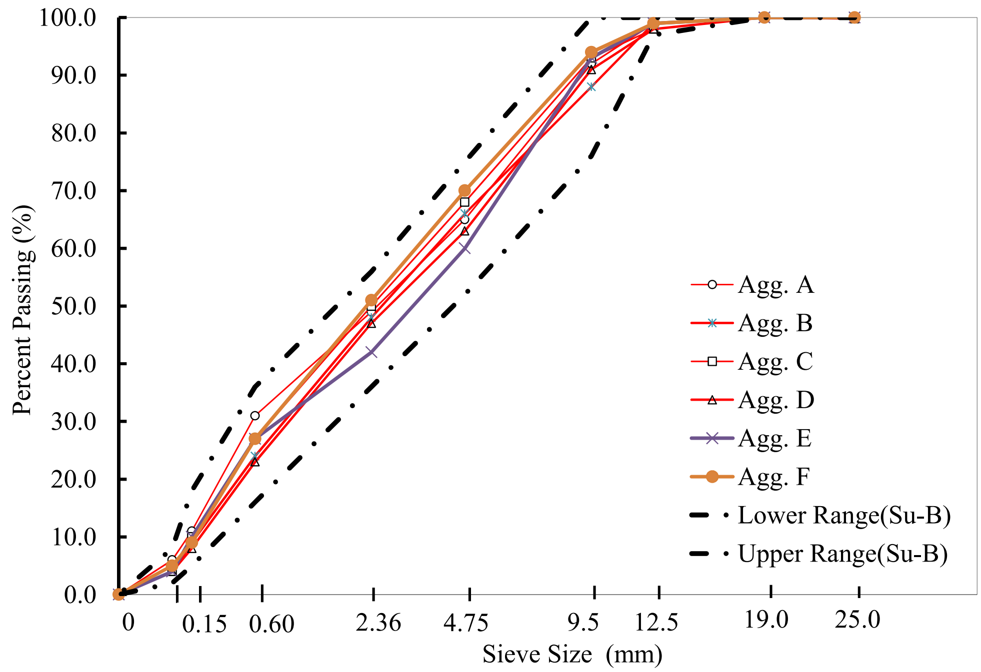


Figure 4-4 Gradations of Various Surface Type B Mixtures

Similarly, as shown in Table 4-6, Table 4-7, Figure 4-5 and Figure 4-6, the gradations of Intermediate Types A and B from various aggregate sources also satisfied SCDOT specifications and were generally similar to one another.

Table 4-6 Superpave Mix Design Gradations of Various Intermediate Type A Mixtures

Int. Type A		19.0 mm 3/4"	12.5 mm 1/2"	9.5 mm 3/8"	4.75 mm #4	2.36 mm #8	0.60 mm #30	0.150 mm #100	0.075 mm #200
	Upper range	100.0	90.0	80.0	54.0	36.0	22.0	10.0	8.0
	Lower range	90.0	75.0	64.0	38.0	22.0	8.0	3.0	2.0
Agg. A	100	99.0	85.0	73.0	42.0	29.0	17.0	7.0	4.0
Agg. B	100	97.0	83.0	71.0	45.0	30.0	16.0	7.0	4.0
Agg. C	100	97.0	83.0	73.0	46.0	30.0	16.0	7.0	4.0
Agg. D	100	98.0	86.0	73.0	47.0	31.0	15.0	6.0	4.0
Agg. E	100	98.0	82.0	73.0	43.0	30.0	20.0	7.7	3.7
Agg. F	100	98.0	87.0	77.0	50.0	33.0	17.0	7.0	4.0

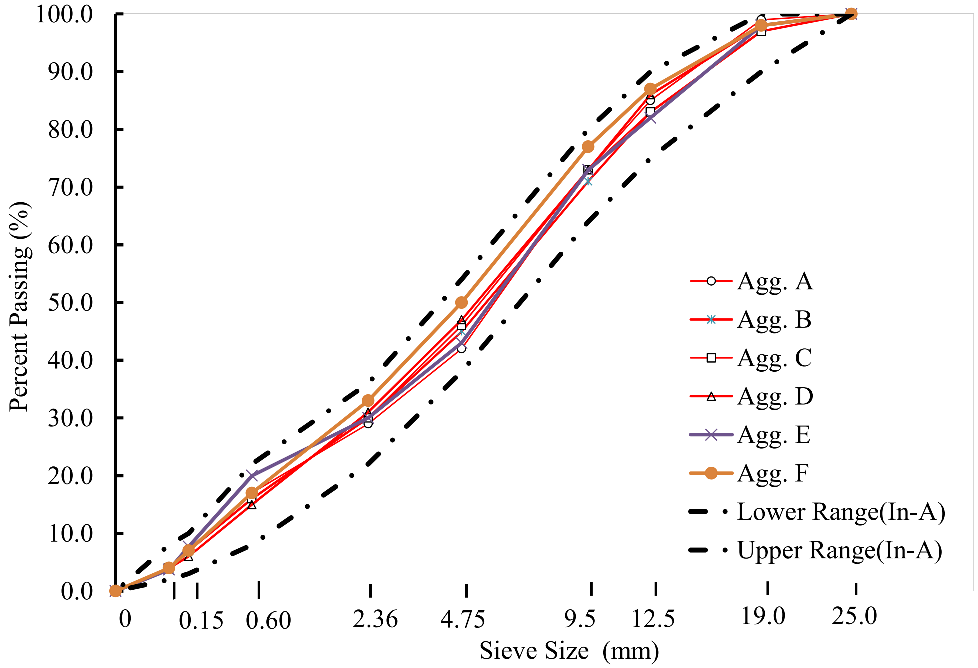


Figure 4-5 Gradations of various Intermediate Type A mixtures

Table 4-7 Superpave Mix Design Gradations of Various Intermediate Type B Mixtures

Int. Type B		19.0 mm 3/4"	12.5 mm 1/2"	9.5 mm 3/8"	4.75 mm #4	2.36 mm #8	0.60 mm #30	0.150 mm #100	0.075 mm #200
	Upper range	100.0	100.0	90.0	62.0	43.0	25.0	12.0	8.0
	Lower range	98.0	90.0	72.0	44.0	23.0	10.0	4.0	2.0
Agg. A	100	100.0	99.0	85.0	53.0	37.0	20.0	9.0	5.0
Agg. B	100	99.0	94.0	81.0	53.0	36.0	20.0	8.0	4.0
Agg. C	100	100.0	97.0	83.0	51.0	32.0	18.0	8.0	4.0
Agg. D	100	99.0	92.0	83.0	57.0	40.0	20.0	8.0	4.0
Agg. E	100	100.0	96.0	82.0	48.0	34.0	20.0	8.0	4.0
Agg. F	100	99.0	92.0	83.0	56.0	38.0	21.0	6.0	4.0

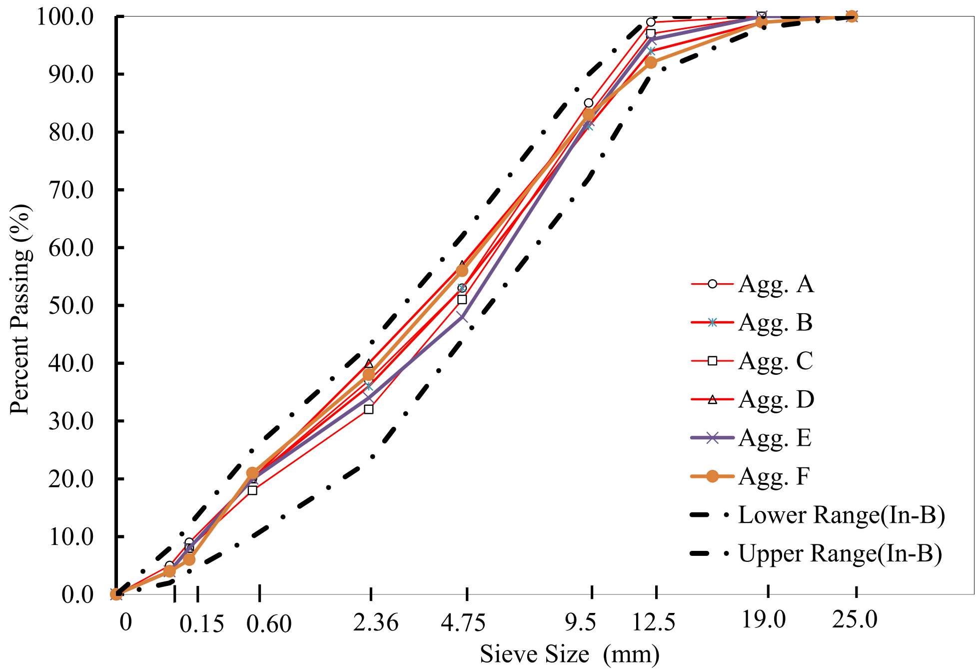


Figure 4-6 Gradations of various Intermediate Type B mixtures

In addition, the Superpave mix design volumetric information from aggregate sources A-F are shown in Table 4-8 to Table 4-10. These JMFs satisfied the requirements of SCDOT specifications for Surface Type B, Intermediate Type A and Intermediate Type B mixtures.

Table 4-8 Superpave Mix Design Volumetric Information of Various Surface Type B Mixtures

Surface B	Air voids (%)	OBC (%)	VMA (%)	VFA (%)	D/A ratio
	3.5-4.5		>14.5	70-78	0.6-1.2
Agg. A	3.66	5.5	16.51	77.86	1.05
Agg. B	4.17	5.8	17.33	75.92	0.84
Agg. C	3.52	5.3	15.62	77.32	1.02
Agg. D	3.97	4.8	14.93	73.43	1.05
Agg. E	3.65	5.5	16.30	77.60	0.83
Agg. F	4.13	5.12	16.24	74.59	1.18

Table 4-9 Superpave Mix Design Volumetric Information of Various Intermediate Type A Mixtures

Intermediate A	Air voids (%)	OBC (%)	VMA (%)	VFA (%)	D/A ratio
	3.5-4.5		>14.5	70-78	0.6-1.2
Agg. A	3.66	5.0	15.44	76.3	0.95
Agg. B	3.61	5.4	15.91	77.34	0.83
Agg. C	3.36	4.7	14.18	76.31	0.72
Agg. D	3.37	4.9	14.65	77.02	0.78
Agg. E	3.69	4.9	15.07	77.10	0.76
Agg. F	3.76	5.0	15.38	75.52	0.91

Table 4-10 Superpave Mix Design Volumetric Information of Various Intermediate Type B Mixtures

Intermediate B	Air voids (%)	OBC (%)	VMA (%)	VFA (%)	D/A ratio
	3.5-4.5		>14.5	70-78	0.6-1.2
Agg. A	3.48	4.7	14.65	76.26	0.82
Agg. B	3.70	5.5	16.35	77.35	0.85
Agg. C	3.43	5.0	14.91	77.02	0.81
Agg. D	3.69	4.7	14.54	74.59	1.02
Agg. E	3.58	5.0	15.17	76.40	0.78
Agg. F	3.58	5.2	15.74	77.25	0.97

In this project, all ITS and boiling test samples were made according to the SC-T-70 and SC-T-69 procedures, respectively. For the ITS samples, a proper mixture weight was calculated and used to prepare four gyratory-compacted specimens (150 mm diameter and 95 mm height) for each JMF. A compaction range of 295°F ± 5°F was used per SCDOT specifications regardless of mixture type and aggregate source. The gyratory compactor was used in “height mode” (height set to 95 mm), and the number of gyrations for the ITS samples generally fell in the range of 15 to 45 gyrations.

For the ITS testing, two samples from each set were tested in the dry condition, and the other two were tested after wet conditioning as per the SCDOT procedure, “SC-T-70: Laboratory Determination of Moisture Susceptibility based on Retained Strength of Asphalt Concrete

Mixture". The obtained ITS and tensile strength ratio (TSR) values were used to identify the possibility of moisture damage for various mixtures in terms of aggregate and ASA type.

For the boiling test samples, an aggregate sample weight of 1,500 g was used to produce each sample. In addition, the optimum binder content from the appropriate JMF was utilized for each sample. Boiling tests were then performed according to the SCDOT procedure, "SC-T-69: Method of Determining the Effectiveness of Anti-Stripping Additives in Hot Asphalt Mixtures".

Chapter 5: Data Analysis and Results

5.1 Effect of Aggregate Source on ITS Values

5.1.1 Surface Type B Mixtures

5.1.1.1 Liquid ASA I

To explore the effects of aggregate source on indirect tensile strength (ITS) value, the ITS values of various mixtures using the same ASA type are discussed in this section. The dry and wet indirect tensile strength (ITS) results for Surface Type B mixtures containing liquid anti-stripping additive (ASA) I and aggregate sources A-F are summarized in Figure 5-1. It should be noted that all ITS values were greater than 448 kPa (65 psi), the minimum value for moisture susceptibility according to SCDOT (2007 Standard Specifications section 401.2.3.4), regardless of dosage and aggregate source. In addition, the dry and wet ITS values of mixtures from aggregate E were generally the lowest, followed by the mixtures from aggregate A. As expected, the dry ITS values were higher than the wet ITS values in most cases. Moreover, there were some differences in wet ITS values when different percentages of liquid ASA I were used. In most cases, wet ITS values were higher for the 0.7% dosage rate than for 0.5%. Although the dry ITS values were generally similar for both liquid ASA dosage rates, the dry ITS values for all sources except aggregate D were slightly higher for the 0.5% dosage than for 0.7%.

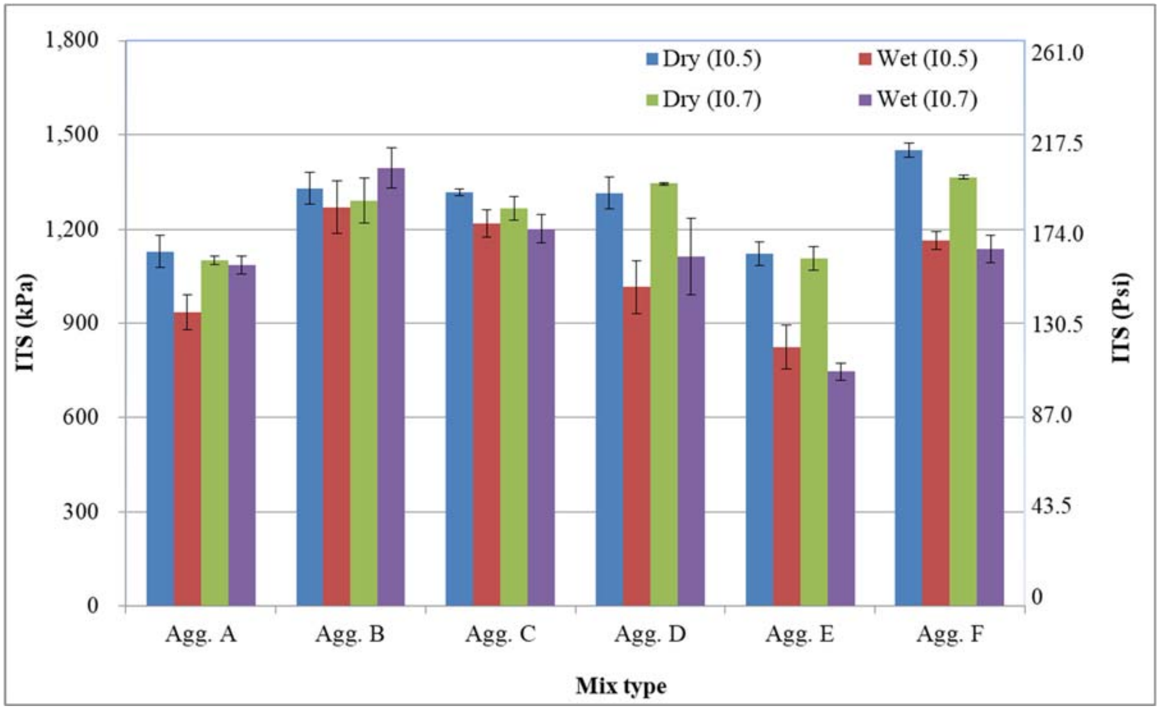


Figure 5-1 Dry and Wet ITS Values of Surface Type B Mixtures Containing Liquid ASA I and Various Aggregate Sources

As shown in Table 5-1 and Table 5-2, the analysis shows statistically-significant differences in the dry and wet ITS values of mixtures made with various aggregate sources. This implies that the aggregate source plays an important role in determining the bond strength between asphalt binder and aggregate during the moisture susceptibility testing procedures.

Table 5-1 ANOVA Analysis of Dry ITS Values from Surface Type B Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	8004.0	1334.0	21467.6
I 0.5	6	7666.6	1277.8	16353.2
I 0.7	6	7474.0	1245.7	13194.9
II 0.5	6	8017.7	1336.3	15681.2
II 0.7	6	7900.5	1316.7	12152.1
III 0.4	6	7373.7	1228.9	31580.9
III 0.7	6	7655.9	1276.0	43772.4
IV 0.5	6	8024.3	1337.4	43608.0
IV 0.7	6	7738.3	1289.7	17060.6
V 0.07	6	7915.4	1319.2	35834.5
V 0.7	6	7502.0	1250.3	21284.5
Agg. A	11	12913.3	1173.9	8464.3
Agg. B	11	15140.3	1376.4	5724.6
Agg. C	11	15741.9	1431.1	7786.6
Agg. D	11	14364.9	1305.9	3015.3
Agg. E	11	11830.3	1075.5	11796.3
Agg. F	11	15281.7	1389.2	1857.0

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	92779.58	10	9277.958	1.579704	0.140278	2.026143
Columns	1066288	5	213257.6	36.31013	1.63E-15	2.400409
Error	293661.3	50	5873.227			
Total	1452729	65				

Table 5-2 ANOVA Analysis of Wet ITS Values from Surface Type B Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	7614.6	1269.1	33506.3
I 0.5	6	6429.5	1071.6	30428.8
I 0.7	6	6680.4	1113.4	44855.7
II 0.5	6	7614.6	1269.1	33506.3
II 0.7	6	6704.0	1117.3	107976.2
III 0.4	6	6317.1	1052.8	56890.2
III 0.7	6	6837.7	1139.6	92989.4
IV 0.5	6	6606.7	1101.1	51320.2
IV 0.7	6	6606.7	1101.1	51320.2
V 0.07	6	6550.0	1091.7	121660.9
V 0.7	6	7028.3	1171.4	76783.2
Agg. A	11	10628.0	966.2	7021.2
Agg. B	11	14264.4	1296.8	15354.3
Agg. C	11	15039.2	1367.2	12220.6
Agg. D	11	12973.2	1179.4	20074.8
Agg. E	11	8463.9	769.4	43061.4
Agg. F	11	13621.0	1238.3	4375.3

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	318126.8	10	31812.68	2.262801	0.028453	2.026143
Columns	2803237	5	560647.4	39.87822	2.62E-16	2.400409
Error	702949.3	50	14058.99			
Total	3824313	65				

5.1.1.2 Hydrated Lime

In South Carolina asphalt mixtures containing hydrated lime, 1% hydrated lime (in slurry form) by weight of the total aggregate is required in producing the mixture. Figure 5-2 summarizes the dry and wet ITS values of Surface Type B mixtures containing hydrated lime and aggregate sources A-F. Similar to the results with liquid ASA I, it was found that the dry and wet ITS values of mixtures containing aggregates A and E were generally lower than the ITS values from the other aggregate sources. Additionally, all of the wet ITS values were still much higher than the minimum SCDOT requirement for moisture susceptibility (2007 Standard Specifications section 401.2.3.4) of 448 kPa (65 psi). In general, the wet ITS values were slightly lower than the dry ITS values. Similar to the results with liquid ASA I, Table 5-1 and Table 5-2 indicate that there were statistically-significant differences in the dry and wet ITS values of the mixtures made with various aggregate sources.

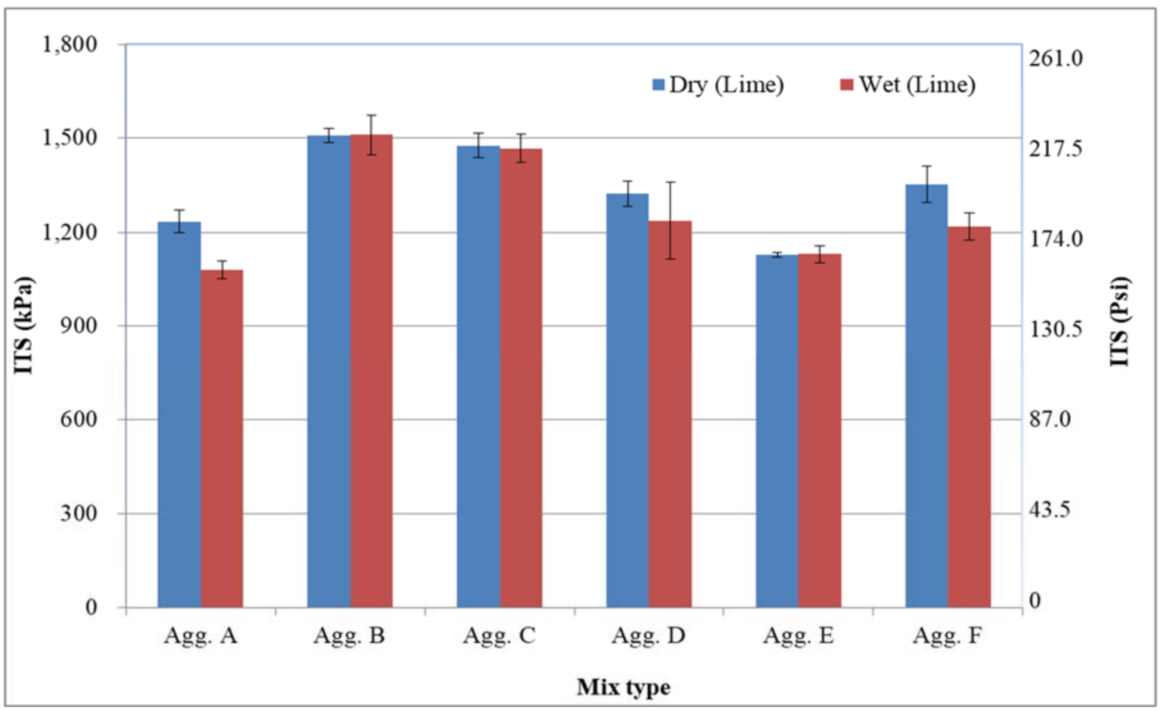


Figure 5-2 Dry and Wet ITS Values of Surface Type B Mixtures Containing Lime and Various Aggregate Sources

5.1.1.3 Other Liquid ASA Sources

The dry and wet ITS values of Surface Type B mixtures containing liquid ASAs II, III, IV, and V and made with aggregate sources A-F exhibited similar trends to those of the mixtures utilizing liquid ASA I, as shown in Appendix A. All dry and wet ITS values were greater than 448 kPa (65 psi) regardless of dosage rate and aggregate source, satisfying the requirements set forth by SCDOT. In general, the ITS values of mixtures from aggregate E were the lowest, followed by the mixtures from aggregate A. In addition, the statistical analysis shows significant differences between the ITS values of mixtures made with various aggregate sources (Table 5-1 and Table 5-2).

5.1.2 Intermediate Type A Mixtures

5.1.2.1 Liquid ASA I

As shown in Figure 5-3, the wet ITS values of Intermediate Type A mixtures containing aggregate sources A-F and liquid ASA I were all greater than 448 kPa (65 psi) regardless of the dosage rate. As with the Surface Type B mixtures, the ITS values of the Intermediate Type A mixtures containing aggregate E had the lowest wet ITS values; however, unlike the Surface B mixtures, the Intermediate Type A mixtures containing aggregate A generally produced the highest ITS values. Also similar to the Surface Type B mixtures, the Intermediate Type A mixtures exhibited slightly higher wet ITS values with the 0.7% dosage of liquid ASA I compared to the 0.5% dosage; however, unlike the Surface Type B mixtures, the Intermediate Type A mixtures exhibited slightly higher dry ITS values at the 0.7% dosage of liquid ASA I compared to the 0.5% dosage.

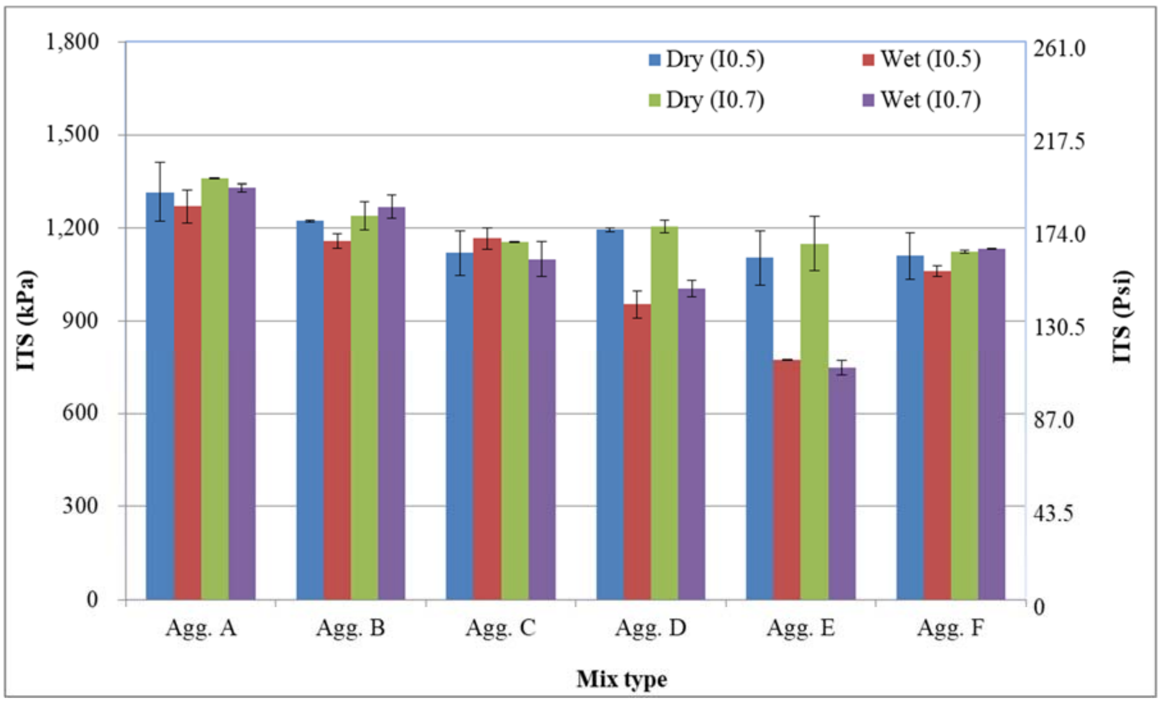


Figure 5-3 Dry and Wet ITS Values of Intermediate Type A Mixtures Containing Liquid ASA I and Various Aggregate Sources

In addition, the statistical analysis shown in Table 5-3 and Table 5-4 indicates that the ITS values of the mixtures from various aggregate sources were significantly different. This implies that the aggregate source plays an important role in determining the bond strength between asphalt binder and aggregate during the moisture susceptibility testing procedures.

Table 5-3 ANOVA Analysis of Dry ITS Values from Intermediate Type A Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	7295.4	1215.9	40041.7
I 0.5	6	7069.8	1178.3	6977.3
I 0.7	6	7235.7	1205.9	7379.8
II 0.5	6	7683.7	1280.6	19189.2
II 0.7	6	7050.4	1175.1	35858.5
III 0.4	6	6845.9	1141.0	15879.6
III 0.7	6	6787.2	1131.2	32785.8
IV 0.5	6	7151.8	1192.0	43364.9
IV 0.7	6	6876.3	1146.0	35510.4
V 0.07	6	7064.2	1177.4	34599.9
V 0.7	6	7171.7	1195.3	24365.3
Agg. A	11	15285.5	1389.6	5774.3
Agg. B	11	13110.6	1191.9	8112.9
Agg. C	11	14152.0	1286.5	9805.6
Agg. D	11	12910.5	1173.7	4851.3
Agg. E	11	10807.8	982.5	13004.6
Agg. F	11	11965.5	1087.8	3702.3

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	103437.5	10	10343.75	1.481603	0.17423	2.026143
Columns	1130688	5	226137.7	32.39118	1.43E-14	2.400409
Error	349072.9	50	6981.459			
Total	1583199	65				

Table 5-4 ANOVA Analysis of Wet ITS Values from Intermediate Type A Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	7195.0	1199.2	12906.8
I 0.5	6	6384.6	1064.1	31857.2
I 0.7	6	6586.9	1097.8	43207.0
II 0.5	6	7152.7	1192.1	11399.7
II 0.7	6	6432.2	1072.0	72568.6
III 0.4	6	6336.4	1056.1	31686.0
III 0.7	6	6546.2	1091.0	62192.6
IV 0.5	6	6471.4	1078.6	38383.6
IV 0.7	6	6495.3	1082.6	39712.8
V 0.07	6	6241.1	1040.2	61167.3
V 0.7	6	6461.9	1077.0	37251.3
Agg. A	11	13614.1	1237.6	3487.7
Agg. B	11	12826.0	1166.0	7441.1
Agg. C	11	13811.4	1255.6	9030.7
Agg. D	11	11866.8	1078.8	10262.2
Agg. E	11	8470.9	770.1	31124.3
Agg. F	11	11714.6	1065.0	2355.4

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	162328.2	10	16232.82	1.709849	0.104518	2.026143
Columns	1736979	5	347395.8	36.59218	1.4E-15	2.400409
Error	474685.9	50	9493.719			
Total	2373993	65				

5.1.2.2 Hydrated Lime

Figure 5-4 shows the results of dry and wet ITS values for Intermediate Type A mixtures containing hydrated lime and made with aggregate sources A-F. Similar to Figure 5-3, the wet and dry ITS values of mixtures containing aggregate A were the generally the highest, while the mixtures containing aggregate E generally produced the lowest wet and dry ITS values. Although in most cases the wet ITS values were lower than the corresponding dry ITS values, for aggregates D and E, the wet ITS values were slightly higher than the dry ITS values. As with the data in all of the previous sections of this report, all of the wet ITS values were greater than the minimum-required SCDOT value of 448 kPa (65 psi). Moreover, it was found that the differences in ITS values among various aggregate sources were statistically significant.

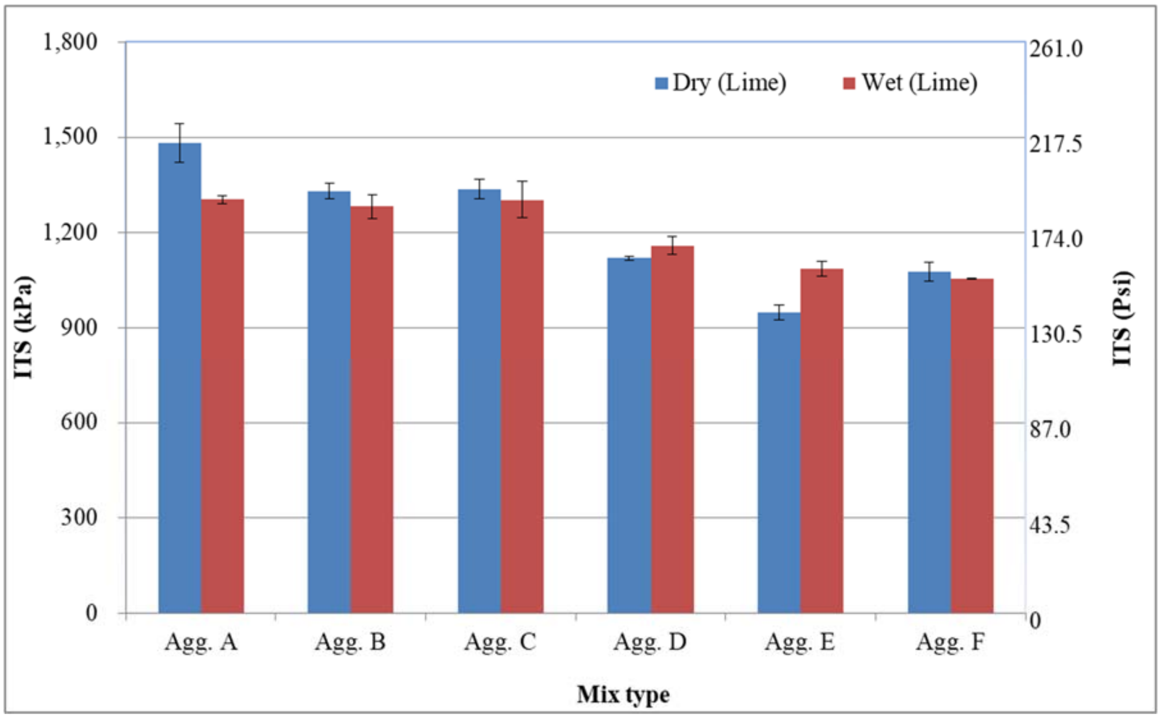


Figure 5-4 Dry and Wet ITS Values of Intermediate Type A Mixtures Containing Lime and Various Aggregate Sources

5.1.2.3 Other Liquid ASA Sources

The dry and wet ITS values of Intermediate Type A mixtures containing liquid ASAs II, III, IV, and V and made with aggregate sources A-F exhibited similar trends to those of the mixtures utilizing liquid ASA I, as shown in Appendix A. As with the Surface Type B mixtures, all wet ITS values were greater than 448 kPa (65 psi) regardless of dosage rate and aggregate source, satisfying the SCDOT's requirements. In general, the ITS values for mixtures from aggregate E were the lowest, while the mixtures from aggregate A produced the highest ITS values. In addition, the statistical analysis shows significant differences between the ITS values of mixtures made with various aggregate sources (Table 5-3 and Table 5-4).

5.1.3 Intermediate Type B Mixtures

5.1.3.1 Liquid ASA I

The ITS values of Intermediate Type B mixtures using liquid ASA I are shown in Figure 5-5. All wet ITS values of Intermediate Type B mixtures containing aggregate sources A-F and liquid ASA I were greater than 448 kPa (65 psi), regardless of the dosage rate. The mixtures from aggregates A and E generally exhibited lower ITS values compared to other aggregate sources. In addition, Figure 5-5 shows that the ITS values of the mixtures using both the 0.5% and 0.7% dosage rates of liquid ASA I were similar. This indicates that the dosage rate of liquid ASA I only had a minimal impact on the ITS values of the Intermediate Type B mixtures.

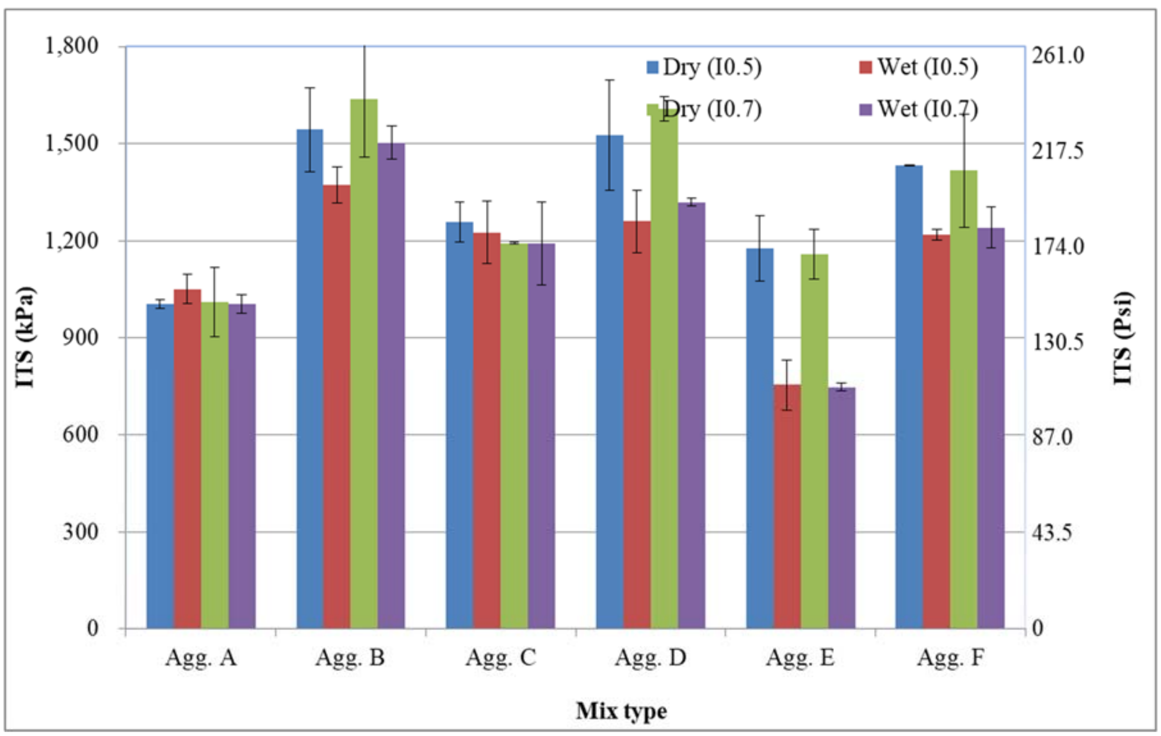


Figure 5-5 Dry and Wet ITS Values of Intermediate Type B Mixtures Containing Liquid ASA I and Various Aggregate Sources

In addition, the statistical analysis shown in Table 5-5 and Table 5-6 indicates that the ITS values of the Intermediate Type B mixtures made with various aggregate sources were significantly different. This implies that the aggregate source plays an important role in determining the bond strength between asphalt binder and aggregate during the moisture susceptibility testing procedures.

Table 5-5 ANOVA Analysis of Dry ITS Values from Intermediate Type B Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	8403.6	1400.6	47778.8
I 0.5	6	7942.3	1323.7	45757.5
I 0.7	6	8024.6	1337.4	65624.9
II 0.5	6	8162.4	1360.4	40291.9
II 0.7	6	7678.7	1279.8	57260.4
III 0.4	6	7519.2	1253.2	74556.7
III 0.7	6	7849.9	1308.3	58416.2
IV 0.5	6	8138.3	1356.4	48337.4
IV 0.7	6	7939.9	1323.3	33273.4
V 0.07	6	7750.9	1291.8	42721.1
V 0.7	6	7858.8	1309.8	27467.8
Agg. A	11	11575.3	1052.3	8437.3
Agg. B	11	16905.7	1536.9	8971.8
Agg. C	11	15021.7	1365.6	6395.7
Agg. D	11	16648.3	1513.5	3629.6
Agg. E	11	11942.1	1085.6	10176.2
Agg. F	11	15175.6	1379.6	4909.3

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	101027.8	10	10102.78	1.558248	0.147149	2.026143
Columns	2383259	5	476651.8	73.51857	7.6E-22	2.400409
Error	324171.1	50	6483.421			
Total	2808458	65				

Table 5-6 ANOVA Analysis of Wet ITS Values from Intermediate Type B Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	7963.3	1327.2	66455.7
I 0.5	6	6883.7	1147.3	47660.3
I 0.7	6	7008.0	1168.0	69011.1
II 0.5	6	7963.3	1327.2	66455.7
II 0.7	6	6901.1	1150.2	131492.6
III 0.4	6	6887.9	1148.0	79830.1
III 0.7	6	7326.2	1221.0	94501.8
IV 0.5	6	7312.7	1218.8	72569.1
IV 0.7	6	7312.7	1218.8	72569.1
V 0.07	6	7066.9	1177.8	137080.6
V 0.7	6	7197.4	1199.6	63551.0
Agg. A	11	10447.8	949.8	4145.9
Agg. B	11	15875.7	1443.2	5857.6
Agg. C	11	14683.3	1334.8	8113.3
Agg. D	11	15704.1	1427.6	12464.0
Agg. E	11	8702.7	791.2	34280.8
Agg. F	11	14409.5	1310.0	3410.0

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	252096.1	10	25209.61	2.927136	0.005776	2.026143
Columns	4075267	5	815053.4	94.637398	2.82E-24	2.400409
Error	430619.1	50	8612.382			
Total	4757982	65				

5.1.3.2 Hydrated lime

The ITS values of Intermediate Type B mixtures containing hydrated lime are shown in Figure 5-6. All wet ITS values of these mixtures were greater than 448 kPa (65 psi), the minimum requirement set forth by SCDOT specifications. It can be observed that the mixtures from aggregate A had the lowest ITS values, followed by the ITS values from aggregate source E. In general, the ITS values of the mixtures from aggregate B produced the highest ITS values. In addition, the wet ITS values of samples made with aggregate D was higher than the corresponding dry ITS values. The statistical analysis shown in Table 5-5 and Table 5-6 indicates that the ITS values were significantly different when the mixtures were made with various aggregate sources.

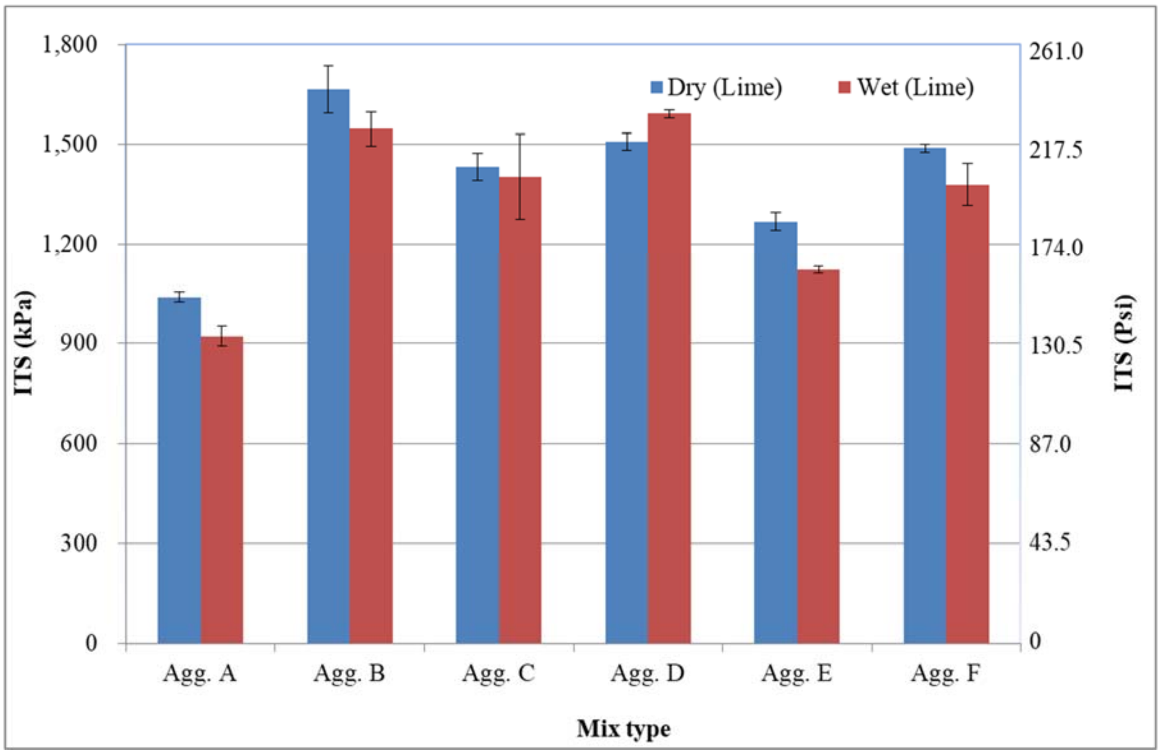


Figure 5-6 Dry and Wet ITS Values of Intermediate Type B Mixtures Containing Lime and Various Aggregate Sources

5.1.3.3 Other Liquid ASA Sources

Similarly, the dry and wet ITS values of Intermediate Type B mixtures utilizing liquid ASAs II, III, IV, and V and made with aggregate sources A-F exhibited similar trends to those ITS values for the mixtures containing Liquid ASA I, as shown in Appendix A. All wet ITS values were greater than 448 kPa (65 psi), regardless of dosage rate and aggregate source. In general, the ITS values of mixtures from aggregates A or E were the lowest. In addition, the ITS values were significantly different when various aggregate sources were utilized, as shown in Table 5-5 and Table 5-6.

5.2 Effect of ASA Type on ITS Values

5.2.1 Surface Type B Mixtures

5.2.1.1 Aggregate A

To explore the effects of ASA type on ITS value, the ITS values of various mixtures from the same aggregate source are compared in this section. As discussed before, the ITS values of mixtures from aggregates A and E were generally lower than other aggregate sources and were discussed in detail in Section 5.1 of this report. As shown in Figure 5-7, the wet ITS values of mixtures using various ASAs were all greater than 448 kPa (65 psi) regardless of dosage, satisfying SCDOT requirements. However, in most cases, the wet ITS values were much lower than the dry ITS values, which translated to lower tensile strength ratio (TSR) values. Additionally, a higher dosage of ASA generally increased wet ITS values, but obviously did not generally increase dry ITS values.

Compared to the mixtures utilizing hydrated lime, the mixtures using liquid ASAs had similar dry ITS values, but their wet ITS values were relatively lower. As shown in Table 5-1 and Table 5-2, the statistical analysis indicates that there were no significant differences in dry ITS values, but significantly different wet ITS values were found (at 95% confidence) between any two mixtures when using various ASAs. Therefore, it can be concluded that the ASA type did have an impact on wet ITS values in the Surface Type B mixtures containing aggregate source A.

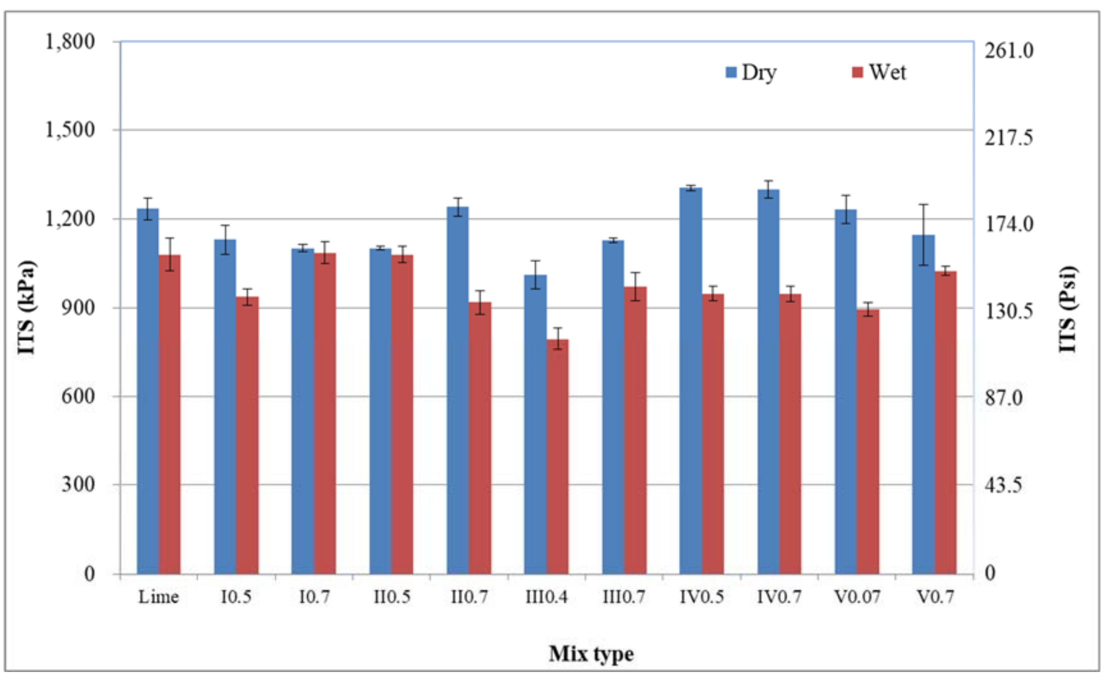


Figure 5-7 Dry and Wet ITS Values of Surface Type B Mixtures Containing Aggregate Source A and Various ASAs

5.2.1.2 Aggregate E

As presented previously, the ITS values of mixtures made with aggregate E were generally lower than samples made from other aggregate sources. However, as shown in Figure 5-8, all wet ITS values were greater than 448 kPa (65 psi), satisfying SCDOT requirements, although it can be noted that some wet ITS values were lower than 600 kPa (87 psi). Additionally, it was found that the wet ITS values of samples made with hydrated lime were close to their corresponding dry ITS values. Wet ITS values of mixtures made with other ASAs were quite lower than their dry ITS values, which resulted in lower TSR values.

Moreover, when different dosage rates of the same ASA were used, the dry ITS values of mixtures were generally close, but the wet ITS values were different. The increase in dosage rate did not always increase the wet ITS values for samples made with aggregate E. The statistical analysis presented in Table 5-1 and Table 5-2 illustrates that the wet ITS values were significantly different for all mixtures, while no statistical differences were found for the dry ITS values.

Therefore, it can be concluded that the dry ITS values of mixtures from aggregate E were not generally affected by the ASA type, but ASA type did have an impact on wet ITS values. The main reasons were the physical and chemical properties of aggregate E, which resulted in the loss of mixture bond strength under wet conditioning.

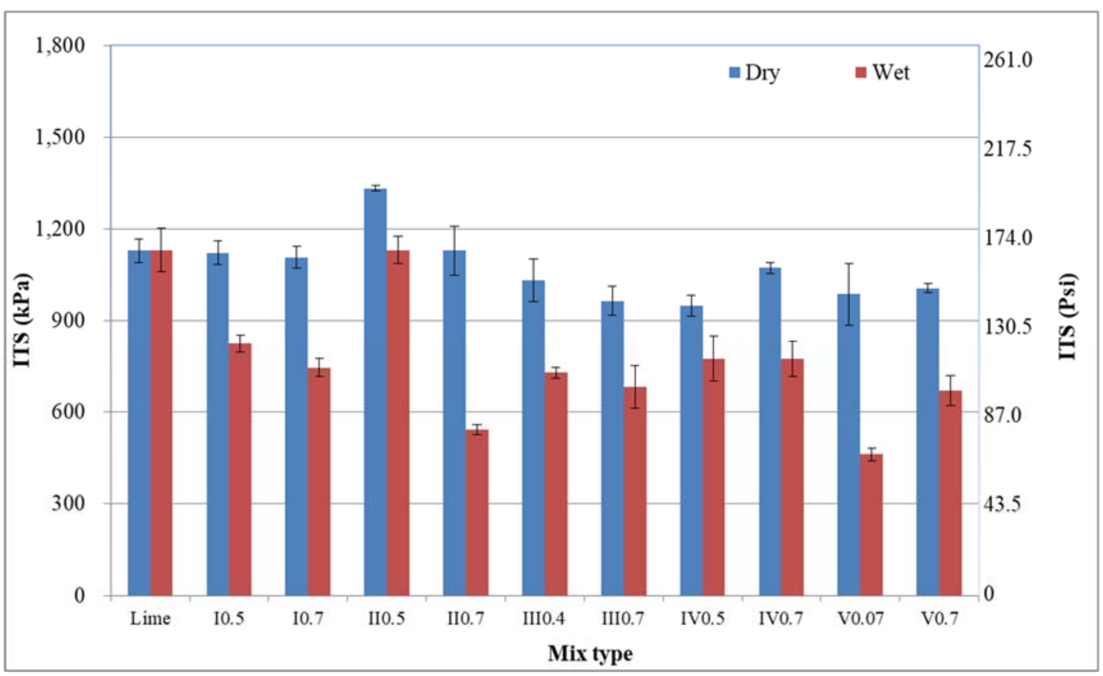


Figure 5-8 Dry and Wet ITS Values of Surface Type B Mixtures Containing Aggregate Source E and Various ASAs

5.2.1.3 Other Aggregate Sources

The ITS values of mixtures from other aggregates in terms of various ASAs are presented in Appendix B. In most cases, the trends were similar to mixtures containing aggregates A and E, but their wet ITS values were generally higher. The impact of various ASAs on the ITS values of these mixtures was not significant. Therefore, similar to the findings for Surface Type B, aggregate source played a key role in determining the ITS values of various mixtures containing different ASAs.

5.2.2 Intermediate Type A Mixtures

5.2.2.1 Aggregate A

As shown in Figure 5-9, all wet ITS values for Intermediate Type A mixtures containing aggregate A and various ASA types were greater than 448 kPa (65 psi), satisfying SCDOT requirements. The wet ITS values were generally lower than the dry ITS values. These ITS values were higher than those from the Surface Type B mixtures. In addition, the mixture containing lime exhibited ITS values similar to those of mixtures utilizing other ASAs. Moreover, the higher dosage rate of 0.7% did not significantly increase the ITS values of these mixtures. As shown in Table 5-3 and Table 5-4, there were no statistical differences between any two dry or wet ITS values utilizing various ASAs; thus, it can be concluded that ASA type did not significantly impact ITS values for Intermediate Type A mixtures containing aggregate A.

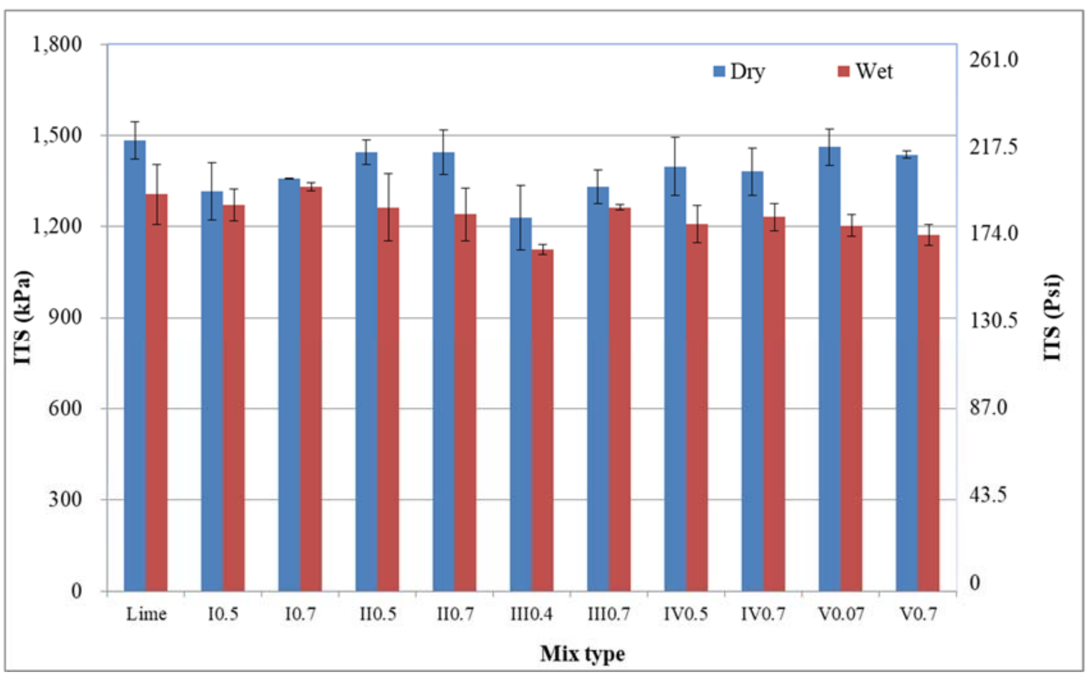


Figure 5-9 Dry and Wet ITS Values of Intermediate Type A Mixtures Containing Aggregate Source A and Various ASAs

5.2.2.2 Aggregate E

As discussed previously, the ITS values of Intermediate Type A mixtures containing aggregate E were generally lower than those values of mixtures containing other aggregate sources. Figure 5-10 indicates that all ITS values were generally lower than those of other mixtures even though they were all greater than 448 kPa (65 psi), satisfying SCDOT requirements. Additionally, the wet ITS values were much lower than the corresponding dry ITS values. The ITS values of mixtures containing hydrated lime were relatively higher than the ITS values of mixtures utilizing liquid ASAs. The dosage rate of the liquid ASAs had a slight impact on the wet ITS values. However, it was found that in some cases, increased liquid ASA dosage resulted in a reduction of both dry and wet ITS values. In addition, the statistical analysis indicates some significant differences among wet ITS values for mixtures containing various ASAs and aggregate E.

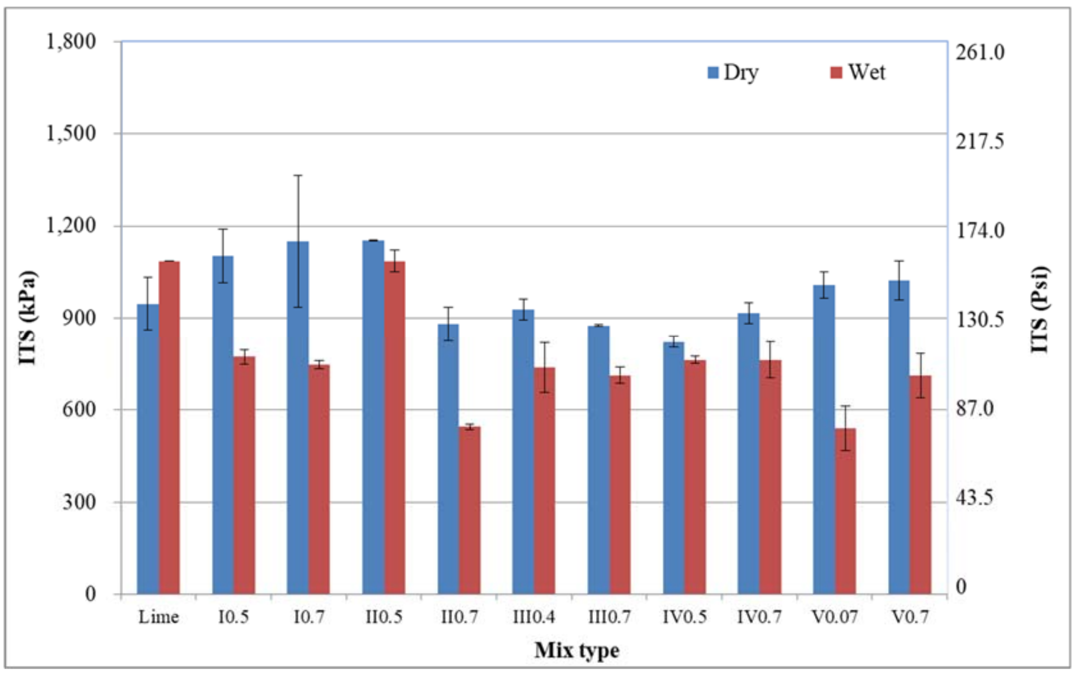


Figure 5-10 Dry and Wet ITS Values of Intermediate Type A Mixtures Containing Aggregate Source E and Various ASAs

5.2.2.3 Other Aggregate Sources

The ITS values of the Intermediate A mixtures made with other aggregate sources and containing various ASAs are presented in Appendix B. As discussed for aggregates A and E, in most cases the trends of these mixtures were similar, but the wet ITS values were generally higher for the other aggregate sources than for aggregates A and E. The impact of various ASAs on the ITS values of these mixtures was not statistically significant. It can be concluded that for Intermediate Type A mixtures, both aggregate source and ASA type had a major impact on ITS values. The mixtures containing hydrated lime generally had higher ITS values than other mixtures.

5.2.3 Intermediate Type B Mixtures

5.2.3.1 Aggregate A

The ITS values of Intermediate Type B mixtures using aggregate A and containing various ASAs are shown in Figure 5-11. It can be noted that all wet ITS values were greater than 448 kPa (65 psi), satisfying SCDOT requirements. These values were generally close to 900 kPa (130 psi), regardless of ASA type. In general, the wet ITS values were lower than the dry ITS values. In addition, the mixtures using 0.4% liquid ASA III have the lowest ITS values. In general, an increase in dosage rates of liquid ASA did not improve the wet ITS values for mixtures made with aggregate A.

The statistical analysis presented in Table 5-5 and Table 5-6 indicates that the dry ITS values were generally similar (no statistical differences), but the wet ITS values were significantly different. Therefore, the ASA type did affect the moisture resistance of Intermediate Type B mixtures made with aggregate A. In other words, both aggregate and ASA type had a major impact on the wet ITS values for mixtures containing aggregate source A.

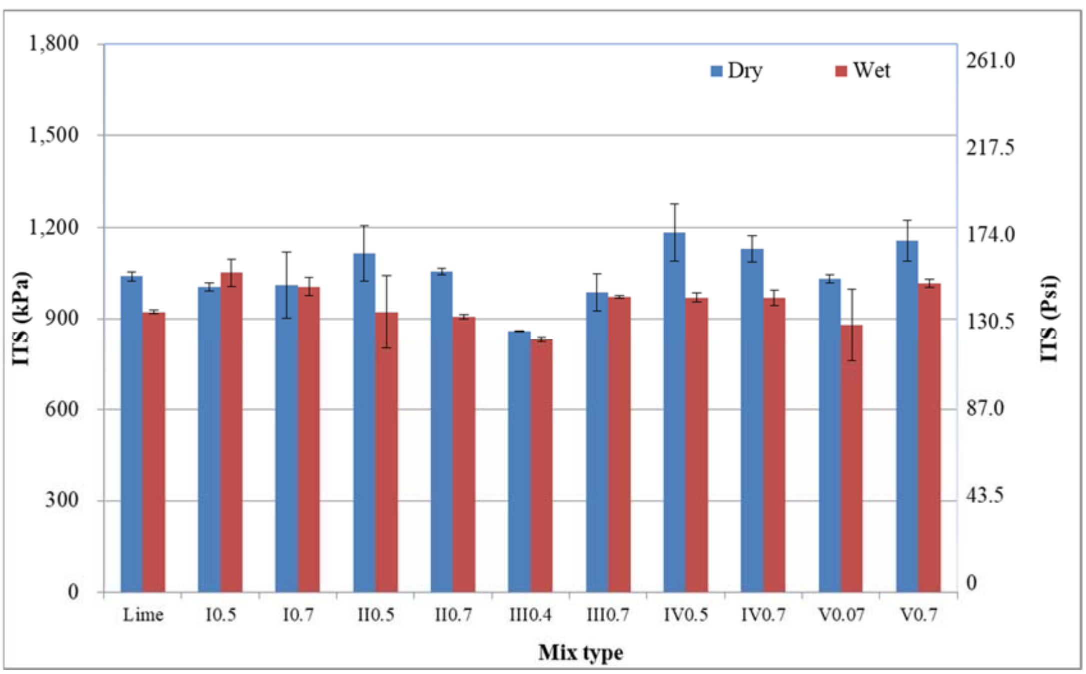


Figure 5-11 Dry and Wet ITS Values of Intermediate Type B Mixtures Containing Aggregate Source A and Various ASAs

5.2.3.2 Aggregate E

As shown in Figure 5-12, when the Intermediate Type B mixtures used aggregate source E, the wet ITS values were quite lower than the dry ITS values even though all of these values were greater than 448 kPa (65 psi), satisfying SCDOT requirements. In addition, an increased dosage rate of liquid ASA did not noticeably result in an increase of wet ITS values. The lowest wet ITS value was found to be for the samples containing 0.7% liquid ASA II. The statistical analysis shows that the wet ITS values of various mixtures in terms of ASA type were significantly different. Thus, ASA type did affect the wet ITS values of Intermediate Type B mixtures made with aggregate E.

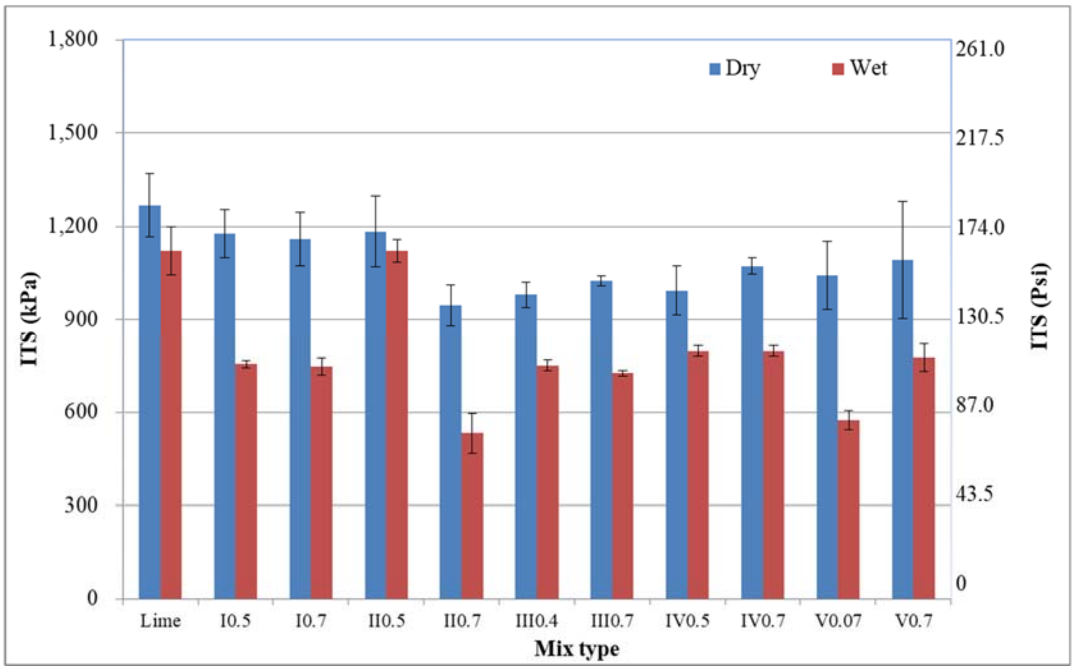


Figure 5-12 Dry and Wet ITS Values of Intermediate Type B Mixtures Containing Aggregate Source E and Various ASAs

5.2.3.3 Other Aggregate Sources

The ITS values of the Intermediate Type B mixtures made with other aggregates and containing various ASAs are presented in Appendix B. As discussed for aggregates A and E, in most cases the trends of these mixtures were similar, but the wet ITS values were generally higher for the remaining aggregate sources than for aggregates A and E. The impacts of various ASAs on the ITS values of these mixtures were not found to be statistically significant. It can be concluded that for Intermediate Type B mixtures, both aggregate source and ASA type played a major role and had an impact on the wet ITS values. The mixtures containing hydrated lime generally produced higher ITS values than other mixtures containing liquid ASAs.

5.3 Effect of Liquid ASA Dosage Rate on ITS Values

5.3.1 Surface Type B Mixtures

The dosages of liquid ASA I were 0.5% (recommended by the supplier) and 0.7% (current SCDOT standard), as selected by researchers. It can be noted in Figure 5-1 (shown previously) that the dry ITS values of Surface Type B mixtures using both dosage rates of liquid ASA I were generally close regardless of aggregate source. However, in most cases, the wet ITS values of mixtures using 0.7% liquid ASA I were higher than the ones that used 0.5%.

With respect to other liquid ASAs, as shown in Appendix A, similar trends can be found for the Surface Type B mixtures using liquid ASAs III, IV, and V, but the mixtures containing 0.5% liquid ASA II generally had higher wet ITS values. Therefore, one can conclude that both dosage rates and ASA types had influence on the wet ITS values.

5.3.2 Intermediate Type A Mixtures

As with the Surface Type B mixtures, the Intermediate Type A mixtures exhibited similar dry ITS values for both dosage rates of liquid ASA I regardless of aggregate source (Figure 5-3, shown previously). However, the wet ITS values were slightly higher when a dosage rate of 0.7% was used for liquid ASA I.

For the Intermediate Type A mixtures using liquid ASAs III, IV, and V, similar trends can be found in Appendix A. For some aggregate sources, the mixtures containing 0.5% liquid ASA II showed slightly higher wet ITS values than those mixtures containing 0.7% liquid ASA II.

5.3.3 Intermediate Type B Mixtures

Figure 5-5 (shown previously) indicates that the dry and wet ITS values of Intermediate Type B mixtures containing either 0.5% or 0.7% liquid ASA I were similar even though the wet ITS values were lower than the dry ITS values. Therefore, it can be concluded that the dosage rate generally did not affect either the dry or the wet ITS values.

In addition Appendix A, illustrates that the Intermediate Type B mixtures with liquid ASAs III, IV, and V had similar trends to the Intermediate Type B mixtures containing liquid ASA I. However, similar to both the Surface Type B and Intermediate Type A mixtures, Intermediate Type B mixtures containing 0.5% liquid ASA II showed slightly higher wet ITS values than those mixtures containing 0.7% liquid ASA II.

5.4 Effect of Aggregate Source on Flow Values

The flow values of ITS samples are commonly used to characterize the resistance to deformation of asphalt mixtures during traffic loading after moisture conditioning. In general, the wet flow of a mixture is greater than its dry flow. In this study, as shown in Figure 5-13, the flow values of the Surface Type B mixtures made with aggregates A-F and containing liquid ASA I were generally less than 1.5 mm (6/100 inch). The mixtures containing aggregate E generally produced higher flow values compared to mixtures containing other aggregate sources.

There were some slight differences in dry and wet flow values when the liquid ASA dosage increased. The statistical analysis indicates that there were significant differences in dry and wet flow values of the mixtures containing various aggregates. The summarized data results are shown in Appendix C.

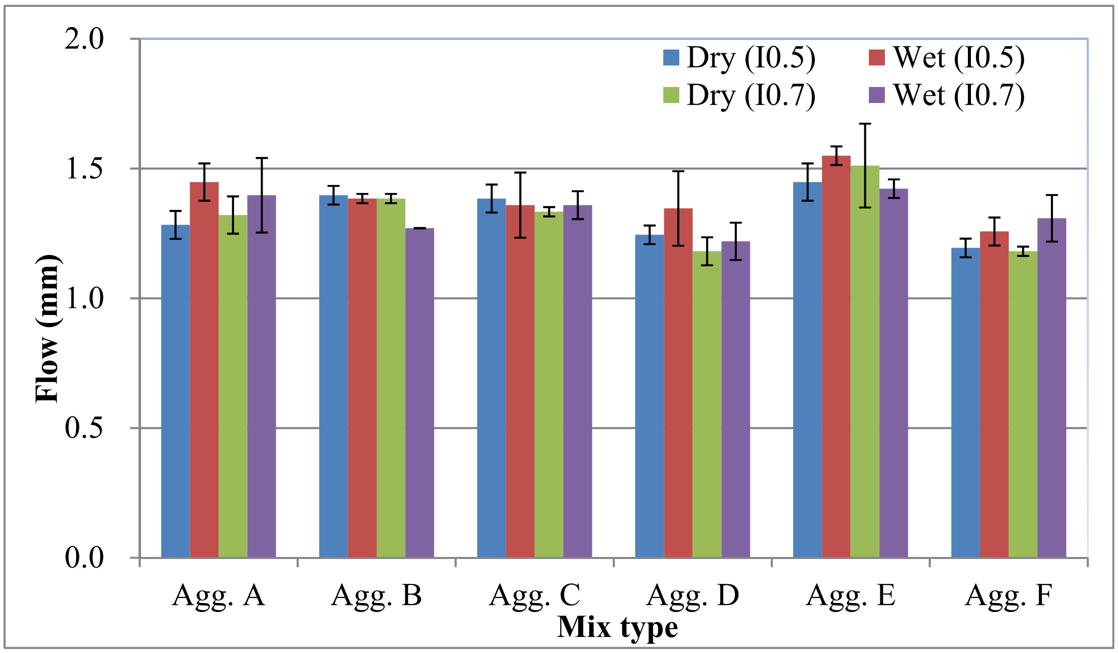


Figure 5-13 Dry and Wet Flow Values of Surface Type B Mixtures Containing Liquid ASA I and Various Aggregate Sources

When hydrated lime was used, similar trends of flow values were found for the mixtures made with various aggregates, as shown in Figure 5-14. The wet flow values were slightly higher than the dry flow values. The mixtures from aggregate A exhibited the highest flow values. In general, the results indicate that the aggregate source did affect the flow value.

The statistical analysis indicates that there were no statistical significant differences in dry flow values, but there were significant differences in wet flow values for the mixtures made with various aggregates. The summarized data results are shown in Appendix C.

Additionally, the flow values for Intermediate Type A and Intermediate Type B mixtures were similar to those of the Surface Type B mixtures. The flow values for these mixtures are shown in Appendix D.

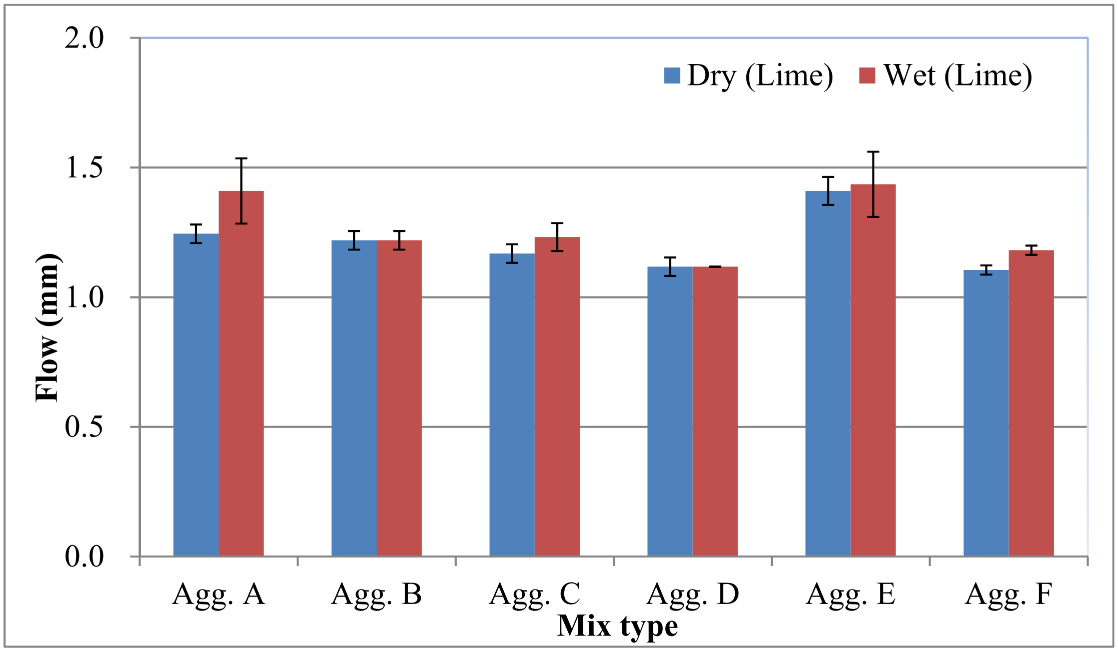


Figure 5-14 Dry and Wet Flow Values of Surface Type B Mixtures Containing Lime and Various Aggregate Sources

5.5 <u>Effect of ASAs on Flow Values</u>

The flow values of Surface Type B ITS samples made with aggregate A and containing various ASAs are shown in Figure 5-15. It can be noted that all samples exhibited flow values less than 1.5 mm (6/100 inch). In addition, the wet flow values were generally higher than the dry flow values. However, in most cases, the flow values of these mixtures were relatively close. The impact of ASA dosage rate on flow value was not noticeable.

Mixtures using other aggregate sources and various ASAs exhibited similar flow properties as the mixtures utilizing liquid ASA I. Additionally, the flow values for Intermediate Type A and Intermediate Type B mixtures made with various ASAs were similar to those of the Surface Type B mixtures. The flow values for these mixtures are shown in Appendix E.

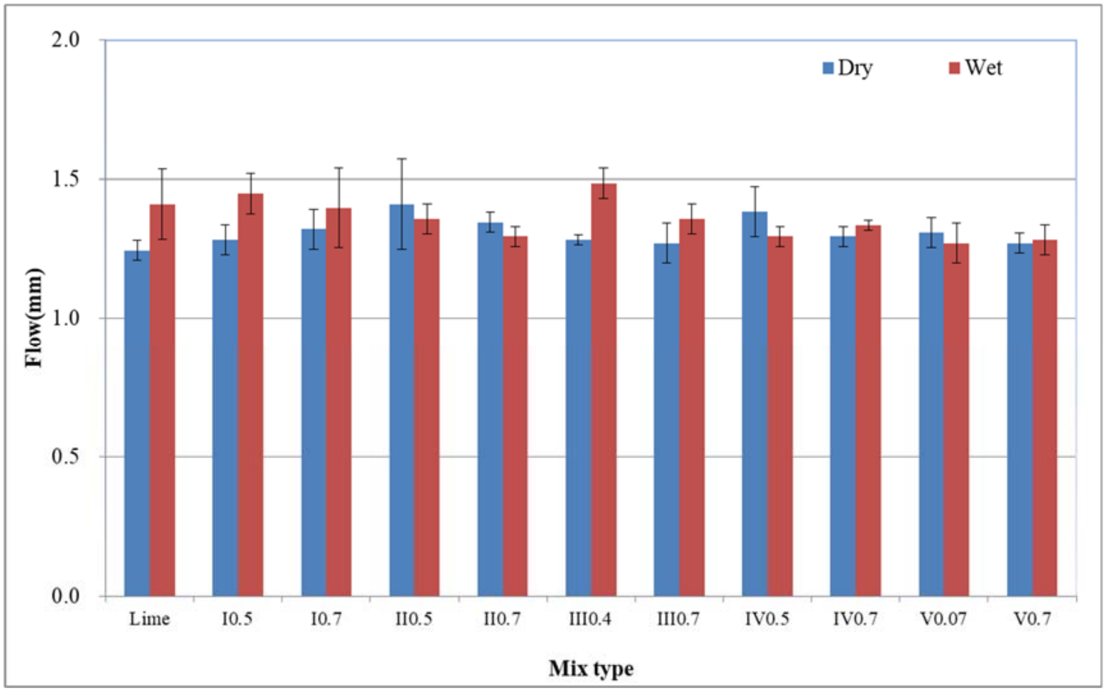


Figure 5-15 Dry and Wet Flow Values of Surface Type B Mixtures Containing Aggregate Source A and Various ASAs

5.6 Effect of Liquid ASA Dosage Rate on Flow Values

As shown previously in Figure 5-13, the dosage rate generally had only a slight impact on the flow values of various Surface Type B mixtures. An increased dosage rate of liquid ASA I from 0.5% to 0.7% did not show a noticeable increase in flow values regardless of aggregate source.

As shown in Appendix E, in most cases, Surface Type B, Intermediate Type A and Intermediate Type B mixtures containing liquid ASAs II, III, IV and V exhibited trends similar to those mixtures containing liquid ASA I. However, for some mixtures, a higher dosage rate resulted in an increase of flow values. Therefore, it can be considered that the dosage rate slightly affected the flow values of various types of mixtures.

5.7 Effect of Aggregate Source on TSR Values

5.7.1 Surface Type B Mixtures

5.7.1.1 Liquid ASA I

Tensile strength ratio (TSR) values are commonly used to evaluate the moisture susceptibility of asphalt mixtures. The TSR results of mixtures using liquid ASA I in terms of various aggregate sources A-F are summarized and shown in Figure 5-16. It should be noted that some of the TSR values were lower than 85%, which is the minimum required TSR value set forth by SCDOT. In addition, the TSR values of mixtures made with aggregate E were generally the lowest, followed by the mixtures made with aggregates D and F. However, the mixtures made with aggregates B and C exhibited TSR values greater than 85% at both dosage rates when liquid ASA I was used. It should also be noted that the increased dosage rate for liquid ASA I slightly improved the TSR values of the Surface Type B mixtures for all aggregate sources except for aggregate E. The statistical analysis, as shown in Table 5-7, indicates that the TSR values of the mixtures containing various aggregates were significantly different.

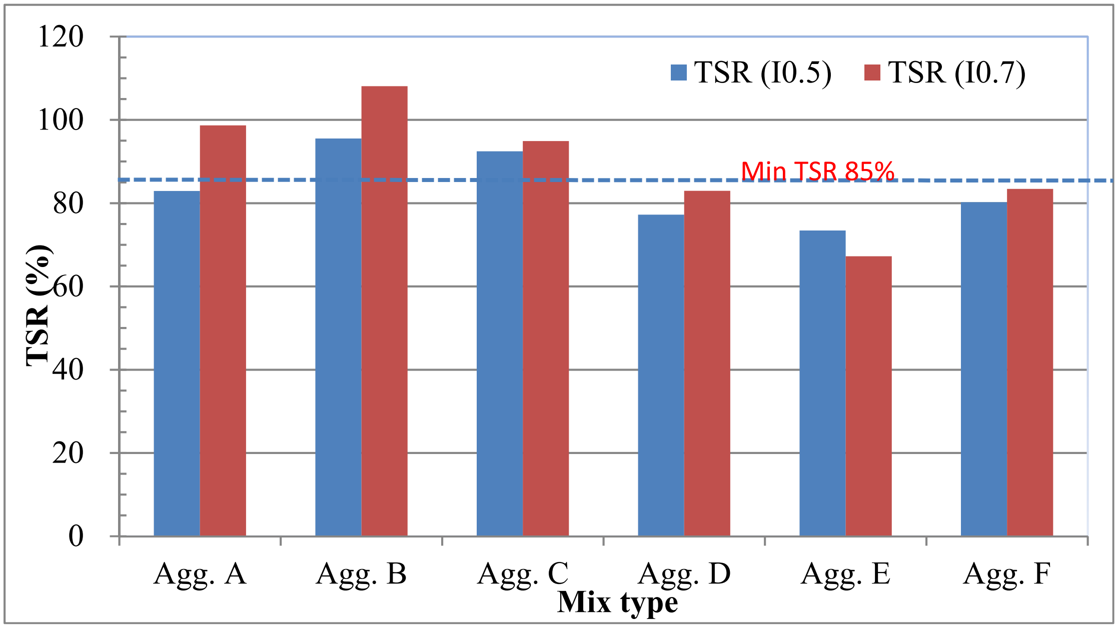


Figure 5-16 TSR Values of Surface Type B Mixtures Containing Liquid ASA I and Various Aggregate Sources

5.7.1.2 Hydrated Lime

Hydrated lime is typically utilized to increase the moisture resistance of asphalt mixtures used in South Carolina. In this study, as shown in Figure 5-17, all TSR values of Surface Type B mixtures containing hydrated lime were greater than 85%. The mixtures from aggregates B, C, and E generally exhibited TSR values close to 100%, which indicates very little moisture susceptibility in those mixtures.

5.7.1.3 Other Liquid ASAs

The TSR values of the mixtures containing other liquid ASAs were less than 85% in some cases. Both the aggregate source and liquid ASA type significantly affected the TSR values. In addition, a higher liquid ASA dosage rate did not automatically translate to a higher TSR value. However, it was found that when a 0.7% dosage rate was used for liquid ASAs II-V, all mixtures from aggregate sources B, C, D, and F produced TSR values greater than 85%. These results are summarized and shown in Appendix F.

Table 5-7 ANOVA Analysis of TSR Values from Surface Type B Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	569.8	95.0	34.4
I0.5	6	501.7	83.6	75.2
I0.7	6	535.2	89.2	206.7
II0.5	6	568.7	94.8	57.1
II0.7	6	501.5	83.6	400.9
III0.4	6	508.9	84.8	73.0
III0.7	6	528.0	88.0	109.3
IV0.5	6	491.9	82.0	42.8
IV0.7	6	508.3	84.7	106.8
V0.07	6	485.1	80.8	360.4
V0.7	6	554.8	92.5	177.9
Agg. A	11	909.9	82.7	87.3
Agg. B	11	1037.4	94.3	70.3
Agg. C	11	1050.9	95.5	23.7
Agg. D	11	992.5	90.2	83.8
Agg. E	11	782.3	71.1	231.3
Agg. F	11	981.1	89.2	25.9

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	1532.103	10	153.2103	2.075272	0.044504	2.026143
Columns	4530.296	5	906.0592	12.2728	8.76E-08	2.400409
Error	3691.331	50	73.82661			
Total	9753.73	65				

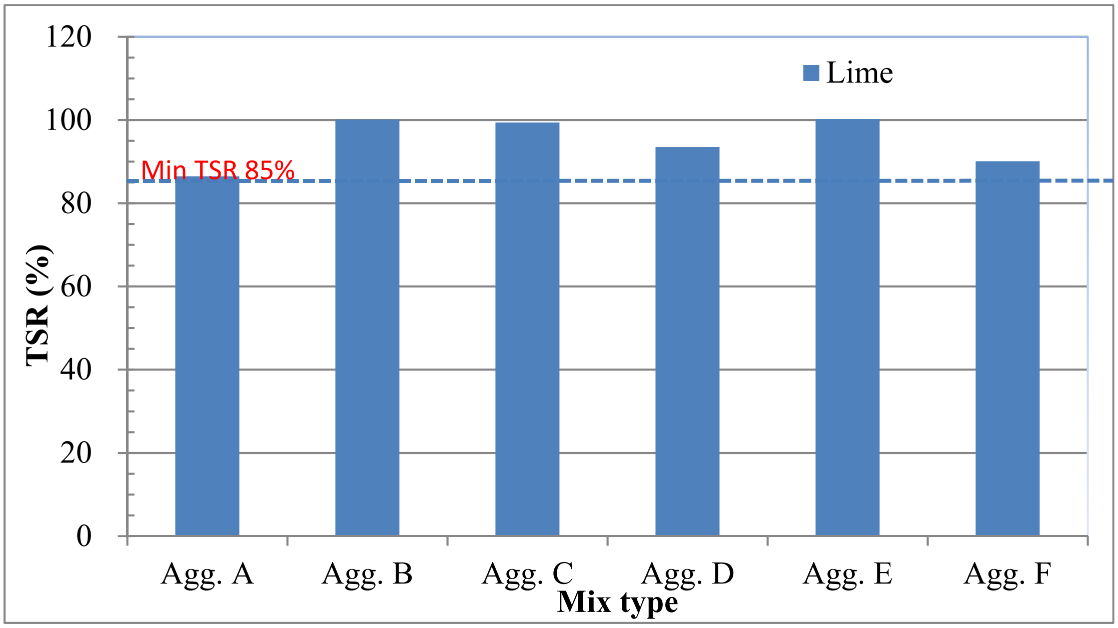


Figure 5-17 TSR Values of Surface Type B Mixtures Containing Lime and Various Aggregate Sources

5.7.2 Intermediate Type A Mixtures

5.7.2.1 Liquid ASA I

The TSR results of Intermediate Type A mixtures using liquid ASA I in terms of various aggregate sources A-F are summarized and shown in Figure 5-18. It should be noted that all TSR values were greater than 85% when mixtures were made with aggregates A, B, C and F. In addition, the TSR values exhibited some slight differences when two dosage rates of liquid ASA I were used. The increased dosage rate did not improve the TSR values in all cases. In addition, the statistical analysis shown in Table 5-8 illustrates that TSR values were significantly different when the mixtures were made with aggregate sources A-F, implying the aggregate source did affect the TSR values when liquid ASA I was used in Intermediate Type A mixtures.

5.7.2.2 Hydrated lime

All TSR values for Intermediate Type A mixtures containing hydrated lime were higher than 85%, as shown in Figure 5-19. The mixture made with aggregate A exhibited the lowest TSR value compared to the mixtures from other aggregate sources. There were some significant differences in TSR values of mixtures from any two aggregate sources. Therefore, it can be concluded that aggregate source played a key role in the TSR values of mixtures containing hydrated lime.

5.7.2.3 Other Liquid ASAs

In general, the TSR values of the mixtures containing other liquid ASAs were greater than 85% in most cases. When the 0.7% liquid ASA dosage rate was used, the TSR values of all of these mixtures were greater than 85% except for those containing aggregate source E. The results for this section of the research work are summarized and shown in Appendix F.

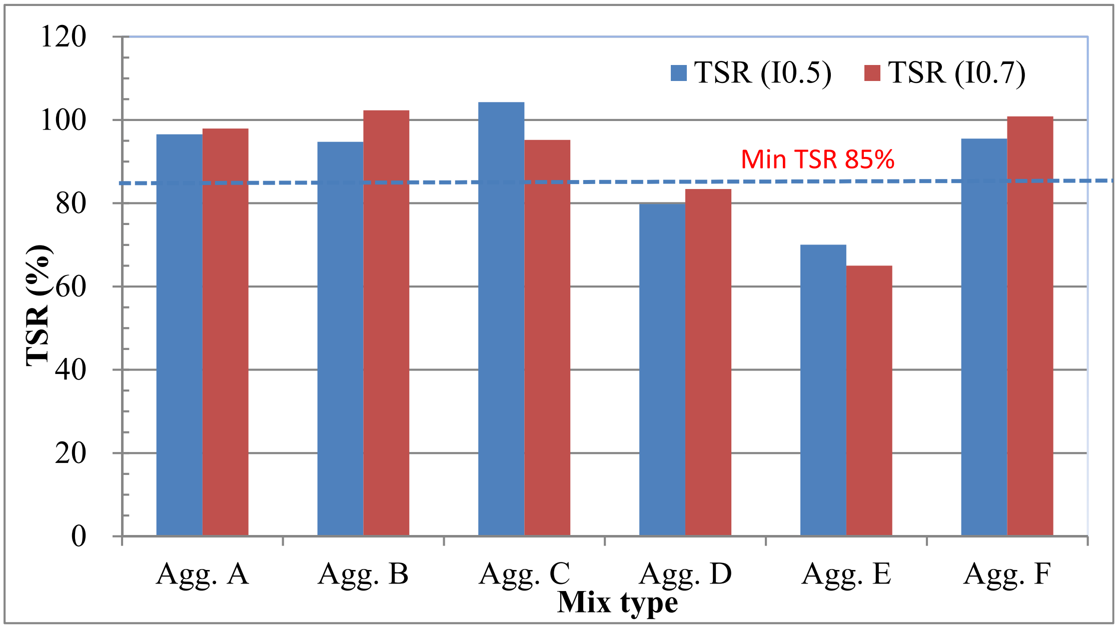


Figure 5-18 TSR Values of Intermediate Type A Mixtures Containing Liquid ASA I and Various Aggregate Sources

Table 5-8 ANOVA Analysis of TSR Values from Intermediate Type A Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	598.3	99.7	78.5
I0.5	6	540.8	90.1	160.7
I0.7	6	544.6	90.8	204.7
II0.5	6	559.8	93.3	19.1
II0.7	6	541.3	90.2	232.4
III0.4	6	552.5	92.1	53.2
III0.7	6	574.2	95.7	104.1
IV0.5	6	543.8	90.6	39.2
IV0.7	6	566.3	94.4	76.8
V0.07	6	532.2	88.7	439.2
V0.7	6	540.2	90.0	146.9
Agg. A	11	981.7	89.2	29.6
Agg. B	11	1078.1	98.0	36.6
Agg. C	11	1074.7	97.7	21.1
Agg. D	11	1012.2	92.0	63.8
Agg. E	11	866.4	78.8	301.2
Agg. F	11	1080.8	98.3	68.5

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	624.4652	10	62.44652	0.681075	0.736627	2.026143
Columns	3189.529	5	637.9058	6.95734	5.32E-05	2.400409
Error	4584.409	50	91.68817			
Total	8398.403	65				

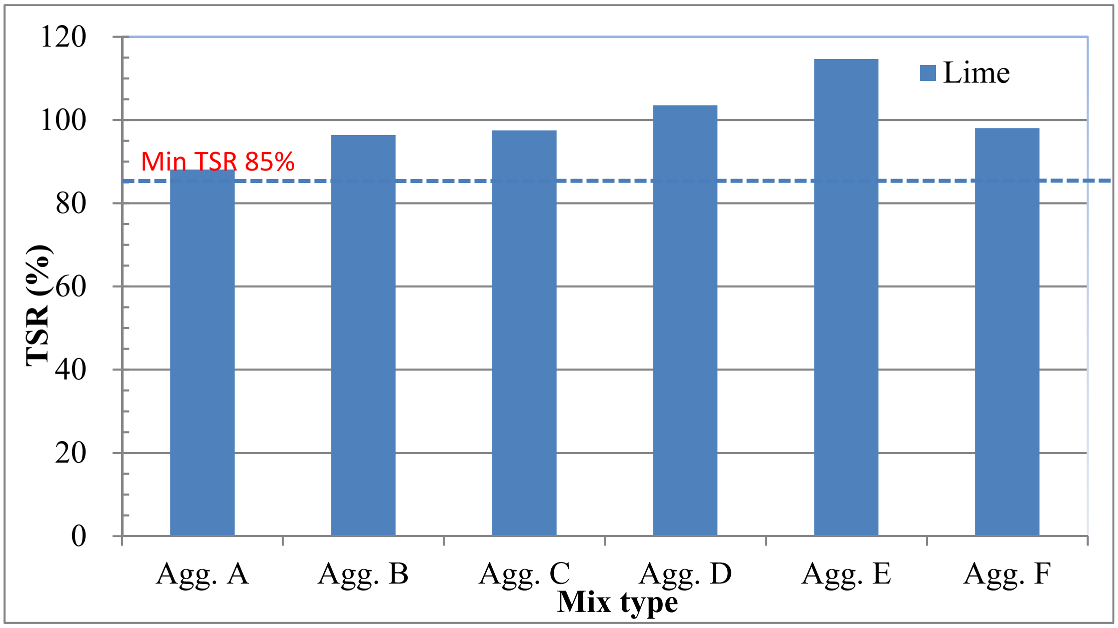


Figure 5-19 TSR Values of Intermediate Type A Mixtures Containing Lime and Various Aggregate Sources

5.7.3 Intermediate B mixtures

5.7.3.1 Liquid ASA I

Figure 5-20 shows that the TSR results of Intermediate Type B mixtures containing liquid ASA I and made with various aggregate sources. The TSR values were all greater than 85% for the mixtures made with aggregate sources A, B, C and F. The TSR values of mixtures made with aggregate sources D and E were less than 85%, regardless of the liquid ASA dosage rate. In general, the dosage rate of liquid ASA I had a minor effect on the TSR value. Table 5-9 indicates that TSR values were significantly different for all mixtures. It can be concluded that aggregate source had a major impact on the TSR values of Intermediate Type B mixtures.

5.7.3.2 Hydrated Lime

As shown in Figure 5-21, all Intermediate Type B mixtures made with various aggregate sources had TSR values greater than 85% when hydrated lime was used. The TSR values for samples containing aggregate E were the lowest, followed by aggregate A. As expected, the results indicate that aggregate source had an impact on the TSR values of Intermediate Type B mixtures.

5.7.3.3 Other Liquid ASAs

In most cases, the TSR values from Intermediate Type B mixtures containing other liquid ASAs were found to be greater than 85%. Similar to the Intermediate Type A mixtures, all TSR values were greater than 85% when 0.7% liquid ASA dosage rate was used except for the mixtures made with aggregate E. Thus, it can be concluded that for the liquid ASA dosage rate of 0.7%, most of mixtures produced TSR values greater than 85%. These results are summarized and presented in Appendix F.

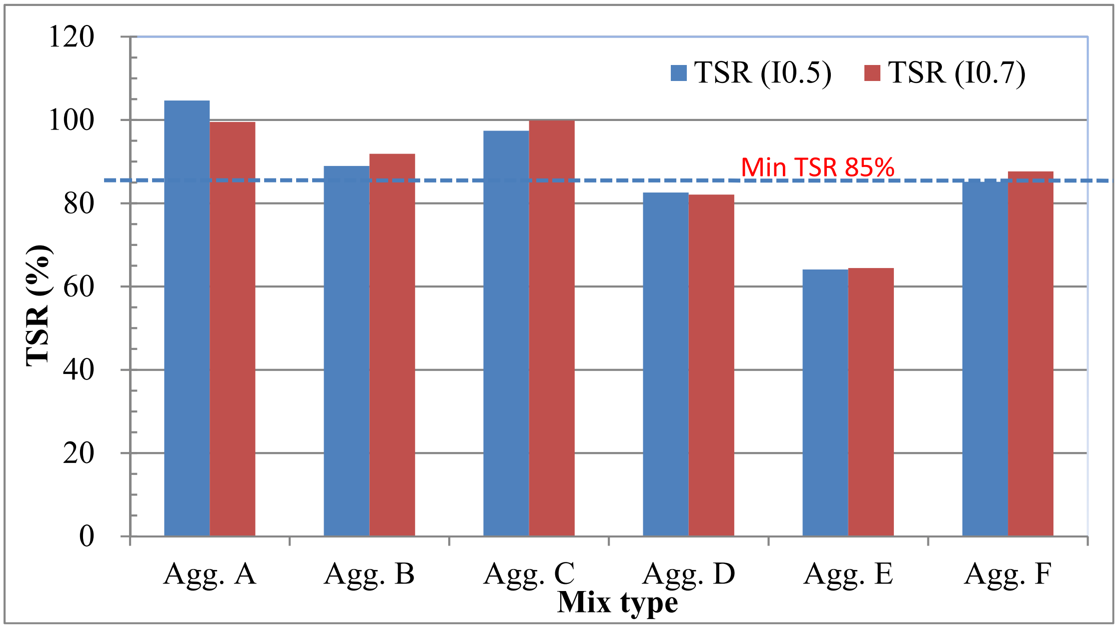


Figure 5-20 TSR Values of Intermediate Type B Mixtures Containing Liquid ASA I and Various Aggregate Sources

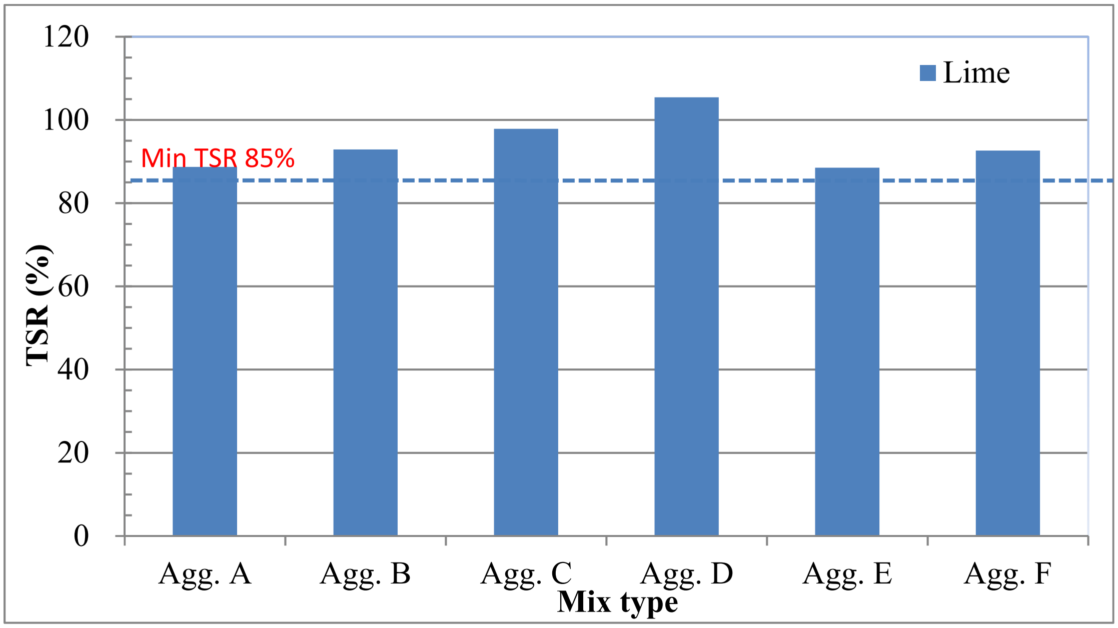


Figure 5-21 TSR Values of Intermediate Type A Mixtures Containing Lime and Various Aggregate Sources

Table 5-9 ANOVA Analysis of TSR Values for Intermediate Type B Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	566.0	94.3	41.2
I0.5	6	522.8	87.1	194.2
I0.7	6	525.3	87.6	175.6
II0.5	6	582.6	97.1	78.2
II0.7	6	527.4	87.9	260.2
III0.4	6	548.0	91.3	77.5
III0.7	6	555.6	92.6	154.2
IV0.5	6	534.2	89.0	38.5
IV0.7	6	547.0	91.2	91.2
V0.07	6	535.7	89.3	315.5
V0.7	6	545.2	90.9	124.4
Agg. A	11	997.6	90.7	60.4
Agg. B	11	1034.5	94.0	19.9
Agg. C	11	1075.8	97.8	21.9
Agg. D	11	1039.0	94.5	65.8
Agg. E	11	796.4	72.4	153.8
Agg. F	11	1046.6	95.1	36.3

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	562.48	10	56.248	0.93195	0.512577	2.026143
Columns	4735.893	5	947.1785	15.69342	2.85E-09	2.400409
Error	3017.757	50	60.35514			
Total	8316.129	65				

5.8 Effect of ASAs on TSR Values

5.8.1 Surface Type B mixtures

5.8.1.1 Aggregate A

To determine the impact of various ASAs, the mixtures from each aggregate source containing various ASAs were analyzed. As shown in Figure 5-22, some TSR values were found to be less than 85%. Only the mixtures containing a dosage rate of 0.7% ASA I, lime, 0.5% ASA II, 0.7% ASA II and 0.7% ASA V had TSR values greater than 85%.

The statistical analysis (shown previously in Table 5-7) indicates that TSR values were significantly different for the mixtures made with aggregate A and containing various ASAs. Thus, it can be concluded that the ASA type influenced the TSR values of Surface Type B mixtures made with aggregate A.

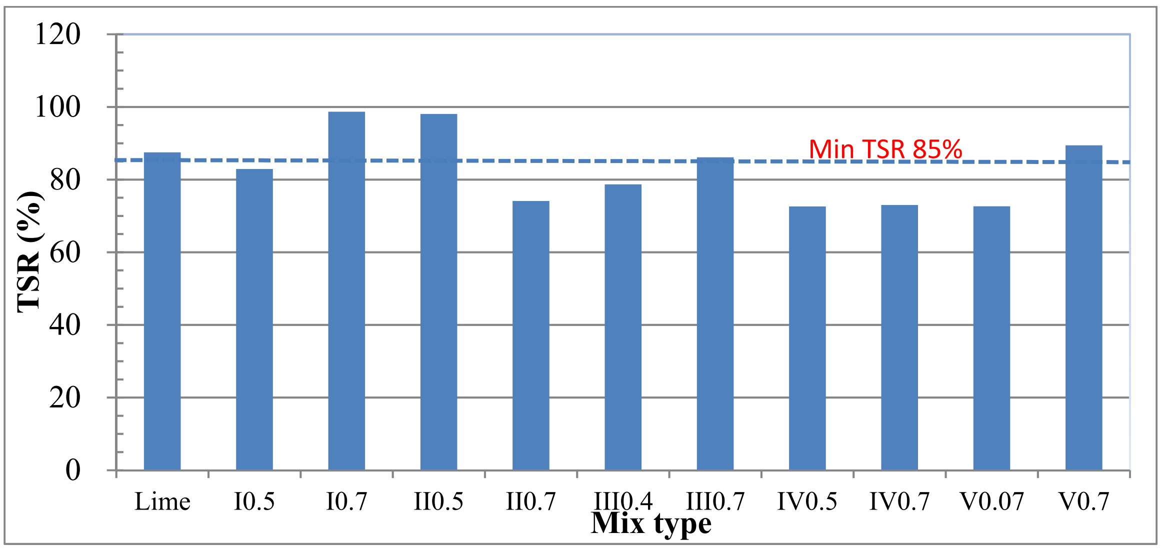


Figure 5-22 TSR Values of Surface Type B Mixtures Containing Aggregate Source A and Various ASAs

5.8.1.2 Aggregate E

In general, the Surface Type B mixtures from aggregate E had the lowest wet and dry ITS values; thus, the TSR values of these mixtures were interesting to examine. As shown in Figure 5-23, only the mixture with hydrated lime had TSR values greater than 85%. All other mixtures failed this minimum requirement regardless of liquid ASA content. As discussed before, even though the wet ITS values were greater than 448 kPa (65 psi), the dry ITS values were much higher, which resulted in low TSR values and failed to meet SCDOT's minimum TSR requirements.

5.8.1.3 Other Aggregate Sources

The TSR values from the Surface Type B mixtures made with other aggregate sources were much higher than the mixtures made with aggregate sources A and E. These TSR values are summarized and presented in Appendix G. It was found that the Surface Type B mixtures containing liquid ASAs II, III, VI and hydrated lime exhibited TSR values greater than 85% regardless of liquid ASA dosage rate. When the 0.7% dosage rate was used, it should be noted that almost all TSR values were greater than 85%.

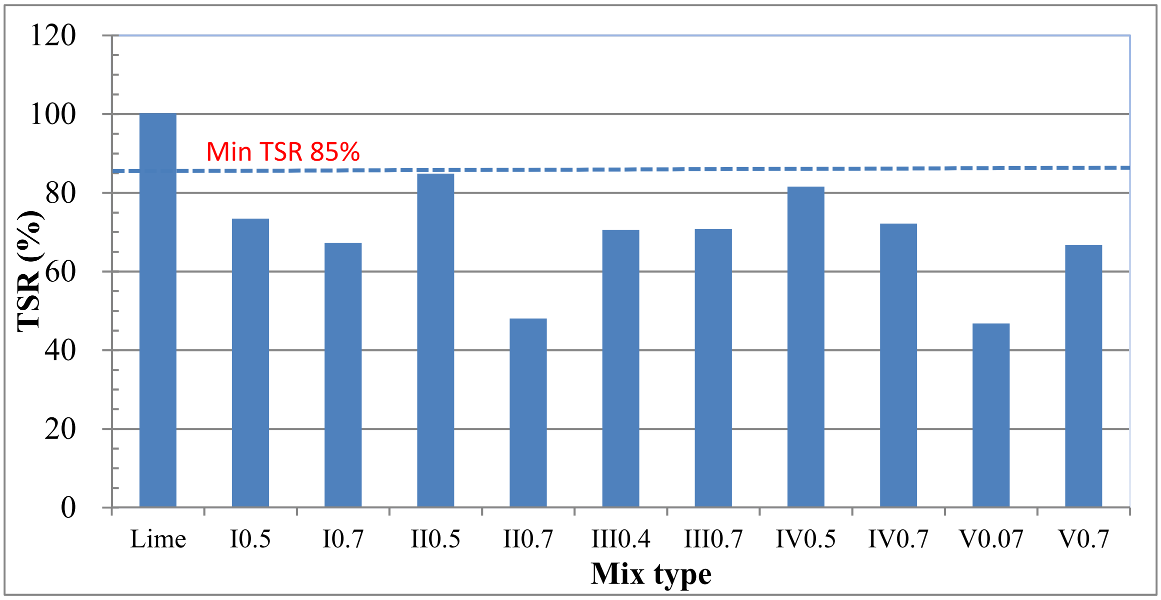


Figure 5-23 TSR Values of Surface Type B Mixtures Containing Aggregate Source E and Various ASAs

5.8.2 Intermediate Type A Mixtures

5.8.2.1 Aggregate A

Figure 5-24 indicates that the TSR values of all Intermediate Type A mixtures containing aggregate A were greater than 85% except for the mixtures containing liquid ASA V (both dosages). The percentage of liquid ASA generally did not have an impact on the TSR values for this aggregate source in Intermediate Type A mixtures. The statistical analysis indicates that no significant difference was noted for these mixtures when various ASAs were used.

5.8.2.2 Aggregate E

Similar to Surface Type B mixtures, the mixtures made with aggregate E exhibited the lowest TSR values. As shown in Figure 5-25, only the mixtures with hydrated lime, 0.5% liquid ASA II, and 0.5% liquid ASA IV had TSR values greater than 85%. All other mixtures failed to meet this requirement regardless of liquid ASA percentage. Similarly, even though the wet ITS values were greater than 448 kPa (65 psi), the dry ITS values were much higher, which resulted in low TSR values and failed to meet SCDOT requirements for Intermediate Type A mixtures. Thus, it is recommended to conduct a more detailed study of this aggregate source in the future regarding moisture susceptibility issues.

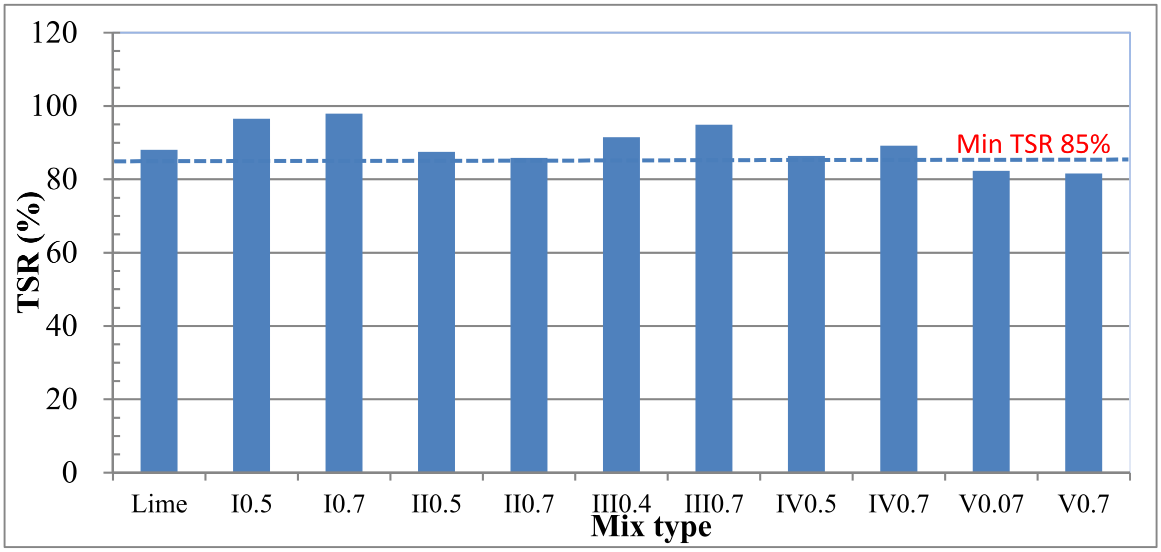


Figure 5-24 TSR Values of Intermediate Type A Mixtures Containing Aggregate Source A and Various ASAs

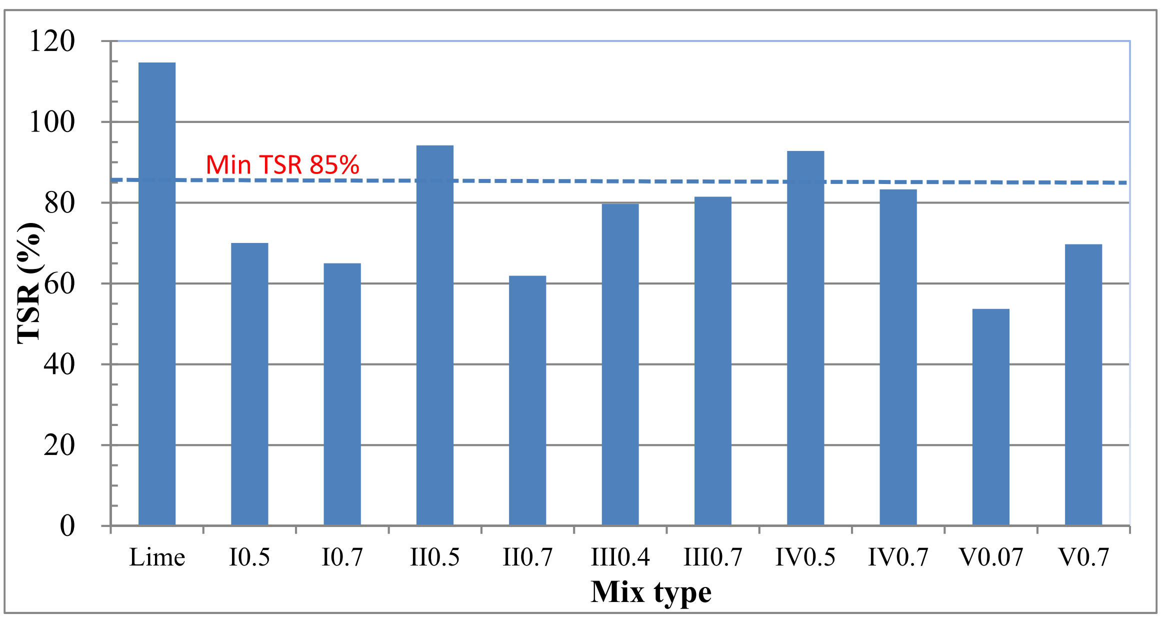


Figure 5-25 TSR Values of Intermediate Type A Mixtures Containing Aggregate Source E and Various ASAs

5.8.2.3 Other Aggregate Sources

It should be noted that the TSR values of Intermediate Type A mixtures made with other aggregate sources were much higher than those of aggregate sources A and E. The results of this section of the report have been summarized and presented in Appendix G. It was found that the Intermediate Type A mixtures from aggregates B, C, D, F containing liquid ASAs had TSR values greater than 85% regardless of liquid ASA percentage, except for the mixtures from aggregate D containing liquid ASA I (both dosages) and 0.5% liquid ASA IV. Therefore, it can be considered that liquid ASAs were generally effective in improving the moisture resistance of Intermediate Type A mixtures.

5.8.3 Intermediate Type B Mixtures

5.8.3.1 Aggregate A

Figure 5-26 indicates that all TSR values of Intermediate Type B mixtures made with aggregate A were greater than 85% except for the mixtures that utilized liquid ASA II (both dosages) and 0.5% ASA IV. It can be concluded that the dosage rate of ASA generally did not have an impact on TSR values when this aggregate source was used. The statistical analysis indicates that no significant difference existed for these mixtures when various ASAs were used. It can be concluded that the ASA type did have an impact on the TSR values of Intermediate Type B mixtures made with aggregate source A.

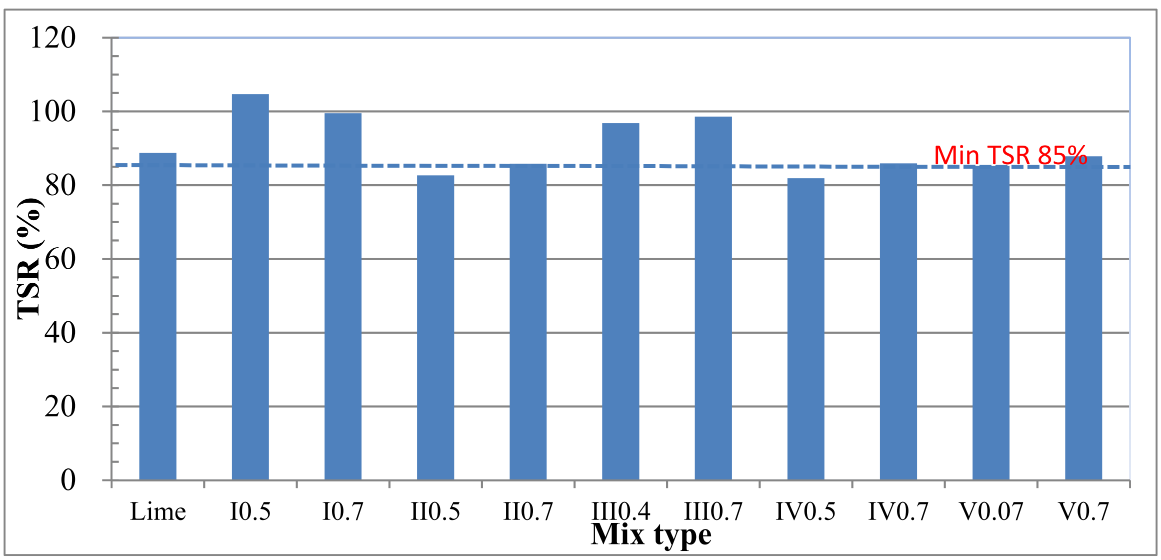


Figure 5-26 TSR Values of Intermediate Type B Mixtures Containing Aggregate Source A and Various ASAs

5.8.3.2 Aggregate E

As with the other mixture types, the Intermediate Type B mixtures made with aggregate E exhibited the lowest TSR values. As shown in Figure 5-27, only the mixtures with hydrated lime and 0.5% liquid ASA II had TSR values greater than 85%. All other mixtures failed regardless of liquid ASA percentage. Similarly, even though the wet ITS values were greater than 448 kPa (65 psi), the dry ITS values were much higher, which resulted in low TSR values and failed to meet SCDOT's requirements for Intermediate Type B mixtures. Thus, it is also recommended to have a more in-depth study of this aggregate source regarding the cause of this issue.

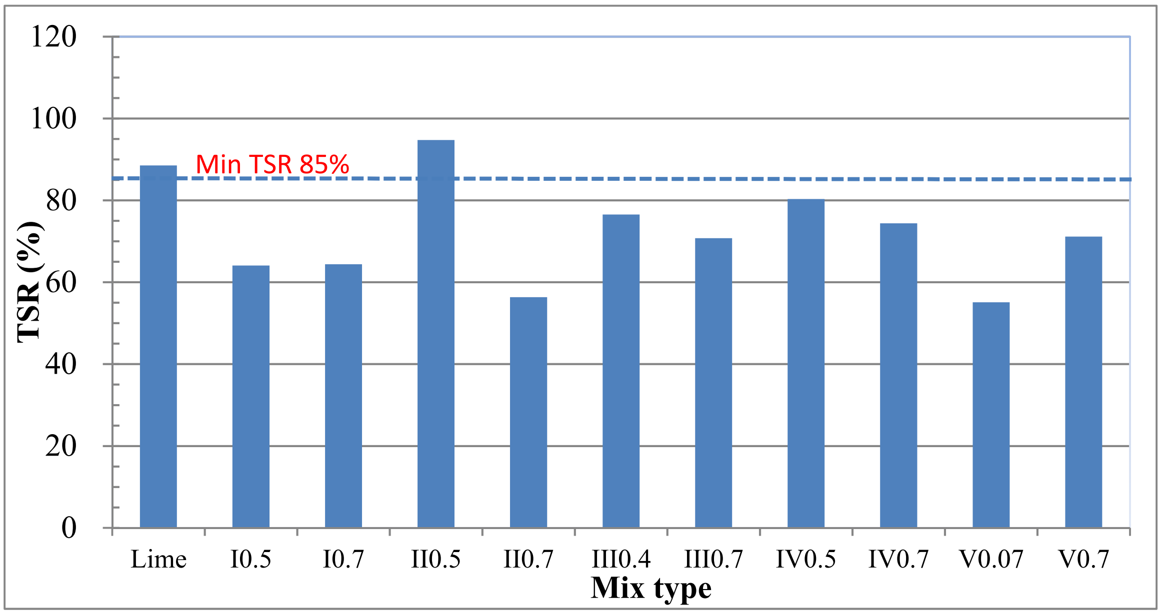


Figure 5-27 TSR Values of Intermediate Type B Mixtures Containing Aggregate Source E and Various ASAs

5.8.3.3 Other Aggregate Sources

Intermediate Type B mixtures made from other aggregate sources all exhibited TSR values that were much higher than the mixtures made with aggregate sources A and E. These TSR values are summarized and presented in Appendix G. It was found that the Intermediate Type B mixtures containing various liquid ASAs and made with aggregate sources B, C, D, and F had TSR values greater than 85% regardless of liquid ASA percentage, except for the mixtures from aggregate D with liquid ASA I (both dosages). Similarly, it can be considered that these liquid ASAs were generally effective in improving the moisture resistance of Intermediate Type B mixtures.

5.9 Effect of Liquid ASA Dosage Rate on TSR Values

5.9.1 Surface Type B Mixtures

As shown previously in Figure 5-16, an increased dosage rate from 0.5% to 0.7% of liquid ASA I generally resulted in an increase of TSR values for Surface Type B mixtures. However, in most cases for Surface Type B mixtures containing liquid ASA II, the increased dosage rate actually resulted in a decrease of TSR values. For the Surface Type B mixtures containing liquid ASAs III, IV, and V, the results indicate that the TSR values increased slightly when the dosage rate increased (Appendix F).

5.9.2 Intermediate Type A Mixtures

Figure 5-18 indicates that in most cases, a higher dosage rate resulted in slightly higher TSR values for Intermediate Type A mixtures containing liquid ASA I. However, the results show that if the TSR value was far lower than 85%, an increase in dosage rate still did not cause the TSR values of those mixtures to be greater than 85%. Similar trends were found when other liquid ASAs were used in Intermediate Type A mixtures (Appendix F).

5.9.3 Intermediate Type B Mixtures

As shown previously in Figure 5-20, the dosage rate did not affect the TSR values of Intermediate Type B mixtures containing liquid ASA I because those TSR values were similar for both dosage rates regardless of aggregate source. However, for other liquid ASAs, there were some differences in TSR values between the two dosage rates. In most cases, an increase in dosage rate resulted in an increase in TSR values for Intermediate Type B mixtures. In some cases, the aggregate source also affected this trend (Appendix F).

5.10 Boiling Test Analysis

5.10.1 Surface Type B Mixtures

The boiling test is typically used to explore the moisture susceptibility of asphalt mixtures. South Carolina test method SC-T-69 provides the procedures for this test. In this portion of the study, a total of 132 samples (66 combinations) of Surface Type B mixtures were tested.

As shown in Table 5-10 and Figure 5-28, it can be noted that in most cases, the Surface Type B mixtures were not stripped when this test was conducted with aggregate sources A-F. None of the samples made with aggregate sources B, D or F exhibited any signs of stripping in this portion of the research. In addition, as shown in Figure 5-29, fewer than 10% of the samples made from aggregate sources A and C were stripped. Additionally, 27.27% of the samples fabricated from aggregate E were stripped. However, it should be noted that when aggregate source E was used with liquid ASA IV as well as with 0.07% liquid ASA V, those mixtures had serious stripping problems (Figure 5-30). These findings generally followed the trends from the ITS test results.

Table 5-10 Boiling Tests of Surface Type B Mixtures Containing Aggregates A-F and Various ASAs

	Surface Type B Mixture					
	Agg. A	Agg. B	Agg. C	Agg. D	Agg. E	Agg. F
Lime	N	N	N	N	N	N
I 0.5	N	N	N	N	N	N
I 0.7	N	N	N	N	N	N
II 0.5	N	N	N	N	N	N
II 0.7	N	N	N	N	N	N
III 0.4	N	N	N	N	N	N
III 0.7	N	N	N	N	N	N
IV 0.5	N	N	N	N	Y	N
IV 0.7	N	N	N	N	Y	N
V 0.07	Y	N	Y	N	Y	N
V 0.7	N	N	N	N	N	N

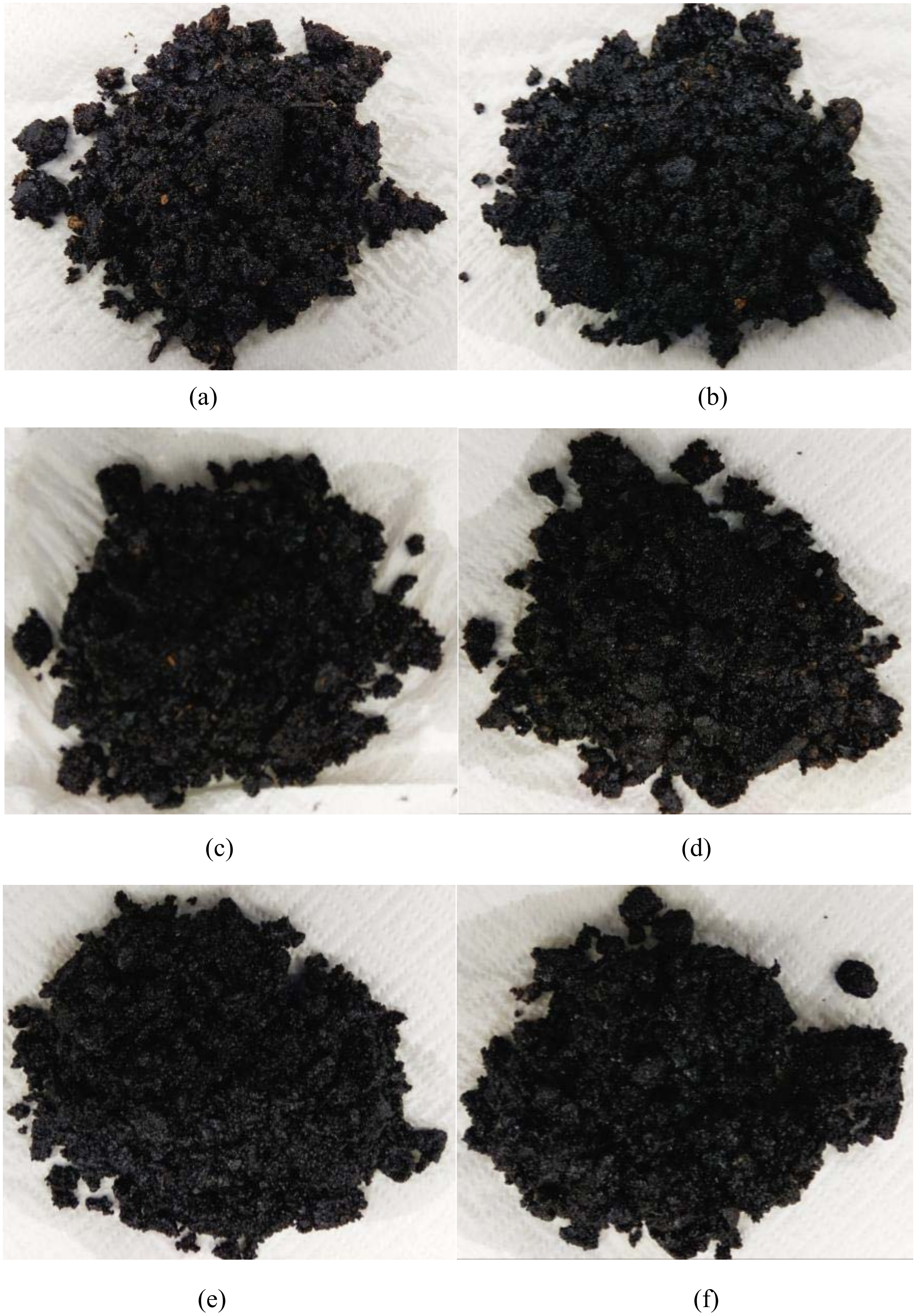
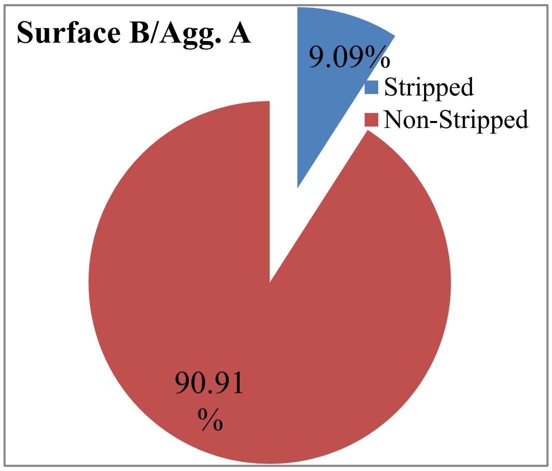
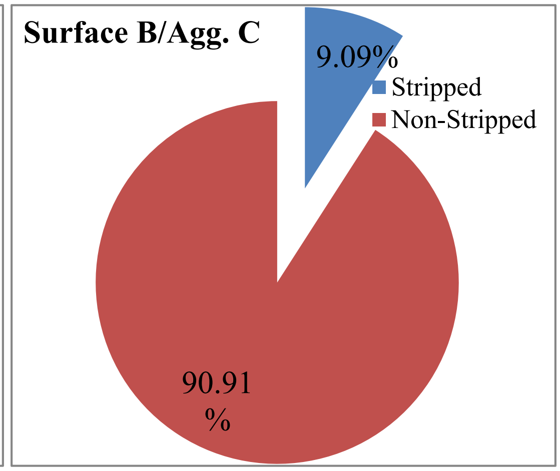
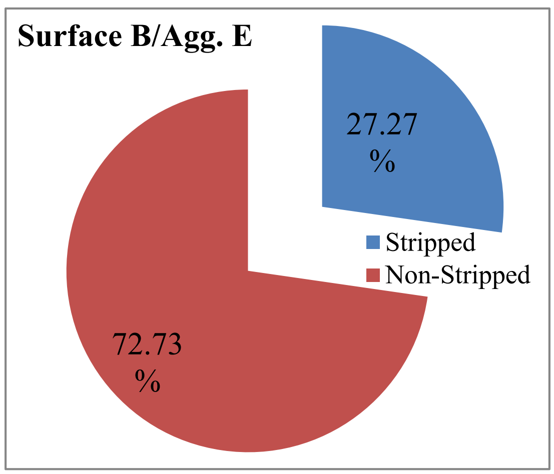


Figure 5-28 Non-Stripped Surface Type B Mixtures from Various Aggregate Sources (A-F) after Boiling Test Procedures: (a)-(f)



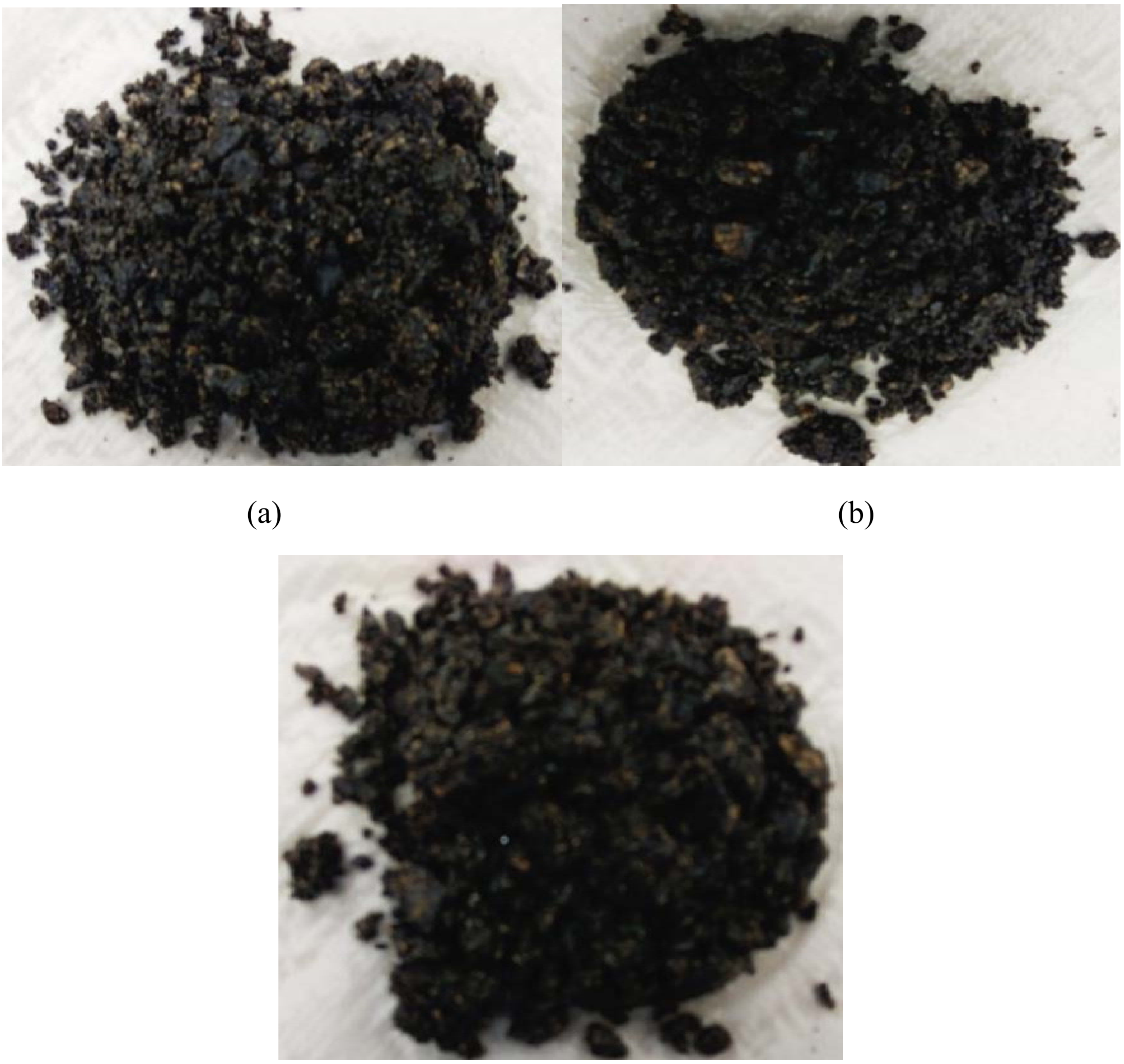


(a) (b)



(c)

Figure 5-29 Stripped vs. Non-Stripped Surface Type B Mixtures from Various Aggregate Sources after Boiling Test Procedures



(a) (b)

(c)

Figure 5-30 Stripped Surface Type B Mixtures from Various Aggregate Sources (A, C and E) after Boiling Test Procedures: (a)-(c)

5.10.2 Intermediate Type A Mixtures

A total of 132 samples (66 combinations) of Intermediate Type A mixtures were tested in this portion of the research study. As shown in Table 5-11 and Figure 5-31, it can be noted that in most cases, the Intermediate Type A mixtures were not stripped when this test was conducted with aggregate sources A-F. None of the samples made with aggregate sources C or F exhibited any signs of stripping in this portion of the research. In addition, as shown in Figure 5-32, fewer than 10% of the samples made from aggregate sources A, B, and C were stripped, as well as only 18.87% of the samples fabricated from aggregate E.

It should be noted that when aggregate sources A, B, D and E were used with 0.07% liquid ASA V as well as when aggregate E was used with 0.5% liquid ASA I, the mixtures had serious stripping problems (Figure 5-33). It could be seen that these aggregate sources significantly lost asphalt binder coverage, which would result in loss of adhesion in the mix.

Table 5-11 Boiling Tests of Intermediate Type A Mixtures Containing Aggregates A-F and Various ASAs

	Intermediate A Mixture					
	Agg. A	Agg. B	Agg. C	Agg. D	Agg. E	Agg. F
Lime	N	N	N	N	N	N
I 0.5	N	N	N	N	Y	N
I 0.7	N	N	N	N	N	N
II 0.5	N	N	N	N	N	N
II 0.7	N	N	N	N	N	N
III 0.4	N	N	N	N	N	N
III 0.7	N	N	N	N	N	N
IV 0.5	N	N	N	N	N	N
IV 0.7	N	N	N	N	N	N
V 0.07	Y	Y	N	Y	Y	N
V 0.7	N	N	N	N	N	N

(a)

(b)

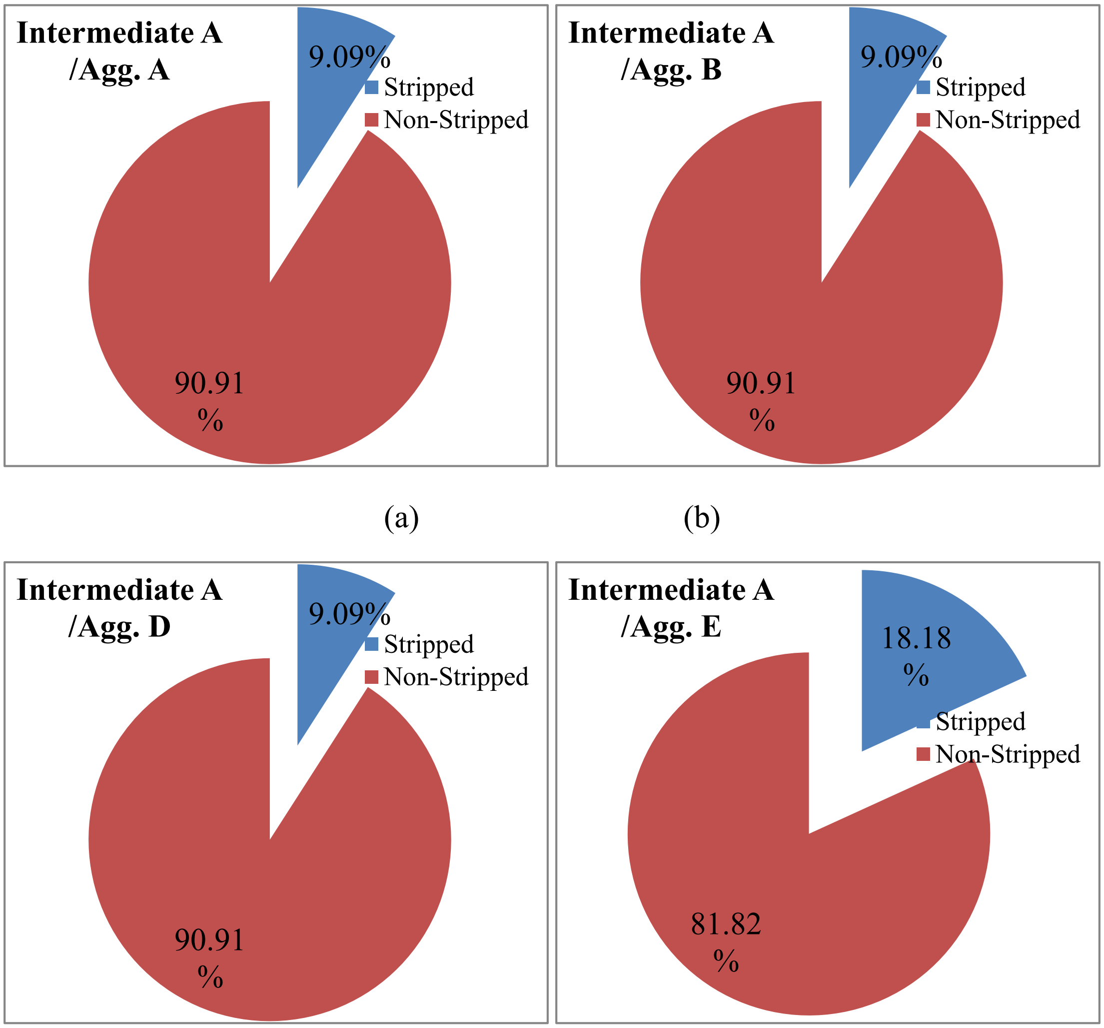
(c)

(d)

(e)

(f)

Figure 5-31 Non-Stripped Intermediate Type A Mixtures from Various Aggregate Sources (A-F) after Boiling Test Procedures: (a)-(f)



(a) (b)

(c) (d)

Figure 5-32 Stripped vs. Non-Stripped Intermediate Type A Mixtures from Various Aggregate Sources after Boiling Test Procedures

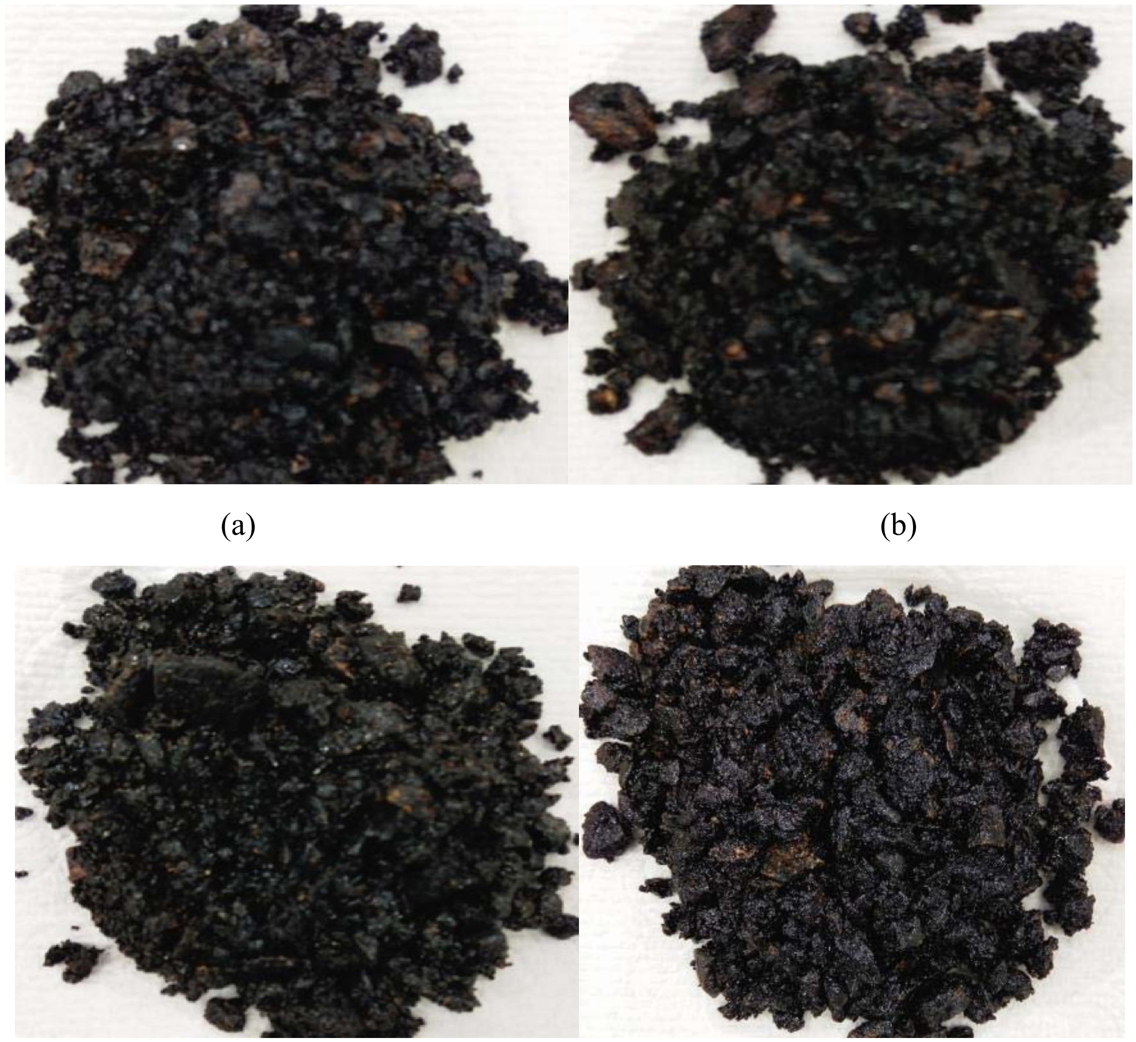


Figure 5-33 Stripped Intermediate Type A Mixtures from Various Aggregate Sources (A, B, D and E) after Boiling Test Procedures: (a)-(d)

5.10.3 Intermediate Type B Mixtures

A total of 132 Intermediate Type B samples (66 combinations) were tested to investigate the stripping characteristics using the boiling test procedures. As shown in Table 5-12 and Figure 5-34, it can be noted that in most cases, the Intermediate Type B mixtures were not stripped when this test was conducted with aggregate sources A-F. None of the samples made with aggregate sources A, B, or D exhibited any signs of stripping in this portion of the research. In addition, as shown in Figure 5-35, fewer than 10% of the samples made from aggregate sources C and F were stripped. However, a relatively high percentage of the samples made with aggregate source E (36.36%) showed signs of stripping.

It should be noted that when aggregate sources C, E, and F were used with 0.07% liquid ASA V, the mixtures exhibited serious stripping issues. In addition, when aggregate source E was used with liquid ASA I (both dosages) and 0.5% ASA IV, the mixtures also exhibited stripping damage. The images shown in Figure 5-36 illustrate that these aggregates significantly lost asphalt binder coverage.

Table 5-12 indicates that the mixtures were generally not stripped when the boiling test was conducted. Figure 5-34 shows that generally the mixtures made with aggregate sources A-F did not have any stripping damage. However, when the 0.07% dosage rate of liquid ASA V was used, the mixtures made with aggregate sources C, E, and F exhibited stripping issues. The images shown in Figure 5-36 illustrate that these aggregates significantly lost asphalt binder coverage. In addition, when liquid ASA I (both dosages) and 0.5% ASA IV were used, the mixtures had stripping damage as well.

Table 5-12 Boiling Tests of Intermediate Type B Mixtures Containing Aggregates A-F and Various ASAs

	Intermediate B Mixture					
	Agg. A	Agg. B	Agg. C	Agg. D	Agg. E	Agg. F
Lime	N	N	N	N	N	N
I 0.5	N	N	N	N	Y	N
I 0.7	N	N	N	N	Y	N
II 0.5	N	N	N	N	N	N
II 0.7	N	N	N	N	N	N
III 0.4	N	N	N	N	N	N
III 0.7	N	N	N	N	N	N
IV 0.5	N	N	N	N	Y	N
IV 0.7	N	N	N	N	N	N
V 0.07	N	N	Y	N	Y	Y
V 0.7	N	N	N	N	N	N

(a) (b)

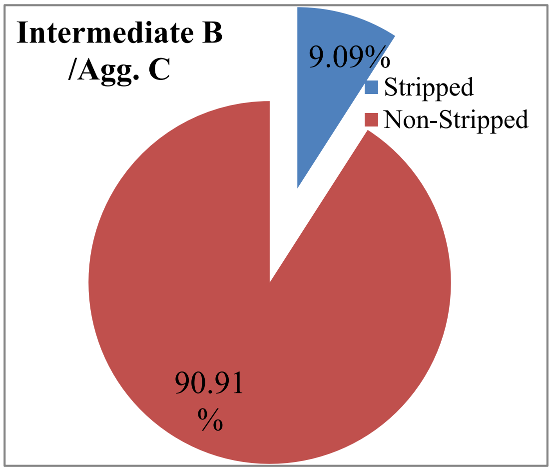
 

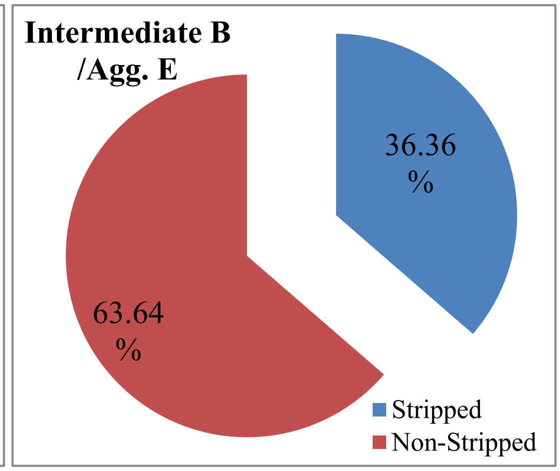
(c) (d)

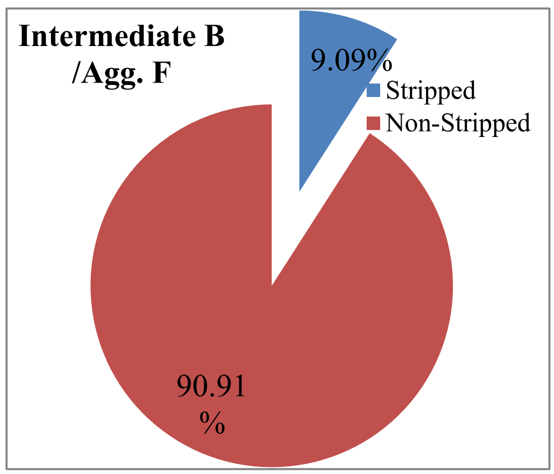
(e) (f)

Figure 5-34 Non-Stripped Intermediate Type B Mixtures from Various Aggregate Sources (A-F) after Boiling Test Procedures: (a)-(f)



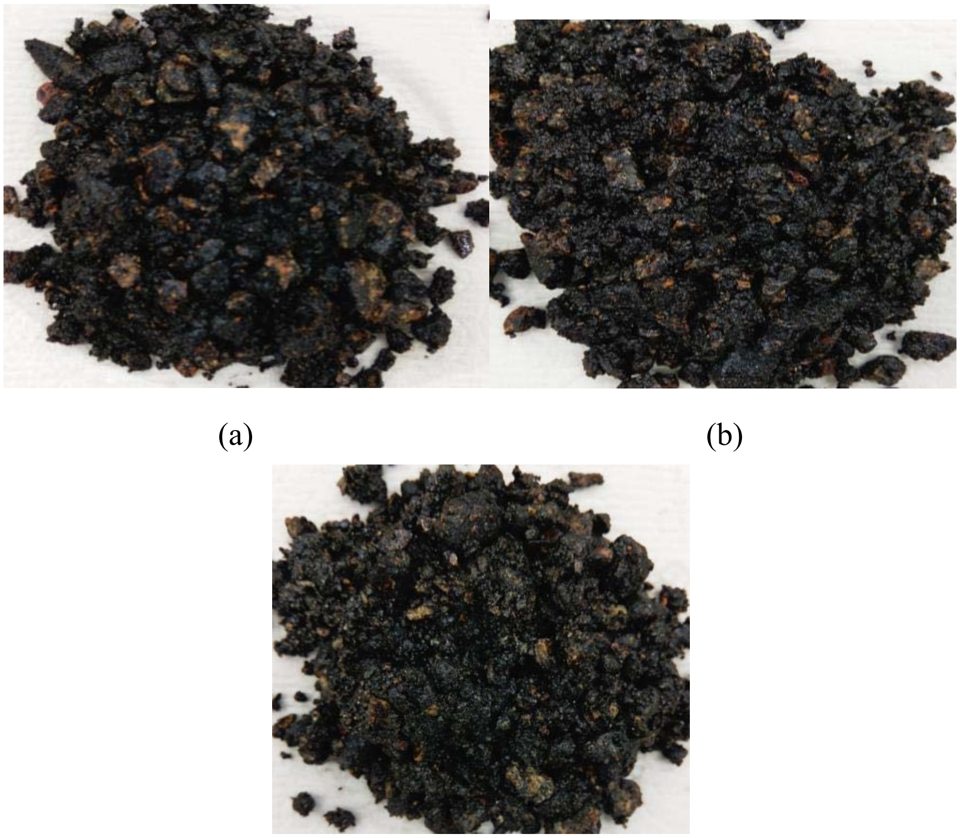


(a) (b)



(c)

Figure 5-35 Stripped vs. Non-Stripped Intermediate Type B Mixtures from Various Aggregate Sources after Boiling Test Procedures



(a) (b)

(c)

Figure 5-36: Stripped Intermediate Type B Mixtures from Various Aggregate Sources (C, E and F) after Boiling Test Procedures: (a)-(c)

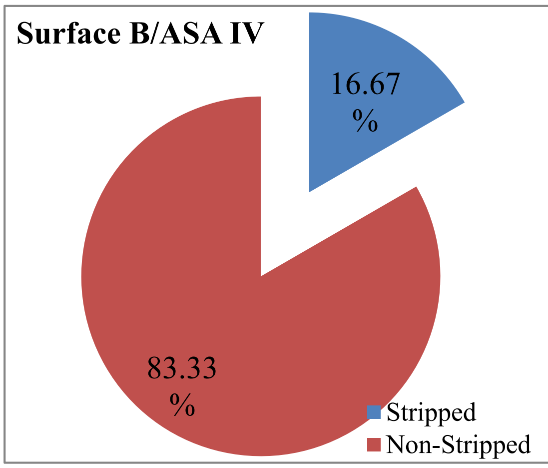
5.11 <u>Effect of ASA Type and Dosage Rate on Boiling Test Results</u>

5.11.1 Surface Type B Mixtures

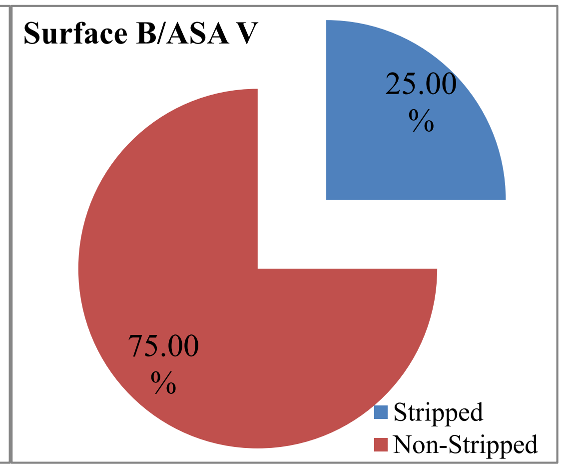
The boiling test is typically used to explore the moisture susceptibility of asphalt mixtures. South Carolina test method SC-T-69 provides the procedures for this test. As stated previously in this report, a total of 132 samples (66 combinations) of Surface Type B mixtures were tested in this portion of the study.

In terms of the influence of ASA type and dosage rate on Surface Type B mixtures, Table 5-10 in the previous section of this report shows that the Surface Type B mixtures containing either hydrated lime or liquid ASAs I-III were not stripped when this test was conducted, regardless of dosage rate and aggregate source. However, it can be noted that liquid ASAs IV and V had remarkable effects on the moisture susceptibility of these mixtures. As shown in Figure 5-37, several mixtures containing either liquid ASA IV or V exhibited signs of stripping. Most significantly, when liquid ASA V was used at the lower dosage rate recommended by the supplier (0.07%), samples made with half of the aggregate sources were stripped. Thus, it is not recommended to use such a low dosage rate of liquid ASA V in Surface Type B mixtures.

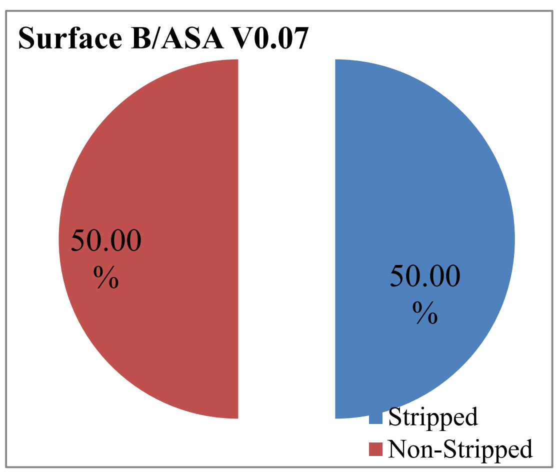
It can also be noted that when the higher dosage rate that meets current SCDOT requirements was utilized (0.7%), none of the mixtures containing liquid ASA V showed signs of stripping, regardless of aggregate source. However, when this same higher dosage rate (0.7%) was utilized for liquid ASA IV, the samples made with aggregate E still showed signs of stripping. Since aggregate E was the only aggregate source to exhibit stripping when used with liquid ASA IV, it may indicate a compatibility issue between aggregate E and liquid ASA IV.



(a)



(b)



(c)

Figure 5-37 Stripped vs. Non-Stripped Surface Type B Mixtures containing Various ASAs after Boiling Test Procedures

5.11.2 Intermediate Type A Mixtures

A total of 132 samples (66 combinations) of Intermediate Type A mixtures were tested in this portion of the research study.

With respect to the influence of ASA type and dosage rate on Intermediate Type A mixtures, Table 5-11 in the previous section of this report shows that the Intermediate Type A mixtures containing either hydrated lime or liquid ASAs II-IV were not stripped when this test was conducted, regardless of dosage rate and aggregate source. However, as shown in Figure 5-38, several mixtures containing either liquid ASA I or V exhibited signs of stripping. Most significantly, when liquid ASA V was used at the lower dosage rate recommended by the supplier (0.07%), samples made with two-thirds of the aggregate sources were stripped. Thus, it is not recommended to use such a low dosage rate of liquid ASA V in Intermediate Type A mixtures.

It can also be noted that with respect to liquid ASA I, only aggregate source E at the lower dosage rate recommended by the supplier (0.5%) showed signs of stripping. When the higher dosage rate that meets current SCDOT requirements was utilized (0.7%), none of the mixtures containing either liquid ASAs I or V showed signs of stripping, regardless of aggregate source.

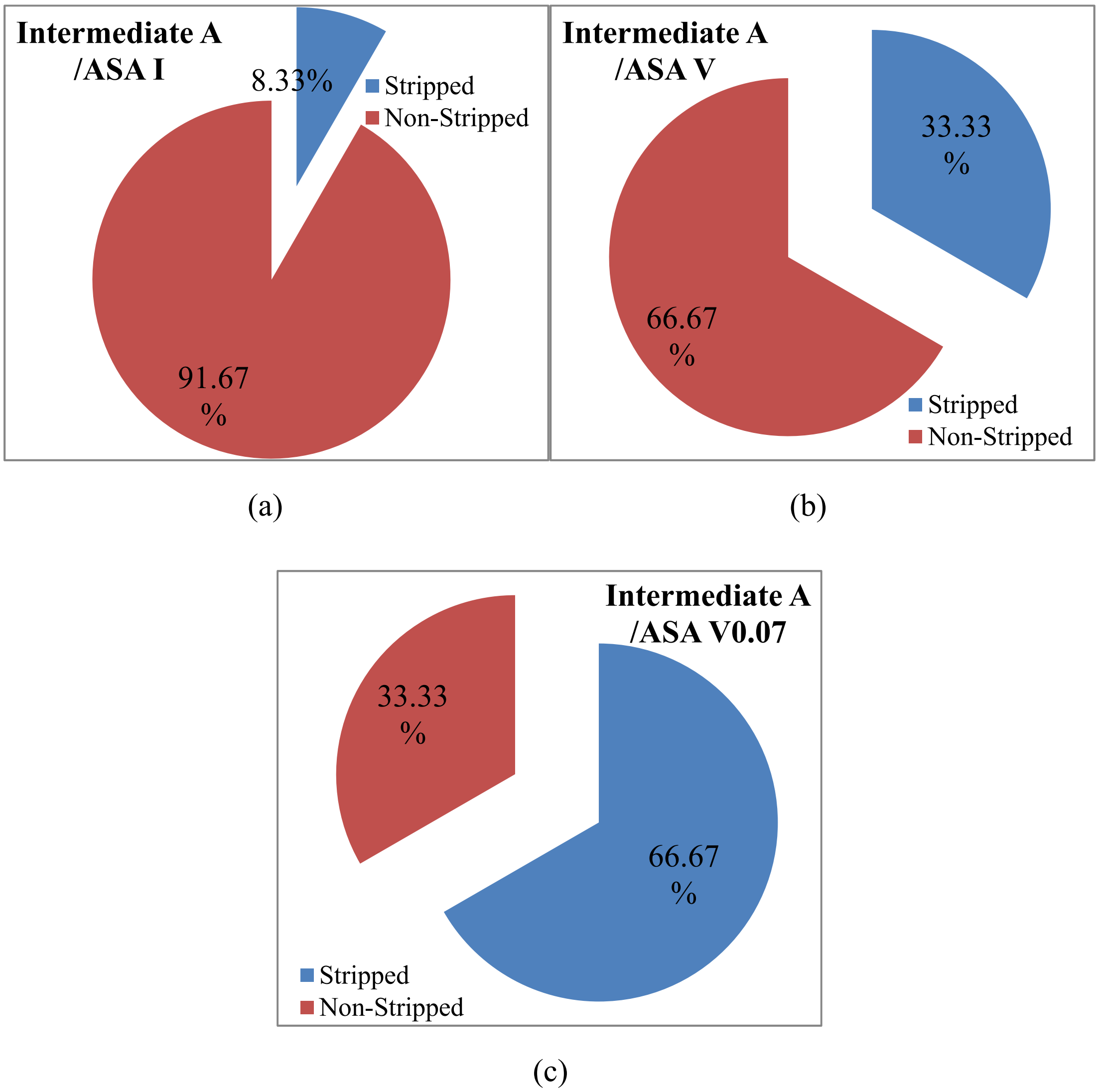


Figure 5-38 Stripped vs. Non-Stripped Intermediate Type A Mixtures containing Various ASAs after Boiling Test Procedures

5.11.3 Intermediate Type B Mixtures

A total of 132 samples (66 combinations) of Intermediate Type B mixtures were tested in this portion of the research study.

With respect to the influence of ASA type and dosage rate on Intermediate Type B mixtures, Table 5-12 in the previous section of this report shows that the Intermediate Type B mixtures containing either hydrated lime, liquid ASA II, or liquid ASA III were not stripped when this test was conducted, regardless of dosage rate and aggregate source. However, as shown in Figure 5-39, several mixtures containing either liquid ASA I, IV, or V exhibited signs of stripping. Most significantly, when liquid ASA V was used at the lower dosage rate recommended by the supplier (0.07%), samples made with half of the aggregate sources were stripped. Thus, it is not recommended to use such a low dosage rate of liquid ASA V in Intermediate Type B mixtures.

It can also be noted that with respect to liquid ASAs I and IV, only aggregate source E showed signs of stripping. In addition, when the higher dosage rate that meets current SCDOT requirements was utilized (0.7%), none of the mixtures containing liquid ASAs IV or V showed signs of stripping, regardless of aggregate source. However, when this same higher dosage rate (0.7%) was utilized for liquid ASA I, the samples made with aggregate E still showed signs of stripping. Since aggregate E was the only aggregate source to exhibit stripping when used with liquid ASA I, it may indicate a compatibility issue between aggregate E and liquid ASA I.

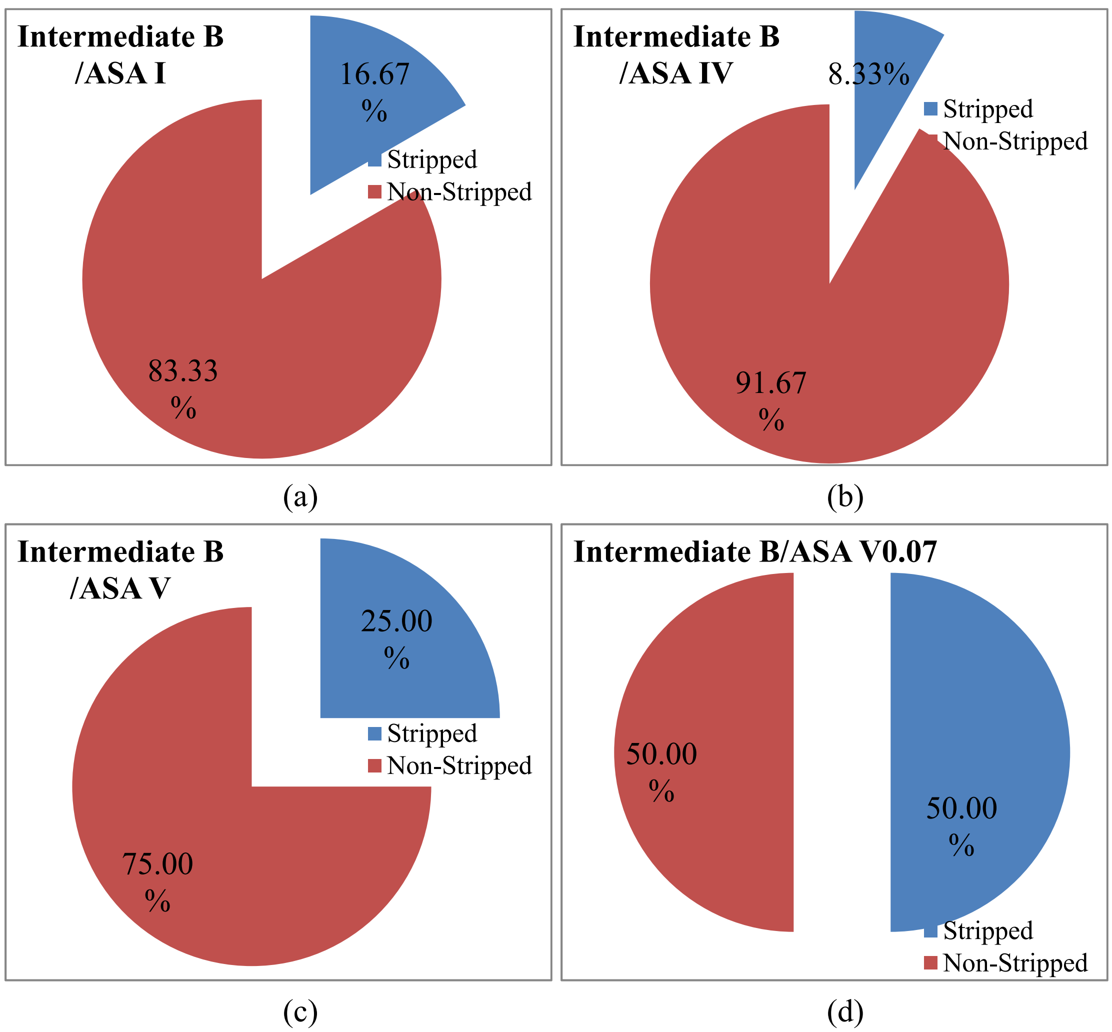


Figure 5-39 Stripped vs. Non-Stripped Intermediate Type B Mixtures containing Various ASAs after Boiling Test Procedures

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

Based on the results, the following conclusions were reached:

1. The literature review indicated that moisture susceptibility is a complex phenomenon dependent upon the mechanisms and interactions of the asphalt binder and the aggregate. The nature of these mechanisms and their interaction makes it difficult to predict with certainty the characteristics of various factors in determining moisture susceptibility. In general, moisture susceptibility is increased by any factor that increases moisture content in the hot mix asphalt (HMA) mixture, decreases the adhesion of asphalt binder to the aggregate surface, or physically scours the asphalt binder.
2. The literature review also indicated that there are many treatments to improve the moisture sensitivity of HMA mixtures. These treatments can be simply grouped into those that are added to the binder and those that are added to the aggregate. The most common chemicals used to reduce moisture sensitivity are alkyl amines, which are generally added to the binder, and hydrated lime, which is added to the aggregates. The results indicate that both liquid ASAs and hydrated lime can improve the moisture sensitivity of HMA. In addition, those ASAs also have influence on pavement behaviors such as rutting, fatigue, raveling and so forth.
3. The wet ITS values of all mixtures were greater than 65 psi (448 kPa) regardless of aggregate source, ASA type, and mixture type, which meets the minimum wet ITS requirements for mix design per SCDOT 2007 Standard Specifications.
4. There were statistically-significant differences between the wet ITS values of mixtures made with various aggregate sources. Aggregate sources E and A were generally the lowest.
5. There were statistically-significant differences between the wet ITS values of mixtures made with various liquid ASA sources when used with aggregate sources E and A but not with the other aggregate sources.
6. As expected, the dry ITS values were generally higher than wet ITS values. The wet ITS values of aggregate sources A and E and/or 0.07% liquid ASA source V were much lower than the corresponding dry ITS values.
7. The flow values of various mixtures were generally close to 0.06 inches (1.5 mm), although the wet flow values were generally higher than dry flow values of the mixtures.
8. Aggregate source significantly affected flow values.
9. Liquid ASA dosage rate slightly affected flow values. For some mixtures, a higher liquid ASA dosage rate resulted in higher flow values.
10. Neither mix type nor liquid ASA type significantly affected flow values.
11. All mixtures containing hydrated lime produced TSR values that were greater than 85%, regardless of mix type and aggregate source.

12. Liquid ASA sources II and III generally produced TSR values of at least 85% regardless of aggregate source and dosage rate.
13. When aggregates A and E were utilized with some liquid ASA sources, the TSR values were found to be less than 85%.
14. Some other mixtures containing liquid ASA source I and 0.07% liquid ASA source V produced TSR values of less than 85%.
15. The boiling test results indicated that there were no stripping issues when hydrated lime was utilized in the mixtures.
16. The boiling test (SC-T-69 test procedure) identified stripping problems of mixtures made with aggregate source E, as well as with mixtures containing 0.07% liquid ASA source V, regardless of mixture type.
17. In general, the aggregate source significantly affected the moisture susceptibility of asphalt mixtures.
18. Intermediate Type A and B mixtures generally exhibited better moisture resistance compared to Surface Type B mixtures. This might be due to their differences in gradations and the interactions of the binder with the aggregate particles.
19. The results indicated that liquid ASAs could generally be used for producing Intermediate Type A and B mixtures. However, for Surface Type B mixtures, the effectiveness of the liquid ASAs was strongly dependent upon the aggregate source.
20. The dosage rate of liquid ASAs affected the moisture susceptibility of mixtures in some cases. For instance, in some cases, the liquid ASA was not as effective at a lower dosage rate compared to the higher dosage rate tested in this research project. Thus, the SCDOT's currently-recommended dosage rate of 0.7% (by weight of base binder) was necessary for some liquid ASAs to be effective.

6.2 <u>Recommendations</u>

Based on the test results and data analysis, the following recommendations are made:

1. It is recommended that SCDOT consider specifying the use of liquid ASAs in Surface Type B mixtures as well as in Intermediate Type A and Intermediate Type B mixtures. However, since most of the aggregate and ASA sources used in this research project played essential roles in determining the moisture susceptibility of these asphalt mixtures, it is also recommended that this decision should be made on a case-by-case basis at the mix design stage based on the results of ITS values, TSR values, and boiling test results of the specific aggregate source and ASA type being proposed in the mix design.
2. It is also recommended that SCDOT conduct a study analyzing the effects of liquid ASAs on the performance of SCDOT mixtures containing PG 76-22 binder (Surface Type A and OGFC mixtures) as well as the performance of SCDOT mixtures containing both hydrated lime and liquid ASAs (occurs in some warm mix asphalt mixtures).
3. It is also recommended that SCDOT conduct a study to investigate the effects of the chemical composition of aggregates on the moisture susceptibility of asphalt mixtures

made with these aggregates. The interaction and bonding capabilities of the aggregate and liquid ASA should be addressed.

Appendix A

Dry and Wet ITS Values of Surface Type B, Intermediate Type A and Intermediate Type B Mixtures Made with Various ASA Types by Aggregate Source

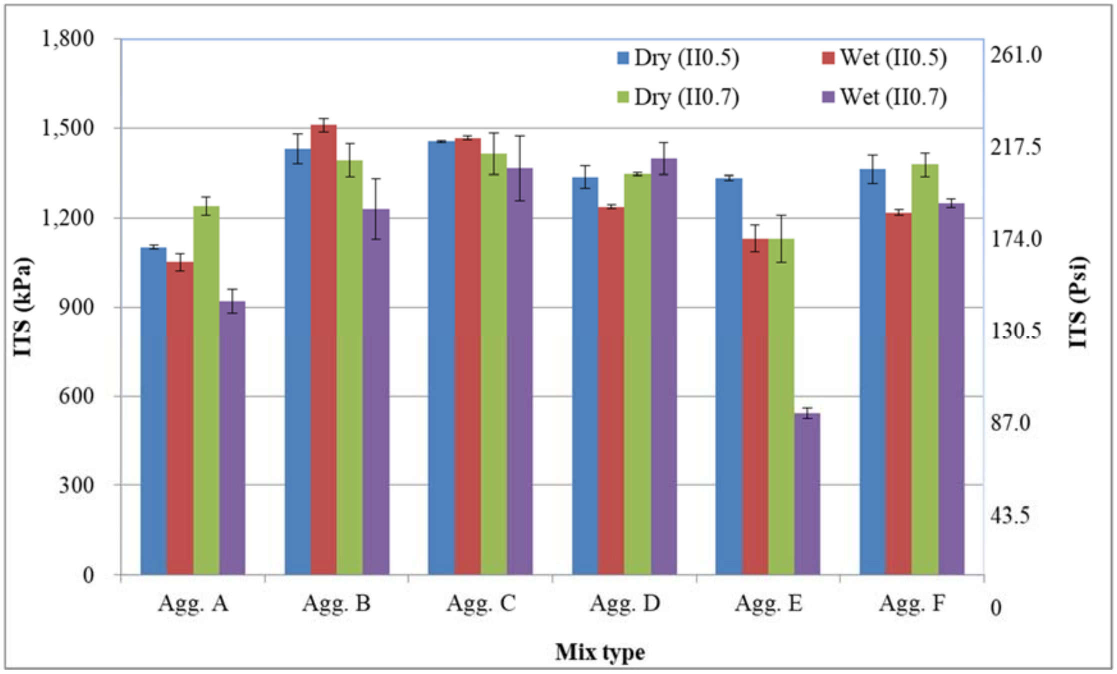


Figure 7-1 Dry and Wet ITS Values of Surface Type B Mixtures Containing Liquid ASA II and Various Aggregate Sources

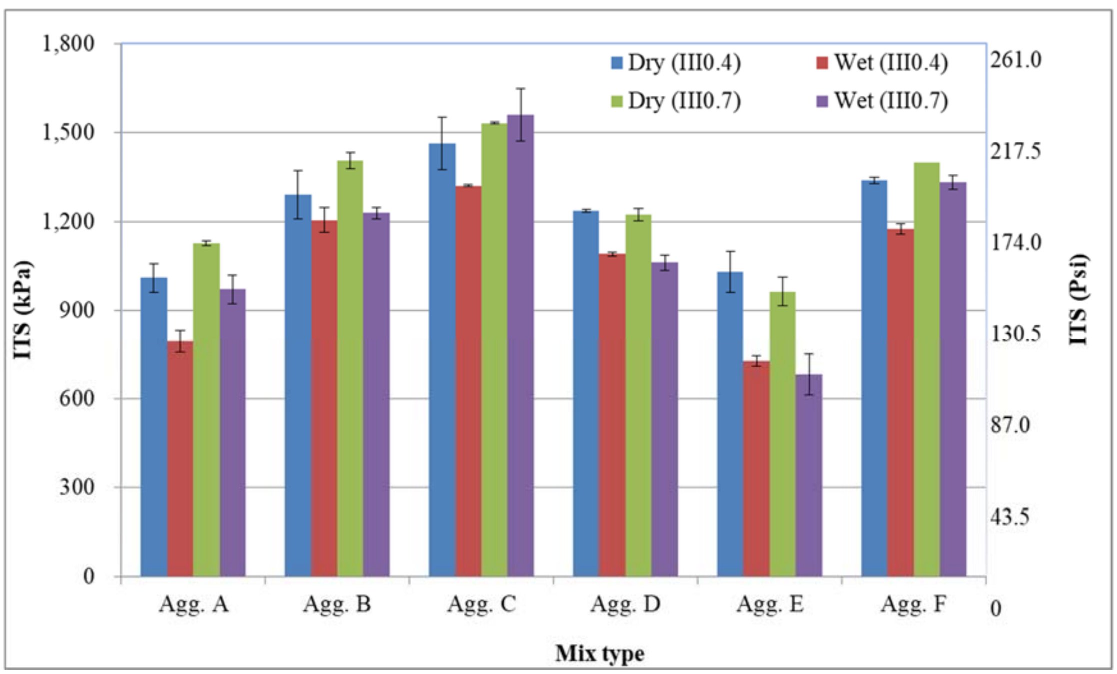


Figure 7-2 Dry and Wet ITS Values of Surface Type B Mixtures Containing Liquid ASA III and Various Aggregate Sources

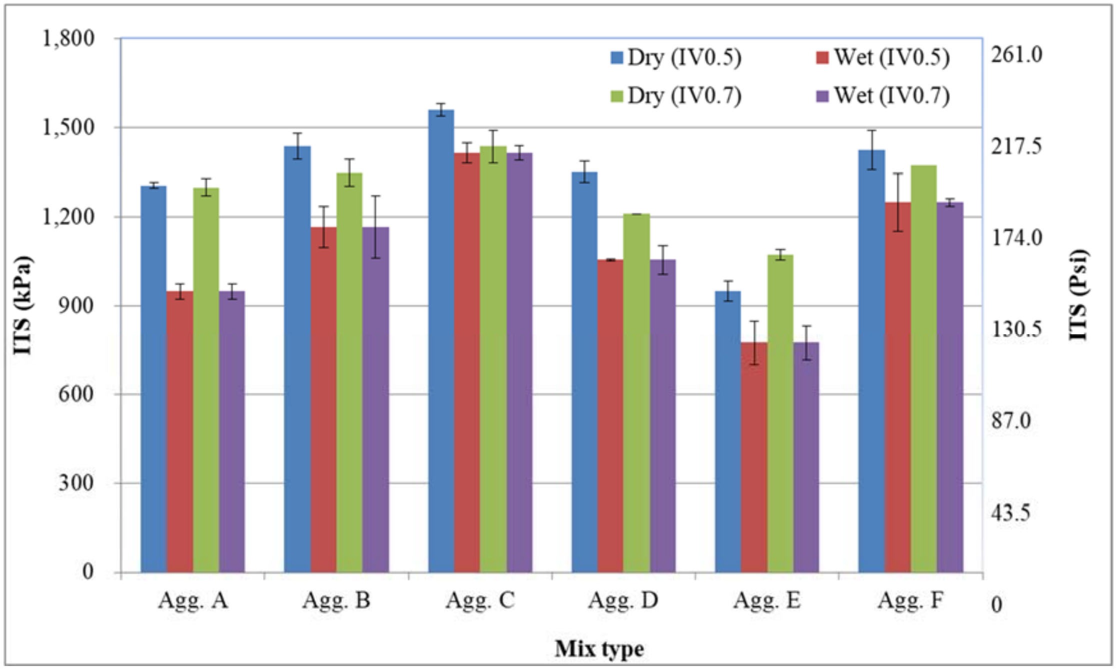


Figure 7-3 Dry and Wet ITS Values of Surface Type B Mixtures Containing Liquid ASA IV and Various Aggregate Sources

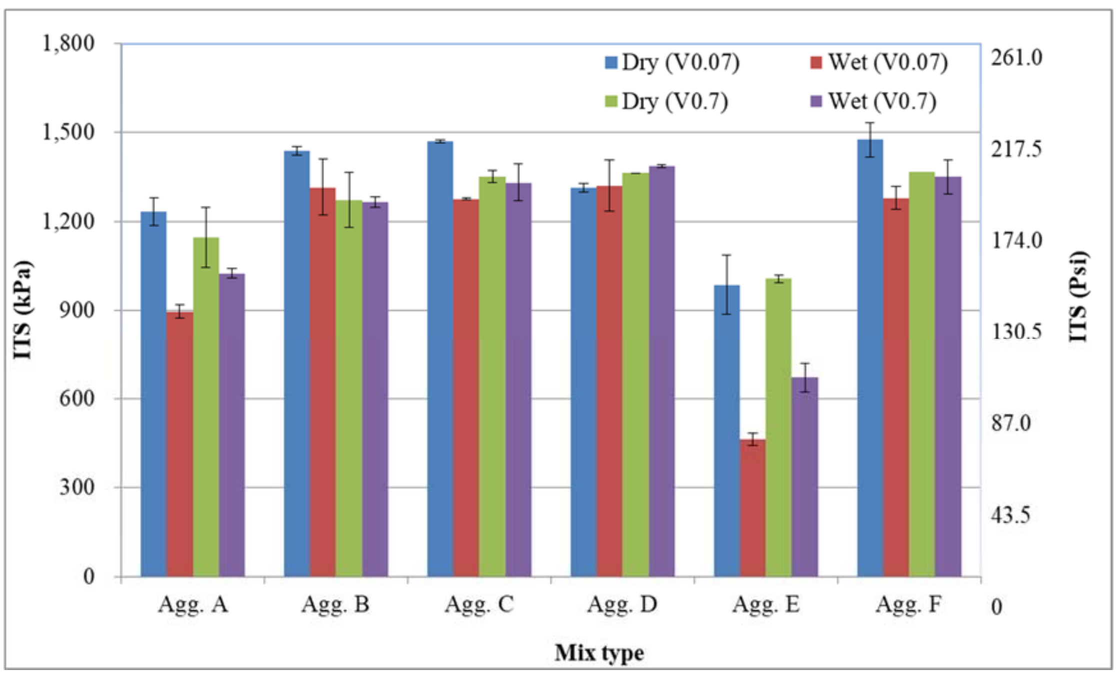


Figure 7-4 Dry and Wet ITS Values of Surface Type B Mixtures Containing Liquid ASA V and Various Aggregate Sources

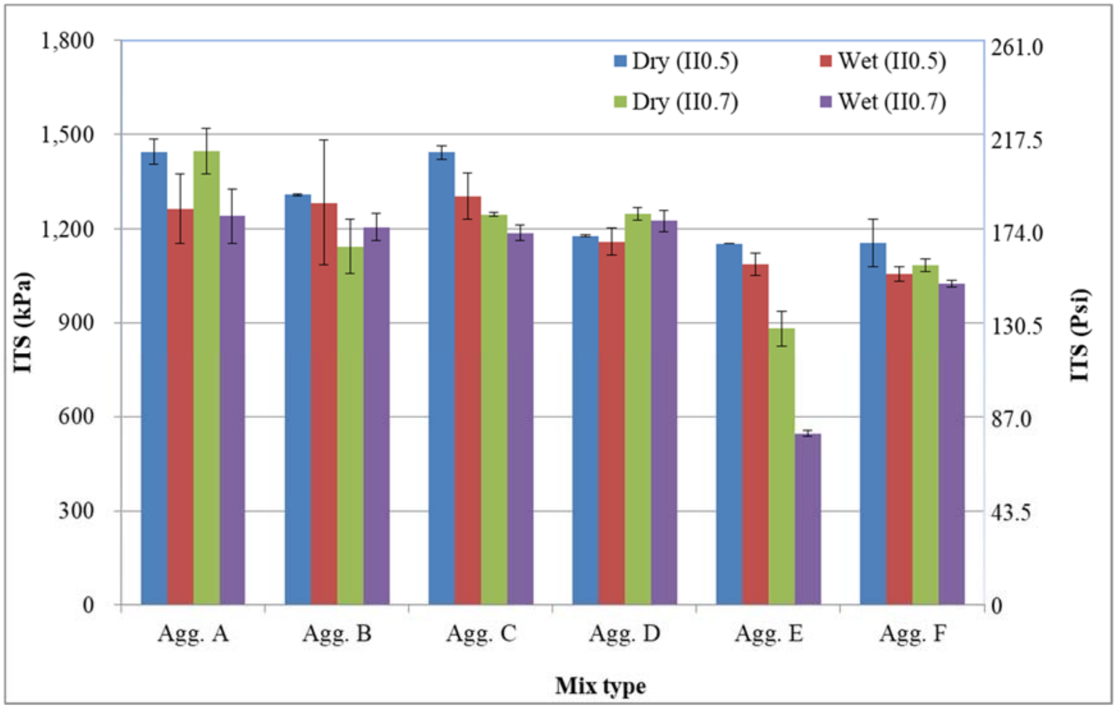


Figure 7-5 Dry and Wet ITS Values of Intermediate Type A Mixtures Containing Liquid ASA II and Various Aggregate Sources

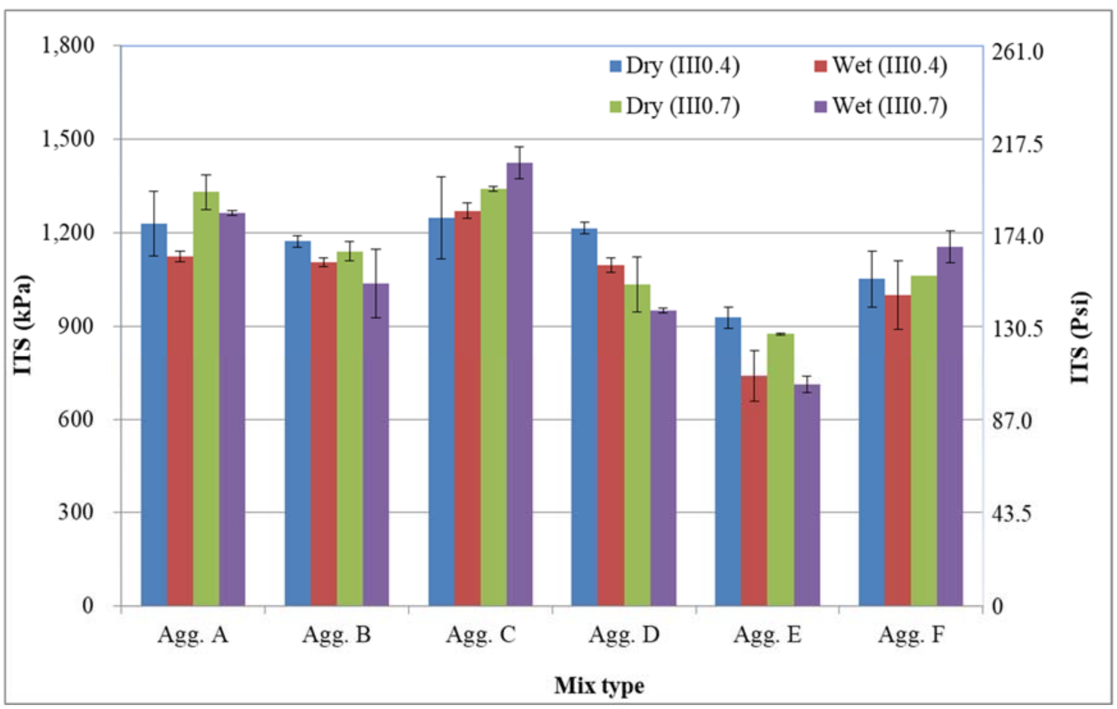


Figure 7-6 Dry and Wet ITS Values of Intermediate Type A Mixtures Containing Liquid ASA III and Various Aggregate Sources

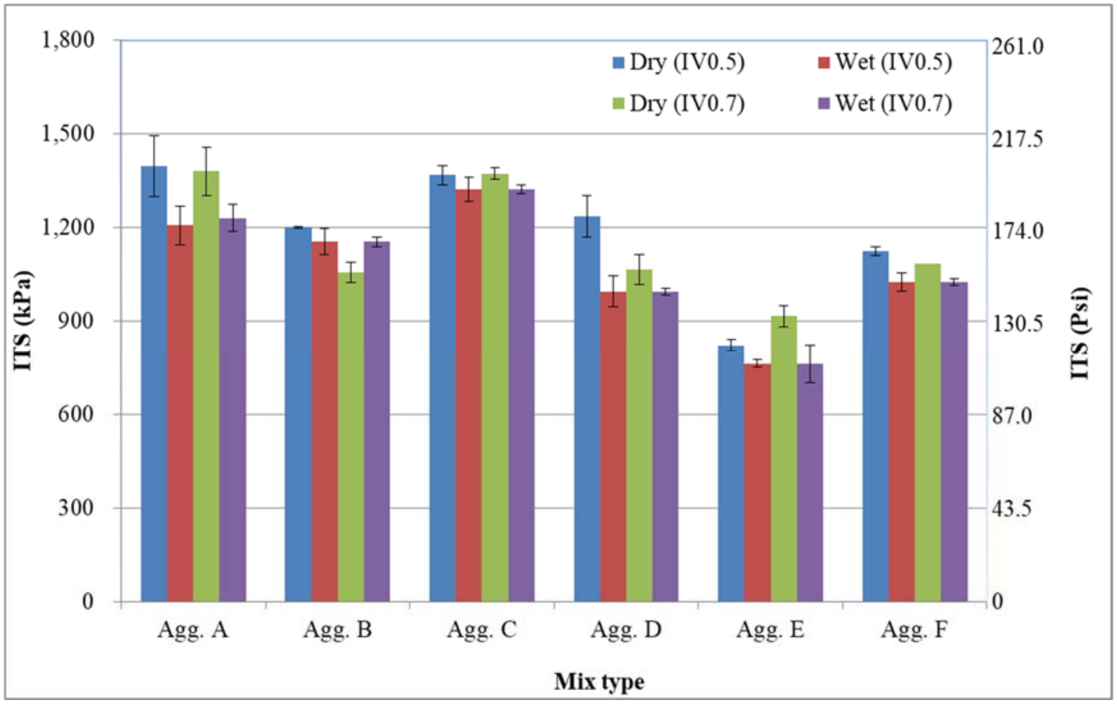


Figure 7-7 Dry and Wet ITS Values of Intermediate Type A Mixtures Containing Liquid ASA IV and Various Aggregate Sources

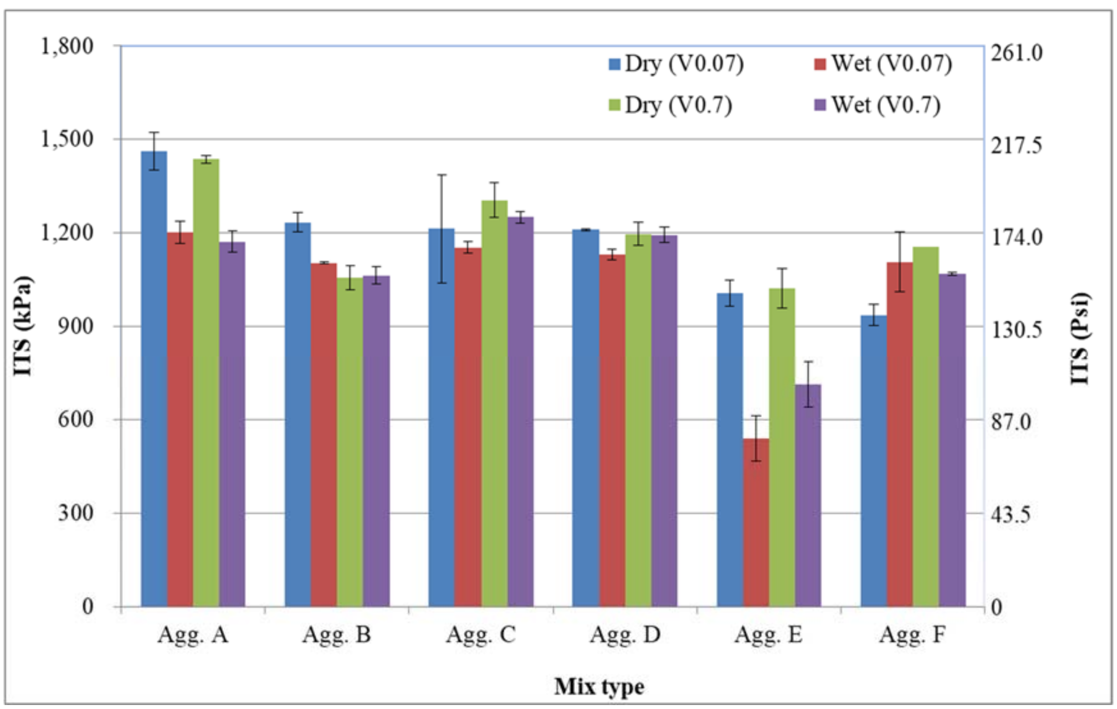


Figure 7-8 Dry and Wet ITS Values of Intermediate Type A Mixtures Containing Liquid ASA V and Various Aggregate Sources

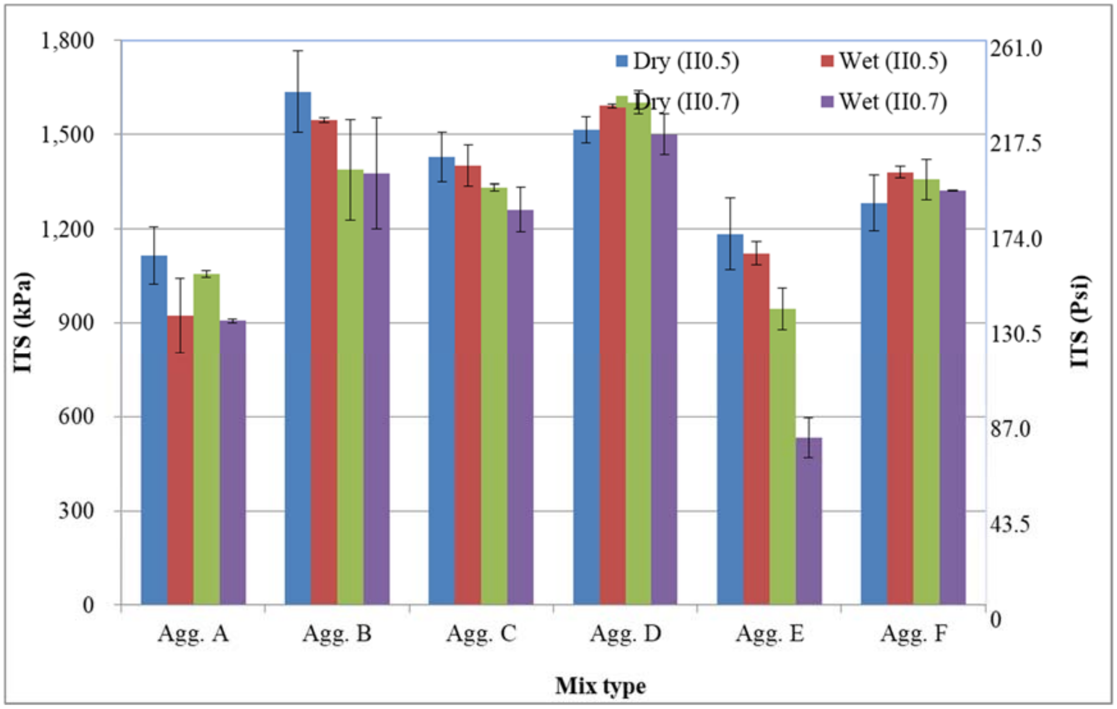


Figure 7-9 Dry and Wet ITS Values of Intermediate B mixtures Containing Liquid ASA II and Various Aggregate Sources

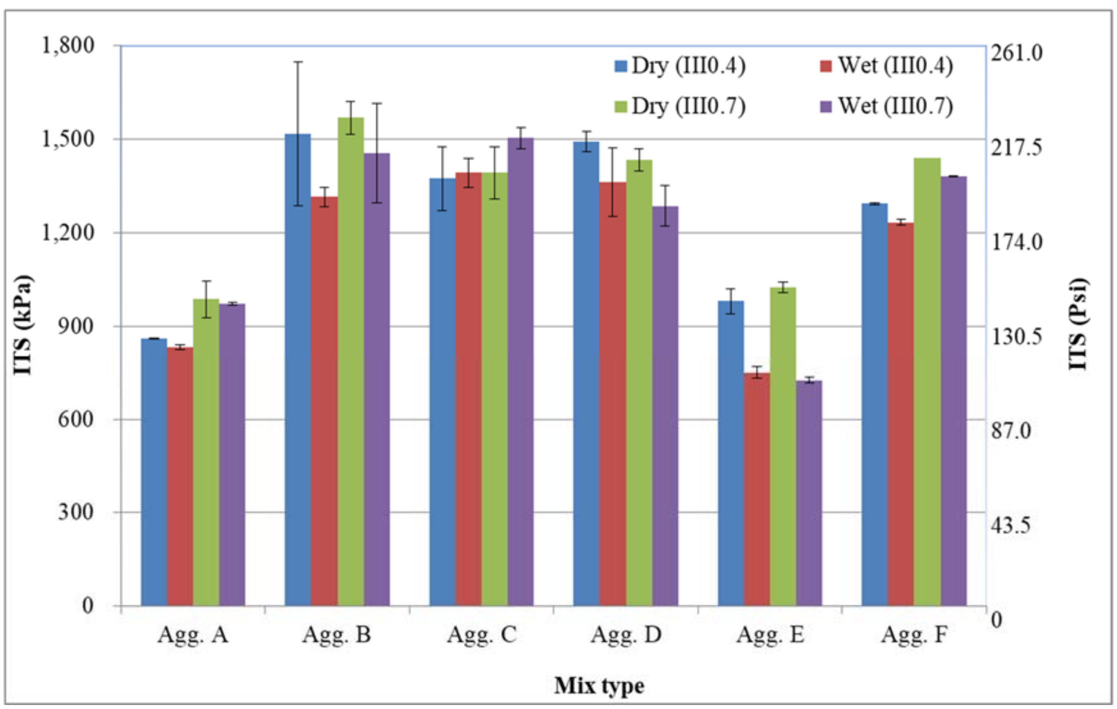


Figure 7-10 Dry and Wet ITS Values of Intermediate B mixtures Containing Liquid ASA III and Various Aggregate Sources

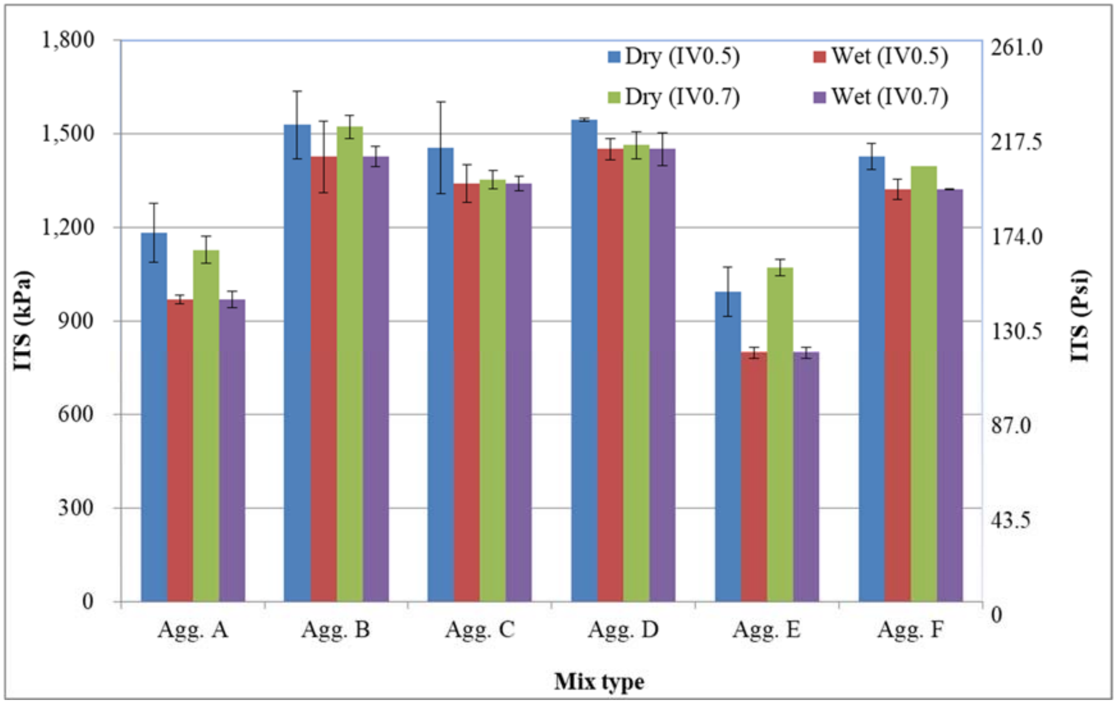


Figure 7-11 Dry and Wet ITS Values of Intermediate B mixtures Containing Liquid ASA IV and Various Aggregate Sources

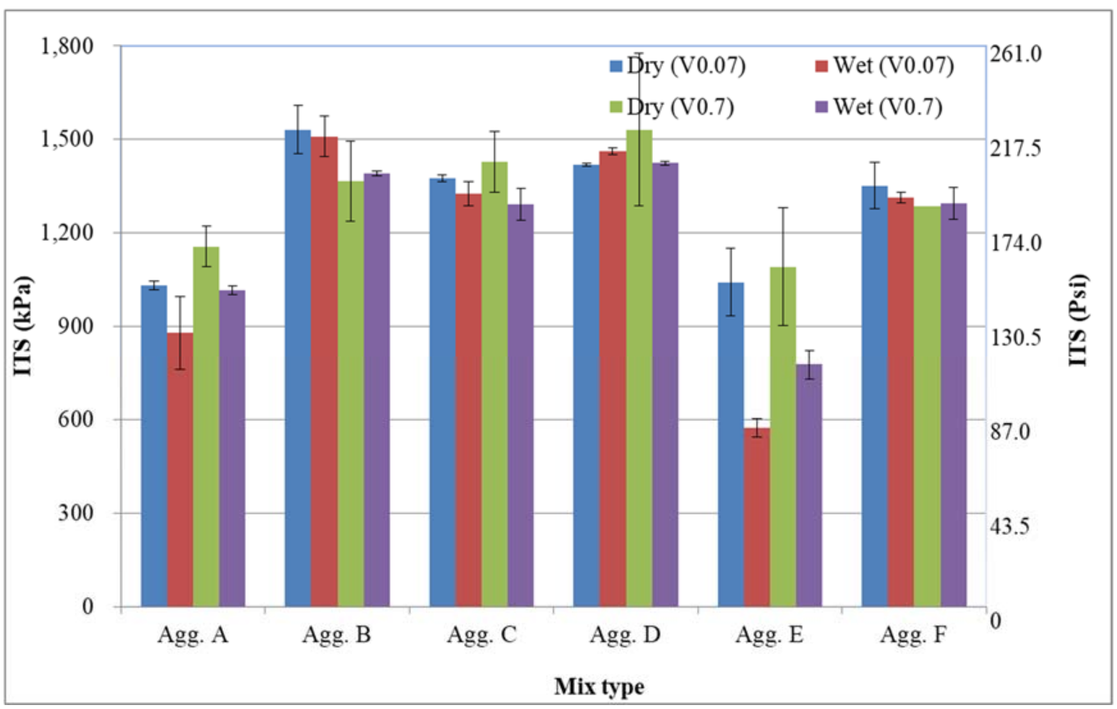


Figure 7-12 Dry and Wet ITS Values of Intermediate B mixtures Containing Liquid ASA V and Various Aggregate Sources

Appendix B

Dry and Wet ITS Values of Surface Type B, Intermediate Type A and Intermediate Type B Mixtures Made with Various Aggregate Sources by ASA Type

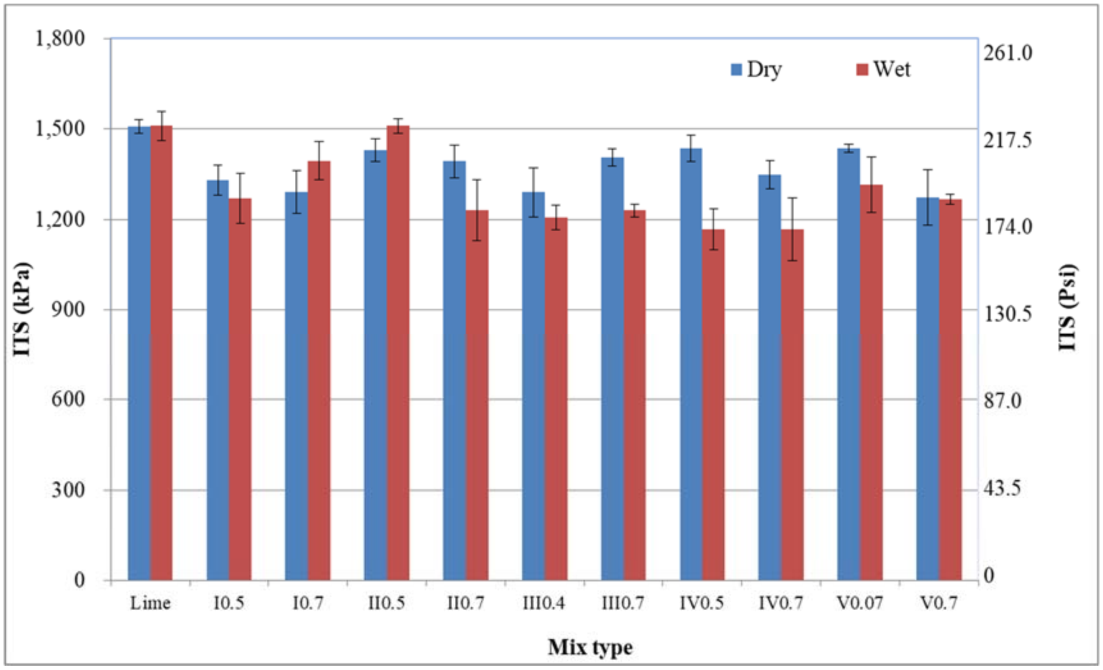


Figure 8-1 Dry and Wet ITS Values of Surface Type B Mixtures Containing Aggregate Source B and Various ASAs

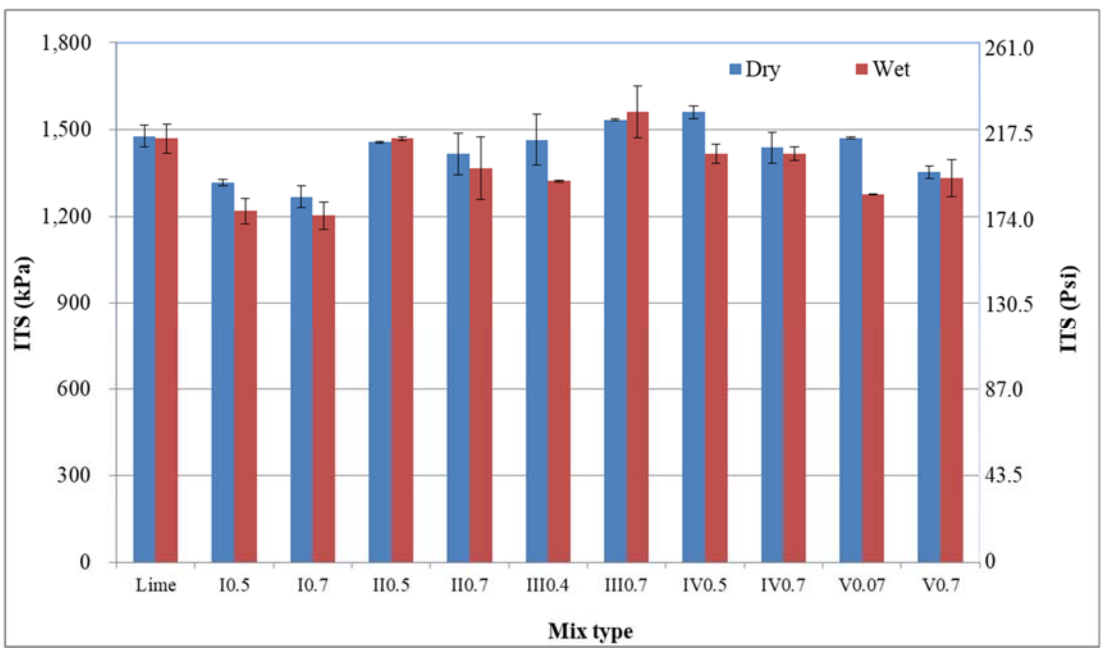


Figure 8-2 Dry and Wet ITS Values of Surface Type B Mixtures Containing Aggregate Source C and Various ASAs

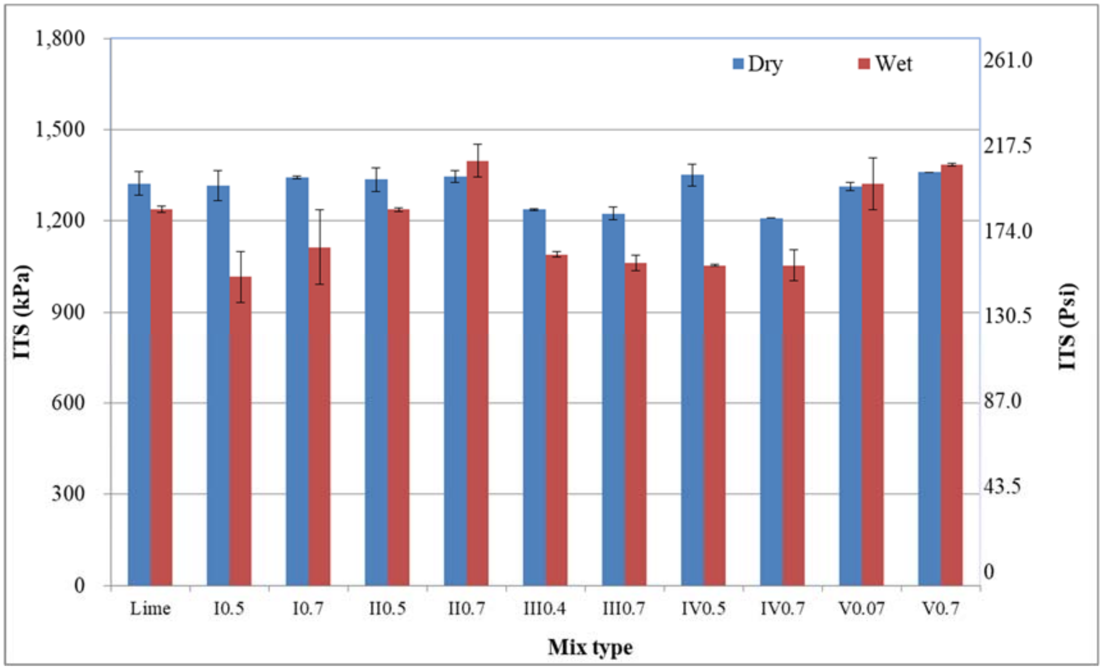


Figure 8-3 Dry and Wet ITS Values of Surface Type B Mixtures Containing Aggregate Source D and Various ASAs

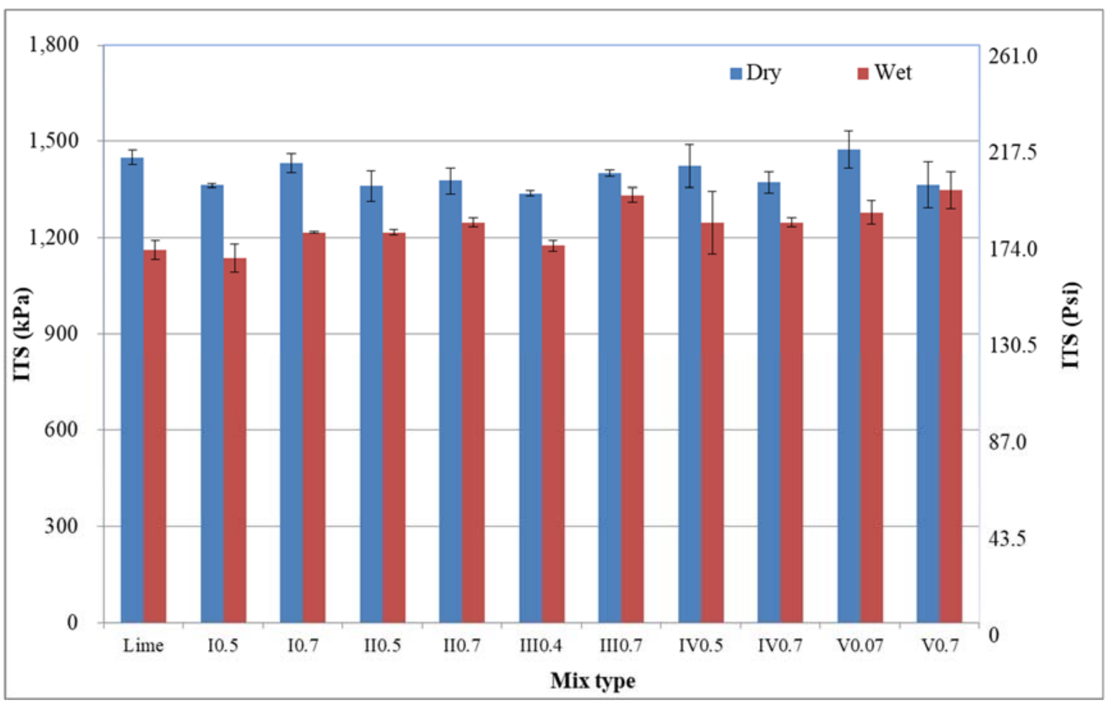


Figure 8-4 Dry and Wet ITS Values of Surface Type B Mixtures Containing Aggregate Source F and Various ASAs

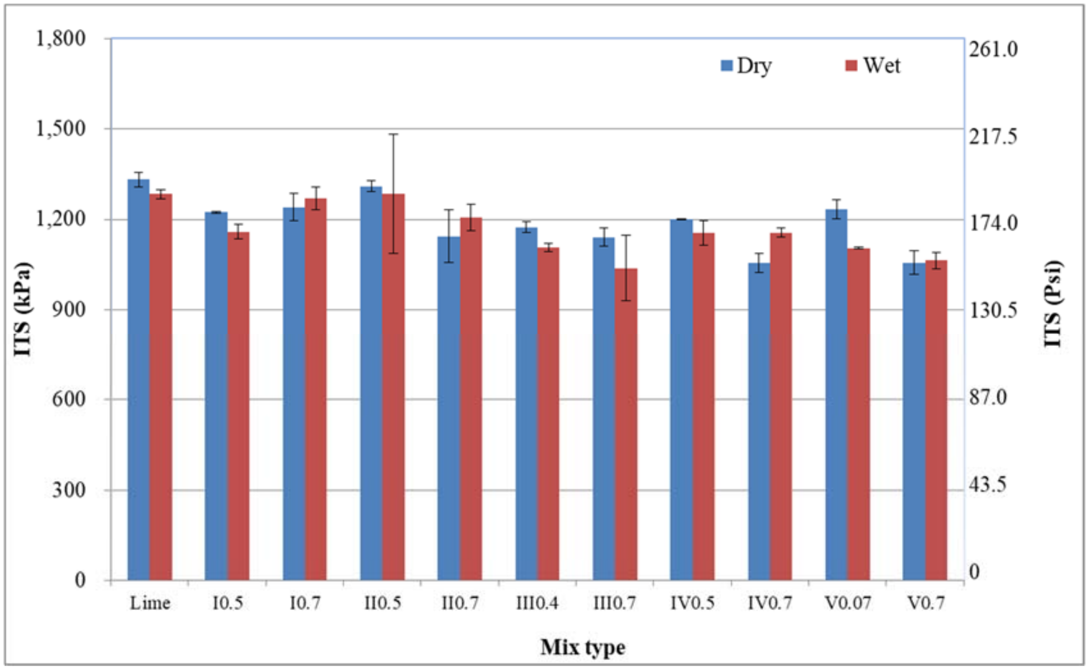


Figure 8-5 Dry and Wet ITS Values of Intermediate Type A Mixtures Containing Aggregate Source B and Various ASAs

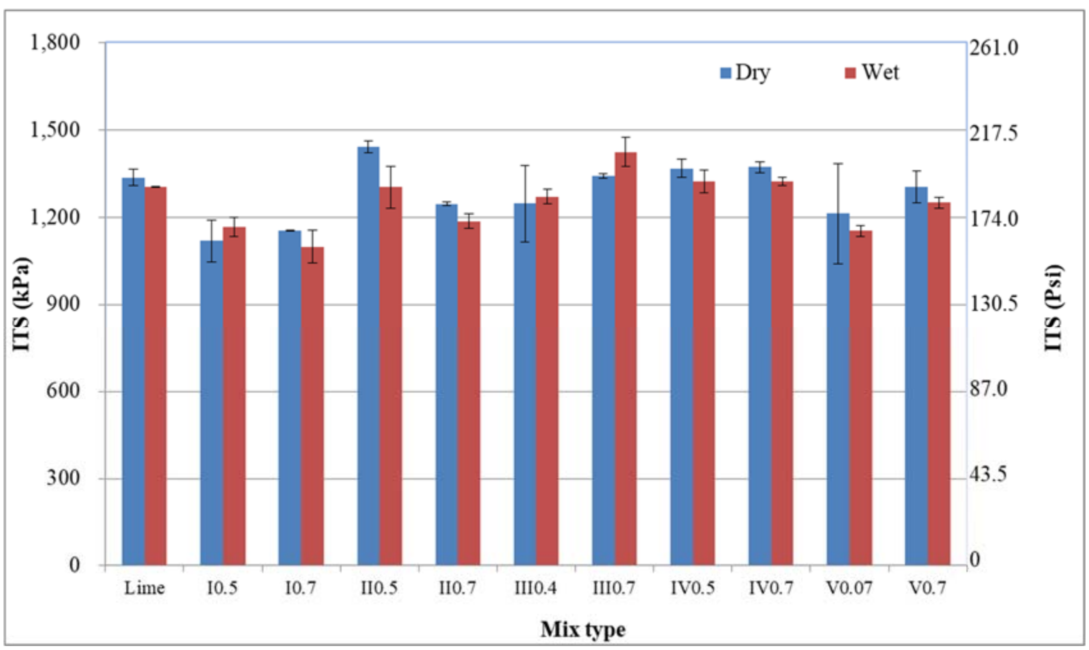


Figure 8-6 Dry and Wet ITS Values of Intermediate Type A Mixtures Containing Aggregate Source C and Various ASAs

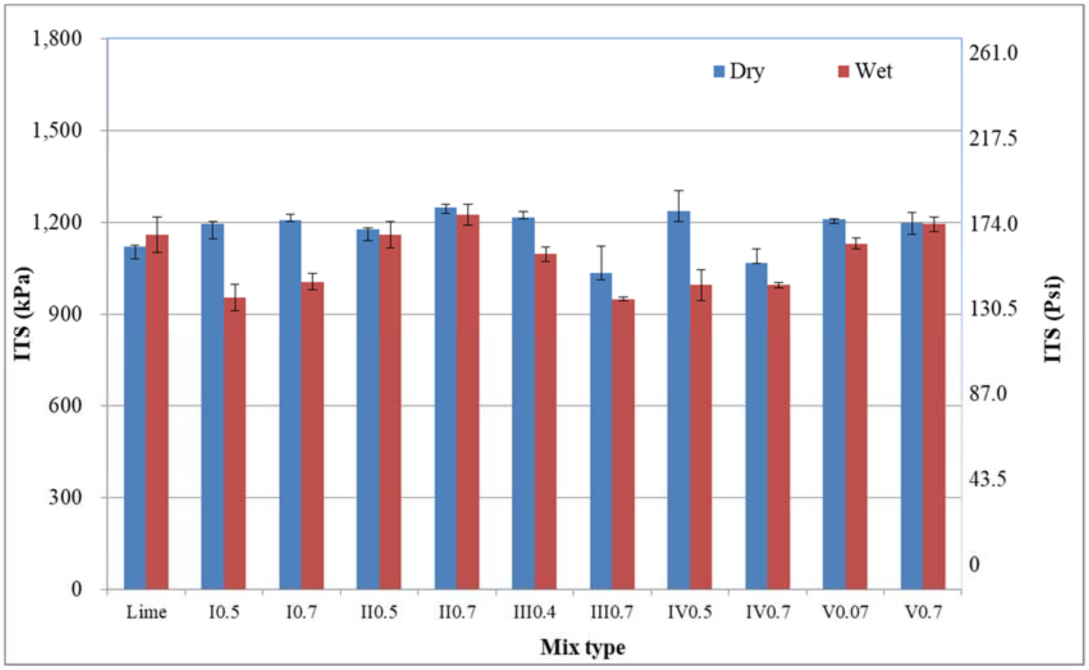


Figure 8-7 Dry and Wet ITS Values of Intermediate Type A Mixtures Containing Aggregate Source D and Various ASAs

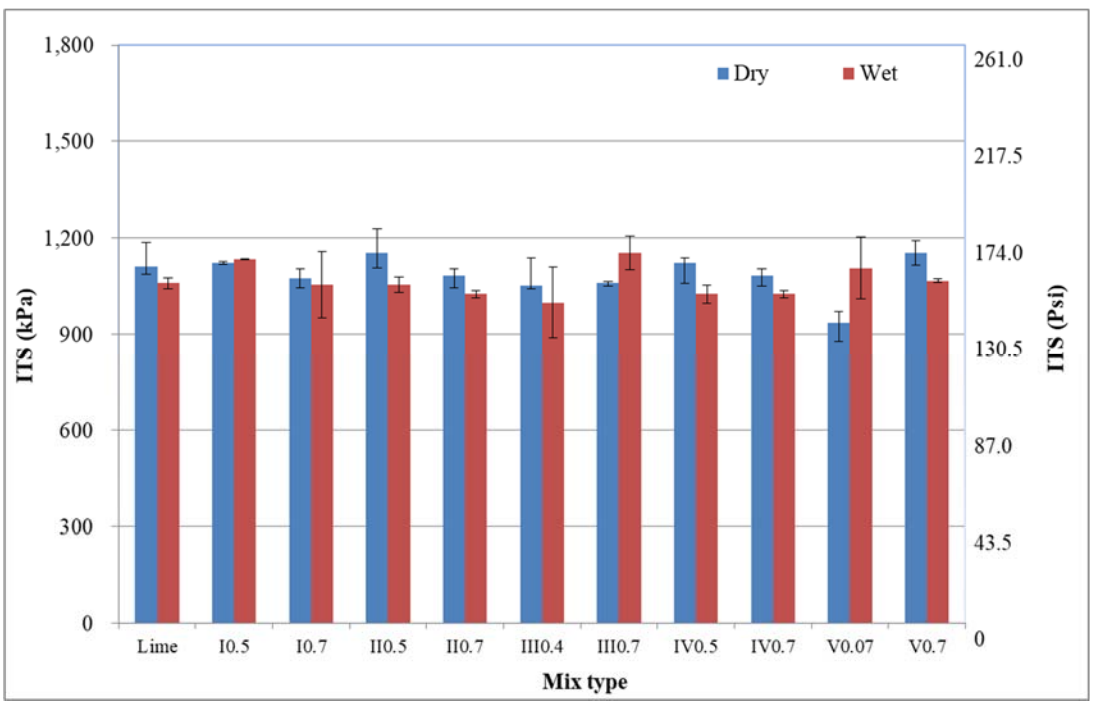


Figure 8-8 Dry and Wet ITS Values of Intermediate Type A Mixtures Containing Aggregate Source F and Various ASAs

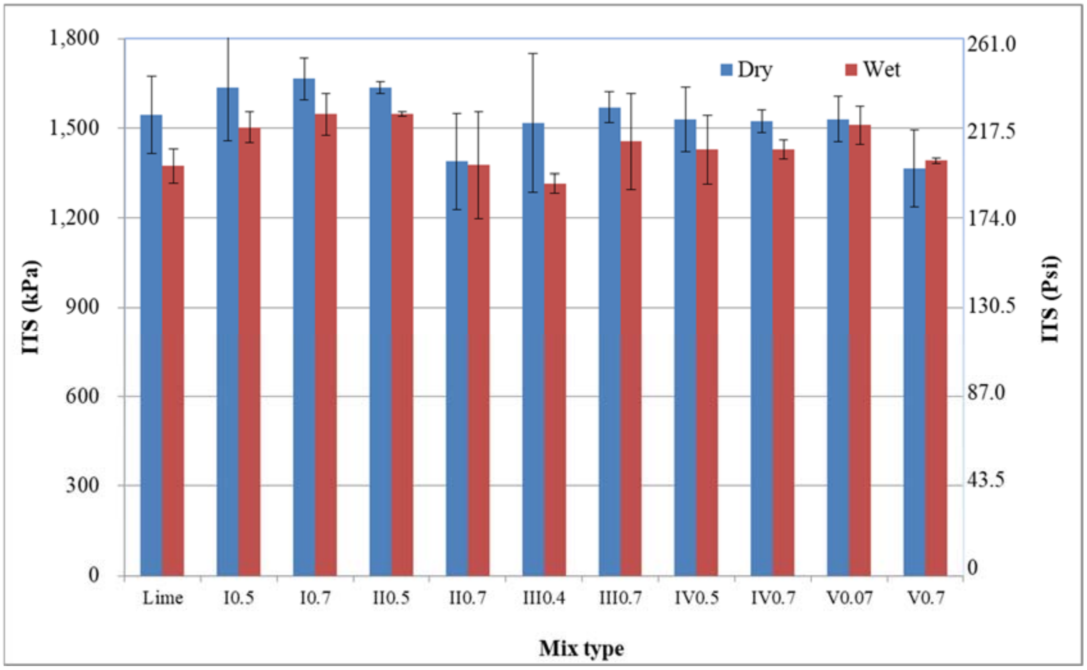


Figure 8-9 Dry and Wet ITS Values of Intermediate Type B Mixtures Containing Aggregate Source B and Various ASAs

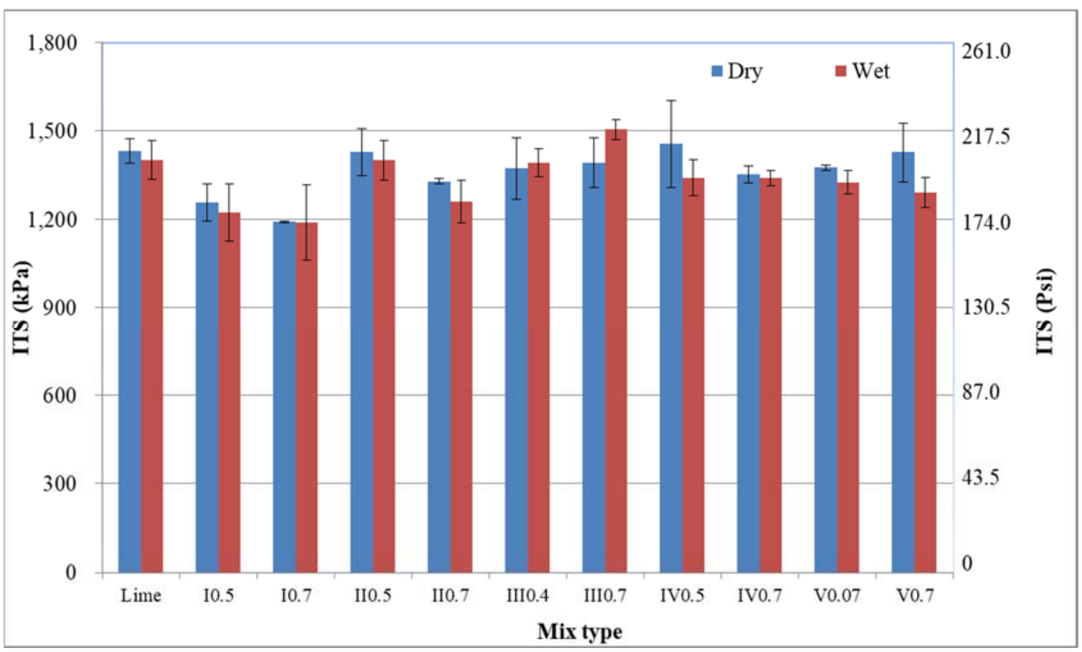


Figure 8-10 Dry and Wet ITS Values of Intermediate Type B Mixtures Containing Aggregate Source C and Various ASAs

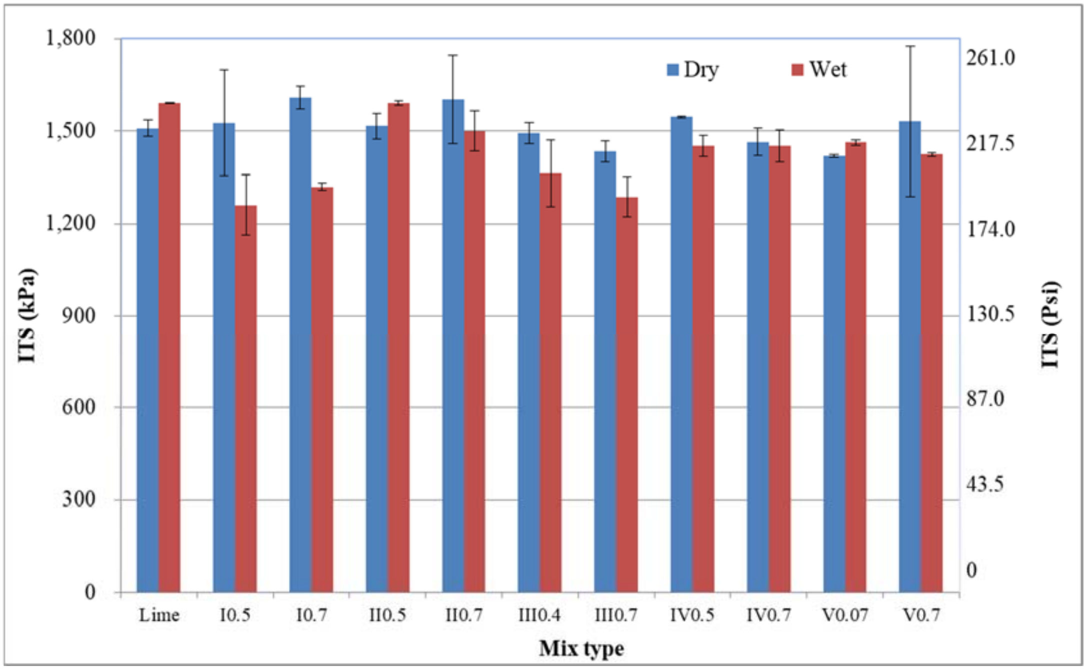


Figure 8-11 Dry and Wet ITS Values of Intermediate Type B Mixtures Containing Aggregate Source D and Various ASAs

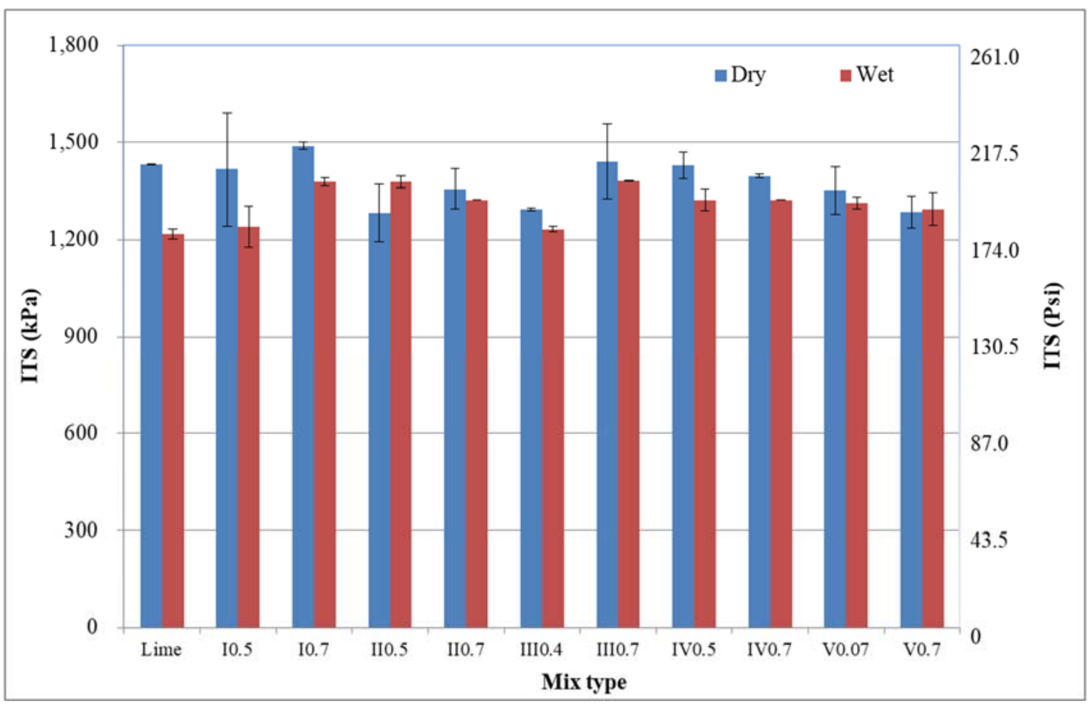


Figure 8-12 Dry and Wet ITS Values of Intermediate Type B Mixtures Containing Aggregate Source F and Various ASAs

Appendix C

ANOVA Analysis of Dry and Wet Flow Values of Surface Type B, Intermediate Type A and Intermediate Type B Mixtures Containing Various ASAs and Aggregate Sources

Table 9-1 ANOVA Analysis of Dry Flow Values from Surface Type B Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	7.26	1.21	0.01
I0.5	6	7.95	1.33	0.01
I0.7	6	7.91	1.32	0.02
II0.5	6	8.01	1.34	0.01
II0.7	6	7.90	1.32	0.01
III0.4	6	7.84	1.31	0.01
III0.7	6	8.10	1.35	0.01
IV0.5	6	7.99	1.33	0.01
IV0.7	6	7.96	1.33	0.01
V0.07	6	8.04	1.34	0.01
V0.7	6	8.34	1.39	0.04
Agg. A	11	14.41	1.31	0.00
Agg. B	11	15.18	1.38	0.01
Agg. C	11	14.90	1.35	0.02
Agg. D	11	13.74	1.25	0.00
Agg. E	11	15.81	1.44	0.00
Agg. F	11	13.27	1.21	0.00

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	0.112903	10	0.01129	2.003539	0.052745	2.026143
Columns	0.401008	5	0.080202	14.23232	1.16E-08	2.400409
Error	0.281759	50	0.005635			
Total	0.79567	65				

Table 9-2 ANOVA Analysis of Wet Flow Values from Surface Type B Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	7.59	1.27	0.02
I0.5	6	8.34	1.39	0.01
I0.7	6	7.98	1.33	0.01
II0.5	6	7.86	1.31	0.01
II0.7	6	7.89	1.31	0.01
III0.4	6	8.24	1.37	0.01
III0.7	6	8.08	1.35	0.00
IV0.5	6	7.63	1.27	0.00
IV0.7	6	8.26	1.38	0.01
V0.07	6	7.66	1.28	0.01
V0.7	6	8.15	1.36	0.01
Agg. A	11	14.94	1.36	0.01
Agg. B	11	14.53	1.32	0.00
Agg. C	11	14.41	1.31	0.00
Agg. D	11	13.64	1.24	0.00
Agg. E	11	16.17	1.47	0.00
Agg. F	11	14.00	1.27	0.01

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	0.118509	10	0.011851	3.983931	0.000487	2.026143
Columns	0.354007	5	0.070801	23.80139	3.66E-12	2.400409
Error	0.148734	50	0.002975			
Total	0.62125	65				

Table 9-3 ANOVA Analysis of Dry Flow Values from Intermediate Type A Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	7.15	1.19	0.00
I0.5	6	8.01	1.34	0.01
I0.7	6	8.05	1.34	0.01
II0.5	6	7.94	1.32	0.00
II0.7	6	8.00	1.33	0.01
III0.4	6	7.90	1.32	0.01
III0.7	6	8.37	1.39	0.02
IV0.5	6	7.87	1.31	0.01
IV0.7	6	8.29	1.38	0.02
V0.07	6	7.92	1.32	0.03
V0.7	6	8.17	1.36	0.01
Agg. A	11	13.23	1.20	0.00
Agg. B	11	15.65	1.42	0.02
Agg. C	11	15.02	1.37	0.02
Agg. D	11	14.59	1.33	0.01
Agg. E	11	15.13	1.38	0.00
Agg. F	11	14.06	1.28	0.00

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	0.166896	10	0.01669	2.45249	0.018048	2.026143
Columns	0.337321	5	0.067464	9.913671	1.25E-06	2.400409
Error	0.340258	50	0.006805			
Total	0.844475	65				

Table 9-4 ANOVA Analysis of Wet Flow Values from Intermediate Type A Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	7.45	1.24	0.00
I0.5	6	7.91	1.32	0.00
I0.7	6	8.05	1.34	0.01
II0.5	6	8.08	1.35	0.02
II0.7	6	8.18	1.36	0.01
III0.4	6	7.85	1.31	0.00
III0.7	6	7.96	1.33	0.01
IV0.5	6	8.00	1.33	0.01
IV0.7	6	8.29	1.38	0.02
V0.07	6	7.82	1.30	0.01
V0.7	6	8.32	1.39	0.01
Agg. A	11	13.25	1.20	0.00
Agg. B	11	15.11	1.37	0.00
Agg. C	11	14.67	1.33	0.01
Agg. D	11	14.41	1.31	0.01
Agg. E	11	14.85	1.35	0.01
Agg. F	11	15.63	1.42	0.01

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	0.097971	10	0.009797	1.742892	0.096895	2.026143
Columns	0.295202	5	0.05904	10.50317	6.27E-07	2.400409
Error	0.28106	50	0.005621			
Total	0.674234	65				

Table 9-5 ANOVA Analysis of Dry Flow Values from Intermediate Type B Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	6.93	1.16	0.01
I0.5	6	7.59	1.27	0.02
I0.7	6	7.56	1.26	0.01
II0.5	6	7.67	1.28	0.02
II0.7	6	7.58	1.26	0.03
III0.4	6	7.43	1.24	0.02
III0.7	6	7.57	1.26	0.02
IV0.5	6	7.37	1.23	0.01
IV0.7	6	7.57	1.26	0.02
V0.07	6	7.54	1.26	0.01
V0.7	6	7.59	1.27	0.01
Agg. A	11	12.90	1.17	0.00
Agg. B	11	14.62	1.33	0.01
Agg. C	11	15.01	1.36	0.01
Agg. D	11	13.54	1.23	0.00
Agg. E	11	14.59	1.33	0.00
Agg. F	11	11.75	1.07	0.00

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	0.068465	10	0.006847	1.798849	0.085163	2.026143
Columns	0.711282	5	0.142256	37.37634	9.29E-16	2.400409
Error	0.190303	50	0.003806			
Total	0.970049	65				

Table 9-6 ANOVA Analysis of Wet Flow Values from Intermediate Type B Mixtures

SUMMARY	Count	Sum	Average	Variance
Lime	6	7.01	1.17	0.01
I0.5	6	7.48	1.25	0.02
I0.7	6	7.35	1.23	0.02
II0.5	6	7.23	1.20	0.01
II0.7	6	7.28	1.21	0.00
III0.4	6	7.47	1.24	0.01
III0.7	6	7.43	1.24	0.03
IV0.5	6	7.58	1.26	0.01
IV0.7	6	7.42	1.24	0.01
V0.07	6	7.68	1.28	0.02
V0.7	6	7.47	1.24	0.01
Agg. A	11	12.55	1.14	0.00
Agg. B	11	14.17	1.29	0.01
Agg. C	11	14.27	1.30	0.01
Agg. D	11	13.31	1.21	0.00
Agg. E	11	14.63	1.33	0.01
Agg. F	11	12.46	1.13	0.00

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	0.054907	10	0.005491	0.944796	0.501711	2.026143
Columns	0.393912	5	0.078782	13.55623	2.29E-08	2.400409
Error	0.290576	50	0.005812			
Total	0.739395	65				

Appendix D

Dry and Wet Flow Values of Various Surface Type B, Intermediate Type A and Intermediate Type B Mixtures Made with Various ASA Types by Aggregate Source

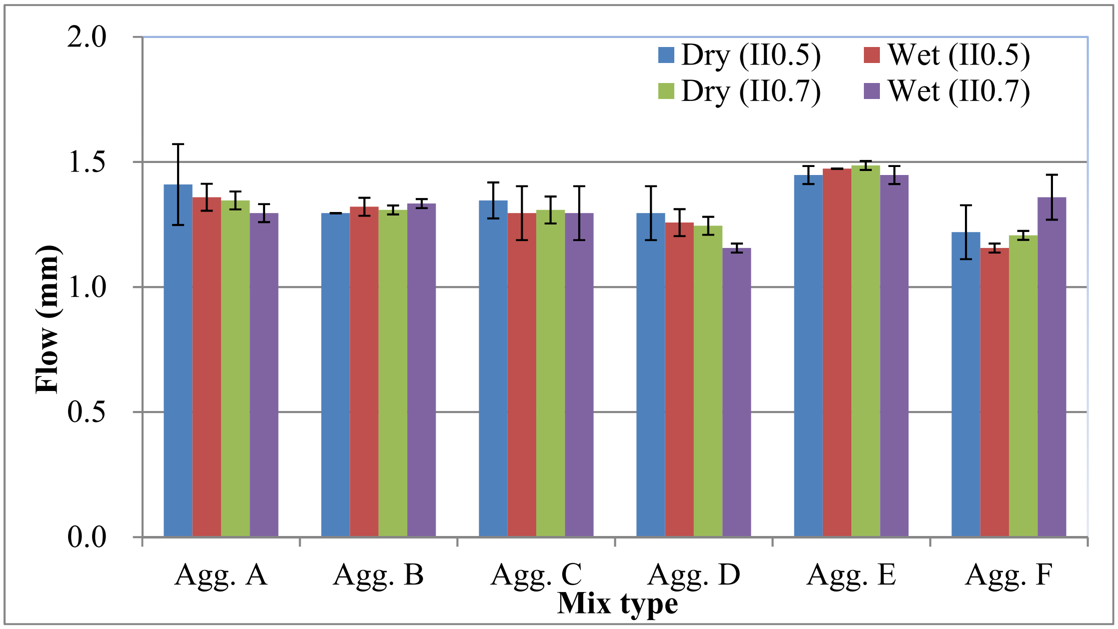


Figure 10-1 Dry and Wet Flow Values of Surface Type B Mixtures Containing Liquid ASA II and Various Aggregate Sources

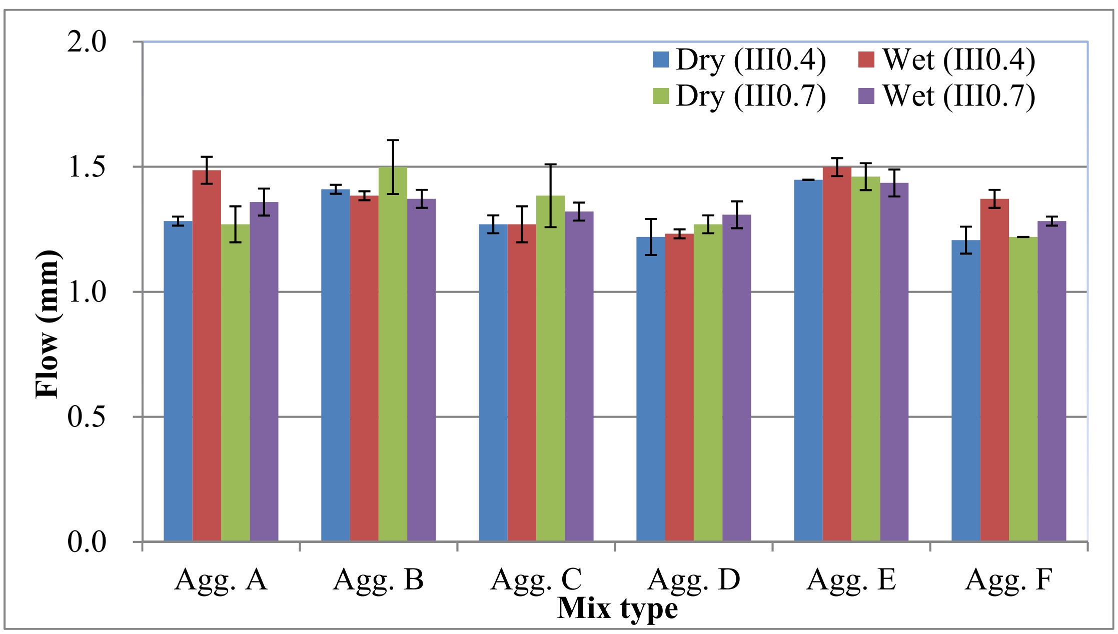


Figure 10-2 Dry and Wet Flow Values of Surface Type B Mixtures Containing Liquid ASA III and Various Aggregate Sources

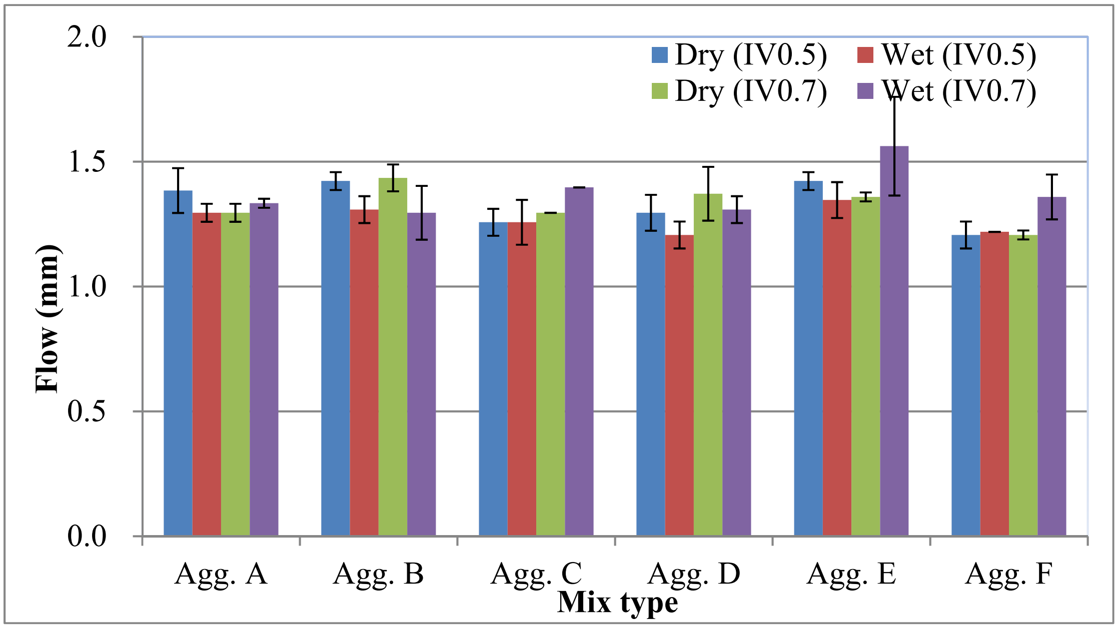


Figure 10-3 Dry and Wet Flow Values of Surface Type B Mixtures Containing Liquid ASA IV and Various Aggregate Sources

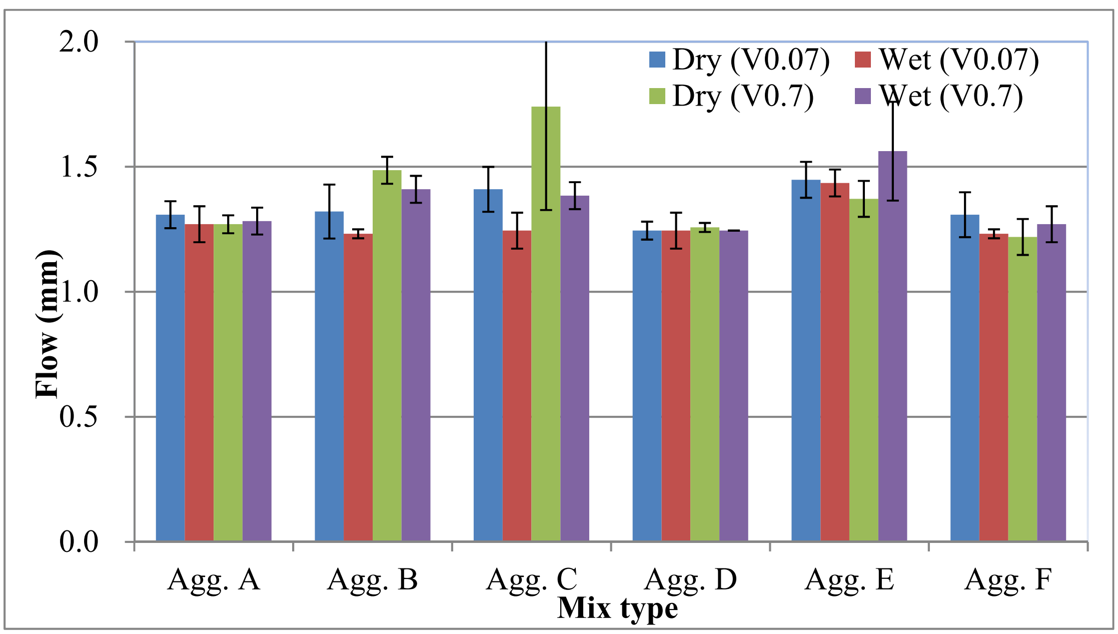


Figure 10-4 Dry and Wet Flow Values of Surface Type B Mixtures Containing Liquid ASA V and Various Aggregate Sources

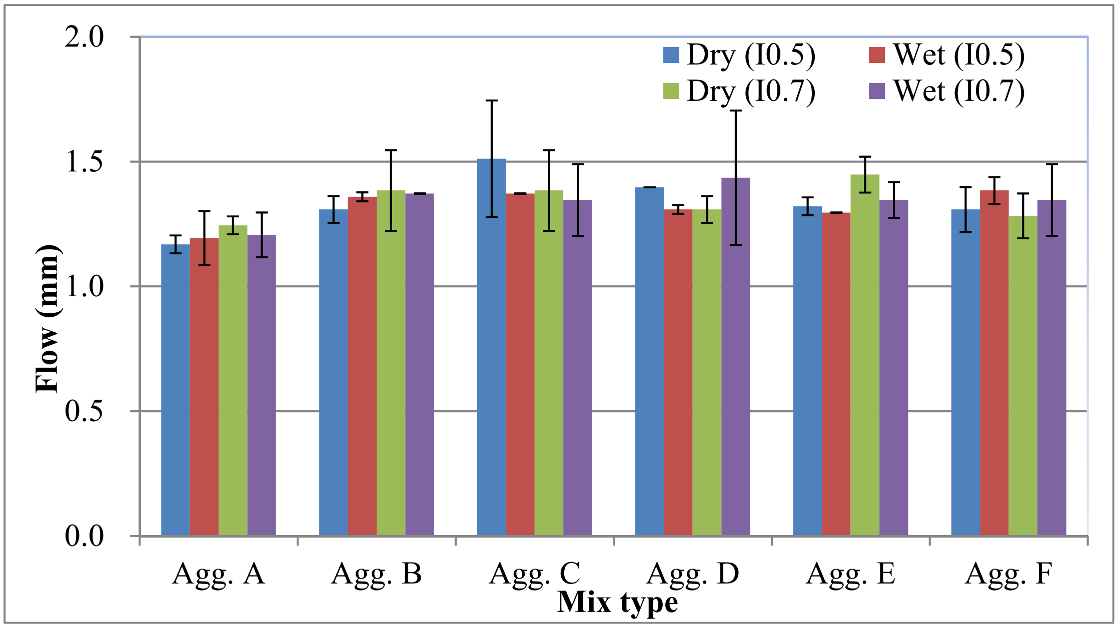


Figure 10-5 Dry and Wet Flow Values of Intermediate Type A Mixtures Containing Liquid ASA I and Various Aggregate Sources

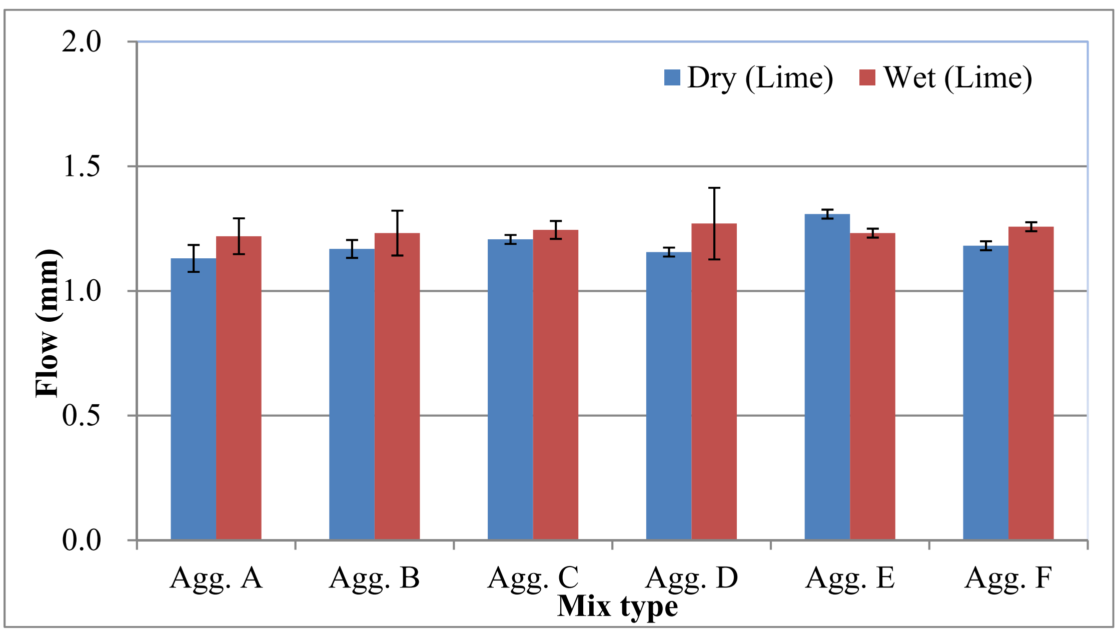


Figure 10-6 Dry and Wet Flow Values of Intermediate Type A Mixtures Containing Lime and Various Aggregate Sources

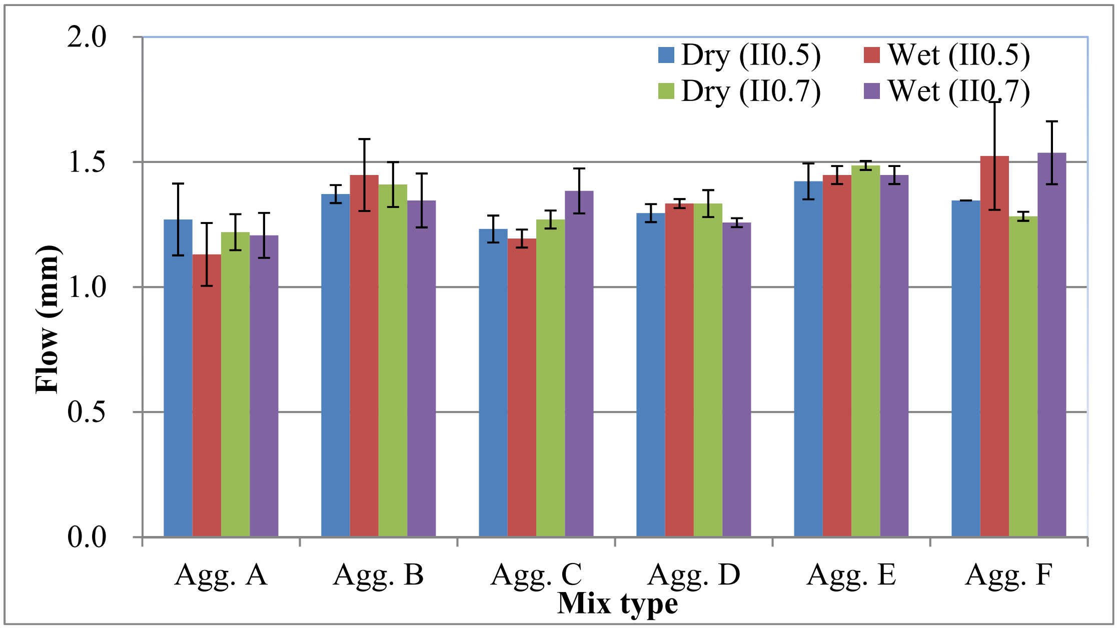


Figure 10-7 Dry and Wet Flow Values of Intermediate Type A Mixtures Containing Liquid ASA II and Various Aggregate Sources

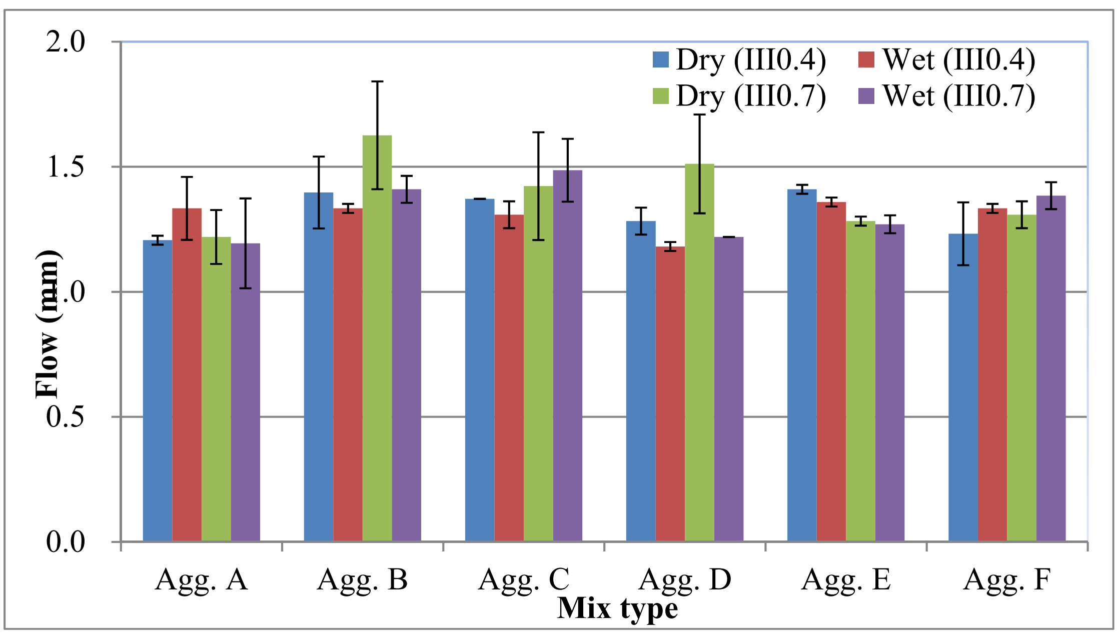


Figure 10-8 Dry and Wet Flow Values of Intermediate Type A Mixtures Containing Liquid ASA III and Various Aggregate Sources

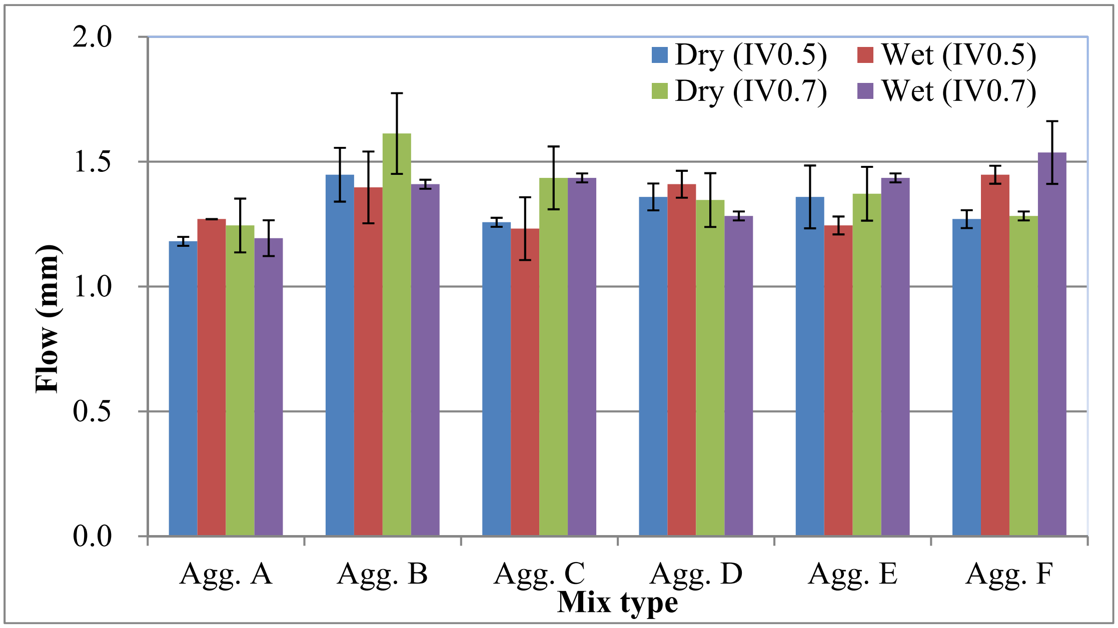


Figure 10-9 Dry and Wet Flow Values of Intermediate Type A Mixtures Containing Liquid ASA IV and Various Aggregate Sources

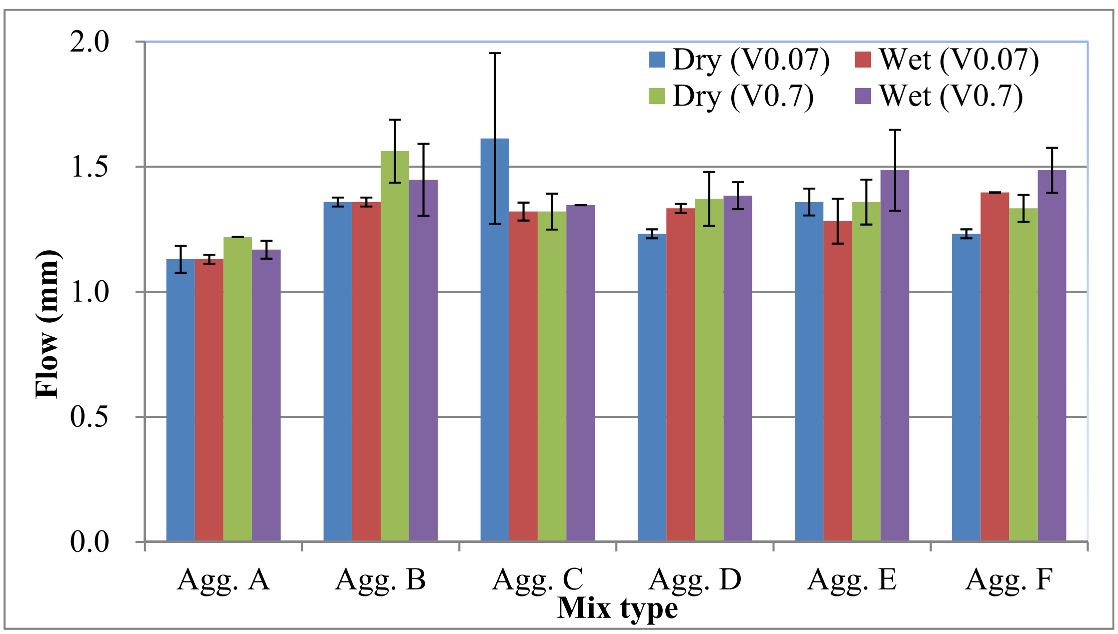


Figure 10-10 Dry and Wet Flow Values of Intermediate Type A Mixtures Containing Liquid ASA V and Various Aggregate Sources

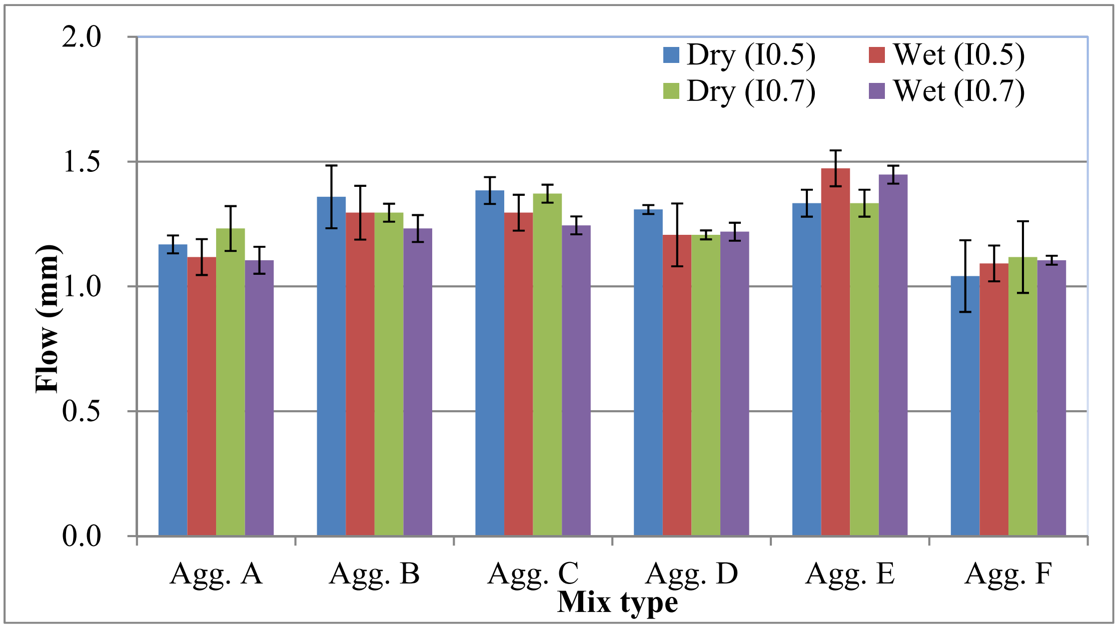


Figure 10-11 Dry and Wet Flow Values of Intermediate Type B Mixtures Containing Liquid ASA I and Various Aggregate Sources

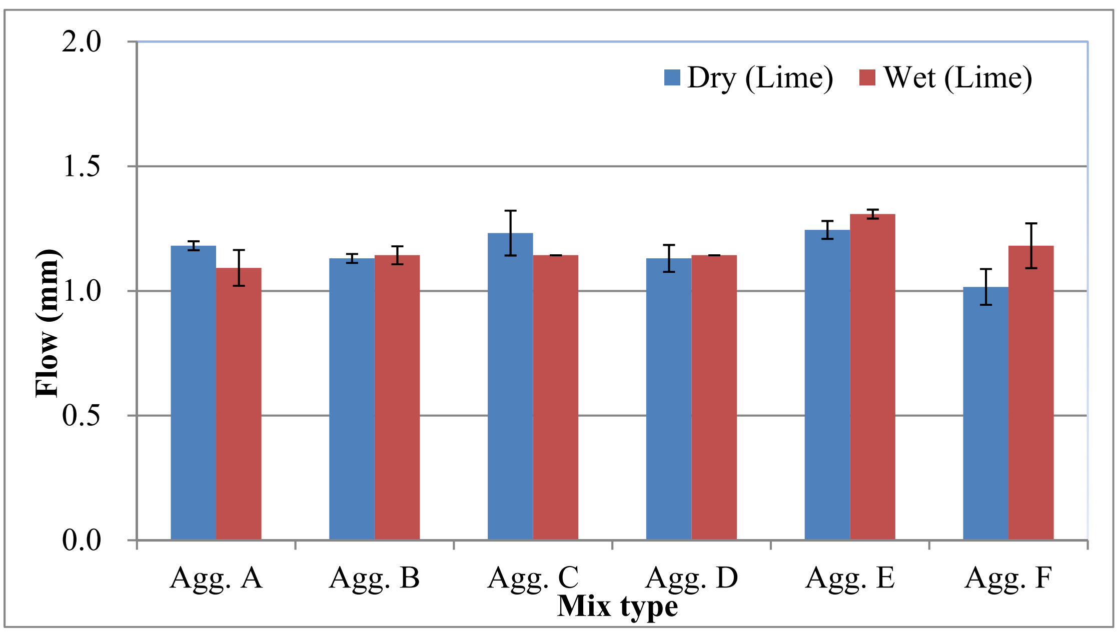


Figure 10-12 Dry and Wet Flow Values of Intermediate Type B Mixtures Containing Lime and Various Aggregate Sources

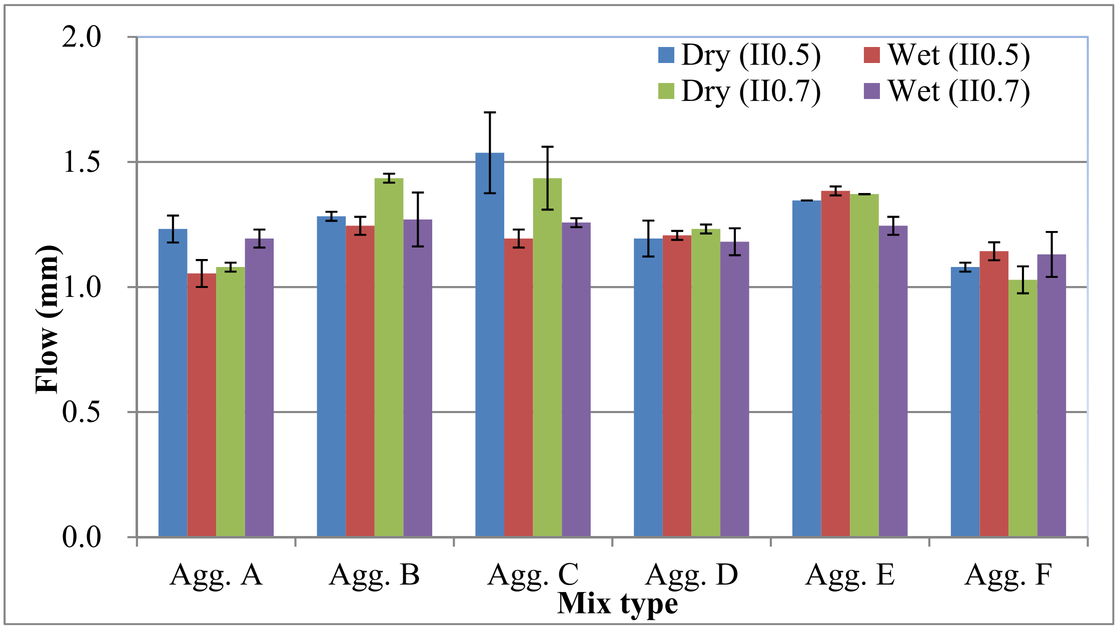


Figure 10-13 Dry and Wet Flow Values of Intermediate Type B Mixtures Containing Liquid ASA II and Various Aggregate Sources

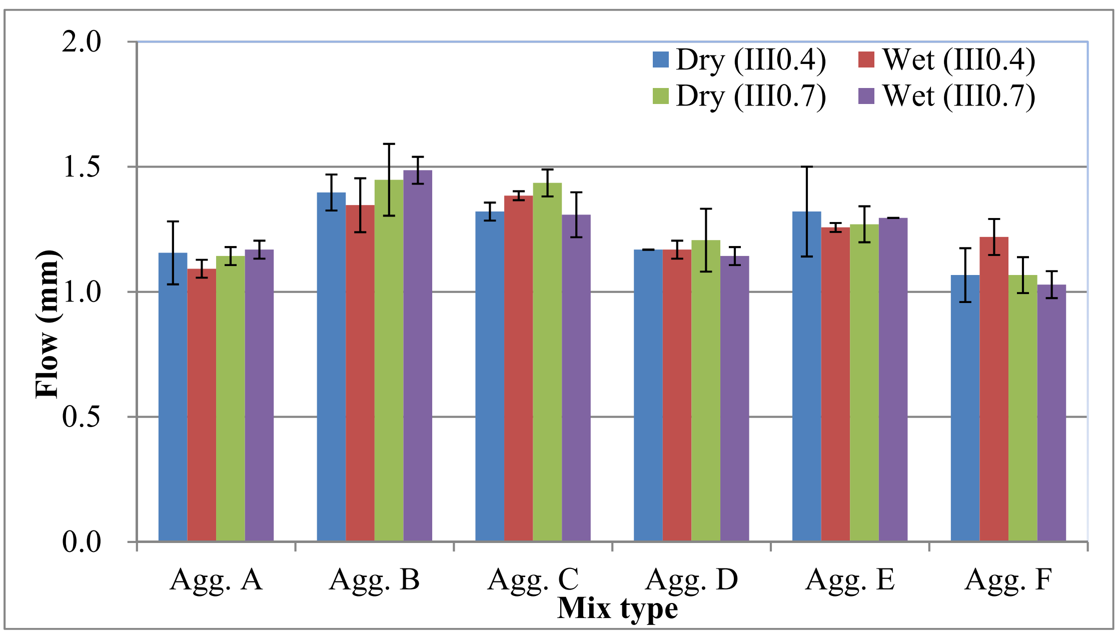


Figure 10-14 Dry and Wet Flow Values of Intermediate Type B Mixtures Containing Liquid ASA III and Various Aggregate Sources

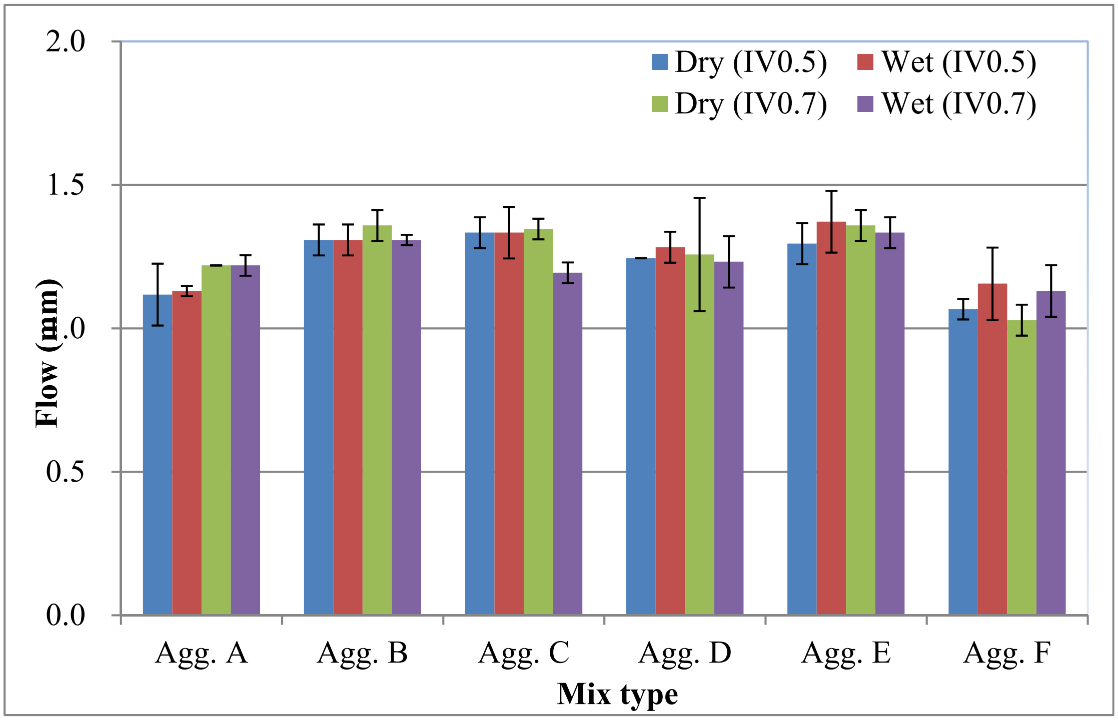


Figure 10-15 Dry and Wet Flow Values of Intermediate Type B Mixtures Containing Liquid ASA IV and Various Aggregate Sources

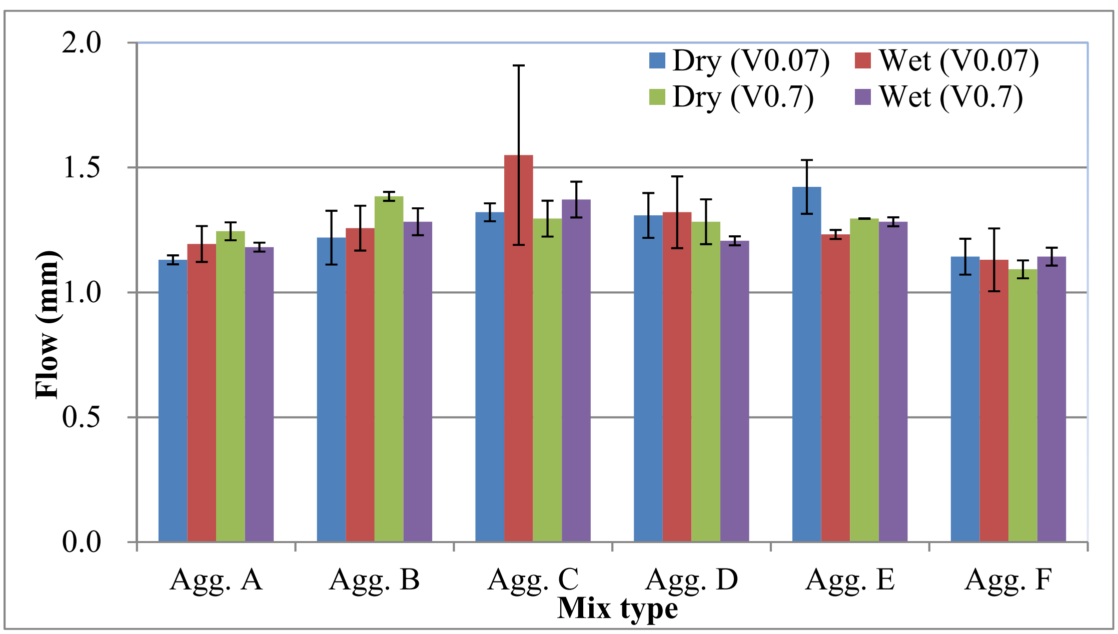


Figure 10-16 Dry and Wet Flow Values of Intermediate Type B Mixtures Containing Liquid ASA IV and Various Aggregate Sources

Appendix E

Dry and Wet Flow Values of Various Surface Type B, Intermediate Type A and Intermediate Type B Mixtures Made with Various Aggregate Sources by ASA Type

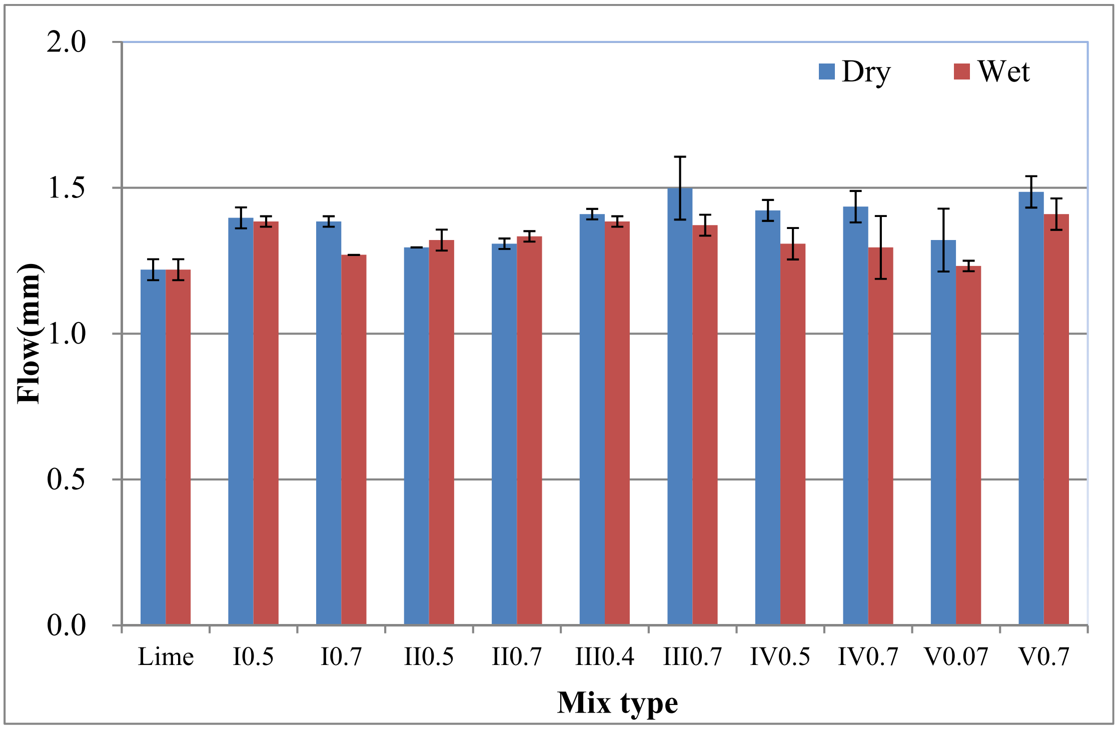


Figure 11-1 Dry and Wet Flow Values of Surface Type B Mixtures Containing Aggregate Source B and Various ASAs

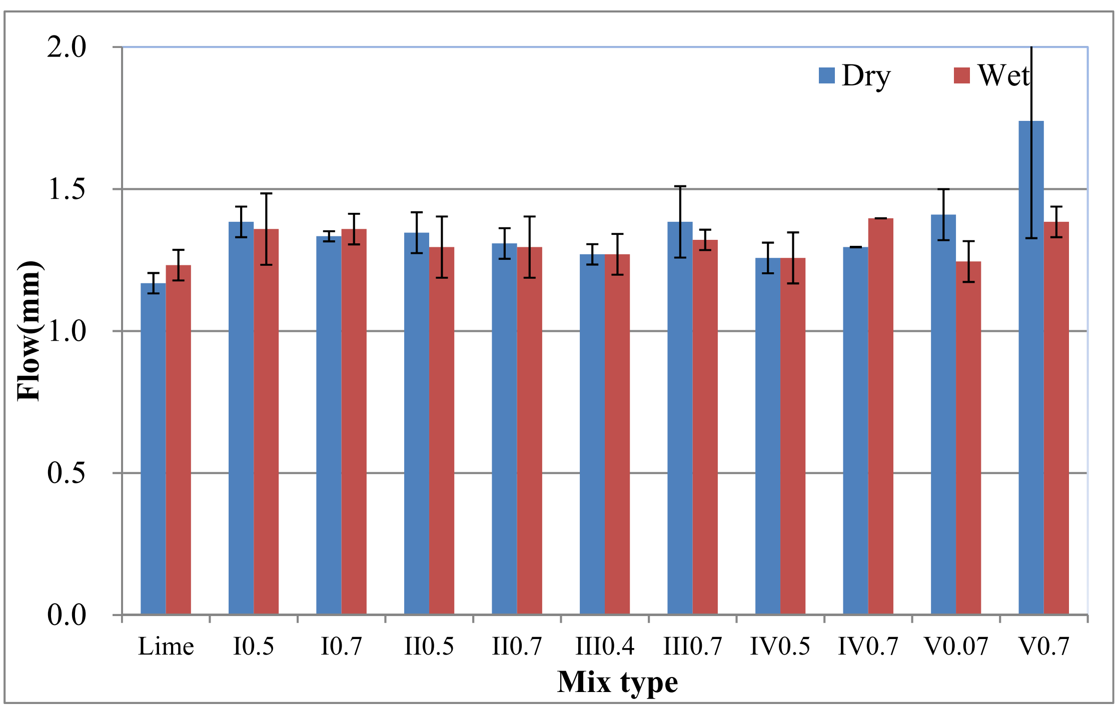


Figure 11-2 Dry and Wet Flow Values of Surface Type B Mixtures Containing Aggregate Source C and Various ASAs

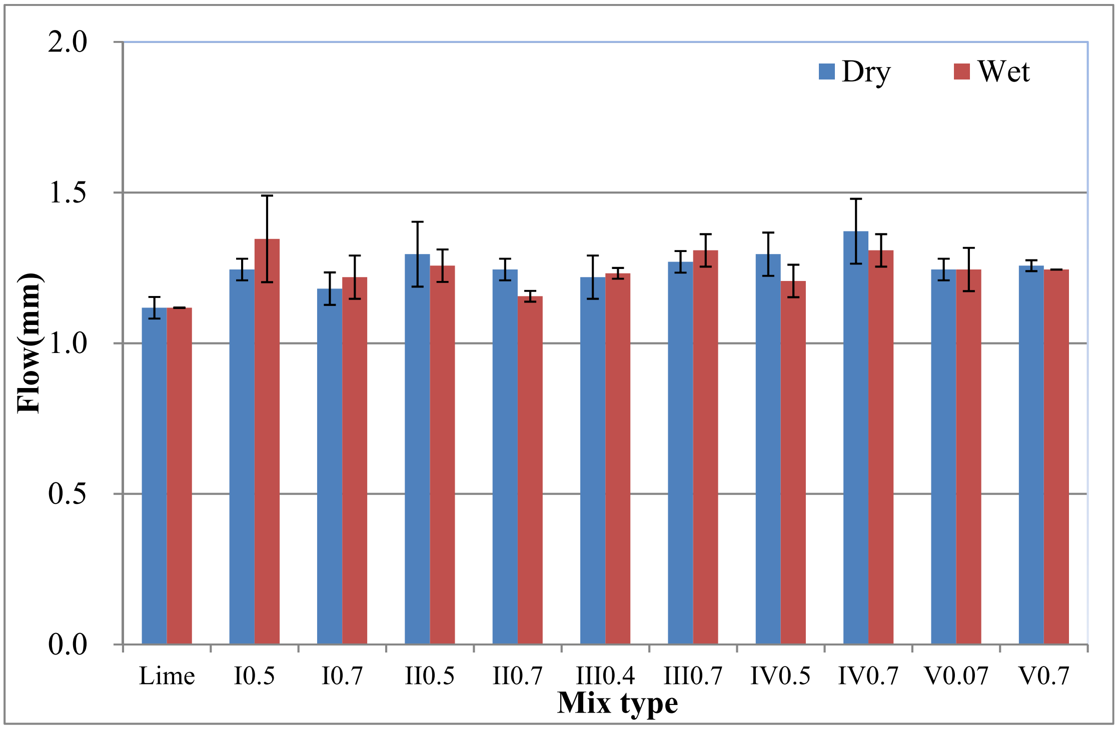


Figure 11-3 Dry and Wet Flow Values of Surface Type B Mixtures Containing Aggregate Source D and Various ASAs

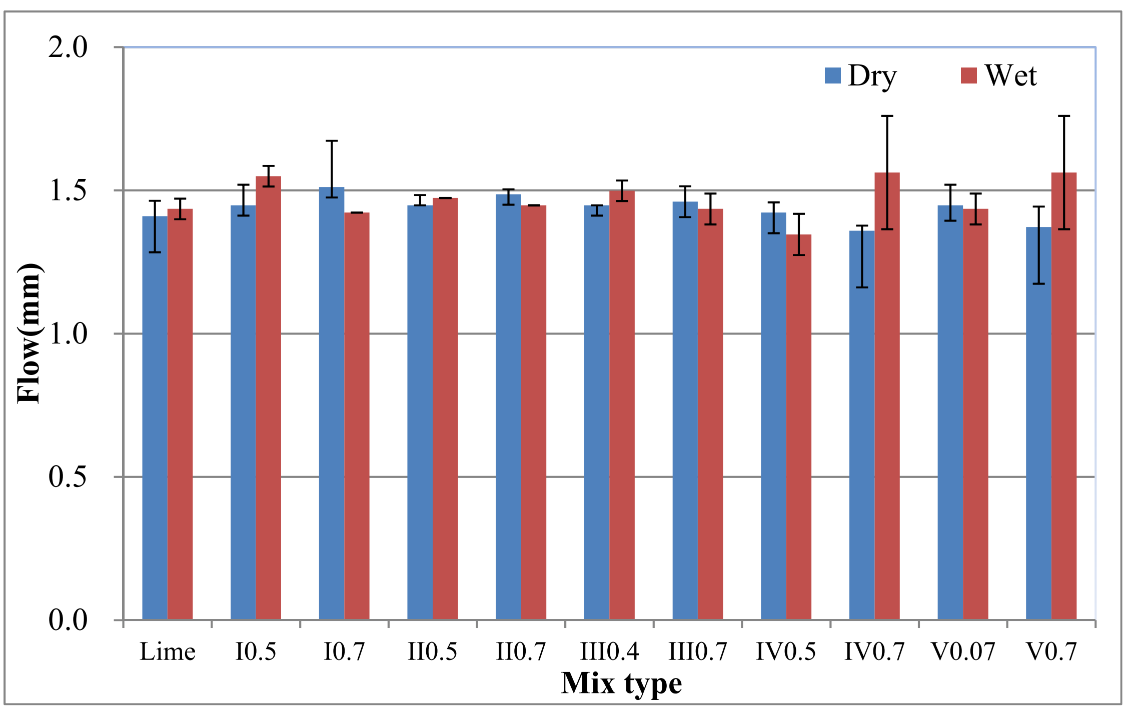


Figure 11-4 Dry and Wet Flow Values of Surface Type B Mixtures Containing Aggregate Source E and Various ASAs

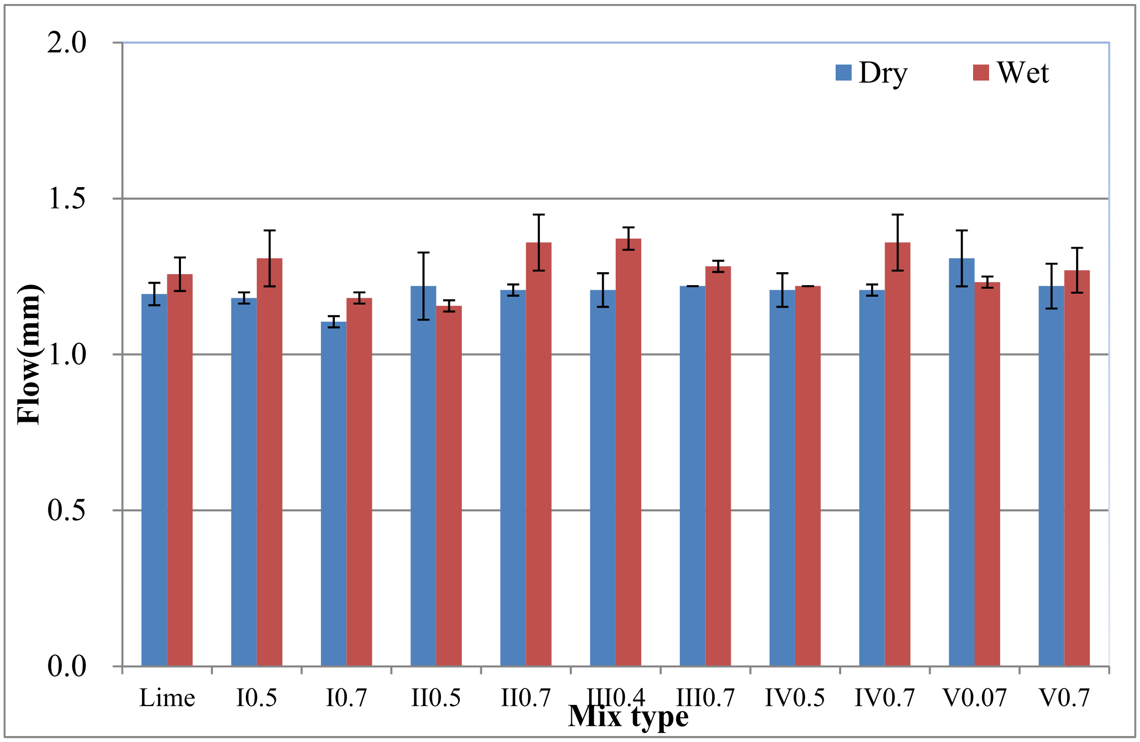


Figure 11-5 Dry and Wet Flow Values of Surface Type B Mixtures Containing Aggregate Source F and Various ASAs

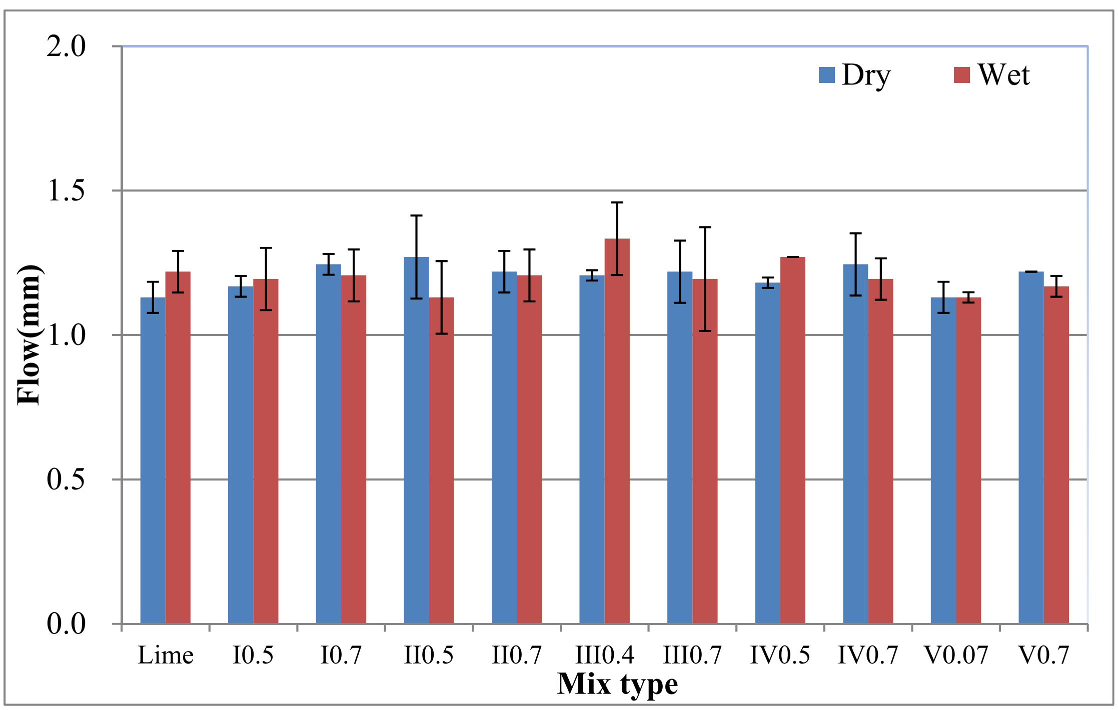


Figure 11-6 Dry and Wet Flow Values of Intermediate Type A Mixtures Containing Aggregate Source A and Various ASAs

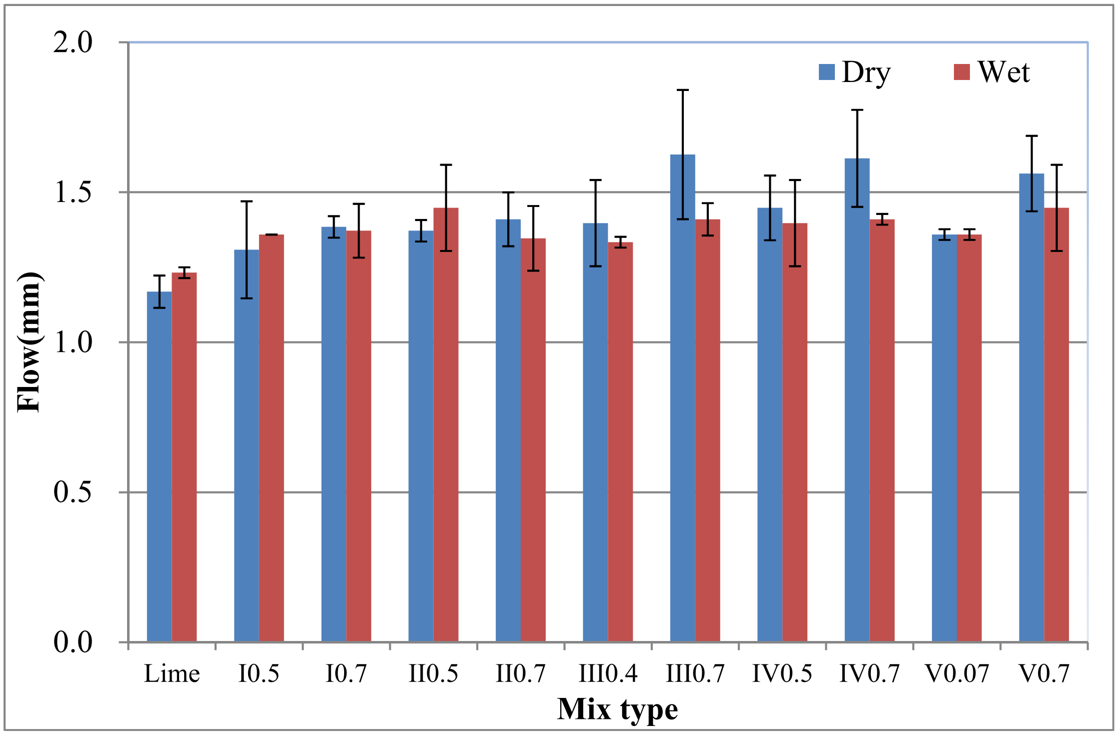


Figure 11-7 Dry and Wet Flow Values of Intermediate Type A Mixtures Containing Aggregate Source B and Various ASAs

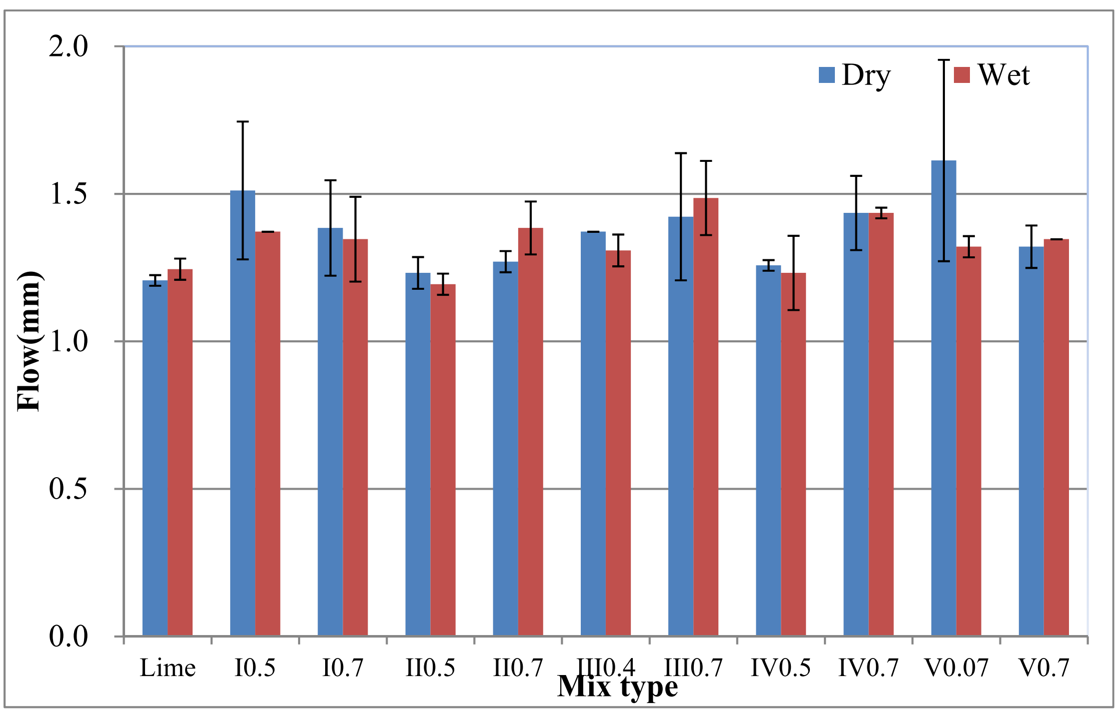


Figure 11-8 D Dry and Wet Flow Values of Intermediate Type A Mixtures Containing Aggregate Source C and Various ASAs

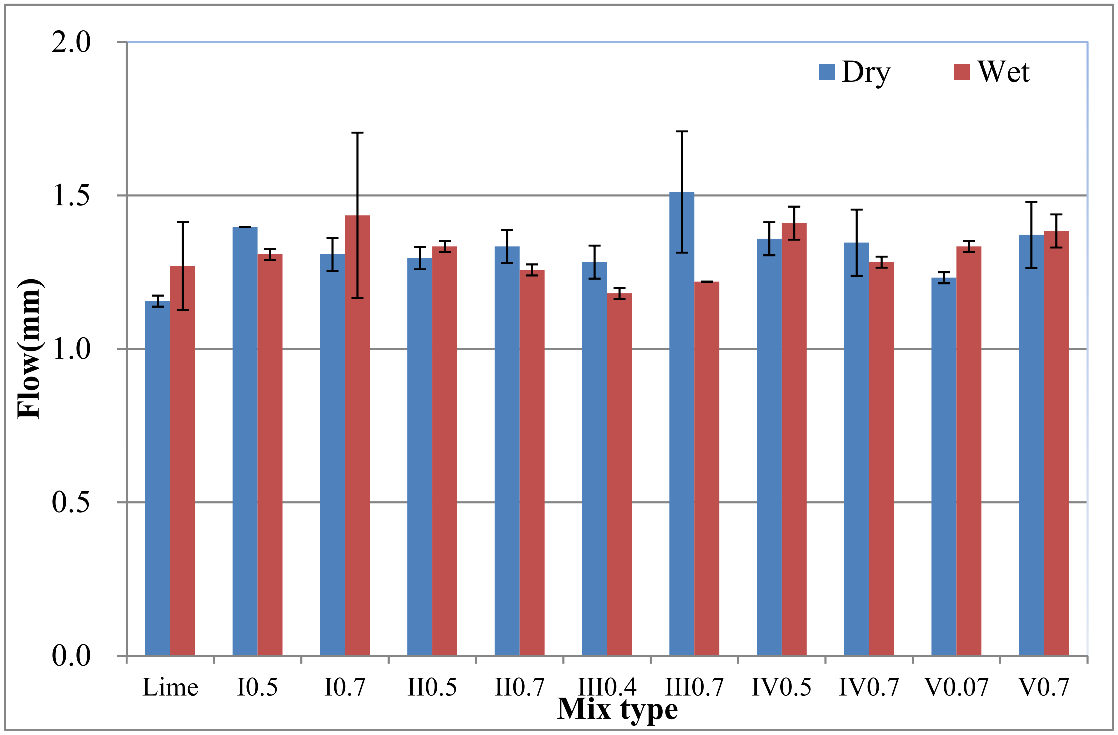


Figure 11-9 Dry and Wet Flow Values of Intermediate Type A Mixtures Containing Aggregate Source D and Various ASAs

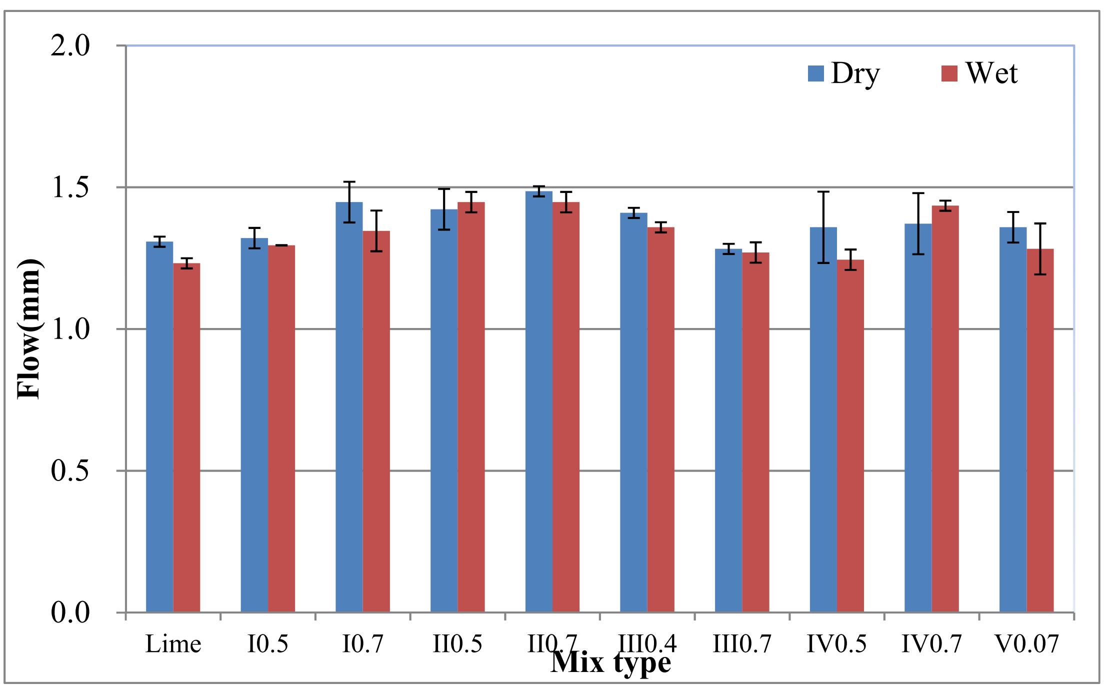


Figure 11-10 Dry and Wet Flow Values of Intermediate Type A Mixtures Containing Aggregate Source E and Various ASAs

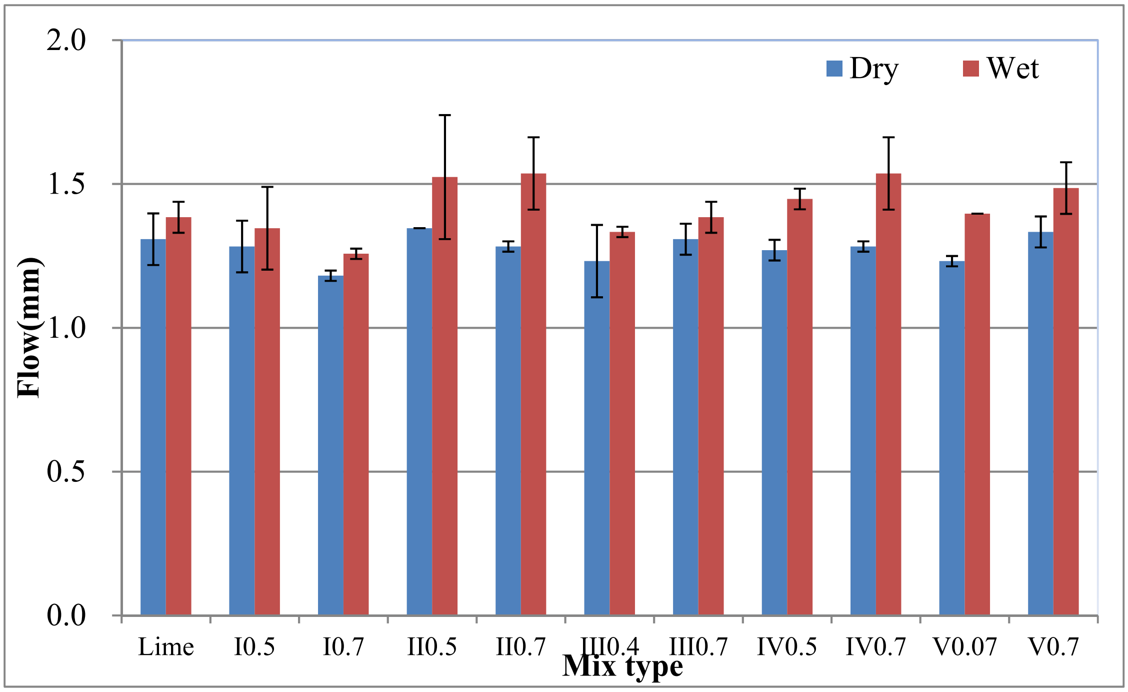


Figure 11-11 Dry and Wet Flow Values of Intermediate Type A Mixtures Containing Aggregate Source F and Various ASAs

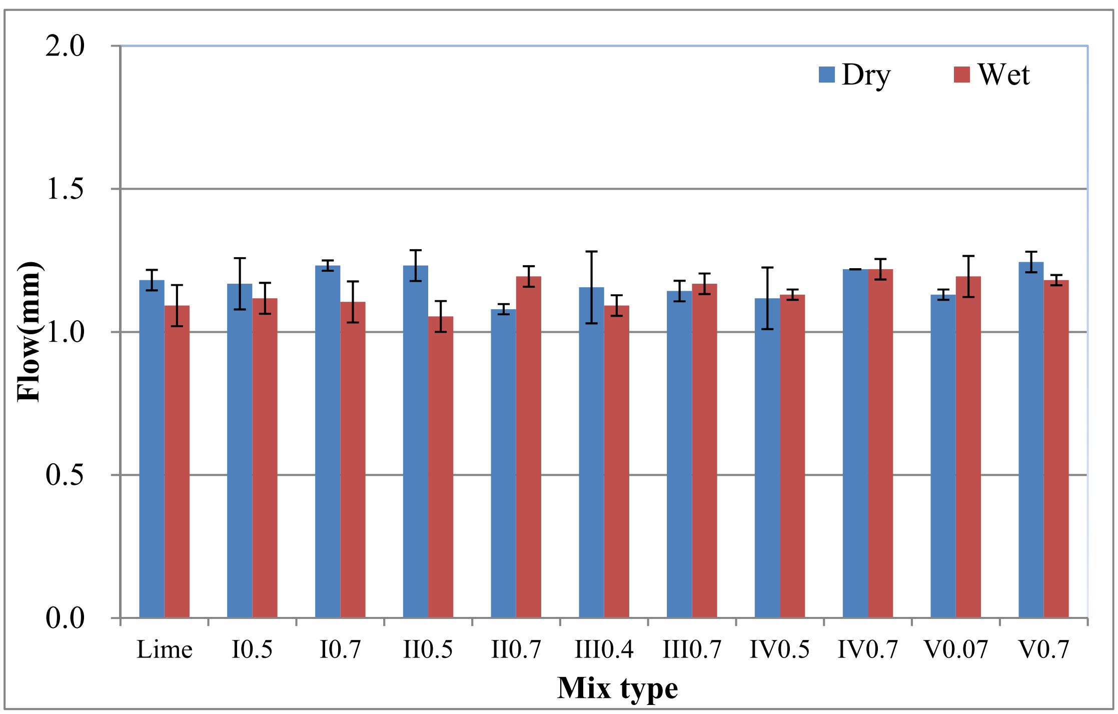


Figure 11-12 Dry and Wet Flow Values of Intermediate Type B Mixtures Containing Aggregate Source A and Various ASAs

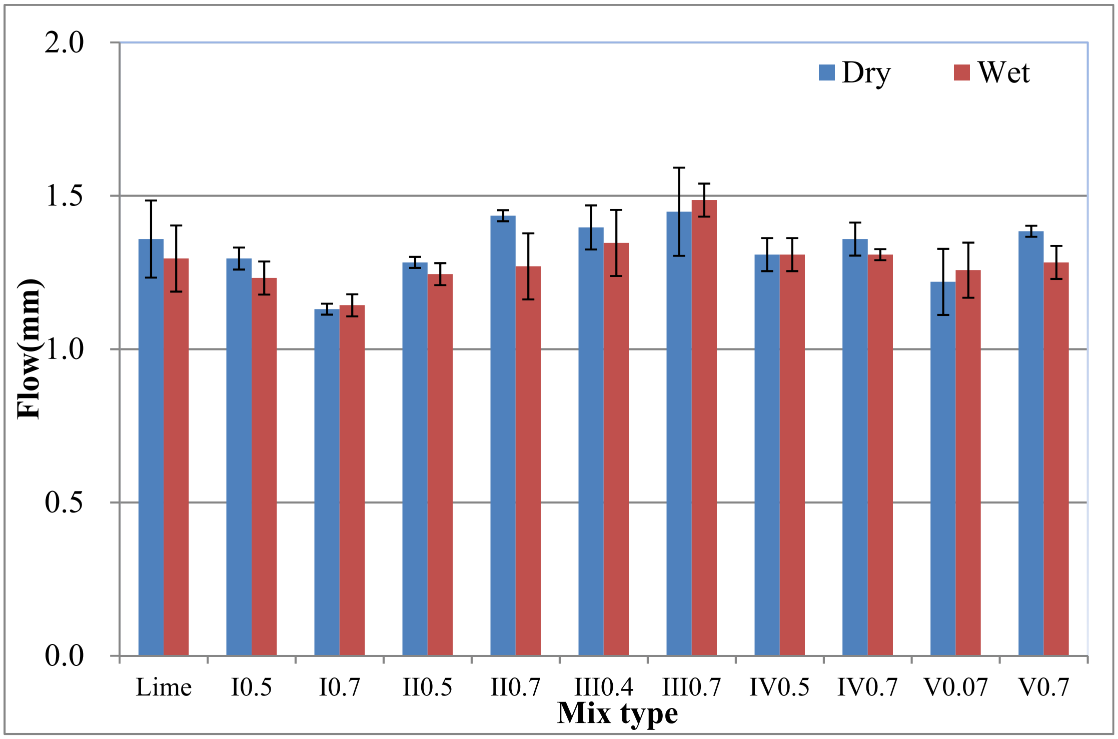


Figure 11-13 Dry and Wet Flow Values of Intermediate Type B Mixtures Containing Aggregate Source B and Various ASAs

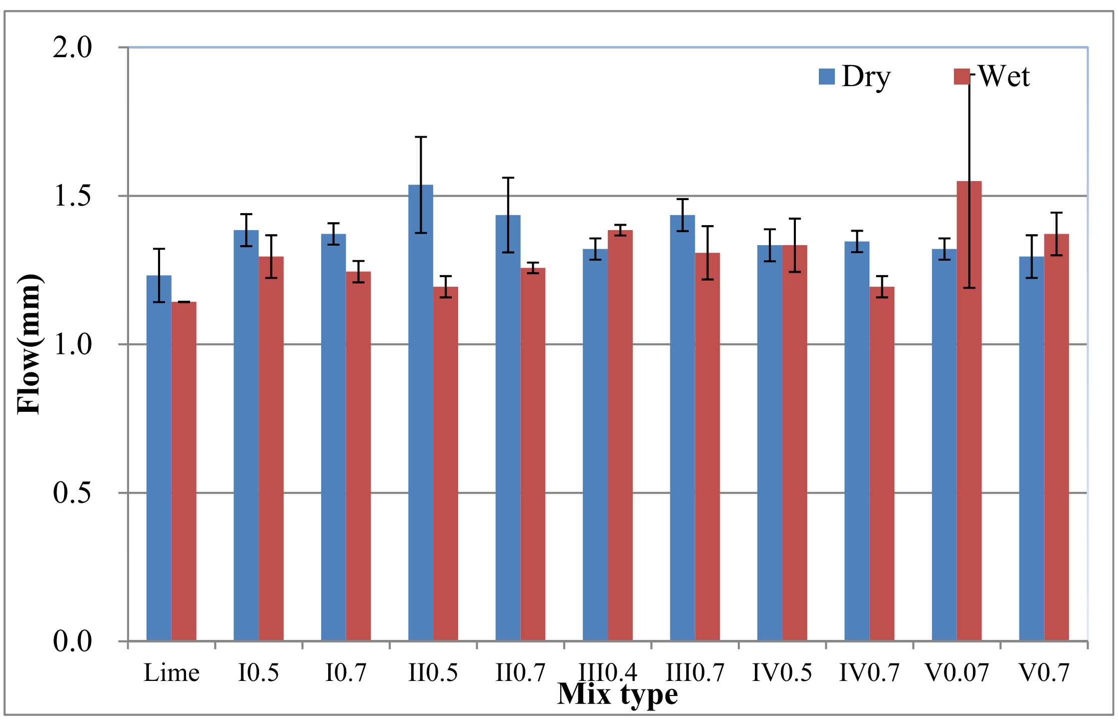


Figure 11-14 Dry and Wet Flow Values of Intermediate Type B Mixtures Containing Aggregate Source C and Various ASAs

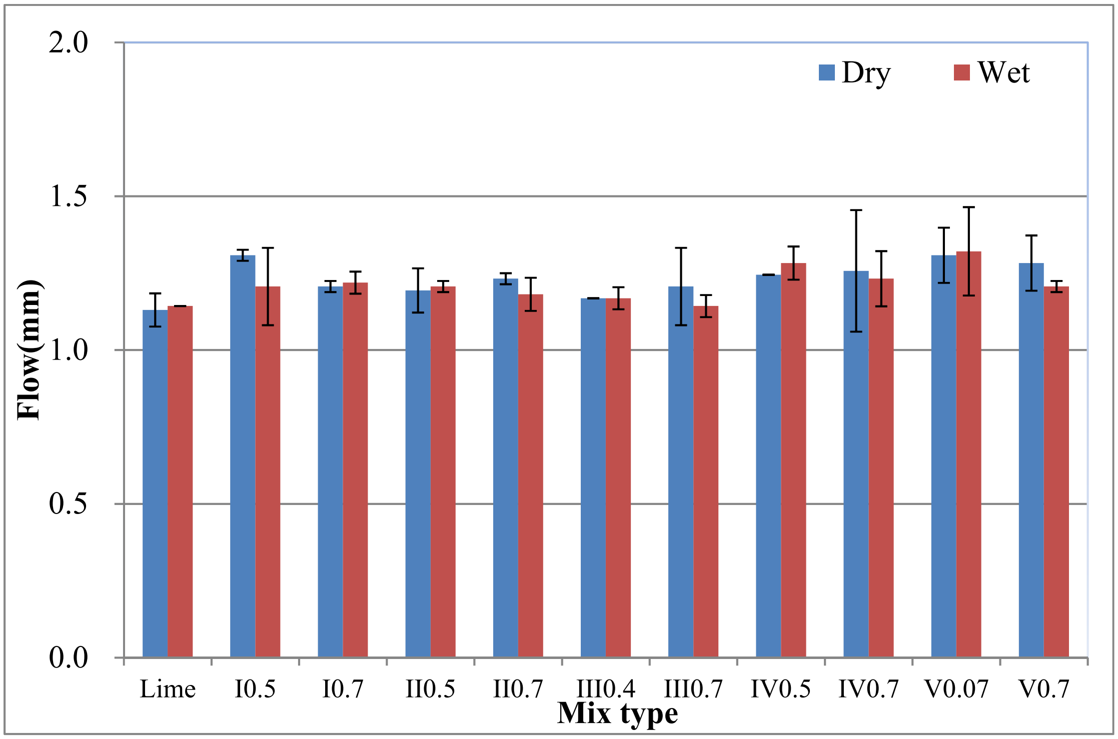


Figure 11-15 Dry and Wet Flow Values of Intermediate Type B Mixtures Containing Aggregate Source D and Various ASAs

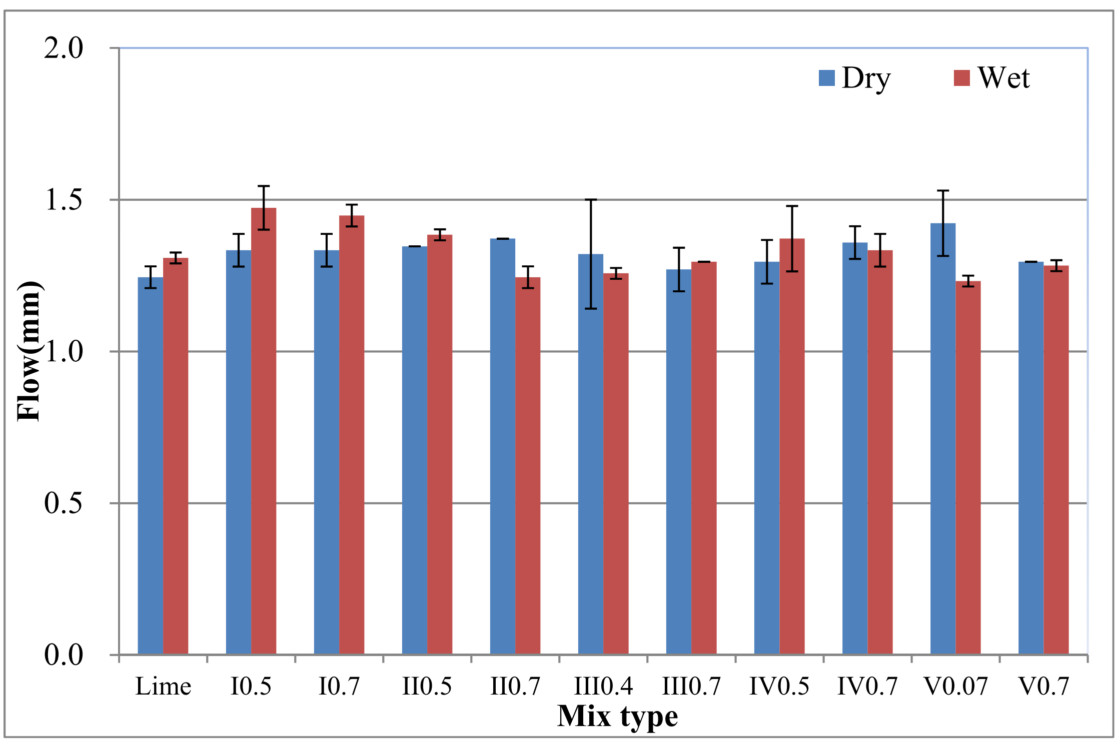


Figure 11-16 Dry and Wet Flow Values of Intermediate Type B Mixtures Containing Aggregate Source E and Various ASAs

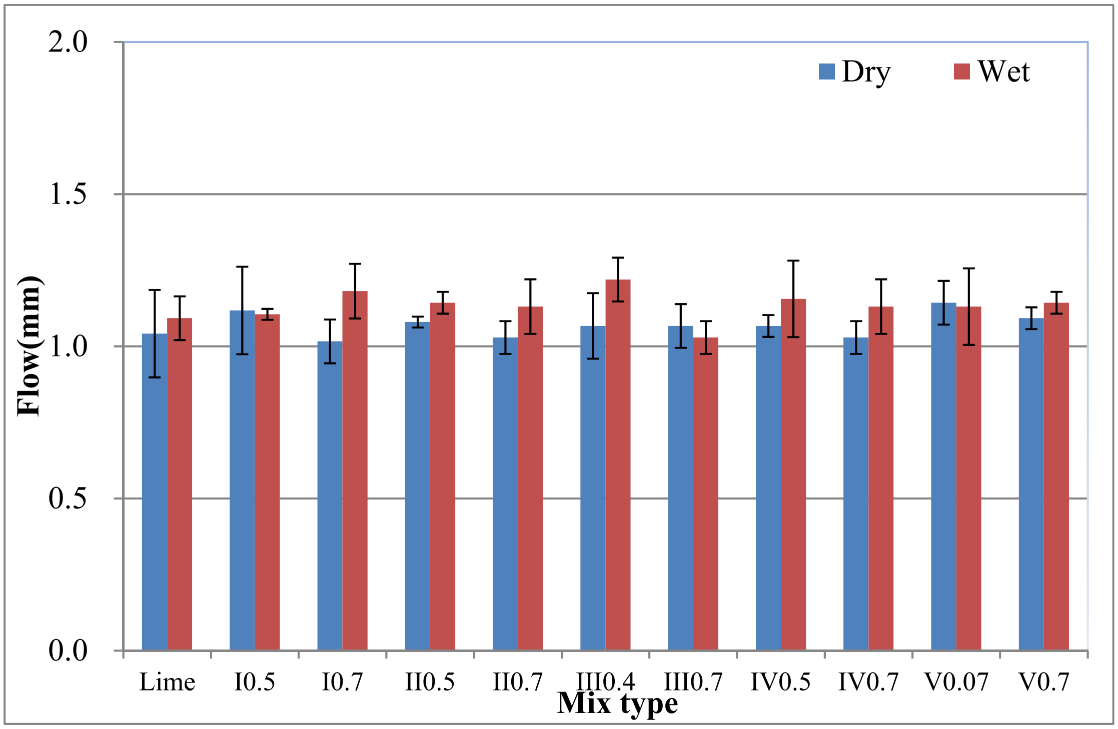


Figure 11-17 Dry and Wet Flow Values of Intermediate Type B Mixtures Containing Aggregate Source F and Various ASAs

Appendix F

TSR (%) Values of Various Surface Type B, Intermediate Type A and Intermediate Type B Mixtures Containing Different ASA Types by Aggregate Source

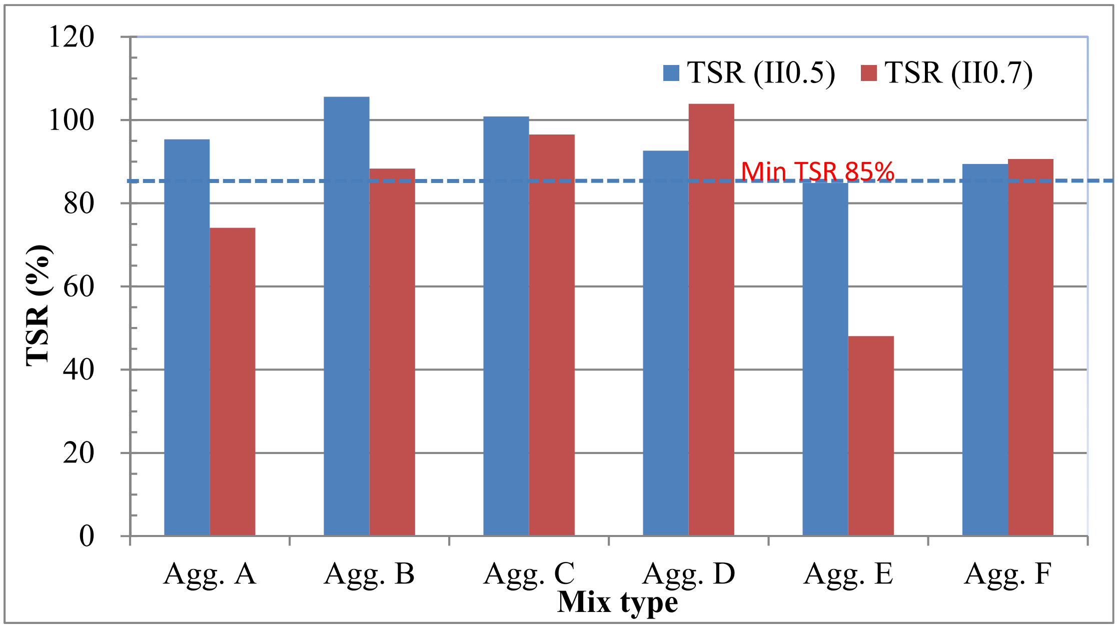


Figure 12-1 TSR Values of Surface Type B Mixtures Containing Liquid ASA II and Various Aggregate Sources

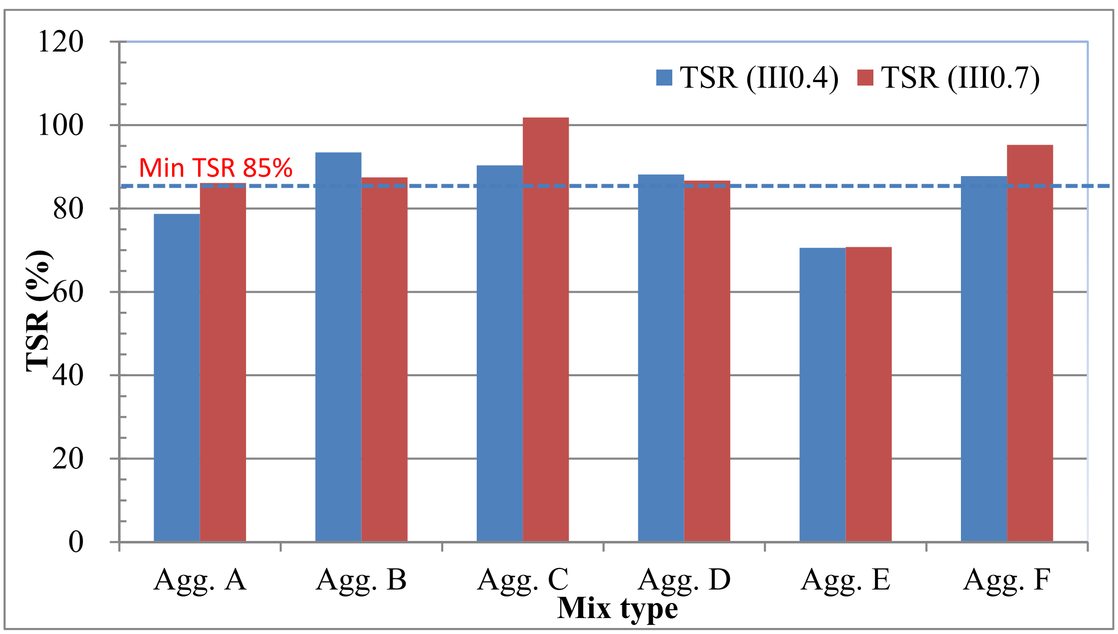


Figure 12-2 TSR Values of Surface Type B Mixtures Containing Liquid ASA III and Various Aggregate Sources

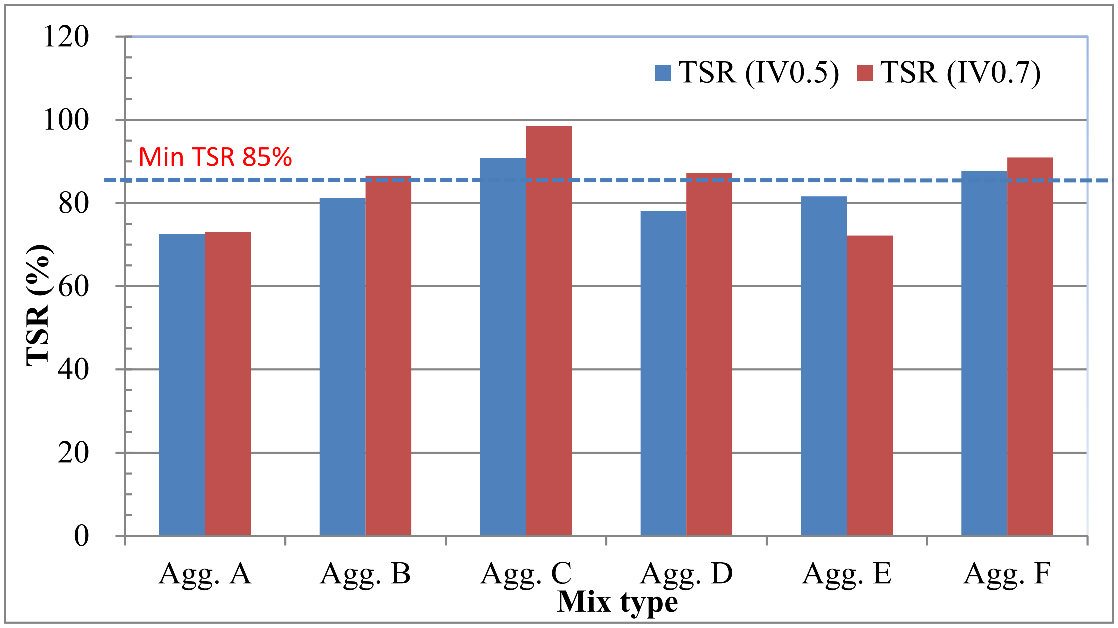


Figure 12-3 TSR Values of Surface Type B Mixtures Containing Liquid ASA IV and Various Aggregate Sources

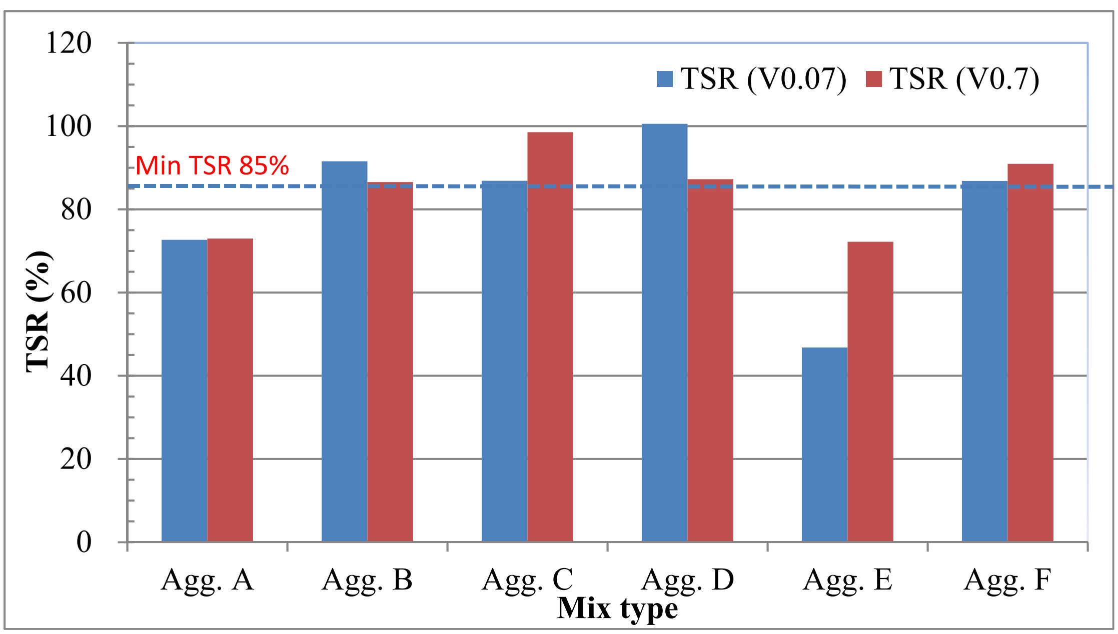


Figure 12-4 TSR Values of Surface Type B Mixtures Containing Liquid ASA V and Various Aggregate Sources

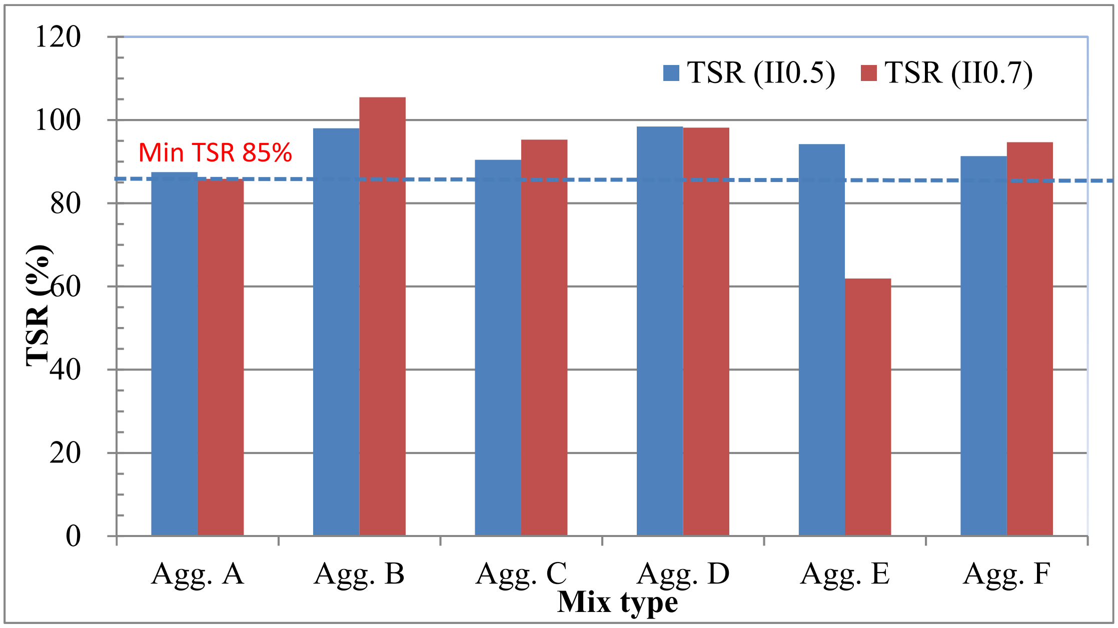


Figure 12-5 TSR Values of Intermediate Type A Mixtures Containing Liquid ASA II and Various Aggregate Sources

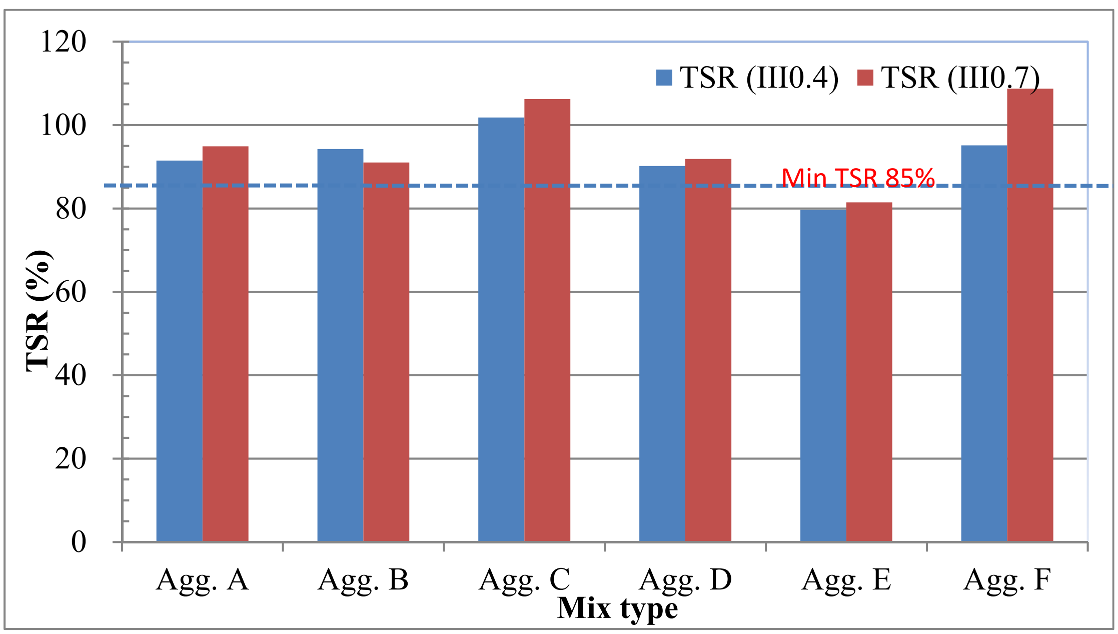


Figure 12-6 TSR Values of Intermediate Type A Mixtures Containing Liquid ASA III and Various Aggregate Sources

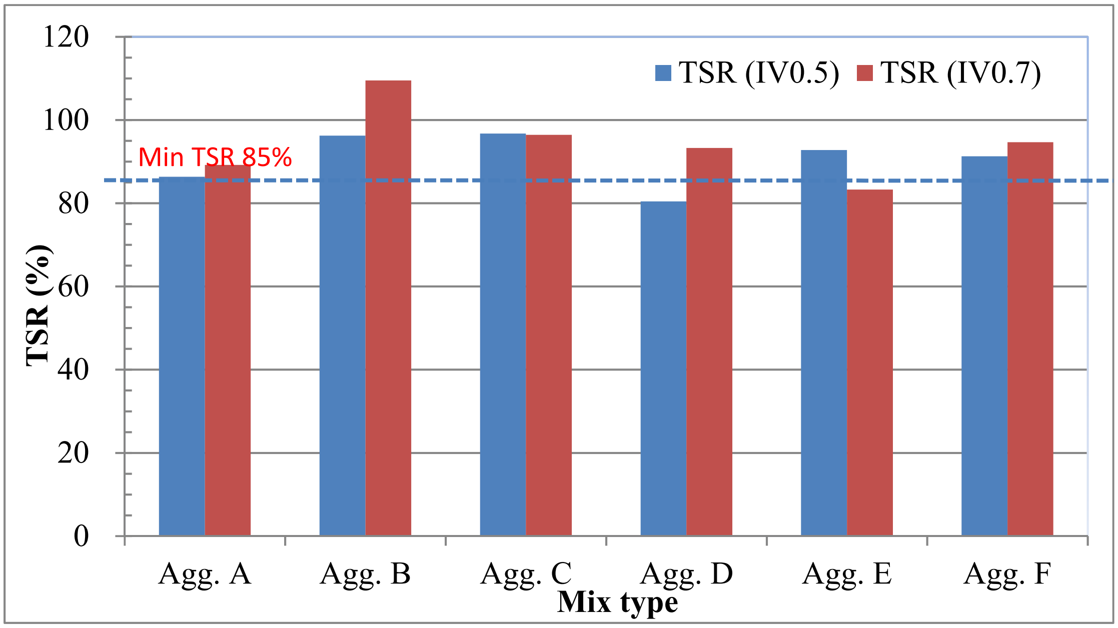


Figure 12-7 TSR Values of Intermediate Type A Mixtures Containing Liquid ASA IV and Various Aggregate Sources

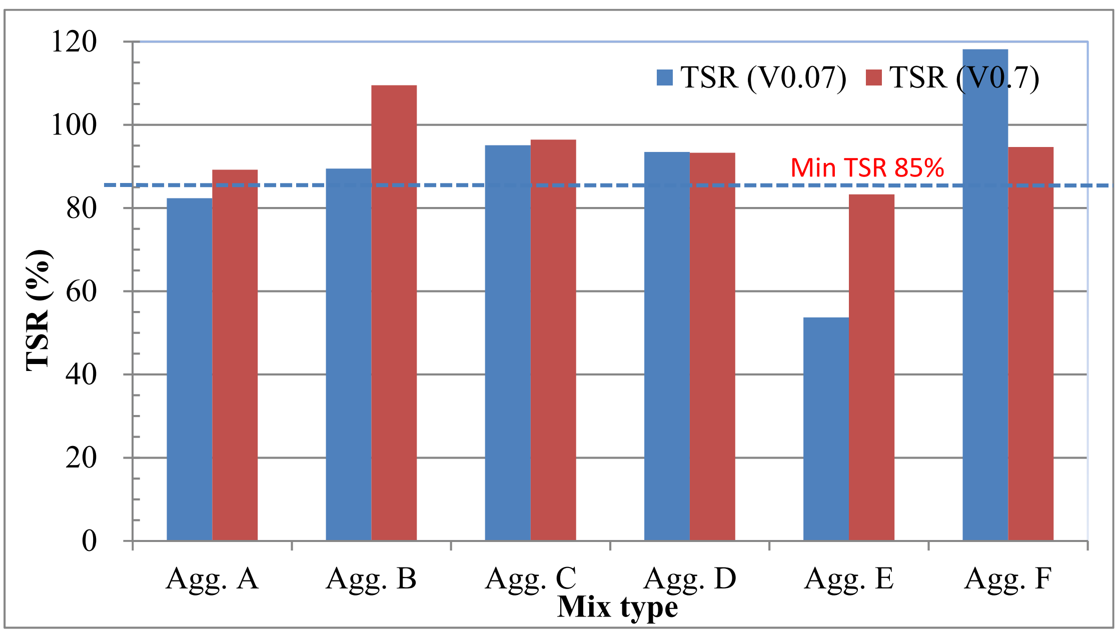


Figure 12-8 TSR Values of Intermediate Type A Mixtures Containing Liquid ASA V and Various Aggregate Sources

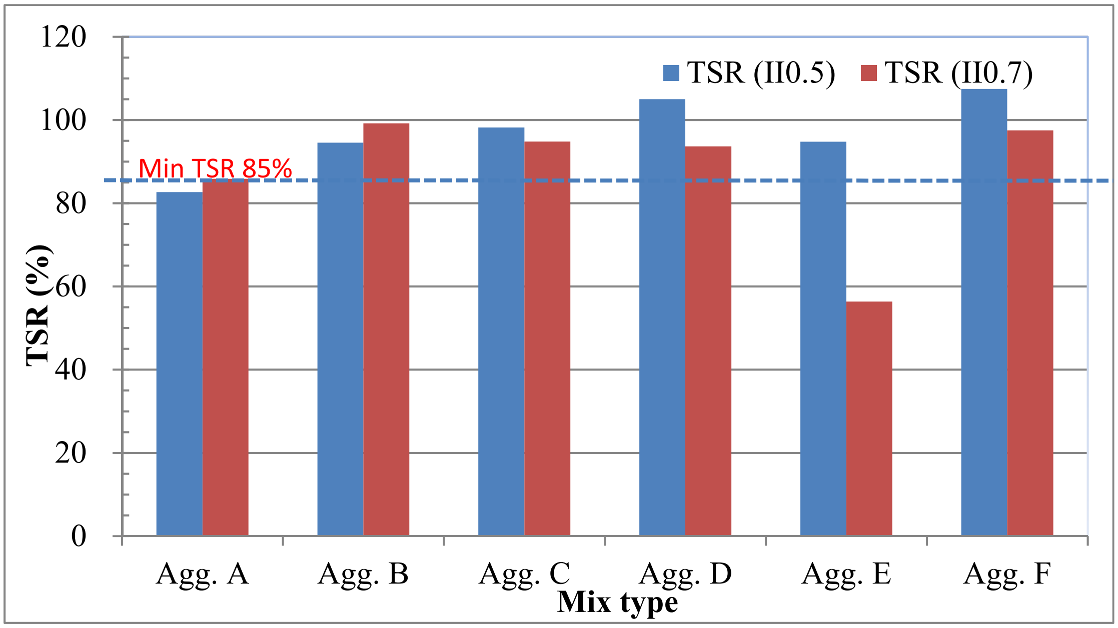


Figure 12-9 TSR Values of Intermediate Type B Mixtures Containing Liquid ASA II and Various Aggregate Sources

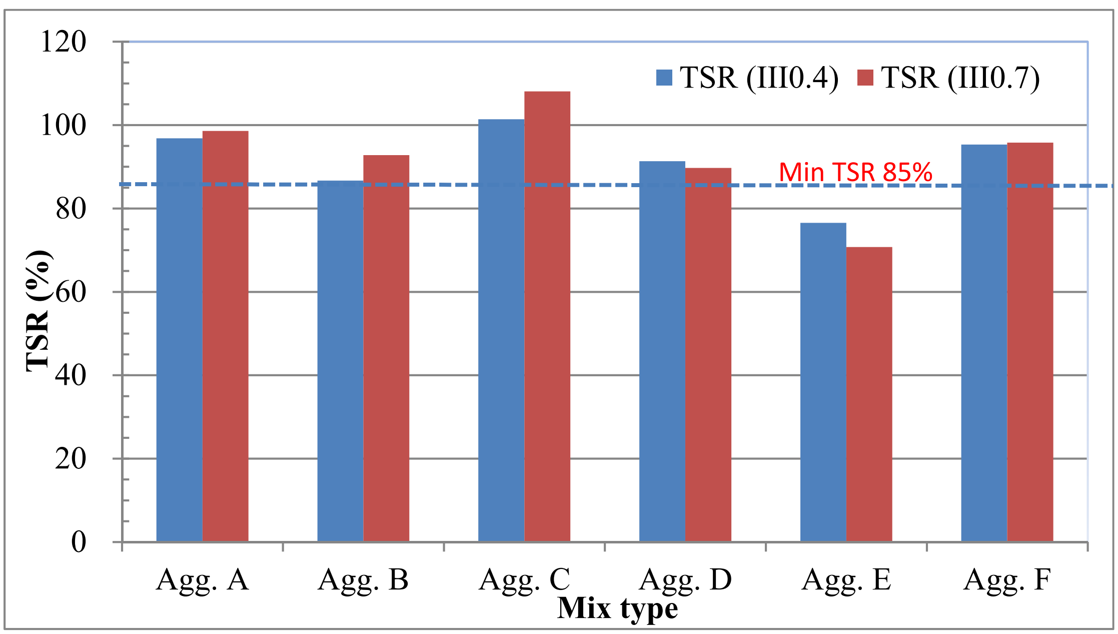


Figure 12-10 TSR Values of Intermediate Type B Mixtures Containing Liquid ASA III and Various Aggregate Sources

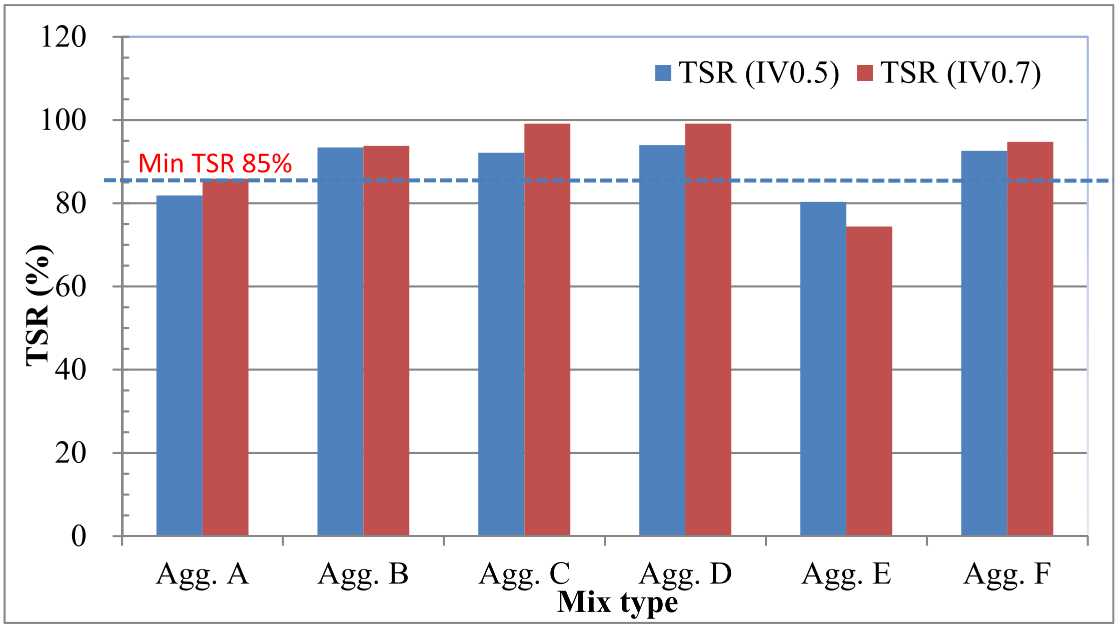


Figure 12-11 TSR Values of Intermediate Type B Mixtures Containing Liquid ASA IV and Various Aggregate Sources

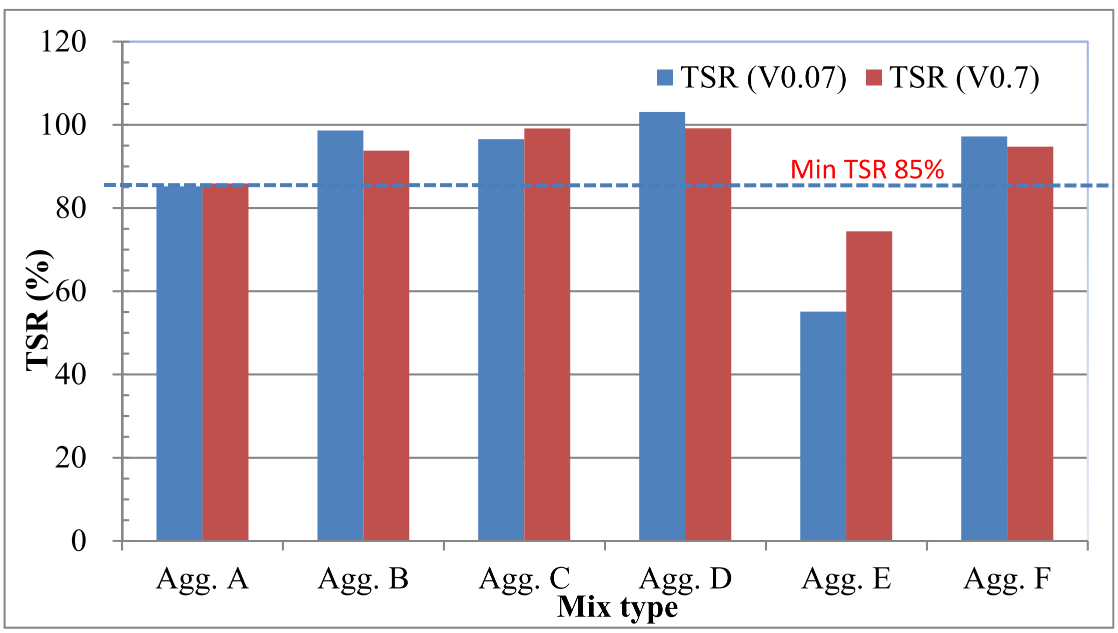


Figure 12-12 TSR Values of Intermediate Type B Mixtures Containing Liquid ASA V and Various Aggregate Sources

Appendix G

TSR (%) Values of Various Surface Type B, Intermediate Type A and Intermediate Type B Mixtures Made with Various Aggregate Sources by ASA Type

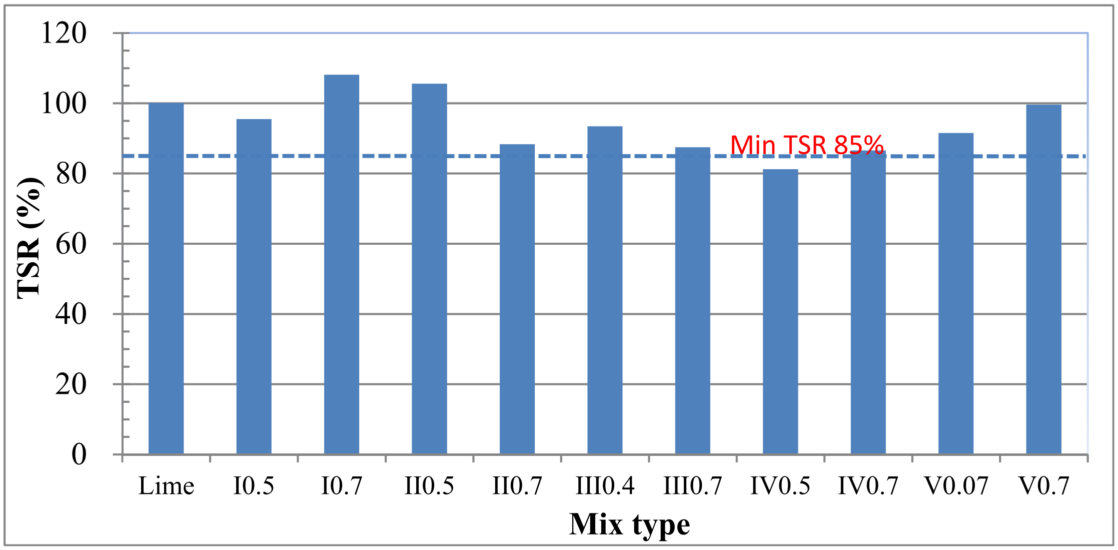


Figure 13-1 TSR Values of Surface Type B Mixtures Containing Aggregate Source B and Various ASAs

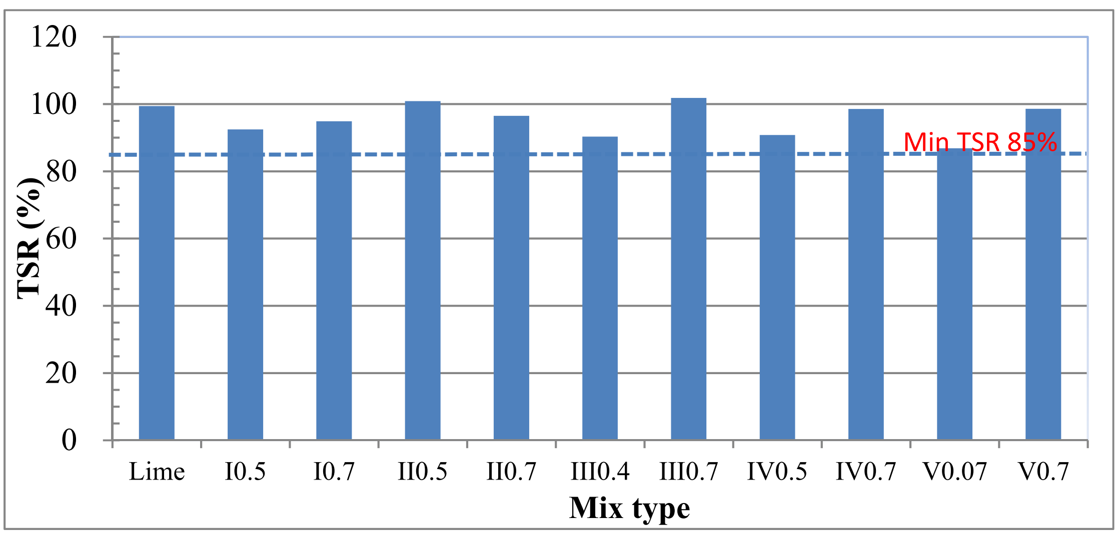


Figure 13-2 TSR Values of Surface Type B Mixtures Containing Aggregate Source C and Various ASAs

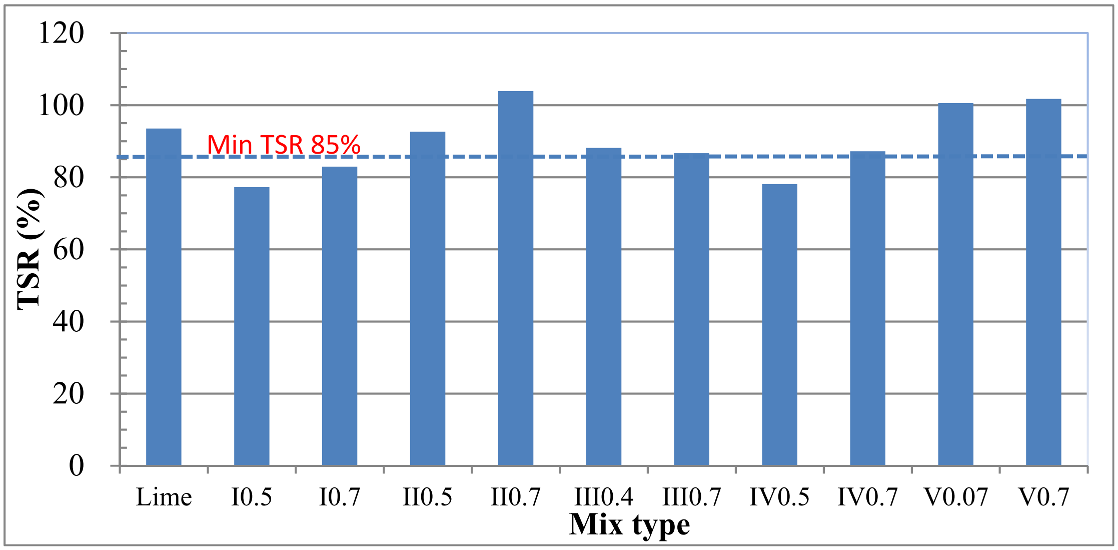


Figure 13-3 TSR Values of Surface Type B Mixtures Containing Aggregate Source D and Various ASAs

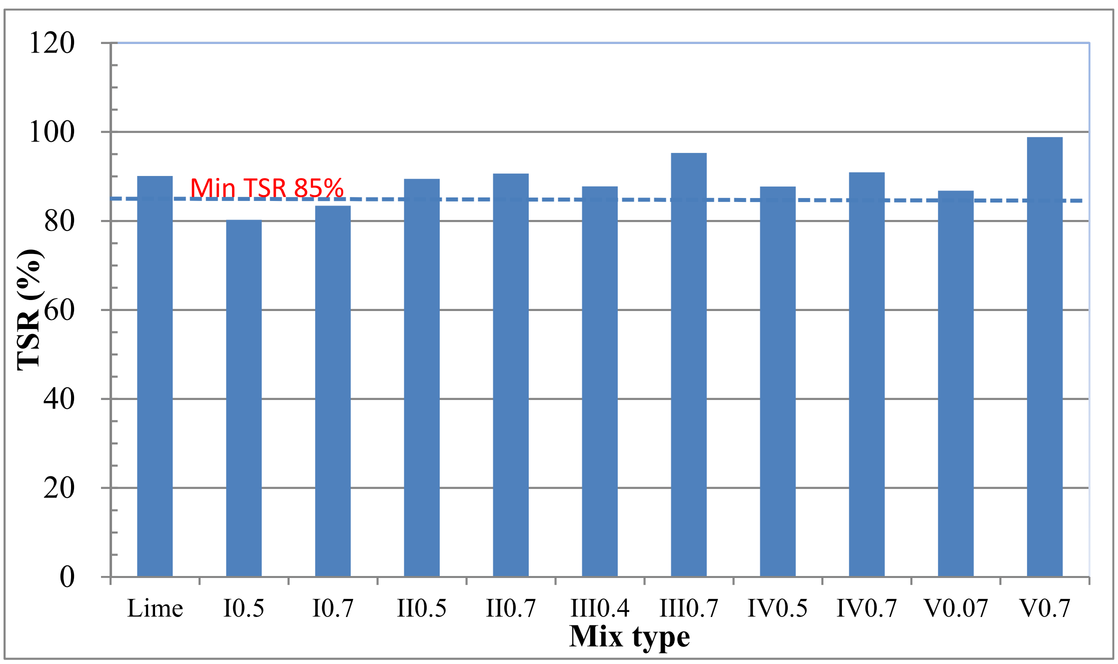


Figure 13-4 TSR Values of Surface Type B Mixtures Containing Aggregate Source F and Various ASAs

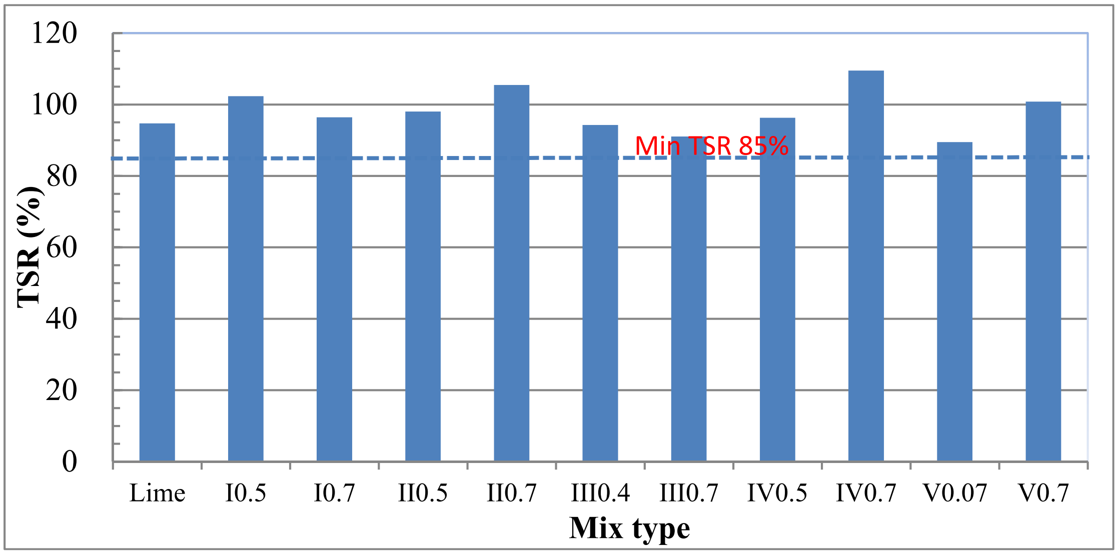


Figure 13-5 TSR Values of Intermediate Type A Mixtures Containing Aggregate Source B and Various ASAs

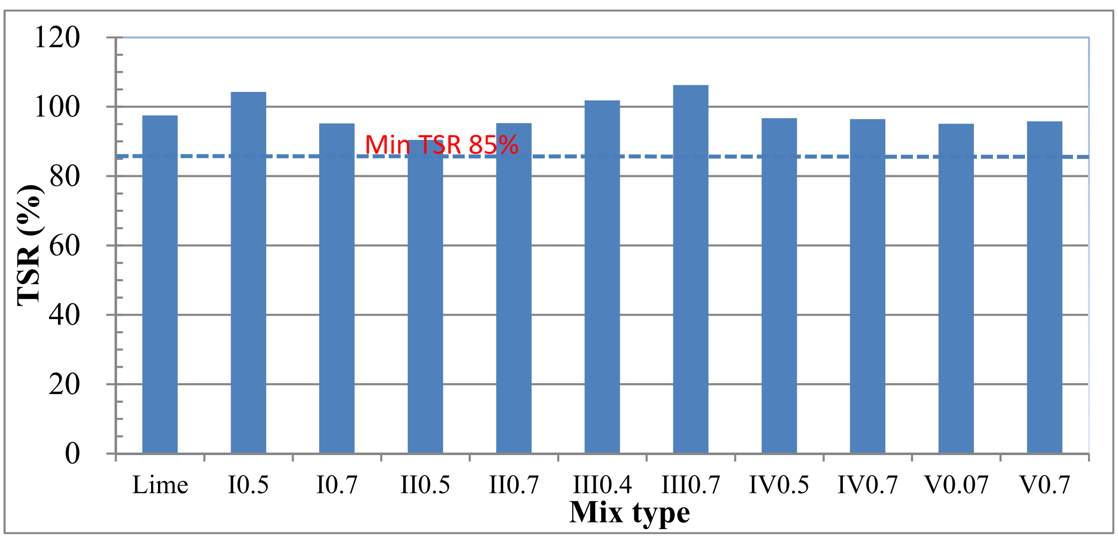


Figure 13-6 TSR Values of Intermediate Type A Mixtures Containing Aggregate Source C and Various ASAs

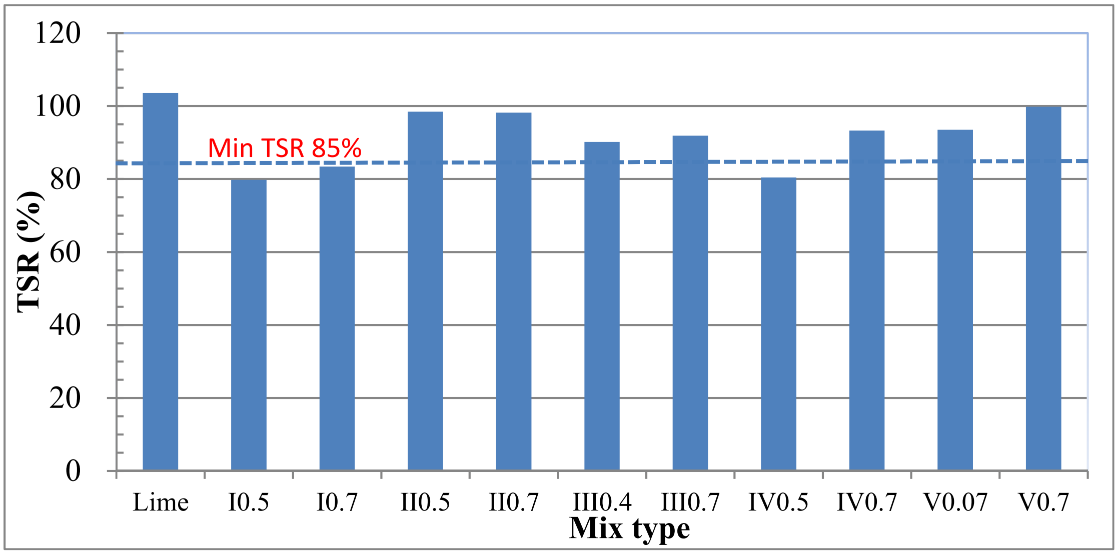


Figure 13-7 TSR Values of Intermediate Type A Mixtures Containing Aggregate Source D and Various ASAs

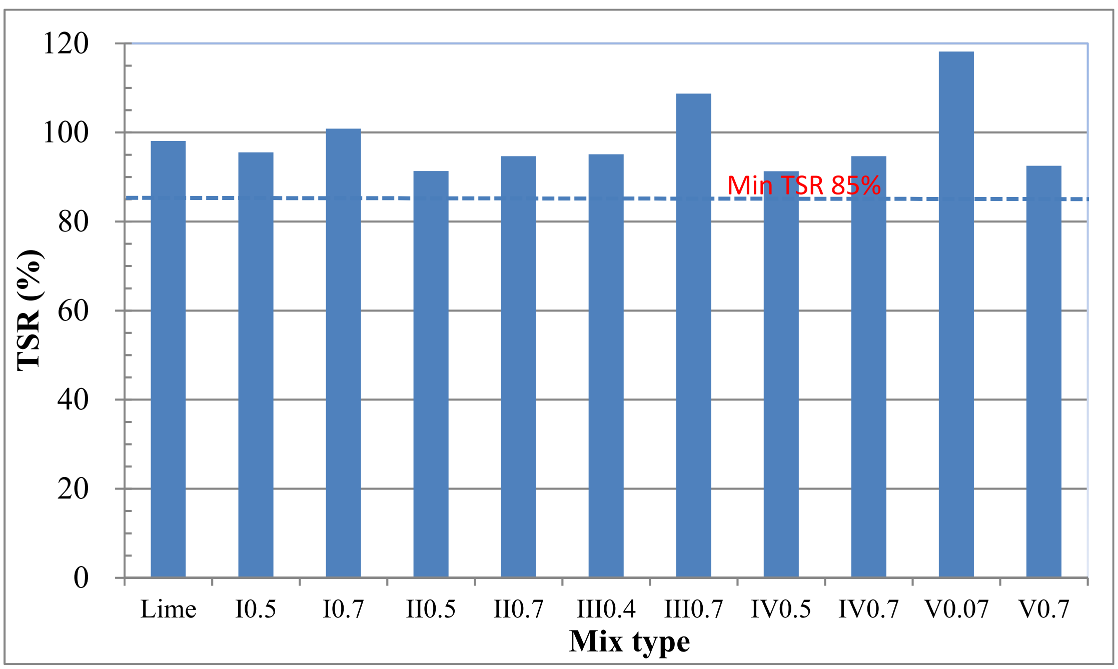


Figure 13-8 TSR Values of Intermediate Type A Mixtures Containing Aggregate Source F and Various ASAs

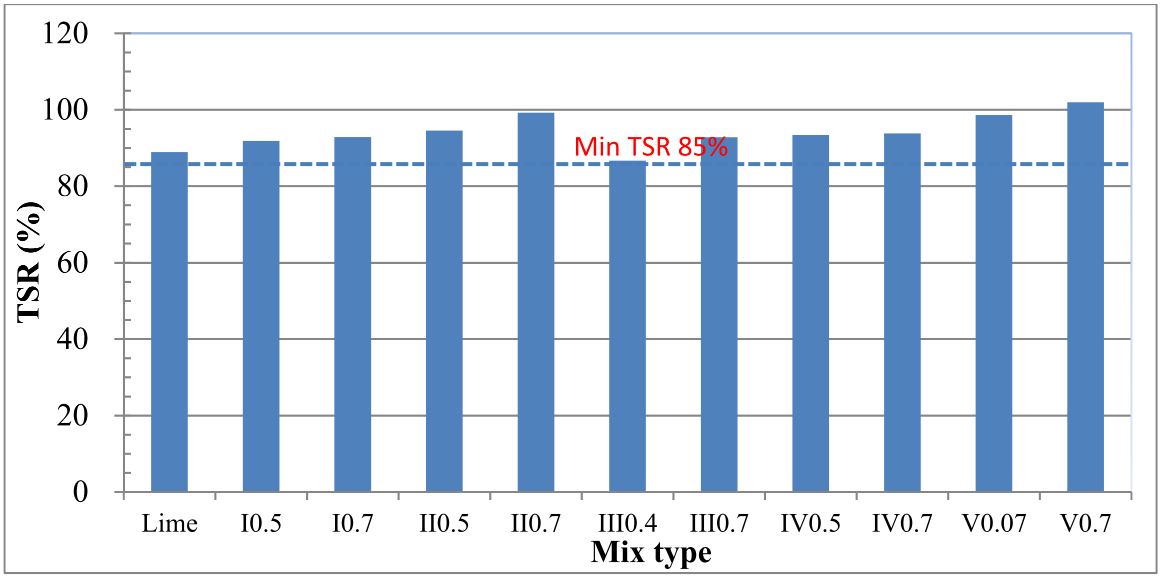


Figure 13-9 TSR Values of Intermediate Type B Mixtures Containing Aggregate Source B and Various ASAs

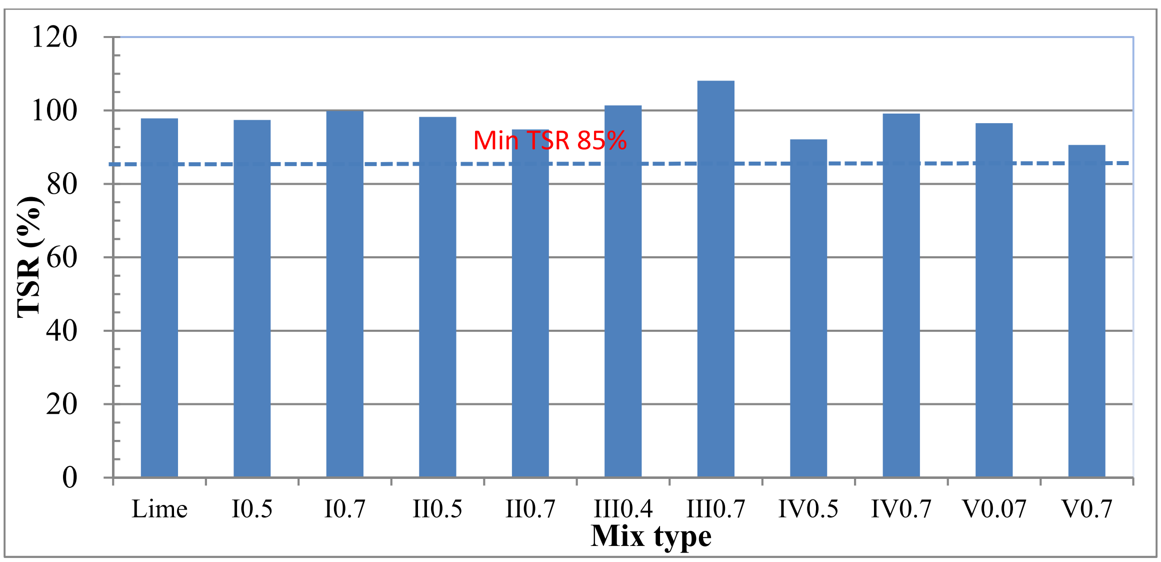


Figure 13-10 TSR Values of Intermediate Type B Mixtures Containing Aggregate Source C and Various ASAs

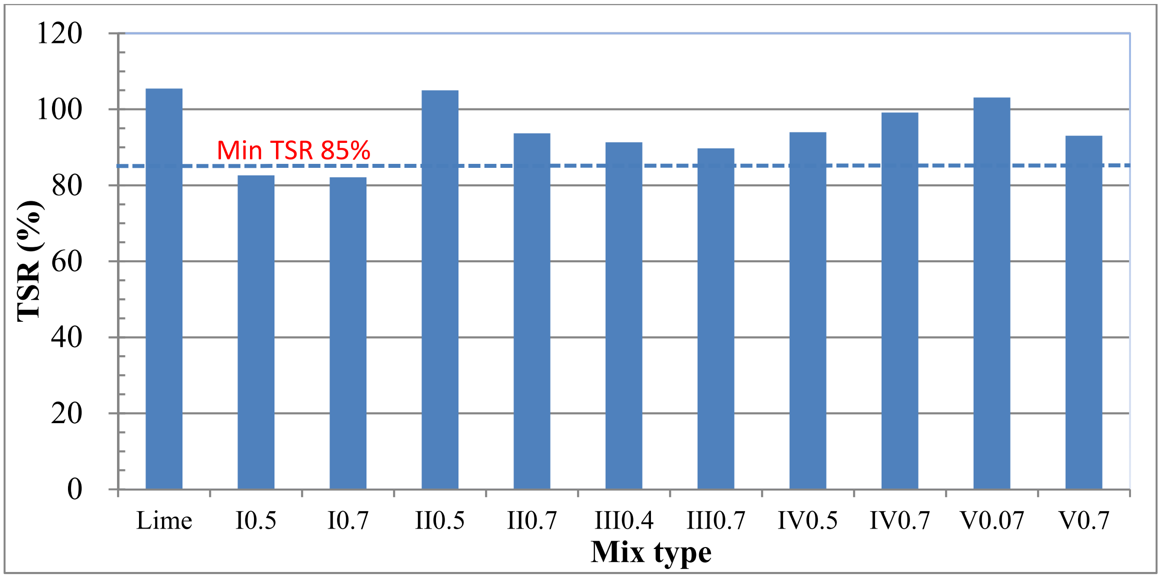


Figure 13-11 TSR Values of Intermediate Type B Mixtures Containing Aggregate Source D and Various ASAs

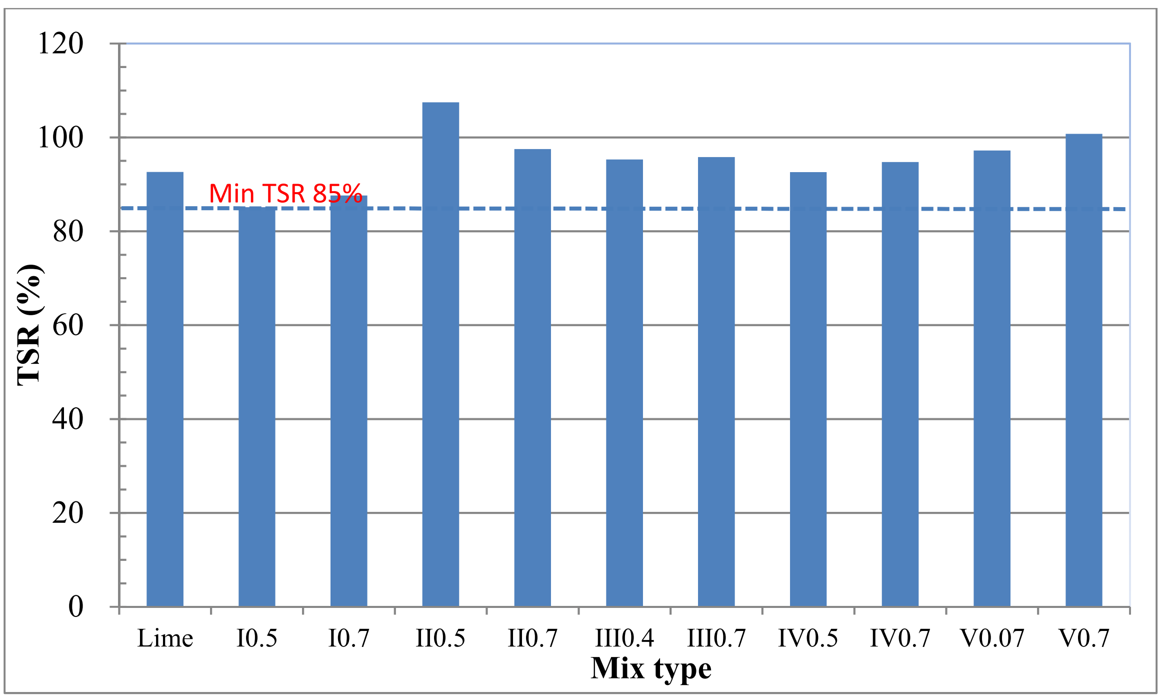


Figure 13-12 TSR Values of Intermediate Type B Mixtures Containing Aggregate Source F and Various ASAs

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