Development of an Improved Mixture Design Framework for Slurry Seals and Micro-Surfacing Treatments

By

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To my beloved family
and in the loving memories of my father

Abstract

Slurry seals and micro-surfacing (slurry surfacing systems) are widely used in pavement maintenance programs as primary surface treatments for extending pavement life and restoring serviceability function of structurally adequate pavements. Compared to hot mix asphalt overlay, these treatments are more cost-effective, energy-efficient, and environmentally friendly. In order to be effective, a rational mixture designed must be carried out to determine mixture components and proportions to be used in the field.

In spite of their widespread use, mixture design and testing methodologies for slurry surfacing systems are still lacking. Current design practices and testing procedures are based on the art and experience of the contractor, and checked with tests with no known relation to field performance. The main objective of this study is to develop an improved the mixture design framework and testing methodologies for slurry surfacing system.

Candidate test methods for evaluating critical mixture performance parameters related to common field distresses were evaluated in the laboratory, and modified as needed. This included test for workability, early raveling, and moisture induced raveling, bleeding and rutting. Promising candidate test methods were selected based on repeatability, sensitivity to design factors, simplicity, and cost. A unified mixture design framework for both slurry seals and micro-surfacing that incorporates the candidate test methods was developed. It allows the optimum emulsion content to be selected based on minimizing moisture induced raveling and bleeding. The mixture design procedure developed was verified with design parameters from field projects around the country. The results showed that the developed procedure yield design parameters similar to those used in the field. This finding is promising given that current mixture

design practices rarely give design parameters in agreement with those known by contractors to give satisfactory field performance.

It is recommended that the modified mixture design procedures developed in this study be adapted as an initial basis for developing a standardized mixture design framework for slurry surfacing systems. Additional materials need to be tested to ensure that the procedure is applicable to common materials used. Finally, evaluation of field projects is needed to establish performance limits.

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1. Introduction

State highway agencies are facing about $25 billion in federal funding backlog for pavement maintenance programs while the existing pavement infrastructure continues to age and deteriorate (Moulthrop, Hicks and Epps 2001).Most pavements have sufficient load bearing capacity but not adequate surface characteristics. Pavement surface characteristics preserve the structural integrity, and provide skid resistance and riding comfort for users. Over the last two decades, SHAs have embraced pavement preservation programs as the best cost-effective approach for extending pavement lives, preserving structural capacity, and providing quality service when funds are limited.

Pavement preservation is a program that applies network level, long-term strategy to enhance pavement performance by using an integrated, cost-effective set of surface treatments (ISSA 2010). The preservation surface treatments do not improve the bearing capacity, but can improve serviceability function and delay costly rehabilitation programs. When applied on the right pavement at the right time, preservation surface treatments can save SHAs up to seven dollars in delayed rehabilitation cost for every one dollar spend on pavement preservation treatment (Chan, Lane and and Kazmierowski 2011).

Over the last three decades, slurry seal and micro-surfacing have become widely accepted as part of the primary pavement preservation surface treatments. Slurry seal is a mixture of a slow setting asphalt emulsion, well-graded fine aggregate, mineral filler, and water (Asphalt Institute 2008). It is applied at room temperature on the prepared surface of the existing pavement in thickness less than ten millimeters. The water evaporates with time leaving behind a product with surface characteristics resembling those of hot mix asphalt (HMA) concrete. Slurry seal is generally applied on low traffic volume roads. Micro-surfacing was developed as a form of “high-performance” slurry seal that can be applied in thicker layers, fill ruts, and improve surface characteristics of high traffic volume. It is made by combining high quality materials such as polymer modified cationic emulsions; special emulsifiers; and manufactured well-graded fine aggregate (Gransberg 2010).

Slurry seal and micro-surfacing are cost-effective, energy efficient and environmentally friendly compared to traditional HMA overlay. They are applied in smaller thicknesses that allow SHAs to resurface three to five times more miles of highways with the same budget than when with HMA overlay (ISSA 2010). Unlike HMA mixes, mixing and construction is all carried out at room temperature, resulting in saving on heating and reduced greenhouse gas emission. Construction is carried out with relatively basic construction equipment, making them attractive alternatives for rural areas and developing countries.

1.1 Problem Statement

Beside the overwhelming use of slurry seals and micro-surfacing, an acceptable laboratory mixture design procedure, and mixture testing methodologies are still lacking. The responsibility of a mixture design is currently left up to contractors or emulsion suppliers to use their years of empirical experiences to determine mixture components and proportions for field construction, rather than relying on sound engineering principles, or set specification of SHAs (Raza 1994a, Fugro 2004). According to Benedict (Benedict 1991), the mixture designs submitted by contractors to SHAs can range from ¼ (pure empirical) of a page to 30 pages (over designed).

The International Slurry Surfacing Association (ISSA) and American Society for Testing and Materials (ASTM) have published guidelines for performing mixture design for slurry seal (ISSA TB A105 (2010) or ASTM D3610 (2010)) and micro-surfacing (ISSA TB A143 (2010) and ASTM D6372 (2010)) respectively. However, only a few agencies completely follow the guidelines (Andrew, et al. 1994) as they suffer from shortcomings that need to be addressed. The following section highlights some areas of concerns about current ISSA and ASTM guidelines reported by other researchers (Andrew, et al. 1994, Raza 1994, Moulthrop, Hicks and Epps 2001, Fugro 2004, Robati 2012):

- The test methods and mixture design specified use outputs that are determined subjectively determined based on the experience of the operator, and the response parameter measured with some test methods are not related to critical pavement distresses observed in the field.
- The mixture design procedure is laborious, over-complicated, require many test equipment.
- Some specified test methods are not repeatable, expensive, time consuming, and operator depended.
- SHAs are not required to specify all tests included in the guidelines and failure to meet specification requirements for an individual test does not necessarily disqualify the system. The decision as to which tests are relevant and irrelevant is arbitrary and made by the engineer as no further guidance is provided regarding which test methods may be omitted.

Many researchers (Bennedict 1985a, Bennedict 1989, Deneuvillers and Samonos 2000, Raza 1994, Andrew, et al. 1994, Fugro 2004, Robati 2012) have all echoed the dire need for a standardized rational mixture design procedure and testing methodologies for slurry seal and micro-surfacing. This will improve the consistency of slurry seal and micro-surface placed and their ability to reduce load and temperature related mode of distresses. Furthermore, a rational mixture will also allow the benefits of using new materials such as polymer modified emulsions, and or manufactured aggregates to be quantified. Specific areas of improvement identified include the use of performance-based test methods, simplified mixture design procedure and establishment of rational specification limits based on field observation.

1.2 Hypothesis

Mixture design can be improved by using performance based-test methods:

1. An automated mixing device for workability
2. The Wet Track Abrasion test for early, late , moisture induced and material compatibility related raveling
3. Bleeding can be evaluated by measuring the surface texture or volume of voids filled with asphalt
4. Resistance to moisture damage induced raveling to establish minimum emulsion content

1.3 Objectives

The main objective of this study is to develop an improved mixture design procedure for slurry surfacing treatments (slurry seal and micro-surfacing). The specific objectives are:

1. Identify the common distresses experienced by slurry seal and micro-surfacing treatments and the mechanisms by which they occur in order to gain a better understanding of factors affecting their performance.
2. Review current mixture design and testing practice and identify opportunities to improve existing test procedures or introduce new methods capable of assessing mixture resistance to the distresses identified.

3. Evaluate candidate test methods to determine if their sensitive to factors know to affect the performance.
4. Develop a modified mixture design framework that uses identified test methods
5. Compare the output of the propose mixture design framework to the design of recently constructed micro-surfacing projects to determine the feasibility of the proposed design method.

1.4 Outline

This dissertation includes seven chapters:

– *Chapter 1: Introduction*

  The introduction, which is the current chapter, includes background information on slurry seal and micro-surfacing, a problem statement, hypothesis, and objectives of this research.

– *Chapter 2: Literature Review*

  The literature review discusses topics related to the difference between slurry seal and micro-surfacing, their advantages over traditional maintenance treatments, common distresses and mechanisms by which they occur, factors affecting performance, current mixture design and problems associated with them and description of promising performance test methods identified.

– *Chapter 3: Materials and Methods*

  This chapter presents materials, experimental methods, and testing procedures followed accomplish the objectives of this research.

– *Chapter 4: Evaluation of Potential Laboratory Test Methods*

This chapter presents results of the evaluation of candidate laboratory test methods for workability, early and late raveling, and asphalt emulsion-filler compatibility, bleeding and rutting. It contains detail information about improvements to current test methods, and initial specification limit for each test method are recommended.

- *Chapter 5: Development of the Improved Mixture Design Framework*

  This chapter details proposed modification for improving current ISSA/ASMT guideline. A modified mixture design framework is also presented and details regarding how the modified procedure can be used to establish mixture components are given.

- *Chapter 6: Comparison of Modified Procedure Results to Field Project*

  This chapter presents the results of field projects whose materials were procured to determine if the proposed modified mixture design procedure yield results similar to those used in the field. Design values used in the field were established by an experienced emulsion supplier with a good reputation of designing long lasting micro-surfacing projects in the country.

- *Chapter 7: Conclusions and Recommendations*

  This chapter summarizes the major findings and contributions of this work. Additionally, recommendations for future research are presented.

2. Literature Review

2.1 General

2.1.1 Slurry Seals

Slurry was developed in Germany in the 1920s as cost effective surface treatment for road maintenance. It was adapted in the United States in the late 1960s with the development of better emulsifiers, and machines capable of continuously proportioning and placing slurry (Benedict 1978). It can be defined as a homogenous mixture of a slow setting emulsion, well-graded fine aggregate, mineral filler (when needed), and water; that is accurately proportioned, mixed and uniformly spread over a properly prepared surface of an existing pavement (Asphalt Institute 2008). The fresh mix has a creamy free flowing-low consistency, which allows for ease of placement, flow into cracks, and spreading in thin and varying layer thickness. The water evaporates, leaving behind residual mixture that is durable, skid- resistant; and resembles HMA in appearance. Figure 1 shows a picture of a slurry seal mixture both its fresh and cured state.

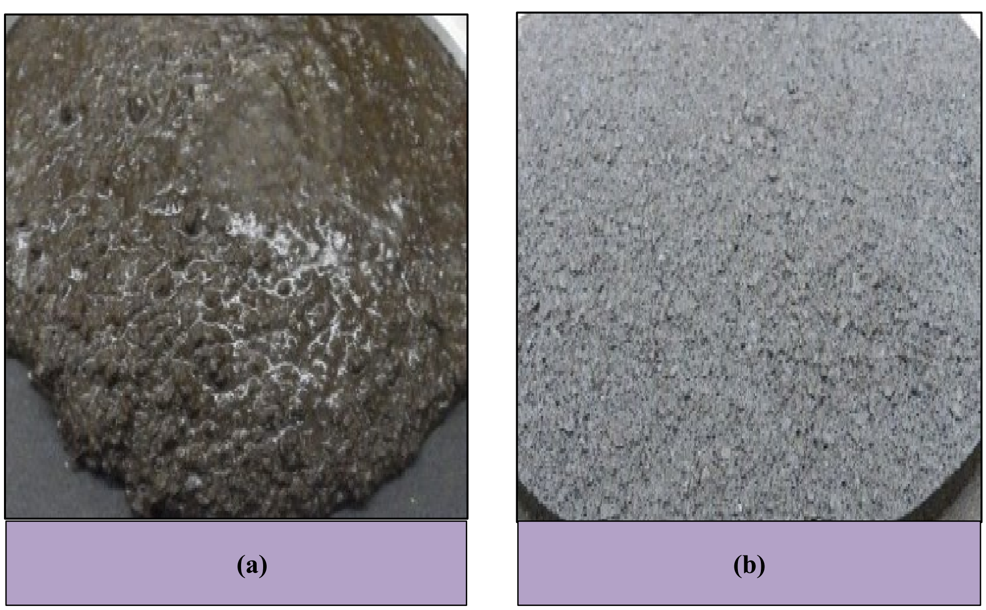

Figure 1. Example of slurry seal mixture in the fresh (a) and cured state (b)

Slurry is made up of 94.5 to 89.5% weights of aggregate and 5.5 to 10.5 % of residual asphalt binder of total aggregate weight when fully cured (ISSA 2010). Typical application thickness ranges from 3 to 9.5 mm, and it is controlled by the maximum aggregate sizes in the gradation (Fugro 2004). Generally, Slurry seal is applied on sections of highway where the design equivalent single axle loads (ESALs) are less than 500,000 and the average daily traffic (ADT) is less than 2,000 (SANRAL 2007). It is mainly used in preventative maintenance, reactive maintenance and in pavement preservation programs of asphalt pavements. In some cases, it is also applied as a wearing course on new low traffic volume roads or can be applied over a chip seal to make a cape seal. The general objective of applying a slurry seal is too:

- Seals the surface (prevents further weathering of the underlying pavement);
- Restores surface texture(improved safety);
- Provides new durable wearing surface;
- Fills cracks and voids;
- Corrects other distresses;
- Raveling;
- Light flushing;
- Minimum loss of cub height;
- No need for manhole or other structure adjustments; and color contrast for lane delineation

While slurry seals can help reduce surface distresses listed above, it does not add any structural capacity to the existing pavement, and hence is not a good candidate for pavements with structurally deficiencies (Raza 1994*b*). According to the SPS-3 Strategic Highway Research Program (SHRP) Study (Morian, Gison and Epps 1998) "*Sections on which pavement maintenance treatments have been applied have generally outperformed the associated control* *sections; treatments applied to pavements in good condition have good results; treatments applied to pavements in poor condition have poor results; and treatments applied to pavements whose conditions are somewhere in the middle have mixed results*." To achieve good result with slurry seal treatments, it is high recommended that any pavement with localized inadequate structurally capacity should be corrected before applying its application (ISSA 2010). This includes "all ruts, humps, low pavement edges, crown deficiencies, and waves" (Asphalt Institute 2008).

2.1.2 Micro-surfacing

Micro-surfacing was also developed in Germany in the late 1960's, and introduced in the United State in the early 1980s (Gransberg 2010). It is defined as a mixture of 100% manufactured well-graded fine aggregate, cationic polymer modified emulsion, water, cement and breaking agents. It is similar to slurry seal, except that only polymer modified emulsions (cationic) and 100% aggregate are used, while slurry can be made with any slow set emulsion and natural aggregate as well. Perhaps the most common cited difference is also the way the two treatments develop cohesive strength after construction to accept traffic. Slurry seals are reported to be solely depended on temperature to develop strength, while micro-surfacing breaks chemically and strength development depended on the chemistry of the system and not only on climate. Micro-surfacing can be used for the same purpose as slurry, except that it has additional benefits such as: the ability to be applied in thicker layers (9.5-16 mm), can be applied in multi-thickness, can fill ruts (40 mm depth), can improve surface texture and do minor profiling (Gransberg 2010). Because of the stability of micro-surfacing mixture arising from polymer modified emulsions and crushed aggregates, they can be applied high traffic volume roads, greater than 2000 ADT recommended for slurry seals. Micro-surfacing is applied to address the following (Raza 1994*b*):

- Seals the surface from moisture and air
- Restores surface texture
- Provides new wearing durable surface
- Fills cracks and voids
- Corrects other distresses
- Leveling Course
- Rut-Filling

When designed and constructed properly on a sound pavement, a micro-surfacing can extend the life of a pavement by 5 to 7 years (Chan, Lane and and Kazmierowski 2011) (Gransberg 2010). Just like in the case of slurry seal, the performance of micro-surfacing also depends on the conditions of the existing pavement. It is not designed to bridge weak spots, stop active cracks, progressive structural deteriorations or to cover underlying pavement deficiencies. Adequate pavement repair to address alligator cracking or potholes is necessary to ensure good performance of micro-surfacing.

2.1.3 Advantages of Slurry Seal and Micro-surfacing

Slurry seals and micro-surfacing have major economic, environmental and sustainable advantages over HMA overlays and other available maintenance treatments. The economic benefit arises from the fact that mixing; coating and construction are carried out at room temperature compared to temperatures in excess of 150°C used for HMA. In addition, no drying aggregate is required, plus simple storage facilities and construction equipment are used, resulting in further cost saving (Dunn and Peltier 2010). They also require less material, which saves on aggregate transportation cost and also allows highway agencies to provide a good level of service to the travelling public with limited budget (Etienne and Jean 2008). Construction can be carried out at night which causes less disruption to the travelling public. They also have an extended construction season, which allows highway agencies to apply preventative maintenance treatments at the right time, which save cost in the long term. Further, low operation temperatures results in improved workers and public safety- as there is no danger of explosion, toxicity fuse emission or burn. The life cycle costs (LCC) of a micro-surfacing can be as much as 28% percent lower than that of the mill and fill operation (Uhlman, et al. 2010).

The environmental benefits arise from the fact that mixing and construction is carried out at room temperature, and no drying of aggregate is required. This reduces greenhouse gas emission and reduces the amount fuel consumed during the construction process. The small quantities of aggregate required also result in environmental benefits, as fewer trucks are required to transport materials to the construction site. It has been reported that micro-surfacing consumes 28% Million Joules per customer benefit than hot and mill, and this number is even higher when compared to HMA overlays (Uhlman, et al. 2010). The sustainability aspect of slurry seals and micro-surfacing results from the fact that they requires less construction materials, less fuel for construction, improved worker and public safety and health and from their low overall LCC. Micro-surfacing consumes about 40% less materials on average compared to mill and fill operation (Uhlman, et al. 2010). Other additional benefits reported includes the fact that utility casting adjustment is not necessary since the treatments do not results in build up at the curb, and also, it a high production level industry leading to less time on project (Dunn and Peltier 2010).

2.1.4 Disadvantages of Slurry Seals and Micro-surfacing

The following limitations of slurry seals and micro-surfacing have been reported (Transit New Zealand 2005):

- Requires the project aggregate to be chemically compatible with the project emulsions
- Require the road to be closed immediately after construction
- Can only be laid when the average air temperature can be expected to exceed 10°C for a few days following construction. Below this temperature, the risk that this may not cure properly and may result in early failure
- Not suitable on flexible pavements having deflections greater than 1.5 mm or where cracking or other pavement failures are structural or extensive. Longitudinal joints may be visible
- May not always be suitable for high speed situations where coarse-texture surfaces are desirable to reduce braking distance in the wet climate due to fine gradations used.
- Cannot be applied over young (<1 to 2 years old) chip seals that contains cutbacks or diluents, as this will lead to early bleeding or flushing of the surfaces.
- Can correct a small degree of flushing or minor cracking, but in moderate to extreme cases the flushing or cracking will reflect through the surfaces.

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2.2 Materials for Slurry Seals and Micro-surfacing

Slurry seals and micro-surfacing are mixture of: asphalt emulsions, fine-graded aggregate, water, and cement. Figure 2 show the mixture components of a slurry seal/micro-surfacing and that of a standard HMA mixture component. As maybe noted, slurry seals and micro-surfacing are much more complex that HMA mixes because of additional presence of water, chemical additives, fillers, and chemical emulsifier presents in the asphalt emulsion. Each mixture component of slurry/micro-surfacing is presented in the following sections.

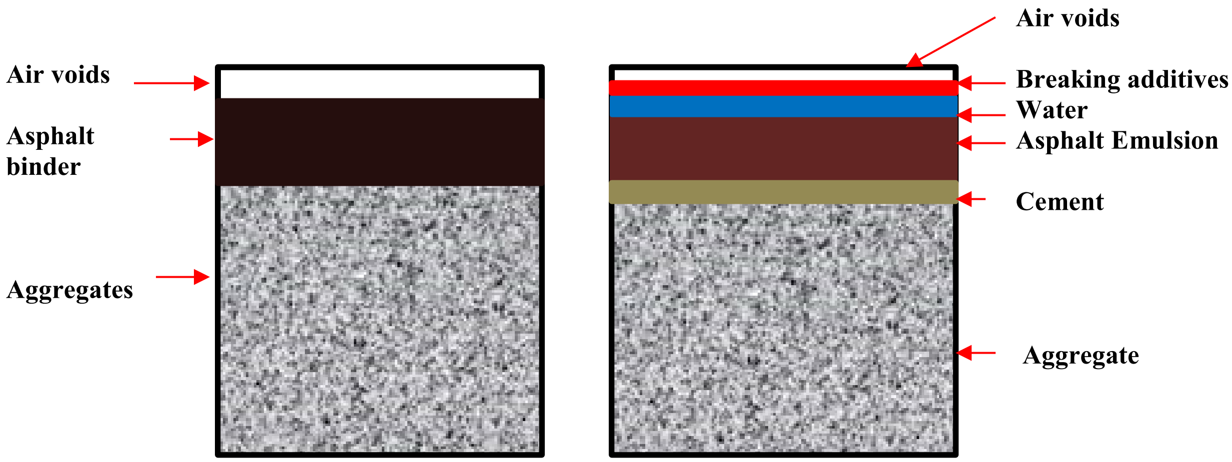


Figure 2. Components of HMA mixture (left) versus components of slurry seals/micro-surfacing mixture (right)

2.2.1 Asphalt Emulsions

An asphalt emulsion is defined as a heterogeneous systems in which asphalt (the dispersed phase) is suspended in water (the continuous phase) in the form of fine droplets in the presence of an emulsifier (SFERB 2008). It is generally made up of three basic components: asphalt cement (40% to 75 %), water (25% to 60%), and an emulsifying agent (0.1 % to 3.5%) (Asphalt Institute 2008). Other additives, such as stabilizers, coating improvers, anti-strips, or break control agents are also sometimes added to enhance the performance of the asphalt emulsion (Asphalt Institute 2008). The asphalt droplets in an emulsion range from 0.1 to 20 micron in diameter, and they have a distribution of particle sizes (James 2006). The asphalt droplets in the emulsion have a small charge resulting from the emulsifier, as well as from the ionisable components of the asphalt itself. These provide an electrostatic barrier that prevents them from coming close to each other, and are responsible for their storage stability (Barnes 2000). Both the physical and rheological properties of asphalt emulsions are affected by asphalt particle size and particle size distribution, emulsifier type and amount and by the properties of the hot asphalt binder emulsified (Harkness 1977, Delfosse, et al. 2000).

The asphalt particles in the emulsion separate from the water phase and fuse together to form a continuous asphalt film on the surface of the aggregate when mixture with aggregate, by undergoing a processes known as the breaking and curing process (Bahia, Jenkins and Hanz 2008). These processes are, however, not well understood. It is hypothesized that breaking refers to the destabilization of the emulsion system, where the emulsifier can longer keep the asphalt particles from fusing together and form an irreversible continuous asphalt film (Redelius 2006). Breaking may occur as a result of the introduction of other ions in the emulsions from the aggregate, fillers, additives, or as a result of the chemical instability of the emulsions (Armak 1974). Curing on the other hand refers to the evaporation of water from the emulsion or mixture, leaving behind an asphalt emulsion residue that has rheological properties similar to those of the base binder (Johannes, Mahmoud and Bahia 2011). Curing depends on the chemistry and physical properties of the emulsions used, aggregate-emulsion compatibility, climatic conditions and conditions of the existing substrates.

The breaking and curing rate of an asphalt emulsions has significant influence of the level of aggregate coating, mixture workability, and the ability of the mixture to be placed to a desired thickness (Chang 1979). The breaking rate should be slow enough to allow for mixing and coating; allow for a sufficient window of workability so that the mixture can be placed, compacted and finished properly with a reasonable effort. Mixtures that break prematurely will results in poor coating of the aggregates, stiffer mixes that are hard to place, has negative impact on the long-term performance on the performance of the surface treatment (Harkness 1977). On the other hand, the breaking and curing process should not be to slow such that it prevents fast return of traffic on the road.

2.2.1.1 Asphalt Emulsions for Slurry Seals and Micro-surfacing

Asphalt emulsions used in slurry seals are required to meet the specifications of the AASHTO M 140 or ASTM D 977 for anionic emulsions, or AASHTO M 208 or ASTM D 2397 for cationic emulsions. Emulsions for micro-surfacing are required to be strictly modified cationic, with a minimum of 3% polymer by weight of asphalt content. These emulsions are also required to meet the specifications of the AASHTO M 208 or ASTM D 2397 with a few exceptions. Common emulsions reported in the literature are presented in Table 1.

Table 1. Common emulsions for Slurry Seals and Micro-surfacing

Emulsions For Slurry Seals	Emulsions For Micro-Surfacing
SS-1h, CSS-1, CSS-1h, CQS-1h or polymer modified versions of these	CQS-1hP, CQS-1hL, CSS-1hP, CSS-1hL

The rheological properties of the fresh emulsion as well as those of the cured residue have profound effects on both short and long term performance of slurry seals and micro-surfacing mixtures. To ensure a minimum level of performance for asphalt emulsions, the ASTM D977 and D2397 specify quality tests and specification limits for each test for all asphalt emulsions. These tests are presented in Table 2 and Table 3 for slurry seals and micro-surfacing emulsions respectively. When these requirements are met, the resulting mixture is supposedly to meet desired performance characteristics related to the properties of the binder. Some state agencies may require other or additional tests to be performed on the asphalt emulsions depending on their policies.

Table 2. Specifications of the ASTM D 977 and D 2397 for slow and quick set emulsions

Material Properties Measured	ASTM	Specification
Test on Fresh Emulsions		
Viscosity, Saybolt Furol at 25°C (77°F) SFS (min-max)	D 244	20-100
Storage Stability Test, 24-h, % (max)	D 6930	1
Particle Charge Test	D 244	+ve (cationic emulsions only)
Sieve Test, % (max)	D 6933	1
Cement Mix Test, % (max)	D 6935	0.1
Residue by Distillation, 5 (min-max)	D 6997	57
Tests on Cured Residue		
Penetration, 25°C, 100 g, 5s	D 244	40
Ductility, 25°C 5cm/min, cm (min)		40
Solubility in trichloroethylene, % (min)		97.5

Table 3. Additional Asphalt Emulsion Tests for Micro-Surfacing (ISSA-A105 2010)

Test	Test Method		Specification
	AASHTO	ASTM	
Test on Fresh Emulsions			
Storage Stability Test, 24-h, % (max)	T 59	D 6930	1% Maximum
Distillation of Emulsified Asphalt[1]	T 59	D 6930	62% Minimum
Tests on Emulsion Residue			
Penetration, 77 degrees F.(25°C)	T 49	D 5	40-90[2]
Softening Point (Ring & Ball), degrees F	T 53	D 36	135°F (57°C) Minimum

1The temperature for this test should be held at 350°F (177°C) for 20 minutes.

2 The climatic conditions should be considered when establishing this range

However, it is important to note that it has been widely recognized that currents test for asphalt emulsions are empirical, and do not relate to distresses observed in the field, and they are even being phased out of the hot mix asphalt industry (Hanz, Johannes and Bahia 2011, Richard et al. 2012). Different emulsions meeting the same specification have been observed to perform differently in the field under similar traffic and climatic conditions (King, et al. 2010). There has been a dedicated effort to identify/develop new performance based test for asphalt emulsions, and ongoing projects such the NCHRP9-50 are expected to develop performance specification for asphalt emulsions used in slurry seals and micro-surfacing applications.

2.2.2 Aggregates

Aggregate for slurry seals/micro-surfacing are required to be clean, angular, durable, well-graded, and uniform (Asphalt Institute 2008). The ISSA TB A105 requires aggregate for slurry seal to 100% crushed, while the corresponding ASTM D3610 allow up 50% of "*smooth-textured sand of less than 1.25% water absorption*" to be used, except in cases of heavy duty surfaces in while 100% are required. For micro-surfacing, however, both ASTM D6372 and ISSA TB A143 require the use of 100% crushed aggregate. Quality test required for the aggregate for both slurry seals and micro-surfacing are given in Table 4 per specification of the ISSA standards.

Table 4. ISSA Quality Tests for Aggregates for Slurry Seals and Micro-surfacing (ISSA TB A105 and A143, 2010)

Test	ASTM	Specification	
		Slurry Seal	Micro-Surfacing
Sand Equivalent Value	D2419	45 Min	65 Min
Soundness	C 88	15% Max. w/NA2SO4 25% Max. w/MgSO4	15% Max. w/NA2SO4 25% Max. w/MgSO4
Los Angeles Abrasion	C 131	35% Max	30%

2.2.2.1 Aggregate Gradation

Aggregate for slurry seals are required to confirm to one of the three gradations given in Table 5 (Types I, II, II), while those for micro-surfacing are required to meet the gradation for Type II and Type III. Type I gradation is recommended for fine seals and cracking sealing; Type II for general seal and medium texture surfaces; while Type III is used highly textured surfaces. Some agencies have been reported to use their own or modified versions of these gradations (Raza 1994*a*).

The primary difference between the three gradations is the aggregate maximum aggregate size. It dictates the amount of residual asphalt required by the mixture and the purpose to which the treatment is most suited. Type I is the finest gradation and it is recommended for crack sealing and fine seals. Type II is coarser and is suggested for urban and residential streets and airport runways. Type III have the coarsest grading and are appropriate for filling minor surface irregularities (micro-surfacing only), correcting raveling and oxidation, and restoring surface friction. It is re typically used on arterial streets and highways (Asphalt Institute 2008).

Table 5. Aggregate Gradations for Slurry Seals and Micro-surfacing (ISSA TB A105 and A143, 2010)

Gradation Type	**I**	**II**	**III**
General Usage	**Crack sealing and fine seal**	**General seal, medium textured surfaces**	**Produces highly textured surfaces**
Sieve Size	**Percent Passing**	**Percent Passing**	**Percent Passing**
3/8 in (9.5 mm)	100	100	100
No. 4 (4.75 mm)	100	90- 100	70-90
No. 8 (2.36 mm)	90- 100	65-90	45-70
No. 16 (1.18 mm)	65-90	45-70	28-50
No. 30 (600 mm)	40-65	30-50	19-34
No. 50 (300 mm)	25-42	18-30	12-25
No. 100 (150 mm)	15-30	10-21	7-18
No. 200 (75 mm)	10-20	5-15	5-15

2.2.3 Mineral Filler

Mineral fillers are used to serves two major purposes in slurry seal/micro-surfacing: (a) minimize aggregate segregation by increasing the viscosity of the mix (b) to accelerate or slow down the breaking and curing rate of the mix. They can also be used to improve specific long-term performance of the treatment, depending on the type of filler used (Raza 1994*a*). Both ISSA TB A105 and A143 allow up to three percent of mineral filler to be added by dry weight of aggregate. The ASTM standards (D3610 and D6372) give no guidelines regarding the minimum or maximum value of filler to be used. Commonly used fillers included Portland cement, hydrated lime, limestone dust, crushed rock screenings, fly ash, kiln dust, and baghouse fines (Gransberg 2010). There are no specifications for these mineral fillers.

2.2.4 Water

The objective of adding water is to improve coating and workability of the mixture. Insufficient water amounts may result in poor aggregate coating and or in stiff mixes that are hard to place (Ackerson 1957). Too much water results in segregation and or in a prolonged curing time (SANRAL 2007). The water is required to be free of harmful salts and contaminants (pH).

2.2.5 Additives

Additives are sometimes added to slurry seals and micro-surfacing mixtures to accelerate or retard the break/set rate. Additives reported in the literature includes: aluminum sulfate crystals, ammonium sulfate, inorganic salts, liquid aluminum sulfate, amines and anti-stripping agents (Gransberg 2010). Current specifications do not specify the type or amount of additives that can be added in the field.

2.3 Factors Affecting Performance

The performance of slurry seals and micro-surfacing is affected by many factors. The main Factors that Affects the Performance of Slurry Seals and Micro-surfacing are discussed below.

- ***Project Selection***

Slurry seal and micro-surfacing are not intended for structural support. They will not stop reflective cracking from showing, and do not perform well on pavement with high deflections (Gransberg 2010). It is therefore very important that the project selected for these treatments are structurally sound.

- ***Experience of the Construction crew***

The experience of the construction crew is very important in delivering the desired final product. The final product will only be as good as the experience of the construction crew. Thus, it is very important to train the crew about these mixes.

- ***Quality of the Mix Design***

The mix design method used to determine mix portion need to be of good quality to ensure good performing treatments.

- ***Material Compatibility***

Aggregate-binder compatibility affects the breaking and curing rate of the mix, aggregate-emulsion bond, durability and wearing characteristics of the mix. It is therefore important to carrying out detailed mix design tests to confirm that the aggregate and the emulsion will mix and break at an appropriate rate. The durability and wear characteristics of the mix are also highly depended on the compatibility of the aggregate and the binder.

- ***Climatic Conditions at the Time of Construction***

The temperature during and immediately after construction should not fall below 10°C (Asphalt Institute 2008). The temperature affects the curing rate of the mix; causing the mix to cure improperly and result in early failure of the seal if it is too low. Humidity also affects early performance of the mix. If the humidity is too high, it will affect the evaporation rate of moisture from the mix; thus increasing its cure time.

- ***Trafficking time***

Slurry seal and micro-surfacing are generally trafficable with care after 10 to 20 minutes of construction when temperatures are above 10°C (Fugro 2004). If the mix is trafficked before it has cured, will result in early failure of the seal. Final curing and hardening of the surface takes place over the following few days.

2.4 Common Distresses

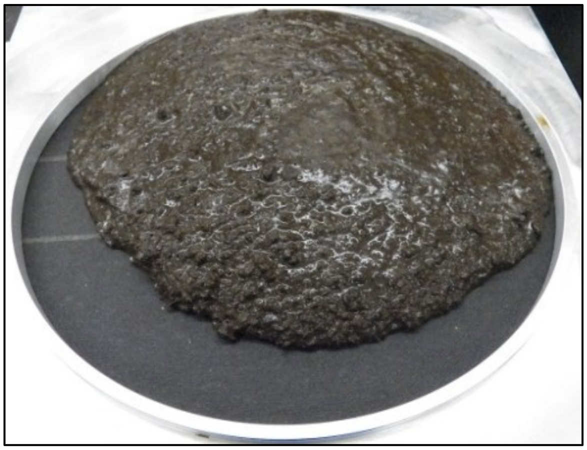
There is technically no difference between how slurry seals or micro-surfacing fails. Common distresses can be divided into three categories: (1) construction related distresses, (2) short-term distresses, and (3) long-term distresses. These are briefly discussed in the subsequent sections.

2.4.1 Construction Relate Failures

These distressed occurs during the construction phase before the surface is opened to traffic. They may occur due to insufficient mix design, poor construction practices or unexpected change in climatic condition. This section will focus on distresses related to mixture parameters.

2.4.1.1 Insufficient Mixing Stability and Poor Consistency for Spreading

Insufficient mixing time occurs when the emulsion breaks during mixing of the components, such that satisfactory aggregate coating and proper mix consistency for placement cannot be achieved (Chang 1979). Mixes experiencing this problem are generally stiff in nature and tend to form “balls” and “lumps, and as such cannot be placed and finished to a desired thickness. Figure 3 show pictures of two slurry seals, one with good consistency or workability (left) and another with insufficient mixing time (right). Lumps and balls can be clearly seen in the in the picture.



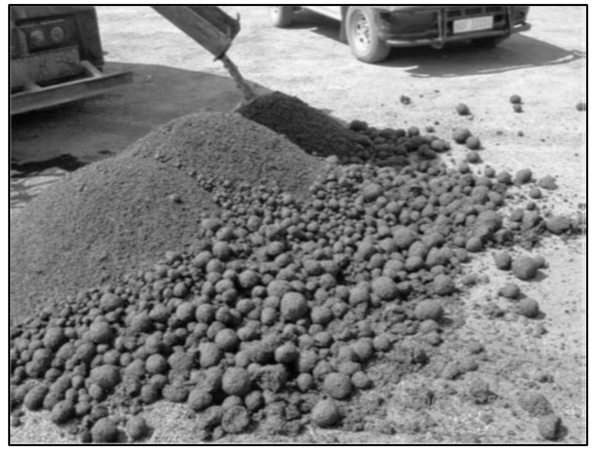


Figure 3. Example of a slurry or micro-surface with sufficient mix time (left) and on with insufficient mixing time (right) (SABITA, 2012)

The mechanisms causing premature breaking are not well understood. Factors contributing to insufficient mixing time include, emulsion properties, aggregate properties, amount of premixing water added, amount of filler added, and temperature of the mixtures at the time of mixing (Ackerson 1957, Benedict 1977, Alan 1986) (Benedict 1977). Emulsions with a high breaking index when evaluated with the Cement Mixing Test in accordance with ASTM D977 have been reported to cause problems of premature breaking in the field (Ackerson 1957). For this reason, both standards for anionic emulsions (ASTM D977) and cationic emulsion (ASTM D2397) limits the breaking rate of the emulsions to 2% totally emulsion broken when tested by the Cement Mixing Test.

Aggregate with high absorption, high zeta potential values, and or high fine/filler or clay contents have been reported to cause problems with premature breaking (Gates 1986, Gorman, et al. 1998, Delfosse, et al. 2000). Insufficient mixing time may also occur as a result of high climatic temperature during the mixing of the mixture ingredients. The breaking rate of asphalt emulsion depends on climatic temperature (James 2006). High temperature tends to increase the breaking rate of the emulsions and this may result in insufficient workability window. It is recommended that surface temperatures be within a range of 10 to 60°C to ensure a proper break (Gransberg 2010). The main factor reported to affect mixing time is the amount of premixing water present in the mix (Ackerson 1957, Chang 1979, Raza 1994*a*). Additional water is generally added to slurry seals and micro-surfacing mixes in order to achieve a desired level of homogeneous mixture consistency and workability window. If the amount of water added is not enough, premature breaking may occurs. However, it should be noted that excess amount of premix water may cause segregation, which in turn leads to premature failure of surface treatment shortly in service.

2.4.1.2 Segregation

Segregation occurs when there is physical phase separation between different components of the mixture due to difference in their density (Barnes 2000). The emulsion and fine particles floats to surface, while the coarser aggregate particles settle out to the bottom. This process leaves an insufficient emulsion in the mix to give a sufficient binder film thickness for durability, and to bind the new surfacing to the existing pavement surface (Kari and Neill 1959). The asphalt emulsions that creams at the top of the surfacing, may create a slick-smooth surface on the road, which may become sticky during hot temperatures, and reduced surface friction.

The life of the treatment can also be significantly compromised as a result of segregation. The asphalt binder that rises to the top of the surface usually wears off due to traffic abrasion, leaving a harsh mixture behind with insufficient binder to bind the aggregate on the road under traffic (Lee 1986). As a result, the mix disintegrates quickly afterward in a form of aggregate loss, and may also de-bond from the existing substrate (Kari and Coyne 1964, SANRAL 2007).

The main factor contributing to segregation is excessive pre-mixing water content, although excessive use of additives has also being reported to result in mixture segregation (Fiock 1969). To prevent segregation, the ISSA TB A105 (ISSA 2010) recommend running a combination of a slump test and a static segregation test (split cup method) to prevent segregation. The horizontal slump is required to be between 2 and 3.5 cm, while results of the segregation test all limited to a maximum of 15% difference in residual asphalt binder content of top and bottom halves of them mixture.

2.4.2 Short-Term Distresses

These are distresses that occur immediately after the construction of a slurry seal or micro-surfacing. Distresses identified from literature are presented in subsequent sections.

2.4.2.1 Early Raveling

One of the main concerns with treatments constructed with asphalt emulsions in general is the curing time required before the surface can be re-opened to traffic. If the treatment is prematurely opened to traffic before it has sufficiently cured, early raveling or shoving may results (Bennedict, New Trends In Slurry Seal Design Methods 1985). Raveling is a term used to describe the loss of cover aggregate from surface of a slurry seal/micro-surfacing. When it occurs, it may lead to loss of skid resistance through bleeding, and can also create path for moisture and oxygen intrusion into the underlying layers. Factors that contribute to premature raveling include: premature opening of the road to traffic, low binder content in the mix, incompatibility between the aggregate and binder, poor emulsions properties, raining before the surface has sufficiently cured, insufficient fines in the mix, de-bonding of poor quality aggregate, abrasion action of tires, temperature, humidity, and poor construction practices (Bennedict 1985*a*). To prevent early raveling, slurry seals and micro-surfacing are required to develop sufficient cohesive strength of the mixture to be able to withstand traffic stresses. Figure 4 shows a classification chart for identifying mixes that are ready to be opened to traffic with minimum potential of early raveling.

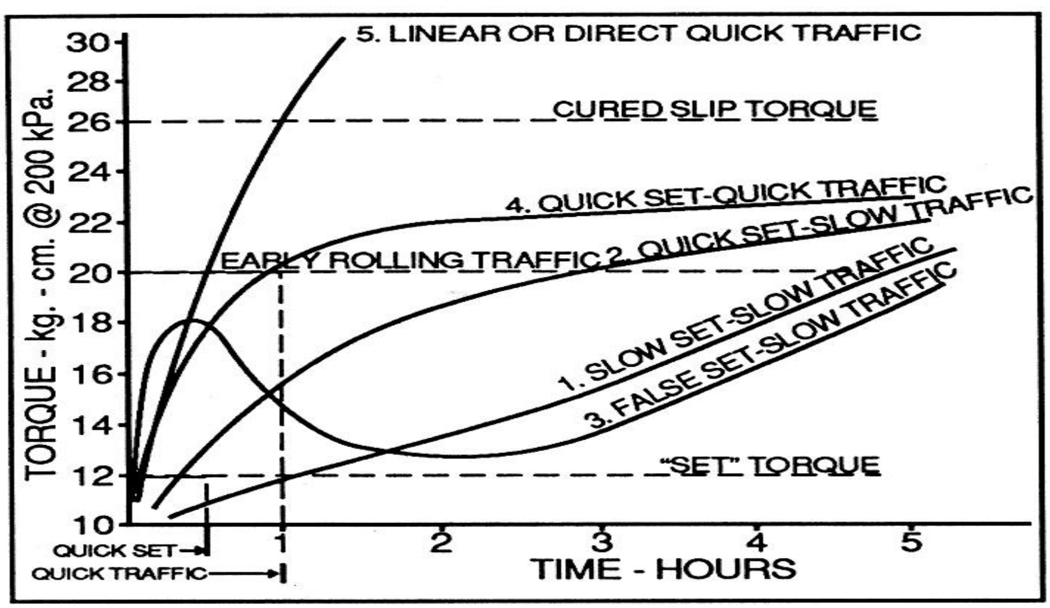


Figure 4. Classification chart of cohesive strength development of slurry seals and micro-surfacing mixes (Bennedict 1985*a*)

Temperature, humidity, high wind seed, cement content, breaking and curing additive and emulsion types have been reported to have direct effects on resistance raveling, provided that the right project is selected (AsphaltInstitute 2008, SFERB 2008, ISSA-A105 2010). Both ISSA and ASTM guidelines specifies the use of the modified cohesion test to determine when a surfacing can be trafficked. Mixes that exhibit a torque value of 20 kg-cm at 200 kPa are deemed as ready for trafficking, and hence not prone to early raveling.

2.4.2.2 Bleeding

Bleeding occurs when the asphalt binder in the mix is squeezed out of the mixture to the surface of the surfacing layer, resulting in a reduced skid resistance and surface texture (Bennedict 1985*b*). Bleeding that occur in the early life of the treatment can results in significant damage of the treatment. The binder that rises to top of the treatment may get soft at higher temperature, which makes it easy to stick to the wheels of the pavement. As results, large chucks of the treatment can be tracked off the pavement. The main factors leading to bleeding in the early life of the treatment include but are not limited to binder issues (too much binder, wrong binder type), environmental conditions (temperature, humidity), traffic effects (heavy traffic, high volume traffic), and construction deficiencies (ISSA-A105 2010) (King, et al. 2010) (Gambatese 2005). Mixtures with excess premixing water content may also bleeding as the binder that creams to the top may soften and get tracked away (Kari and Neill 1959).

To prevent bleeding, slurry seals and micro-surfacing are generally constructed with emulsions emulsified from hard base asphalts to prevent them from softening in the summer (ASTM-D977 1995). In some cases polymer modified emulsions are used to prevent bleeding as they high stiffness of their residue prevent them from getting too soft at high temperatures (Lawson, Leaverton and Senadheera 2007). Both ISSA and ASTM guidelines for slurry seals and micro-surfacing specified the use of the sand adhesion test to establish the maximum asphalt content allowed in the mixture to prevent bleeding.

2.4.2.3 Rutting

Rutting is a permanent deformation of the pavement within the wheel paths caused by plastic movement of the micro-surfacing mix either in hot weather or from inadequate compaction during construction (Huang 2004). Significant rutting can lead to major structural failures and a potential for hydroplaning. Early rutting is caused by insufficient mixture design, high emulsions content, soft asphalt emulsion or placed on exiting surface with active progressive rutting. ISSA TB A143 specified the use of the Loaded Wheel Test (LWT) to evaluate mixture's resistance to rutting. Mixes experiencing lateral displacement greater than 5% are deemed susceptible to rutting.

2.4.2.4 Cracking (Reflective and Thermal cracking)

Generally, thermal cracking in asphaltic mixtures occurs due to either a single rapid drop in temperature or to repetitive temperature cycling (Huang 2004). In either case, the restrained motion of the slurry surfacing system leads to the build-up of stresses as the temperature drops. If the built-up stress exceeds the strength of the material, or if the stress occurs repetitively cracking will result. These cracks are characterized as being relatively straight transverse cracks with regular spacing. When such cracks form in the pavement, water can infiltrate the system and accelerate further deterioration (Huang 2004). Another type of cracking that can occur in a slurry surfacing system is a reflective crack, which can occur, when the system is applied to a cracked surface or a jointed pavement. In this case, the cracks on the existing surface propagate upward with time and can show up on the new surface in a relatively short period of time (Harkness 1977). Aging of the slurry surfacing system can accelerate these processes because, as the asphalt ages, it becomes stiff and brittle. It is recommended not to place slurry seals and micro-surfacing mixes on pavement with active structural cracks as these have been known to quickly reflect through the new surfacing (Asphalt Institute 2008).

2.4.3 Long-Term Distresses

These are distresses that generally occur during the services life of a slurry seal or micro-surfacing, usually after 6 months or more of good performance in field (Fugro 2004). Common distresses identified in the literature are described in the next section.

2.4.3.1 Late-Raveling

This distress is similar to early raveling discussed in earlier, except that it occurs in the long-term. It occurs as a result of insufficient binder content, loss of fine matrix from the mix, abrasion by traffic and due the aging and oxidation of the binder (Fugro 2004). Proper mixture design and careful selection of materials components, specifically ensuring that materials are compatible has been reported to reduce long-term raveling (Coyne and Ripple 1975). The Wet Tract Abrasion Test (WTAT) specified in ISSA TB100 is used to evaluate the resistance to long-term raveling of slurry seals and micro-surfacing. The test generally limit the maximum amount of aggregate lost from the samples after being abraded with a rubber hose the WTAT that simulates the breaking and turning of traffic on the surface. Figure 5 show an example of the effects of the emulsion type on the resistance to late raveling of slurry and micro-surfacing when the same aggregate type, gradation and curing conditions are used. It can be seen that emulsion type can have profound effect on the ability of these surfacing to resist early raveling.

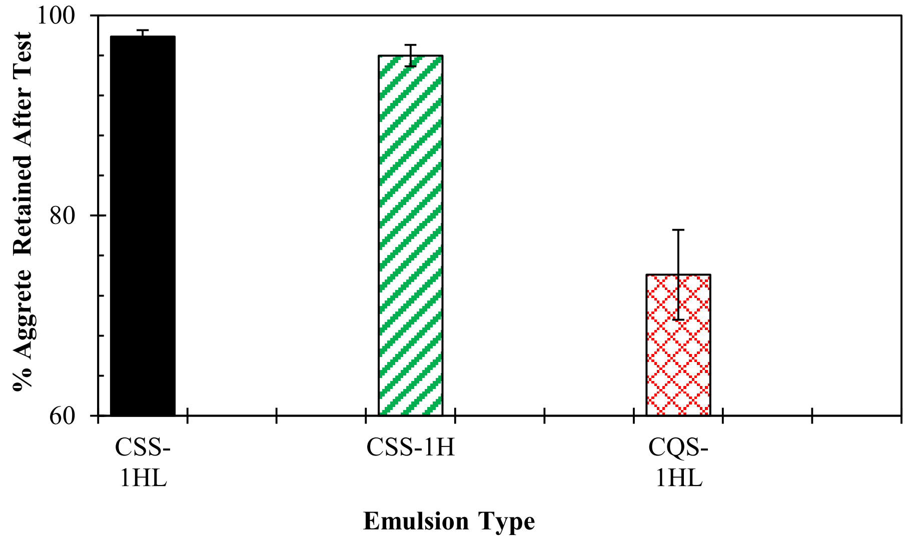


Figure 5. Example of the effects of emulsion type on the late raveling

2.4.3.2 Moisture Induced Raveling (Stripping)

Stripping is the loss of aggregate particles in the presence of moisture. The moisture deteriorates the bond between the aggregate and the binder, or may change the chemical make-up of the asphalt binder thus causing the aggregate to become loose (Moraes, Velasquez and and Bahia 2011). The same factors that lead to raveling can also cause stripping. Many researchers have reported that stripping of slurry seals and micro-surfacing is largely related to aggregate binder compatibility and to the size of the film thickness of the asphalt binder coating the aggregate (Ackerson 1957, Clifton 1967, Landise 1977, Benedict 1978, Gates 1986). Figure 6 show an example of the effects of aggregate mineralogy and emulsion chemistry on the ability of a slurry seal mixture to resist moisture damage related raveling. Figure 7 shows an illustration of ionic exchange that takes place between an anionic emulsion and a limestone aggregate.

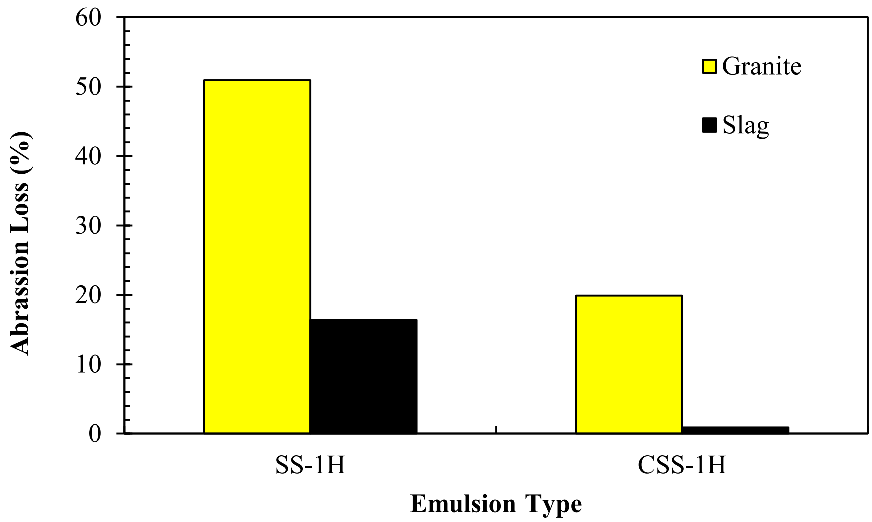


Figure 6. Effects of aggregate mineralogy and emulsion chemistry on resistance of stripping of slurry seals (6-day soaked test)

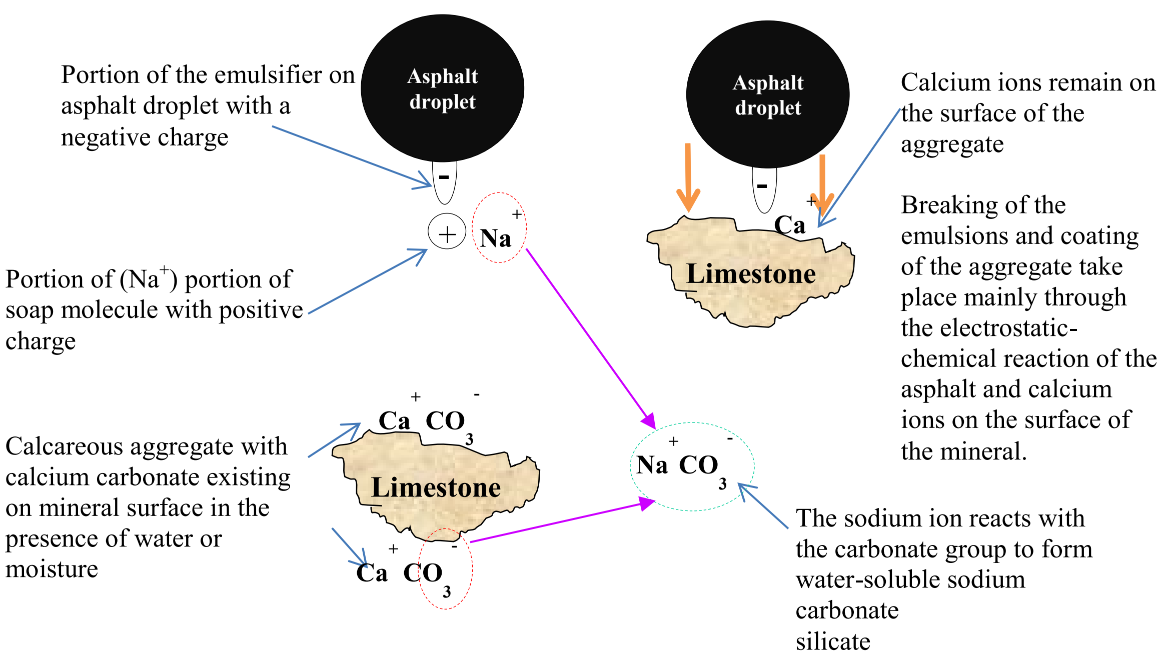


Figure 7. Illustration of the chemical and electrostatic interaction that takes place between an anionic emulsion and a limestone aggregate surface in the present of moisture (Gates 1986).

The ionic compound that remain the on the surface of the aggregate and form a bond with asphalt emulsions residue are also shown. When a different aggregate is used with the same emulsion or vice versa, the components involved in the formation of bond between the aggregate ate changes. Because each aggregate-emulsions combination has its unique chemical compounds responsible the resulting bond between the aggregate and emulsion residue, their ability to resist moisture damage also varies.

2.4.3.3 Bleeding

Bleeding may also occur as a long term failure. Factor leading to long-term bleeding, include mix densification with time and temperature, excessive binder content and use of incorrect binder grade for the climate (Gransberg 2010). In the long-term, bleeding does not result in tracking, but more in reduced surface texture which pose safety problems to the traveling public.

The same factor that causes early bleeding have also been reported to cause late bleeding.

2.4.3.4 Rutting

Long term rutting occurs under conditions similar to those discussed under Section2.4.2.3. Factor contributing to rutting in the long-term include high residual asphalt binder content, incorrect binder grade for the climate, high traffic volume, and aggregate gradation (Anderson 1994, Bahia, et al. 2001).

2.5 Current Mixture Design Methods

There is currently no widely accepted mixture design for slurry seals and micro-surfacing, but there many non-standardized different mix design procedures used both in the United State and around the globe. A recent study by Fugro (Fugro 2004) reported that the most commonly used are ISSA Technical Bulletins (TB A105 and TB A143) and the corresponding ASTM standards (D3910 and 6372) for slurry seals and micro-surfacing respectively (Fugro 2004). Some state agencies have developed their own mix design procedures which in many cases are modified versions of the ISSA and ASTM mix design methods (Raza 1994*b*, Andrew, et al. 1994, Fugro 2004)). Countries like Germany, France, Spain, and South Africa have also developed their own mix design that works best for them, but most of them are also main modified version of the ISSA and ASTM guidelines (Fugro 2004). Commonly used mixture designs found in the literature are presented in the next sections. Of special interest are the mixture design methods contained in the ISSA and ASTM standard which this study will heavily focus on.

2.5.1 ISSA Design Method for Slurry Seal (ISSA TB A105) and Micro-surfacing (ISSA TB A143)

The mixture design for slurry seals is contained in ISSA TB A105 guidelines. It was developed from papers presented by Huffman, Benedict, Gordillo, and other industry experts at the ISSA World First Congress in Madrid and the Asphalt Emulsion Manufacturers Association (AEMA) convention in Phoenix, in 1977 according to Robati, 2012. These guidelines were later adapted for micro-surfacing with minor modification in the early 1980 (Bennedict 1985*b*). The mixture design guidelines for micro-surfacing are contained in the ISSA TB A143. Figure 8 present chronological steps generally followed to establish optimum mixture components to be used in the field.

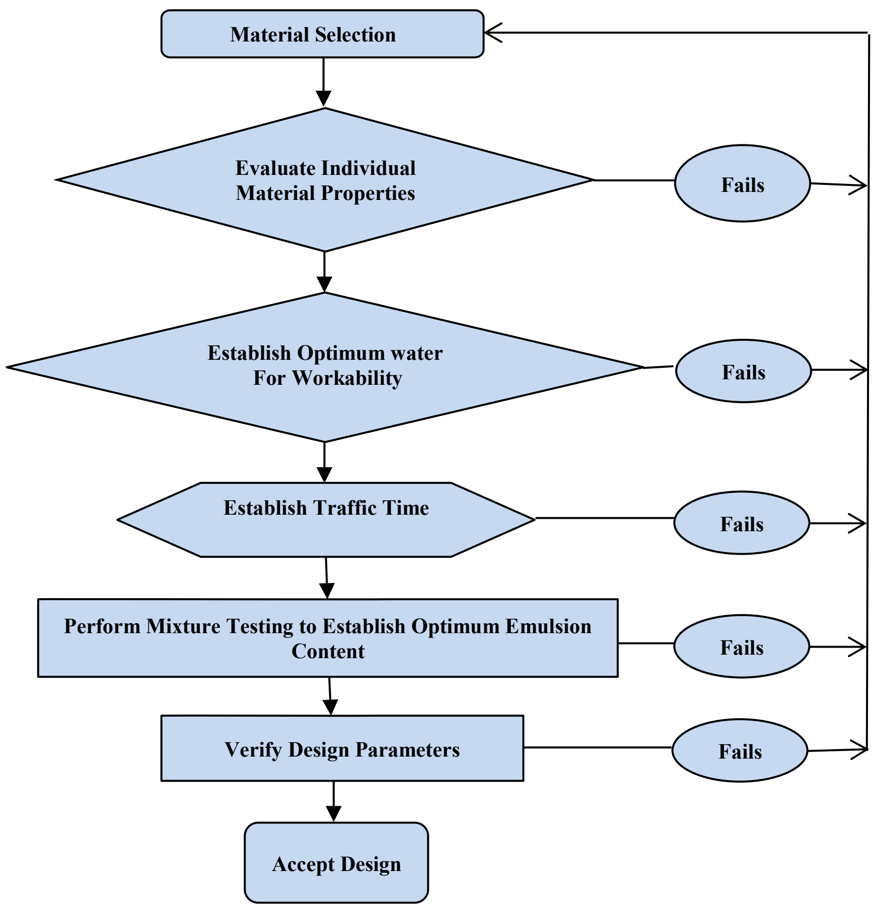


Figure 8. Typical Job Mix mixture design flow diagram for slurry seals and micro-surfacing mixes

This process generally include following the steps described below:

1. Asphalt emulsions, aggregate, filler type, additives (if desired) are selected to meet all applicable project specifications
2. Aggregate gradation is selected based on the objectives of the surface treatments e.g., crack filling, fill ruts, improve skid resistance etc.

3. Trial mixes are prepared and mixability and constructability parameters evaluated. This requires samples to be prepared and evaluated at a single asphalt content to determine optimum water content for workability, quality of aggregate coating, filler amount, and traffic time. Each parameter listed about requires a different sample size, and test equipment to evaluate.
4. Samples are prepared at different asphalt emulsions content using the mixture components established in Step 3 and evaluated for long term performance: resistance to dry raveling, wet raving (optional), bleeding, rutting aggregate filler compatibility. Again, each parameter listed about requires a different sample size, and test equipment to evaluate.
5. The optimum design emulsion content is selected as the design content that meets a set of specification limits for dry raveling, wet raveling, bleeding, and filler compatibility.
6. The ISSA guidelines provide advices for selecting materials, sample preparation and a series of tests for mixture samples to determine optimum water content, filler amount, minimum design emulsion content and maximum emulsion content.

The optimum emulsion content for the mix is chosen by combining graphs from the wet track abrasion test and the loaded wheel test on one graph, and the envelope defined is termed as the allowable range. Three percent tolerance for contractor proficiency is subtracted from the maximum emulsion content range defined by the loaded wheel test. The mid-ranged emulsion content between the envelope defined by the maximum emulsion content as defined by the loaded wheel test and the minimum tolerance is termed the optimum emulsion content ± 1.5 percent. Figure 9 show an illustration of determining the optimum design emulsion content.

The tests recommended for different stages of the design methods for selecting optimum mixture components for slurry seals and micro-surfacing components are presented in Table 6. Details description of each test method is given in the next sections. Problems associated with each test method are also discussed under the section of each test.

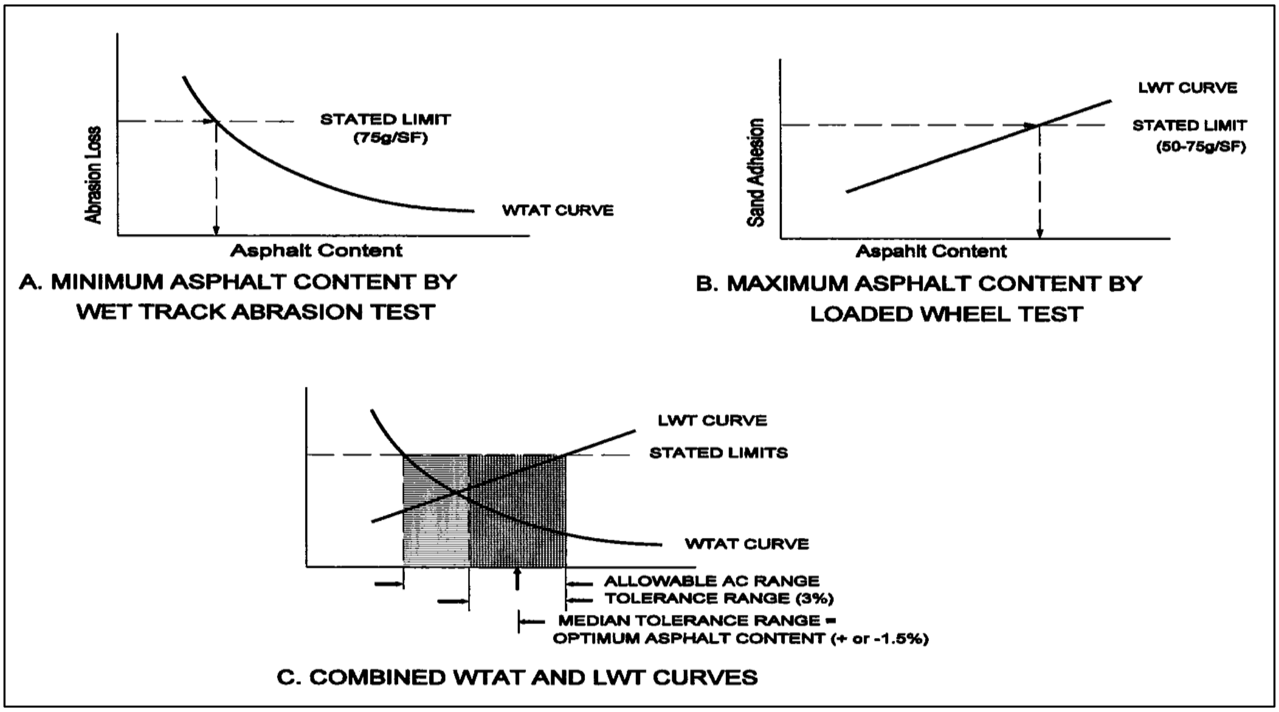


Figure 9. Determination of optimum asphalt content (Andrew, et al. 1994)

2.5.1.1 Mix Time Test ISSA TB 113

This test is used to determine the allowable minimum water content in the mix, by measuring the length of time the mix remain workable before the emulsions start to break. It is carried out by preparing a series of 100 or 200 gram trial mixes in disposable cups at different water contents while keeping the emulsion content the same. Mixing of the mixture components is carried out manually by hand. Mixes that remain workable for less 3 minutes (or 2 minutes for micro-surfacing) are rejected. The minimum water content resulting in a mixture that is workable for at least three minutes (2 minute for micro-surfacing) is selected and used to prepared samples to be further performed the mixture. No guideline is given regarding the number of replicates to be prepared. The test is however subjective and highly dependent operator since mixing is carried out by hand, and the characteristics of the mix judged based on experience.

Table 6. Recommended Mixture Tests and Specification Criteria for Slurry Seal and Micro-surfacing

Treatment	Description	ISSA	Specification Limits
Slurry Seal	Mix Time@ 25 °C	TB 113	120 seconds (minimum)
	Consistency	TB 106	2 to 3 cm
	Wet Cohesion	TB 139	12 kg-cm @ 30 minutes
			20 kg-cm @ 1 hour
	Wet Stripping	TB 114	Pass : 90% (min)
	Wet-Tack Abrasion Loss	TB 100	538 g/m^2 (max) @ 1 day Soak
	Excess Asphalt by LWT Sand Adhesion	TB 109	538 g/ m^2 (max)
Micro-surfacing	Mix Time@ 25 °C	TB 113	120 seconds. (minimum)
	Consistency	TB 106	Not Required
	Wet Cohesion	TB 139	12 kg-cm @ 30 minutes
			20 kg-cm @ 1 hour
	Wet Stripping	TB 114	Pass :90% (min)
	Wet-Tack Abrasion Loss	TB 100	538 g/m^2 (max) @ 1 day Soak
			807 g/m^2 (max) @ 6 day soak
	Loaded Wheel Test	TB 147	5% (Max) after 1,000 Cycles
			2.10 (max) after 1,000 Cycles
	Excess Asphalt by LWT Sand Adhesion	TB 109	538 g/ m^2 (max)
	Classification Compatibility	TB 144	11 Grade Points Min. (AAA, BAA)

2.5.1.2 Consistency Test, ISSA TB 106

This test is used to determine the amount of water required to produce a mix with a specific consistency, through the measurement of a slump. The test is carried out by preparing 400 gram samples at various water and or filler content. The sample is poured in a hollow cone

(0.8mm metal frustum, 75 mm high with 40 mm top and bottom diameters), which is centered on the flow scale. The flow scale has 7 concentric circles that are 1 cm apart. Immediately after sample is pour into the cone, it is removed in a smooth vertical motion, and the mixture allowed to flow. A sample passes the test when the horizontal slump is between 2 and 3 cm. One of the shortfall of this test is that is not applicable some polymer modified and quick-set emulsions type.

2.5.1.3 Wet Stripping Test, ISSA TB 114

This test is used to check the compatibility of the slurry seal/micro-surfacing mixes components by means of evaluating the coating of the aggregates. The test carried out on fully oven cured sample, which can either be taken from the mix test sample, consistency or cohesion test samples. A 10 gram sample is immersed in 400 mL of boiling water for three minutes, after which the system is allowed to cool down. The sample is dried, visually examined for uncoated areas and an estimate is made of the area of aggregate remaining coated with asphalt. The mix passed the compatibility requirement if the retained coating is higher than 90. Concerns with test are that the test is subjective, and the sample is directly place in contact with the heat source which may significantly affect the results (ASTM D866).

2.5.1.4 Modified Cohesion Test, ISSA TB 139

This test is used to evaluate the curing characteristics of slurry seal/micro-surfacing mixes that have passed the mix and consistency test. It is used to determine the time at which the mixture develop sufficient strength to stand traffic. In some cases, this time is established by varying the filler amount in the mixture. The test is carried out by fabricating disk shaped samples with dimensions of 6 mm thick and 60 mm in diameter. A pressure of 200 kPa is applied through the neoprene foot while the cylinder is rotated 90 to 120 degrees. The torque needed to rotate the cylinder in contact with the specimen is measured with a torque wrench at 30-minutes curing intervals. A sample has reached a set point if the torque level is 12 kg-cm, and is ready to accept early rolling traffic when torque-level if 20 kg-cm. Samples that reach a 12 to 13 kg-cm cohesion torque within 30 minutes and a 20 kg-cm cohesion torque within 60 minutes are termed quick-set/quick-traffic system.

Raza (Raza 1994a) has reported that some mixes that fails to reach a 12 to 13 kg-cm cohesion torque within 30 minutes, attains a 20 kg-cm cohesion torque within 60 minutes. Benedict (Bennedict 1985*a*) reported the problems related to the variability in the friction from the cylinder rods and piston packing's and lubrication; and repeatability issues. In a different paper, Benedict (Benedict 1991*b*) detailed factors affecting the accuracy and repeatability of the Cohesion test based on mixture tested by his company. He also noted in another paper (Benedict 1991*a*) the results of the Cohesion test are only reliable when field temperature are close to those evaluated in the laboratory. Fugro (Fugro 2004) reported repeatability, operator dependency, and the fact that the test is carried out on samples cured at only one climatic condition (60 °C) as three main concerns with test.

2.5.1.5 Wet-Track Abrasion Loss Test (WTAT), ISSA TB 100

This test procedure is used to establish the minimum asphalt content required to prevent long-term aggregate loss. The test is also used to evaluate the effects of moisture damage induced raveling of moisture conditioned samples. It is carried out by casting a fresh slurry mix into a 6 mm thick and 280 mm in diameter mold, using mix proportions that have pass the mixing, consistency and boiling test. The sample is fully cured to a constant weight for no less than 15 hours at 60°C in the oven. After curing, the dry weight of the sample is recorded. The sample is placed in a water bath at 25 °C for one hour and then mechanically abraded under water with a rubber hose for 5 to 6 minutes depending on the model of the equipment used. The abraded specimen is washed free of debris, dried in the oven, and weighed. For a design to be accepted, the WTAT loss should be less than 807 g/m^2. Moisture damage is carried out the same way, except those samples are conditioned for 5 days at room temperature.

Several concerns have been raised in the literature regarding the test. Several researchers (Bennedict (Bennedict 1985*a,* Raza (Raza 1994b, Deneuvillers and Samonos 2000, Fugro 2004) have identified thickness of the test sample (6 mm), the use of unrepresentative gradations and the fact that currently specification were derived based on limited field data in the early 1960s as the major concerns with the test. Raza (Raza 1994) has also reported that mixtures meet the WTAT standard for one-hour soak period, could fail to meet maximum abrasion loss after a 6-day soak. He proposed that the minimum emulsions content be determined using moisture conditioned samples rather that based on a 1 hour soak. Deneuvillers and Samonos (Deneuvillers and Samonos 2000) have reported that the WTAT does not give repeatable result when coarser aggregate gradations (0/6, 0/8, and 0/10) are used. They modified the test by replacing the hose with a set of wheels to allow for representative gradations and layer thicknesses to be used. Also the current standard does not give guidance is given regarding the number of replicates that needs to be carried out.

2.5.1.6 Loaded Wheel Test (LWT) ISSA TB 109 & Sand Adhesion Test

This test is used to determine the maximum asphalt emulsions content that will prevent problems related mix instability and bleeding under heavy traffic. The test is carried out by casting fresh slurry mix into a mold of a specific thickness, and then dried to a constant weight for minimum of 12 hours at 60°C. The cured sample is compacted by means of a loaded, rubber tired, reciprocating a wheel. A sample is first conditioned to 1000 cycles, after which it is weighted and cured to a constant weight at 60°C. Hot sand heated to 82.2 °C is poured on the sample and 100 cycles are run on the sample. The sample is weighted again in weight due to sand adhesion is recorded as the sand adhesion value. For a mix design to be acceptable, the LWT sand adhesion has to be less than 538 g/m^2. This test is only required when designing a slurry seal that is going to be used on a road with high traffic volume, otherwise it is not required.

According to Bennedict (Bennedict 1985*b)* the sand adhesion approach has some shortcoming. He report that when emulsions from low penetration grade binders and or high modified emulsions are evaluated, a low sand adhesion value is observed irrespective the emulsion content present in the sample. This has caused some field projects constructed with such binders to fail premature by either bleeding or permanent deformation. He further noted that the test also yield unreliable results especially when mixes with coarse gradations are used. Raza (Raza 1994*a*) has reported that the reproducibility of the loaded wheel test is questionable. He also noted that for some aggregates, LWT has permitted excessive amounts of binder, and this has resulted in unacceptable mixtures in the field when placed on high shear stress areas such as intersections. He has also reported that in some cases, mixtures that failed the test produced goods results in the field. Other researchers such as Andrew et al. (Andrew, et al. 1994) and

Robati (Robati 2012) have reported the hot sand approach to be far from accurate. They have presented results that showed that the test is more sensitive to the amount moisture in the sample rather than to emulsion content, emulsion type and or aggregate gradation.

2.5.1.7 Lateral Displacement Test, ISSA TB 147

This test is used to measure the stability of micro-surfacing intended for multi-layers or rut filling, and is not applicable to slurry surfacing mixes. It measures the amount of compaction or displacement characteristics of a micro-surfacing mix under simulated traffic compaction. Three devices are suggested in the ISSA TB 147 for this purpose. However, the standard does not clarify whether the designer can use only one of the three tests or if all three tests are required. However, it appears that only one test is commonly used in the industry to evaluate rutting of micro-surfacing, and this the only test that will be discussed here in.

2.5.1.7.1 The Loaded Wheel Test

The test procedure for this test is similar to that described in Section 2.5.1.6 for determining the maximum asphalt content by the sand adhesion method. The only difference is that the width and thickness of the specimen are measured before and after 1,000 cycles of the LWT compaction, just prior to the sand adhesion stage. The information is used to calculate the vertical and lateral displacement of the sample. In addition the density of the sample before and after compaction is also calculated. Mixes that show vertical deformations greater than 10 percent or a specific gravity greater than 2.1 are deemed unsatisfactory for multi-layer or rut applications.

2.5.1.8 Aggregate Filer Compatibility Test, Schulze-Breuer and Ruck ISSA 144

This test is used to determine the relative compatibility between the aggregate filler of a specific gradation and emulsified asphalt residue. The end result is a grading value, or the rating system, for adhesion (percent in coated), abrasion loss (in grams loss), and high temperature cohesion characteristics (absorption in grams absorbed and integrity in percent retained mass). In this test, the aggregate is mixed with 8.2 percent asphalt cement and pressed into a 40 gram specimen, about 30 mm in diameter x 30 mm thick, and then soaked for 6 days. The weight of that sample is recorded, and the sample is tumbled in the Schulze-Breuer and Ruck machine's shuttle cylinders for 3,600 cycles at 20RPM. The weight of the sample is recorded, immersed in boiling water for 30 minutes, and then weighed again. The sample is air drying for 24hours, and examined for coating. This information is used to calculate absorption, abrasion loss, integrity, and adhesion, and to assign a rating to identify the best asphalt for the given aggregate source. For design to be acceptable, the mix must achieve 11 grade points minimum (i.e. AAA, AAB).

Although the test can identify mixes that could have potential poor performance, the test is empirical and not related to field performance. Andrew et al. (Andrew, et al. 1994) reported that the Ruck procedure which produces the integrity part is not a very precise test. They reported that certain mixture combinations have been known to fail this procedure all the time but have, nevertheless, performed adequately in the field.

2.5.2 ASTM D3610 Design Method for Slurry and ASTM D6372 Method for Micro-surfacing Seal

ASTM guidelines are similar to those of the ISSA presented in Section 2.5.1. They contain guidelines for selecting asphalt emulsions, mineral aggregate, filler, additive and water.

Recommended test procedures and specification limits for determine optimum water contents, filler and design asphalt emulsion content are also provided. The D3610 requires the same test equipment and procedure similar to those specified in the ISSA TB A105 with minor differences. The D6372 refer the use to ISSA TB A147, and hence two are technically the same. The tests methods and specification limits recommended by ISSA and ASTM guidelines are presented in Table 7. As can be seen, some differences exist beside the fact that the same test equipment and mix design procedures are similar as maybe noted. The only performance criterions that are the same are consistency test and 1 hour-soak WTAT loss values, while the rest differs. It should also be noted here that the D3610 also allows up to 50% natural for the sand, provided that the absorption does not exceed 1.5%, while ISSA TB A105 strictly require the use of 100% crushed aggregate.

Table 7. Micro-surfacing Mix design: ISSA TB 147 versus ASTM D6372

Test	**Specification**	
	ASTM D6310 (Slurry Seals)	**ASTM D6372 (Micro-surfacing)**
Mix Time@ 25 °C	60 seconds < mix time< 180 seconds	60 seconds < mix time< 180 seconds
Consistency	2 to 3 cm flow	2 to 3 cm flow
Set Time: Cohesion Test	15 minutes< blot test < 12 hours	15 minutes< blot test < 12 hours
Cure Time: Cohesion Test	Time required for the rotating neoprene cylinder to ride free. The time should be < than 24 hours.	Time required for the rotating neoprene cylinder to ride free on the surface. Time should be < 24 hours.
Wet Stripping	Not Required	Not Required
Wet-Tack Abrasion Loss ▪ @ 1-day soak ▪ @6-day soak	807 g/m^2 Maximum	▪ 538 g/m^2 (max) ▪ 807 g/m^2 (max) (required)
Loaded Wheel Test ▪ Lateral Displacement ▪ Specific gravity after 1,000 Cycles	Not Required	▪ 5% (Max) ▪ 2.10 (max)
Excess Asphalt by LWT, Sand Adhesion	Not Required	538 g/ m^2 (max)
Classification Compatibility	Not Required	11 Grade Points Min. (AAA, BAA)

2.5.3 Texas Transportation Institute Mixture Design Methods for Micro-surfacing

The Texas Transportation Institute (TTI) has carried out extensive review of the ISSA TB A143 mixture design for micro-surfacing. It has documented serious issues associated with the test methods and guidelines for selection the design emulsion content, filler amount and water content following these guidelines. It has subsequently developed a new mix design procedure for micro-surfacing slightly different from ISSA and ASTM mix design procedures, and it is contained in Texas Transportation Institute (TTI) TTI 1289.

In the TTI 1289, optimum water for workability is determined with a modified cup flow test for all emulsion content/filler combinations. For each emulsion/filler combination, optimum water for workability is defined as the water content at which the separation of fluids and solids in mixture is greater than 5mm (TTI-1289-1 1995). The Modified Cohesion Test is recommended for selecting optimum cement content that will results in quick return of traffic. Optimum cement content is determined for each emulsion content, it defined as the cement amount resulting in a cohesion torque greater than 12 kg-cm at 30 minutes and 20 kg-cm at 60 minutes. The last test involves determining the optimum emulsion content from the results of the WTAT (ISSATB 100). It is selected as the minimum bitumen content at which aggregate loss of sample is less than 807 g/m2 (75g/ft2) for 6-day soaked samples (TTI-1289-1 1995). A safety margin of 0.5% is added to minimum asphalt content established to account for variability (TTI-1289-1 1995). One disadvantage of the TTI 1289 is that it does not contain criteria for selecting maximum allowable asphalt content or for evaluating resistance permanent deformation.

2.5.4 California Department of Transportation Mixture Design

The California Department of Transportation (Caltrans) has recently developed a single mix design procedure for both slurry seal and micro-surfacing. Table 8 presented recommended test methods and mixture specifications from the Caltrans Study (Fugro 2004) . As may be noted, the new Caltrans procedure applies the same concept for selecting optimum mixture components as ISSA TB A105 and TB A143, with the difference being on the test methods specified. The optimum water content for workability is determined by replacing the manual Hand Mixing Test with a new automated test called Automated Mixing Test (AMT). The Modified Cohesion Test was replaced by automated test equipment called the Automated Cohesion Test. A new test for evaluating early raveling or establishing traffic time termed the Cohesion Abrasion Test (CAT) was also introduced. The test is similar to the wet track abrasion test (ISSA TB 100), except that it uses a set of wheels rather than a rubber hose.

The main underlying differences between the Caltrans mix design procedure the ISSA design guidelines is that it uses automated equipment to eliminated operator variability currently associated with the test methods specified in ISSA/ASTM guidelines. In addition the Caltrans procedure attempt to include the effects of climatic condition on the test results into account. Another major difference between the procedures lies in selecting the optimum design emulsion content. Caltrans specifies only running the CAT test at 30 minutes, 1 hour and 3 hours to select the design emulsion content. It appears that the main short fall of the Caltrans procedure is that no test are specified on fully cured samples, and gives not guidelines for evaluating bleeding and or rutting.

Table 8. Slurry Surfacing Mixture Design Requirements (Fugro 2004)

Set Time	Test or Field Condition	Units	Traffic Hi	Traffic Med	Traffic Low	Temperature Hi 35 C	Temperature Med 25 C	Temperature Low 10 C	Humidity Hi 90%	Humidity Normal 50%
Rapid	PFS-1 (Mixing)									
	Mixing Torque - maximum	kg-cm	9	9	9	9	9	9	9	9
	Mixing time - minimum	sec.	120	120	120	120	120	120	120	120
	Spread index - maximum @ 120 sec.	kg-cm	12	12	12	12	12	12	12	12
	Boil test - 30 sec.	-	clear water	clear water	N/A	clear water	clear water	clear water	clear water	clear water
	Coating	-	100%	100%	95%	95%	95%	100%	100%	95%
	PFS-2 (Wet Cohesion)									
	30 min. cohesion - minimum	kg-cm	12	12	12	12	12	12	12	12
	60 min. cohesion - minimum	kg-cm	23	20	20	20	20	20	20	20
	90 min. cohesion - minimum	kg-cm	25	25	25	25	25	25	25	25
	12 hr. cohesion - minimum	kg-cm	29	29	29	29	29	29	29	29
	PFS-3 (Abrasion Loss)									
	30 min. loss - maximum	g/m²	200	200	400	300	300	300	300	300
	1 hr. loss - maximum	g/m²	100	100	300	100	200	100	100	200
	3 hr. loss - maximum	g/m²	100	100	200	100	100	100	100	100
Slow	PFS-1 (Mixing)									
	Mixing Torque - maximum	kg-cm	9	9	9	9	9	9	9	9
	Mixing time - minimum	sec.	120	120	120	120	120	120	120	120
	Spread index - maximum @ 120 sec.	kg-cm	12	12	12	12	12	12	12	12
	Boil test - 30 sec.	-	clear water	clear water	N/A	clear water	clear water	clear water	clear water	clear water
	Coating	-	100%	100%	95%	95%	95%	100%	100%	95%
	PFS-2 (Wet Cohesion)									
	30 min. cohesion - minimum	kg-cm	12	12	12	12	12	12	12	12
	60 min. cohesion - minimum	kg-cm	23	20	20	20	20	20	20	20
	90 min. cohesion - minimum	kg-cm	25	25	25	25	25	25	25	25
	12 hr. cohesion - minimum	kg-cm	29	29	29	29	29	29	29	29
	PFS-3 (Abrasion Loss)									
	30 min. loss - maximum	g/m²	200	200	400	300	300	300	300	300
	1 hr. loss - maximum	g/m²	100	100	300	100	200	100	100	200
	3 hr. loss - maximum	g/m²	100	100	200	100	100	100	100	100

2.6 Problems Associated With Current ISSA (A105 & A143) and ASTM (D3610 & D6372)

As state already in prior sections, many agencies in the United State, Canada and around the whole prefer using either the ISSA (TB A105 and A143) or the ASTM (D3610 or D6372) for their slurry seal or micro-surfacing mixture design. However, these guidelines specify too many test methods that requires different samples sizes for evaluating mixture properties. This does not only make the mixture design process time consuming, but may also comprise the quality of the results. Even more importantly, most of these tests are empirical and do not measure mixture properties related to distresses observed in slurry seals and micro-surfacing. Problems associated with each test methods are described under ISSA mixture design in Section 2.5.1. Additionally, a study by the Texas Transportation Institute (Andrew, et al. 1994), California Department of Transportation (Fugro 2004), and other researchers (Raza 1994*a*, Robati 2012) have shown that current mixture design guidelines for slurry seals and micro-surfacing do not always yield design asphalt emulsions content that result in good in service performance.

In additions, Fugro (Fugro 2004) has reported that there is a need for a unified mixture design for the two treatments. They have reported that these two surfacing are similar in a sense that they require the same materials, test methods and have similar distresses. The only difference is in terms of performance requirements, in a sense that micro-surfacing mixes are required to meet higher performance specifications. A single mixture design will significantly increase the efficiency with which these treatments are designed.

2.7 Potential Laboratory Test for Short and Long-term Mixture Properties

It was apparent from the literature review that the most critical area of the ISSA/ASTM guidelines needing improvement are test method used to determine design parameters and not approached (performance characteristics) used to determine allowable design quantities. This will require promising laboratory test methods capable of evaluating mixture parameters related distress observed in the field either to be developed, to improve/modify existing methods. Potential laboratory test methods were identified from the literature, and are presented in

Table 9.

Table 9. Existing and Proposed Test Methods for Slurry Surfacing System

Mixture Characteristics	Current (ISS/ASTM)	Proposed
Test Methods for Constructability Mixture Properties		
Workability	Hand Mixing Test	Automated Mixing Test
	Cone Test	
	Split-Cup Test	
Aggregate Coating	Boiling Test	Boiling Test
Early Raveling/Traffic Time	Wet Cohesion	Cohesion Abrasion Test/Wet Track Abrasion Test
Test Methods for Long-Term Performance Mixture Properties		
Late Raveling	Wet Track Abrasion Test	Cohesion Abrasion Test/Wet Track Abrasion Test
Wet Raveleing	WTAT (Optional)	
Filler Compatibility	Ruck and Puck Test (Recommended)	
Bleeding	LWT (Sand Method)	LWT -Laser Profilometer (MPD)/Marshall Design-%VFA
Rutting	LWT Test (Horizontal deformation)	LWT -Laser Profilometer (MPD)/Marshall Design-IDT, E_f

2.7.1 Test Method for Evaluating Workability

2.7.1.1 The Automated Mixing Test (AMT)

3. Fugro (Fugro 2004) developed an automated mixing test for evaluating mixing time. This test in described in the following section.The Automated Mixing Test is similar to the current Hand Mixing Test (ISSA TB113), except that test procedure has been automated and computerized to minimize operator dependency and as wells as operator induced variability. Test has been reported to be a good candidate for evaluating mixture component compatibility, and mixing time for slurry systems. Good correlation between the test and the Hand mix test has been shown by Fugro (Fugro 2004) .The AMT uses a torque transducer to measure stiffness of a mix during mixing. Figure 10 show an example of the output curve of the AMT. The total system assembly comprises of the following components:

- Agitator with and electronic torque measurement and constant speed.

- Data Acquisition System
- Acquisition Software

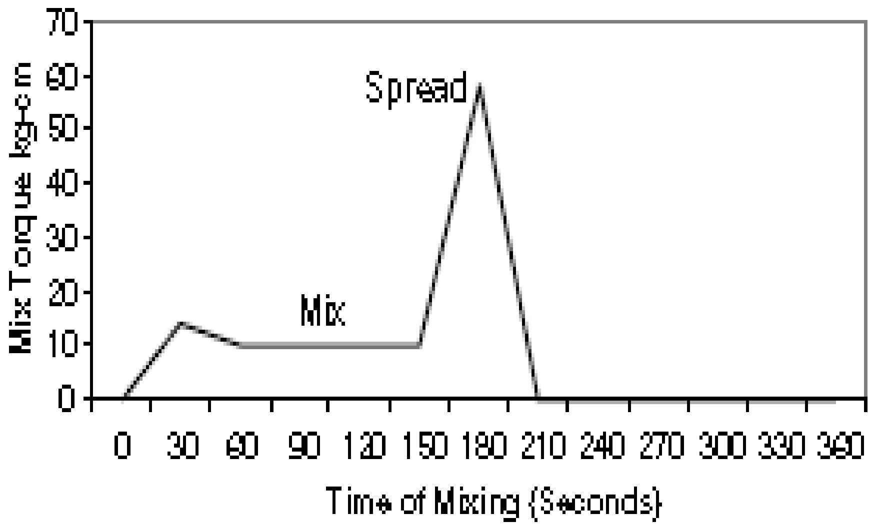


Figure 10. Example of the Automated Mixing Test Torque versus Time Curve (Fugro 2004)

The schematic of the test device and its components is shown in Figure 11. An agitator connected to the electric mixer is immersed in the mixture sample. The electric mixer has a torque transducer which allows for the torque of a mixture to be measured during the mixing process. The electric mixer is connected to a computer, which automatically records the torque level during the testing process. At the end of the test, the torque is plotted against time, and the resulting curve analyzed for workability and constructability indices to establish optimum water content for workability. The main advantage of the AMT is that, it is an automated process, and if proved useful, could eliminate operator dependency and experience required to the run the Hand Mixing Test.

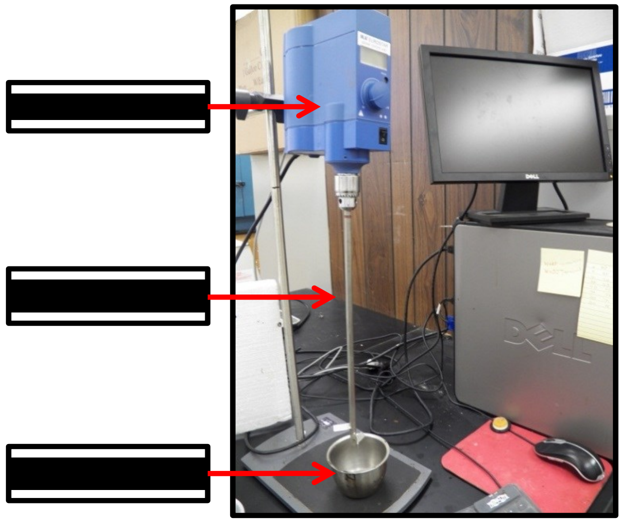


Figure 11. Automated Mixing Test (AMT)

2.7.2 Test Methods for Establishing Trafficking Time: Early Raveling

Three test methods potential methods for establishing trafficking time were identified from the literature:

- Modified Cohesion Tester (MCT)
- Cohesion Abrasion Test (CAT)
- Wet Track Abrasion Test (WTAT)

The modified cohesion tester and problems associated with tests are in details in Section 2.5.1.4. The Cohesion Abrasion Test (CAT) is a raveling test, and is used to evaluate the raveling tendencies of slurry and micro-surfacing mixes in their early stages. The test uses the same equipment and principles of the WTAT, except that it uses a set of wheel fixture to subject samples to an abrasion forces.

The CAT was developed by Deneuvillers & Samonos (Deneuvillers and Samonos 2000), and further advanced by Fugro (Fugro 2004) as a better approach for evaluating early raveling of slurry seals and micro-surfacing mixes. One advantage of the CAT over the Modified Cohesion

Tester is that it measures raveling as performance parameter, a distress similar to failure observed in the field. In addition, the test uses the same samples size as those used to evaluate resistance to term-raveling and resistance to moisture damage as described later. This will not only minimize the number of test equipment required to execute the mixture design, but will also reduce the overall variability of the test results, improve the efficiency of the procedure and make the process more cost effective. Compared to the WTAT, the test allows for representative gradation and sample thickness to be used (Deneuvillers and Samonos 2000). Deneuvillers & Samonos (Deneuvillers and Samonos 2000) have reported good field performance of micro-surfacing mixes evaluated with this test equipment during the mixture design. Figure 12 shows typical results from the test for different mixes at different curing times.

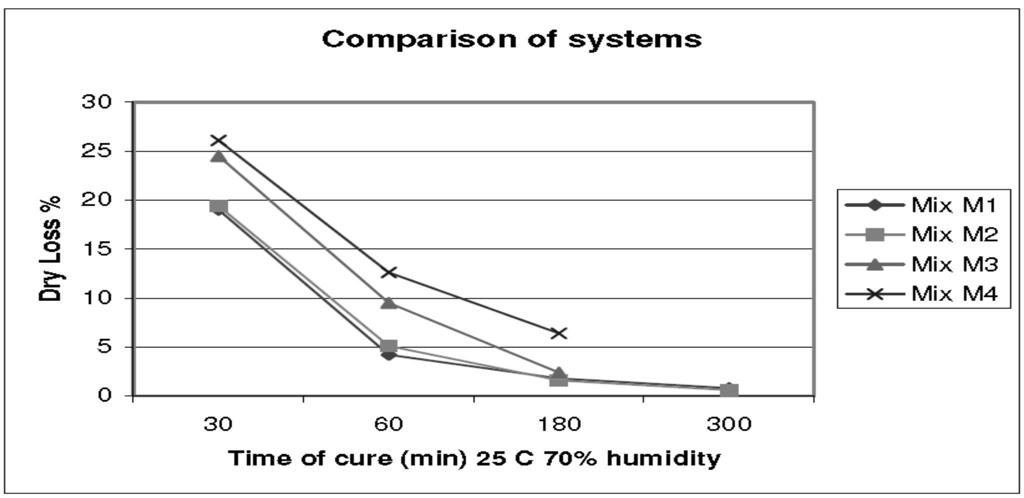


Figure 12. Example of CAT test results for determining curing time (Fugro 2004)

There currently no established specification limits for determining when the mixture has developed enough strength for accepting traffic. A maximum of 10 percent is currently recommended in the ASTM D7000 for judgment resistance to early raveling as well as to establish traffic time for chip seals and maybe also be applicable to slurry seals and micro-surfacing mixes. Both the CAT and WTAT were be evaluated in this study for their ability to quantify early raveling and thus establish trafficking time.

2.7.3 Test Method for Late Raveling

The following tests for evaluating long-term raveling were identified from the literature:

- Wet Track Abrasion Test (ISSA TB 100)
- Cohesion Abrasion Test (CAT)

Wet Track Abrasion Test (WTAT) (ISSA TB 100) currently is used to quantify both dry raveling and wet raveling (also referred wet raveling, stripping or moisture induced raveling) of slurry and micro-surfacing mixes. The WTAT is described in details in Section 2.5.1.5, while the details of the CAT are presented in Section 2.7.2 although the CAT has not yet been used to evaluate raveling on fully cured samples; it has potential, and maybe a better test than the WTAT. Current practice for the WTAT requires the response parameter to be reported as the weight loss per area, either in pound per square inch or grams per squared kilometer. Since the hose head does not cover the whole sample area, factors to take this into account are provided in the ISSA TB 100. Different WTAT equipment requires different conversion factors. It maybe be better to use percent change in sample weight approach as a better for quantity performance of slurry seal mixtures than then the current weight per area approach. This will also eliminate the need for many conversion factors currently used.

2.7.4 Test for Aggregate-Emulsions Compatibility

Material compatibility is one of the most important factors that need to be considered when selecting aggregate and asphalt emulsions for slurry seals and micro-surfacing. It has been reported that when an emulsions is not compatible with the project aggregate, either poor coating of the aggregate will result, and or the resulting mixture will be susceptible to moisture damage (Landise 1977). The following potential test methods were identified in the literature for evaluating aggregate emulsions compatibility:

- Schulz Ruck & Puck Test (SRP)
- 6-day Soak WTAT

The Schulz Ruck &Puck (SRP) Test is described in details elsewhere. The aim of the test is to determine asphalt filler compatibility, and is performed on mastic samples. A defined 0/#10 aggregate mix, including reactive filler, is prepared, cured, compacted and then subjected to water immersion, abrasion and boiling stripping tests. The results of the tests are combined to give an overall compatibility score. Although the SRP has been reported to give repeatable results (Bennedict 1989*b*), the meaning and relevance test has been questioned by many researchers. Martinet.al (Andrew, et al. 1994) have reported that SRP ranks mixture results 80% of the time as the WTAT as shown in Thus that it may be sufficient to only use the results of the 6-days soak WTAT for quantifying aggregate-emulsions compatibility.

The 6-day soak WTAT is performed on samples that have conditioned in water for 6 days at room temperature. ISSA TB A147 states this test is for evaluating the effects of moisture on resistance to raveling. The test is currently only a recommended test and is not mandatory. However, it has been shown by many researchers that mix that meet specification for dry raveling may not have good moisture damage resistance (Raza 1994*a*, Raza 1994*b*). Figure 13 show an example of the effects of moisture on the resistance to raveling of different mixes prepared with different emulsion type and same aggregates. These mixes all had an aggregate loss below 2 percent when evaluated in dry condition.

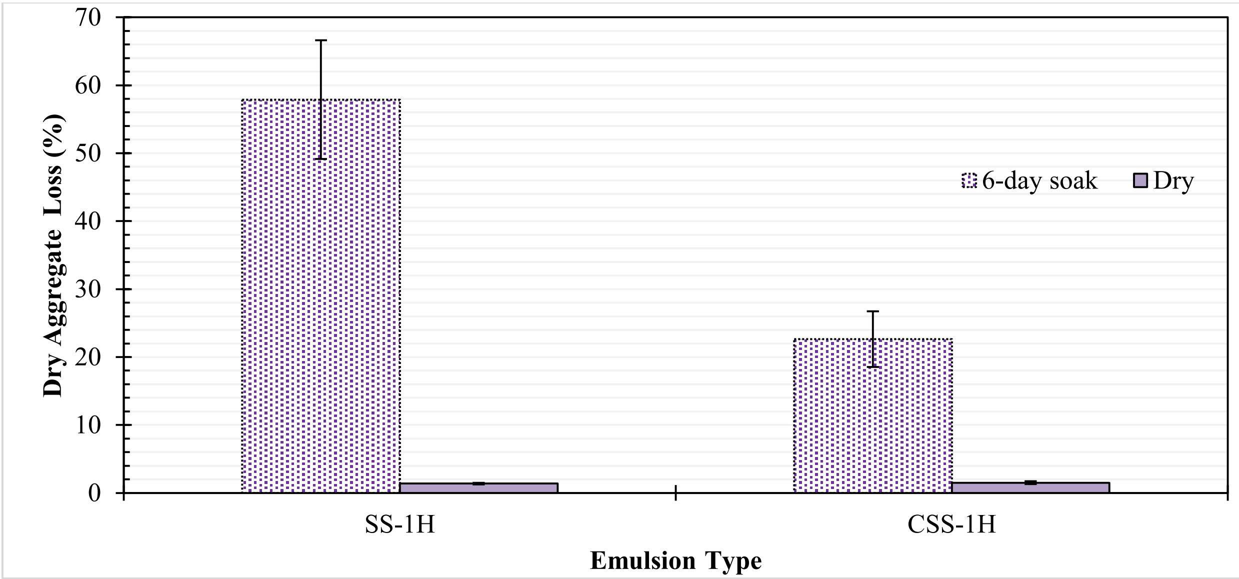


Figure 13. Effects of moisture on resistance to raveling

However, this number increased by over 2000% in some cases depending the chemistry of the emulsions used as shown. This research evaluated the use of an aggregate loss test (WTAT or CAT) on moisture conditioned sample as a better method of characterizing material compatibility.

2.7.5 Test Method for Bleeding

Three methods for evaluating bleeding were identified from the literature:

- Sand Adhesion Method (ISSA TB 109)
- Mean Profile Depth
- Volumetric by the Marshall Method

Current specification requires the use of Loaded Wheel Test (LWT) and Sand Adhesion Method (ISSA TB 109 or ASTM D 6372) to determine the maximum allowable residual asphalt content for bleeding. The test was discussed in detail under Section 2.5.1.6. The result of the test, however, has been brought in to question by many researchers. The test has been reported to be more sensitive to other factors, such as the amount of water in the mix and aggregate gradation more than by the amount emulsion content used (Andrew, et al. 1994, Raza 1994*b*). Figure 14shows an example of the how the Sand Adhesion method is affected by the amount moisture used to fabricate the sample.

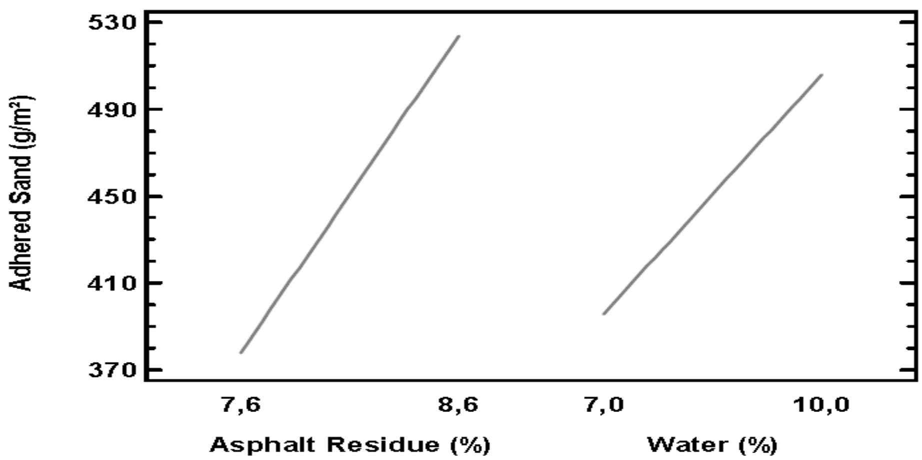


Figure 14. Example of the Effect of Water Content on the Results of the Sand Adhesion Method (Robati 2012)

Another procedure identified uses surface texture to quantify bleeding. This procedure is the Stationary Laser Profilometer (SLP) recently developed by Miller et al (Miller, et al. 2012).The SLP assembly is shown in Figure 15. The SLP measures the linear pavement profile using a laser as shown in Figure 16. The results of the SLP can be used to measure the mean profile depth (MPD) by using analysis techniques outlined in ISO standards (ISO 13473-4 2008). The SLP can be used to measure the profile of LWT samples after subjected to a specified number of cycles, and the MPD can be used to identify mixture with insufficient surface texture. Methods for acquiring samples and analyzing profile data will be detailed in the next chapter.

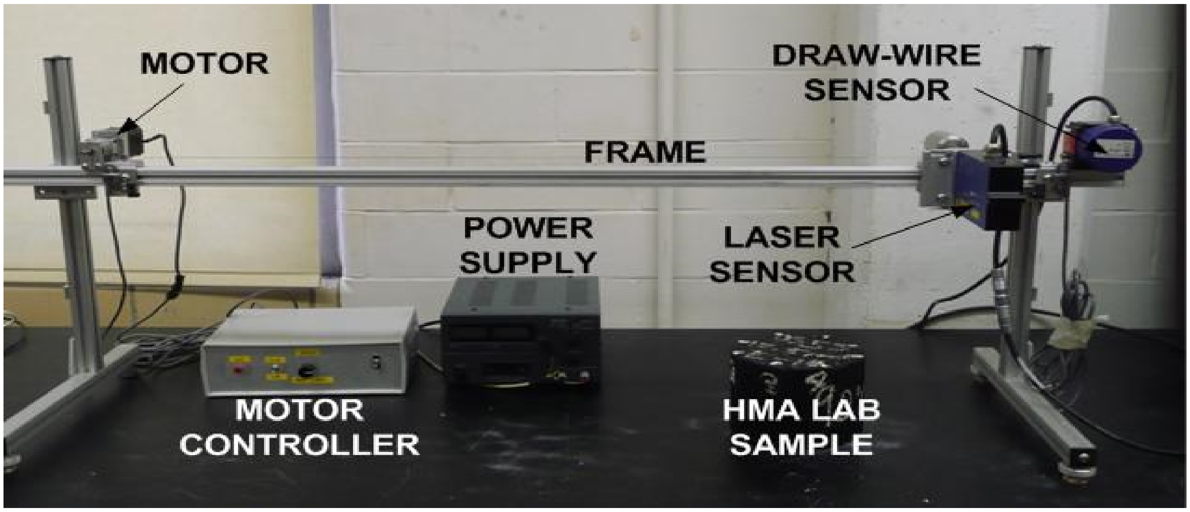


Figure 15. Photograph. A Stationary Linear Profiler (SLP) evaluates micro-texture and macro-texture (Miller, et al. 2012).

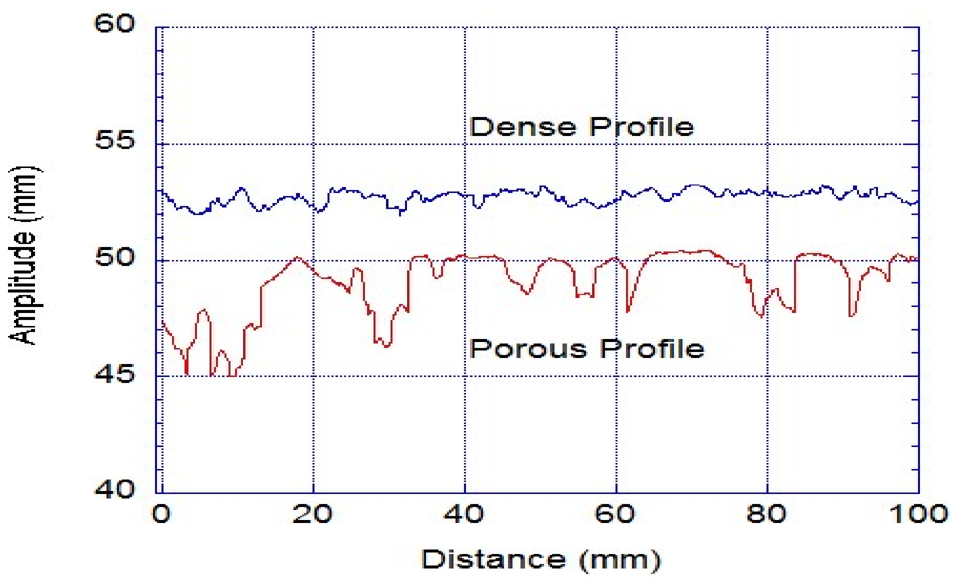


Figure 16. SLP Profiles of Dense and Porous Pavements (Miller, et al. 2012)

Another potential test method identified in the literature is the use the volumetric approach currently used in the design of hot asphalt mixes. This procedure requires sample to prepared and compacted by the Marshall hammer at different compaction level. The compacted samples are evaluated for their volumetric, and the parameter voids filled with asphalt can be used to limit bleeding. While this procedure is well established in the HMA industry, it is barely used in the design of slurry seals and micro-surfacing treatments. However, it promising to note that several attempts have been made, and different methods for preparing Marshall Samples from slurry/micro-surfacing mixtures are available.

One of these methods is contained in ISSA TB 148. In this procedure slurry mixtures are cured to a constant weight in a pan at 60ºC, and then allowed to stand at the compaction temperature for 2 ± 5 hours. The compaction temperature recommended the one at which the viscosity of the base binder from which the emulsion is 280° ± 30°cST. After the curing period, samples are compacted with a Marshal Hammer using 30 blows on both sides. Complete voids analysis is performed on the test. No guidance is given in ISSA TB 148 for identifying mixes prone to bleeding. Other variation has been reported in the literature (Reinke, et al. 1989, Labuschagne, Louw and Gerrie 2012), but they also either require very high compaction temperature of use unrepresentative sample sizes, or do not give repeatable results. A new procedure for preparing Marshall Samples is developed in this study and is presented in other chapters.

2.7.6 Test Method for Rutting

The following test procedures for evaluating resistance to permanent deformation were identified:

- Loaded Wheel Test (ISSA TB 147)
- Indirect Tensile Strength Test (ASTM D6931)

The first procedure is similar to the current ISSA TB 147 described in Section 2.5.1. This procedure appears to give satisfactory results according the survey by Fugro (Fugro 2004) and

Gransberg (Gransberg 2010). Figure 17 shows an example of the rutting results from the LWT test.

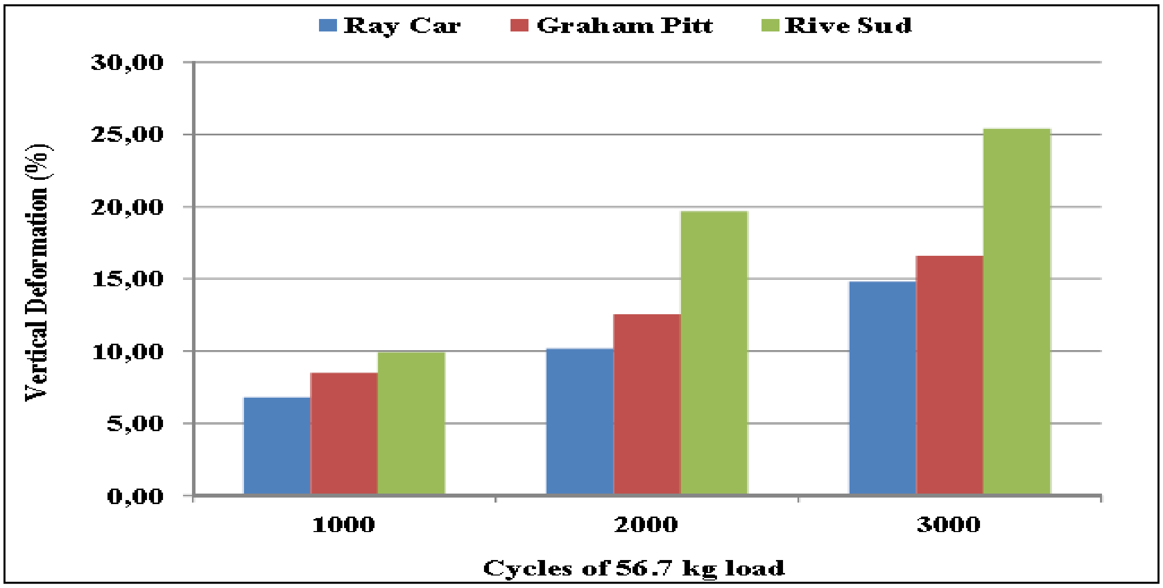


Figure 17. Typical LWT test results (Robati 2012)

However, there is great benefit in having an engineering strength test supplementing the LWT for better characterization of mixture rut filling or multi-layer applications. The test identified is the Indirect Tensile strength test contained in ASTM D6321. The test allows for the tensile strength and strain at failure of the mixture to be measured. The information can be used to fully characterize the resistance to rutting of the mixture. Even more attractive is that, the test can be run on Marshall Samples on which the volumetric has been measured, which reduced time.

2.7.7 Summary of Proposed Test Methods

The summary of test methods identified to be evaluated in order proposed modification to the current ISSA/ASTM mixture design guideline is presented in Table 10.

Table 10. Summary of Proposed Test Methods

Description	Mixture Parameter	Potential Test Method
Test Methods for Short-Term Performance Mixture Properties		
Workability	Mixing Time Consistency Segregation	Automated Mixing Test (AMT)
Early Raveling	% Aggregate Loss	Cohesion Abrasion Test (TBD)/Wet Track Abrasion Test (ISSA TB 100)
Test Methods for Long-Term Performance Mixture Properties		
Late Raveling	Dry Raveling	Cohesion Abrasion Test/Wet Track Abrasion Test (ISSA TB 100)
Moisture Damage	Wet Raveling	
Filler Compatibility		
Bleeding	% VFA /Surface Texture (MPD)	Modified Marshall Method (ASTM D1559)/LWT (ISSA TB 147)+SLP
Rutting	Vertical /horizontal deformation or IDT and ε_f	LWT (ISSA TB 147)+SLP/ IDT (ASTM D6931)

3 Materials, Test Methods and Experimental Design

This chapter provides information on the materials used and their properties. In addition, sample preparation procedures and results analysis methods for candidate test methods are also presented. Experimental plans formulated to evaluate candidate test methods are also presented under corresponding sections.

3.1 Materials Used

The materials used were selected to represent common aggregate and asphalt emulsions currently used for in slurry surfacing system. All aggregate and emulsion used meet the specification criteria for aggregate and asphalt emulsions given in ISSA guidelines. The description of the materials used is presented in the following sections.

3.1.1 Project Aggregate Selection

Two aggregate types commonly used in Wisconsin in slurry surfacing systems were selected based on availability:

- Slag aggregate from Farhner Asphalt Sealer, Waunakee, Wisconsin
- Granite from Pitlik and Wick Inc., Eagle River, Wisconsin

The properties of the two aggregate are given in Table 11.

Table 11. Aggregate Properties

Aggregate Properties	Granite	Slag
Bulk Specific Gravity	2.61	2.58
Absorption (%)	0.7	0.9
Sand Equivalent Value	64	75

The aggregate were taken from the stock piles of manufactured aggregate from the suppliers. They were dried at 120°C overnight to remove all water to allow for better control of the mixing water. The aggregate were sieved into different sizes and stored in sealed buckets. This approach has been reported to give unrepeatable results in cases were the segregation of the aggregate has taken place. The method of aggregate separation used in this study, while somewhat time and labor intensive, allowed for strict control and exact replication of mixture's aggregate gradation.

3.1.2 Asphalt Emulsions Selection

Four emulsions with varying chemistries representing those of commonly used asphalt emulsions in slurry systems in the United States were selected. This allowed for a better understanding of the effect of chemistry (cationic vs. anionic), and polymer modification (latex and polymer) on mixture performance to be evaluated. The emulsions selected are given in Table 12 together with properties. The emulsions were supplied by various emulsion suppliers from Wisconsin and other states around the country. All asphalt emulsion used meet ISSA A143 specification for both modified and unmodified emulsions.

Table 12. Emulsion Properties

Engineering Properties	ASTM Standard	Emulsion Type			
		SS-1H	CSS-1H	CSS-1HL	CSS-1HP
Saybolt Furol sec.viscosity @ 25C	D7496	24	26	30	32
Residual Asphalt Content (%)	D7497	64.9	65	67.4	63
MSCR, Jnr@64C	D7405	5.2	4.1	2.1	1.3
ER DRS	-	15	18	32	31

3.1.3 Selection of Aggregate Gradations

Three aggregate gradations, fine, medium and coarse were selected. These gradations were all in the range of the two commonly used ISSA gradations, Type II and Type III (Gransberg 2010). The gradations selected are shown in Figure 18. The lower limit (LL) of ISSA Type II and upper limits (UL) of ISSA Type III gradations are also presented to indicate how the selected gradation fall within these gradation bounds.

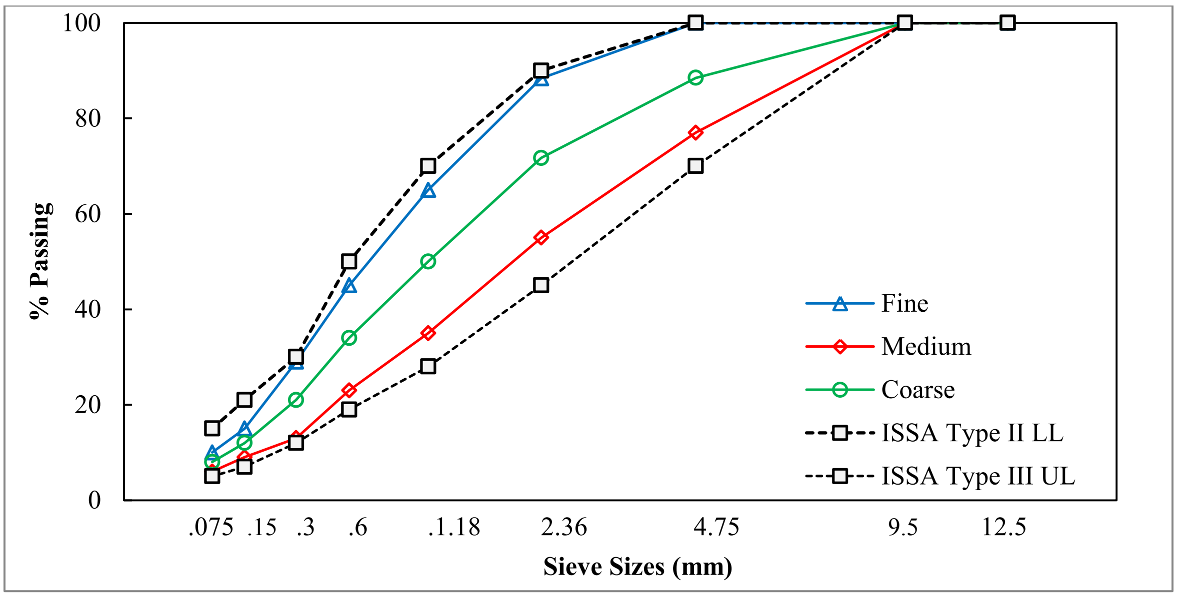


Figure 18. Selected project gradations

In selecting these gradations, the Bailey Method (Vavrik 2002) was applied to ensure that sufficient void in mineral aggregate (VMA) required to accommodate the commonly high residual emulsion contents used in slurry surfacing systems. This was done by calculating the Bailey's Ratios for the Coarse Aggregate ratio (CA), the Fine Aggregate-Coarse ratio (FA_C), and the Fine Aggregate-Fine ratio (FA_F) following the procedure outlined in Vavrik (Vavrik 2002). In general, decreasing the specified CA ratio while keeping all other ratios constant tends to decrease the mixture VMA, while decreasing either the FA_C or FA_F ratios tends to increase the mixture VMA (Vavrik 2002).The Bailey's Ratios for the three gradations are displayed in Table 13.

Table 13. Bailey's Ratios for the Selected Gradations

Descriptions	Fine	Medium	Coarse
CA Ratio	2.02	2.00	0.96
FAc Ratio	0.45	0.40	0.42
FAf Ratio	0.43	0.43	0.39

3.1.4 Aggregate Filler

Two aggregate fillers were selected to be used in the aggregate filler-emulsion compatibility study. The mineral filler used were materials passing sieve 0.075mm of limestone aggregate, and baghouse dust. The baghouse dust was supplied by an aggregate quarry that process limestone, natural aggregate and rap materials. No detail characterization tests were performed on the mineral fillers used.

3.1.5 Mixing Water Selection

Deionized was selected as mixing water to be used to prepared all samples evaluated in the entire study. Using deionized water allows for problems arising from incompatibility between the asphalt emulsion and dissolved-ions sometime present in tap water to be eliminated.

3.1.6 Mixing and Breaking Additives

No mixing or breaking agents were used.

3.2 Method for Calculating Emulsion Application Rates

The application rate for the asphalt emulsion was calculated using the Surface Area Method (SAM) contained in ISSA TB 118. The method allows for the theoretical amount residual asphalt content required to give a specified asphalt film thickness around the aggregate to be determined. In this method, the surface area of the aggregate is first calculated by multiplying the percent of aggregate passing a given sieve size by empirically established surface area factors for each sieve. The total surface area (SA) for a given gradation is determined by summing up surface area of the individual sieve sizes. Equation [1] is applied to the total surface area calculated to obtain the corrected surface area (CSA). The amount of residual asphalt binder required to coat the CSA at a specified film thickness is determined from Equation [2]. The total residual asphalt content (TRAC) that will give the specified thickness is calculated from Equation [3], and it is determined by adding the percent asphalt binder required for absorption. The required percentage of emulsion (AEC) is calculated by dividing the TRAC by the percentage of the asphalt residue in the emulsion using Equation [4].

$$CSA = SA \times \frac{2.65}{ASG} \quad [1]$$

$$SAB = CSA \times t \times 0.09996 \times SG_B \quad [2]$$

$$TRAC = (CSA \times t \times 0.09996 \times SG_B) + A \quad [3]$$

$$AEC = \frac{TRAC}{RAC} \quad [4]$$

Where:

SA = total aggregate surface area (m^2/kg)

ASG = Apparent specific gravity of the aggregate (m^2/ kg)

CSA = corrected surface area (m^2/ kg)

t = asphalt film thickness, microns (μm)

SG_B = specific gravity of the asphalt

TRAC = total residual asphalt content required, percent of dry aggregate weight

A = aggregate absorption

RAC = percent residual asphalt content (%)

AEC = Asphalt emulsion content

The original method in ISSA TB 118 requires using the Centrifuge Kerosene Equivalent test (CKE) to establish the amount asphalt binder that will get absorbed by the aggregate. The CKE was replaced with aggregate absorption in this study as per the recommendation of Andrew et al. (Andrew, et al. 1994).

3.3 Experimental Plans and Testing Procedures for Candidate Test Methods

3.3.1 Experimental Plan for Evaluating Mixture Workability

The automated mixing device was renamed in this to the Slurry Surfacing Workability Test (SSWT). The test is based on the concept of using an automated device to evaluate the mixing and breaking characteristics of mixture samples prepared at varying water contents. This is accomplished by mean of rotating mixing paddle that is attached the automated device on one end, and immersed into the mixing container on one the other. The mixing paddle is rotated at a set constant speed through the test, even though the viscosity of the mixture may change with time for a given sample. The automatic mixing device instead record the amount energy required to keep the mixing paddle at the same speed and makes changes accordingly. This informal is displayed on the test device in the form of torque value. The device can be connected to a computer equipped with the labsoft software that is capable of recording mixing torque as a function of time during the testing procedure. The results of torque versus time for different mixing water contents are used to analyze the workability of different mixtures at different water contents. The A prototype automated mixing device (referred to a as the SSWT in this study) is presented in Figure 19 along with other various components. This device was selected based on previous work (Fugro 2004). It comprised of the following components:

- IKA® EUROSTAR Power Control-Visc Stirrer kit with a speed range of 50 to 2000 rpm and a stirring capacity of 40 liters;
- An analog interface for recording speed and torque and plus RS-232-C interface.
- The Labworlsoft 4.5 software by IKA Werke that enables simple and efficient automation of experiments. It allows for the mixing torque to be automatically recorded in Microsoft excel during the experiment.
- Stirring shaft propellers
- Stainless mixing bowl with a capacity of 10 oz, 7cm tall, 5 cm radius with a rounded flat bottom (Vollrath #99637).

Once the testing procedure was established, the experimental plan presented in Table 14 was followed to establish if the SSWT is a suitable test procedure for evaluating workability of the slurry surfacing mixtures prepared at different water contents. The factors were selected such that the effects of emulsion chemistry, modification, aggregate gradation, and water content on the workability could be evaluated.

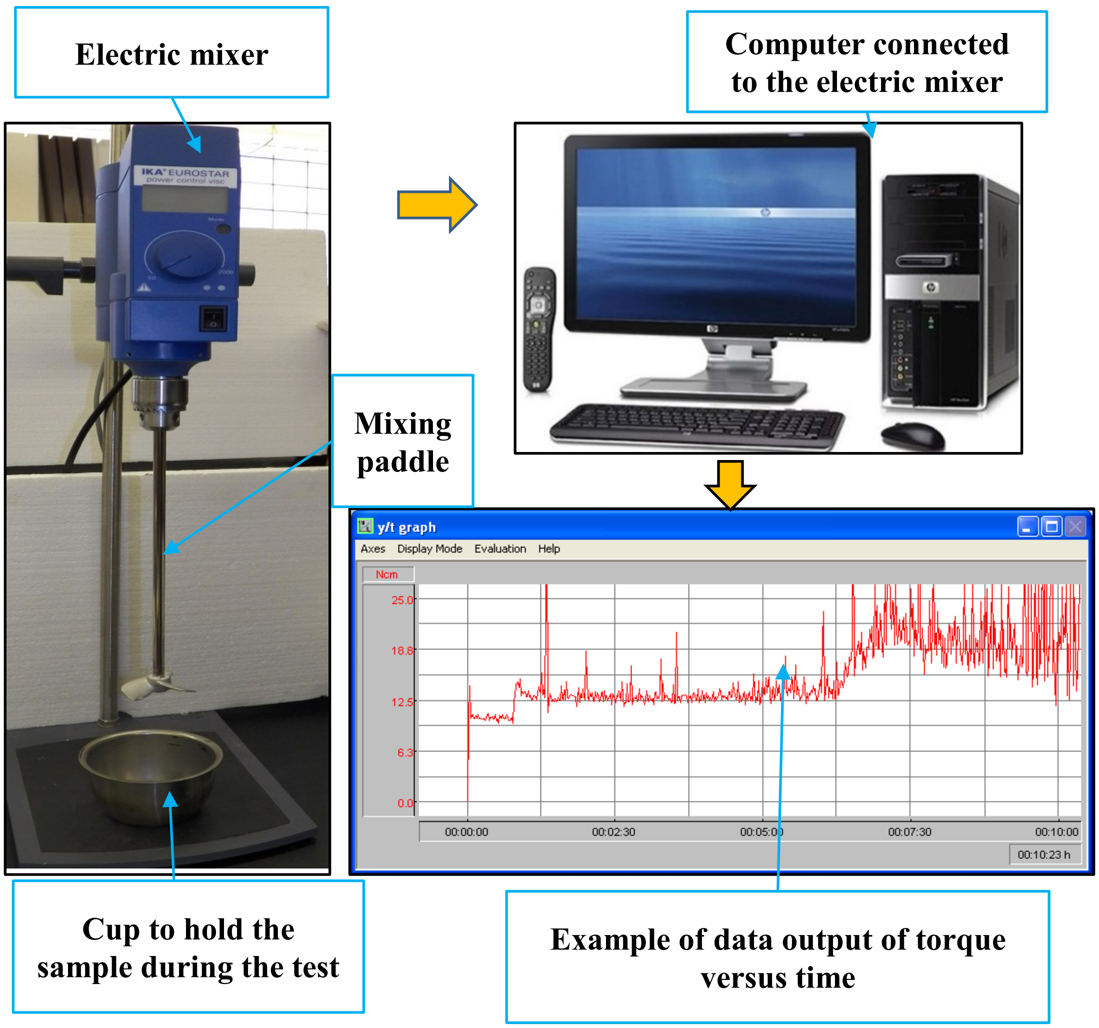


Figure 19. Schematic of the various components required for the slurry system workability test

The amount of water content required to reach the saturated surface dry (SSD) condition of the aggregate was selected as a base for measuring the amount of water content used. This was chosen as a better approach compared to the current practice where water is added as a percentage of the dry weight of the aggregate. The later approach is affected by the specific gravity of the aggregate used, while the SSD method used in this study is not. The water required to reach the SSD is taken as the one unit. For example 4 SSD implies that the amount of water added was four times higher than the amount need to reach the SSD condition.

Table 14. Experimental Plan the Automated Mixing Test

Factors	Levels	Description
Emulsion Type	3	CSS-1H, CSS-1HL,SS-1H
Water Content (× SSD)	4	4, 8, 10, 16
Gradation	2	Fine and Coarse
Replicates	2	N/A
Total	48	

× SSD mean that the water amount added was equal to what ever number shown, multiplied by the water required to reach aggregate surface dry.

Testing was carried out using a sample size of 350g of dried aggregate, batched to match each gradation. Three replicates were measured for each level of water content, allowing for the repeatability to be established. All the sample were test at the same speed of 50 revolutions per minute (RPM) based on the recommendation of previous researchers (Fugro 2004). The absorption of the aggregate was determined and used as benchmark for varying mixing water content. It is indicated as ×SSD, meaning the shown number multiplied by the amount water required to reach saturated surface dry.

3.3.2 Testing Plan for Evaluating Resistance to Raveling

3.3.2.1 Testing Plan for Selecting Candidate Test Methods for Raveling

Two test methods, the Wet Track Abrasion Test (WTAT) ISSA TB 100 and the Cohesion Abrasion Test (CAT) were identified as candidate tests to evaluate raveling. Both tests use a Horbart Mixer to apply abrasive force on the slurry surfacing sample. For the WTAT, reinforced rubber hose is used to abrade slurry surfacing mixture samples. In the case of the CAT, a set of rubber wheels are used instead of a rubber hose. Both methods use the change in sample weight before and after test as performance parameter for quantifying raveling. These methods are discussed in details in Section 2.7. This objective of this study task was to evaluate the two test methods and recommended the one most sensitive factor know to affect raveling and as wells one that give better repeatability. The experiment shown in Table 15 was developed to achieve these objectives. The factors were selected based on the information reported in the literature affecting raveling.

Table 15. Experimental Plan for Selecting the Best Test Method for Raveling

Factors	Levels	Description
Emulsion Type	2	CSS-1h & CSSh-1H
Aggregate Type	2	Granite & Slag
Testing Conditions	2	Dry & Wet (6-day-soak)
Replicates	3	N/A
Total	24	

3.3.2.1.1 Sample Preparation Procedure

The samples were prepared following the procedure in ISSA TB 100. Aggregate were dried overnight at 120°C before being sieved into individual sizes. The aggregate were batched into 900 gram samples accordingly to match the fine gradation. The asphalt emulsions content was determined using the surface area method outlined in Section 3.2. The asphalt emulsion content required for a film thickness of 8 micron was used. Optimum water content for workability was determined as required for optimum workability using the procedure outlined in ISSA TB111. The samples were prepared by first mixing the aggregate with water thoroughly, and then adding the required asphalt content afterward. The mixture was casted onto stainless steel 6.5 mm thick by 210 mm diameter circular mold overlaying an impregnated asphalt felt paper. A glass rod was used to spread the sample uniformly to the desired thickness. The sample preparation procedure is schematically shown in Figure 20.

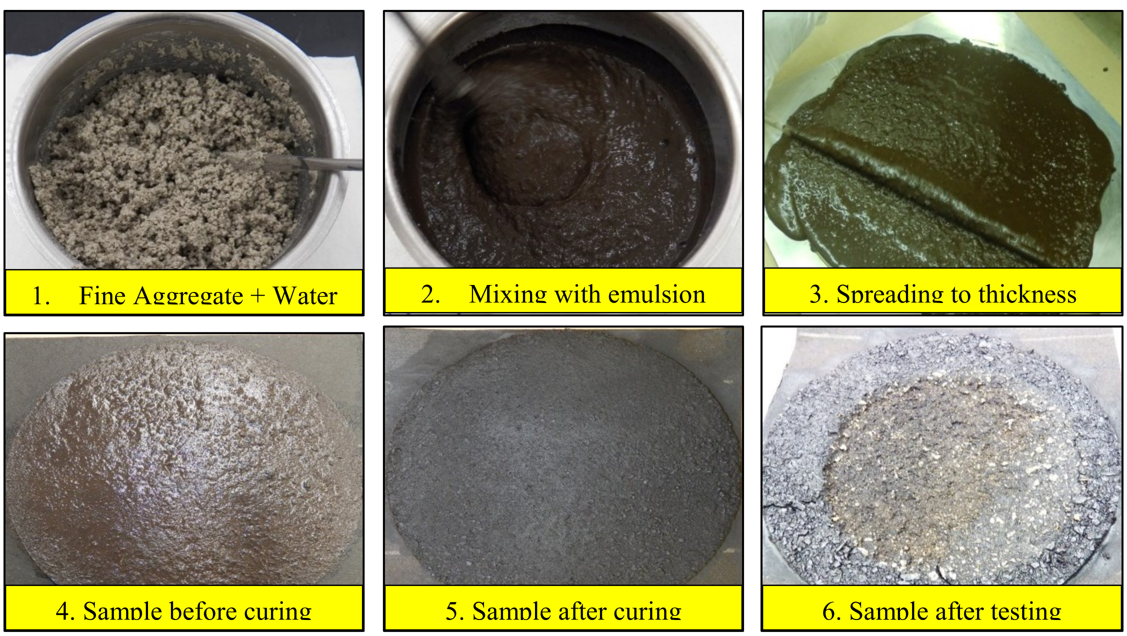


Figure 20. Illustration of the sample preparation procedure for evaluating raveling

The samples were cured for 24 hours at 60° in a forced drat oven. The sample that were evaluated in the dry condition without being condition in water were cool to room temperature and tested under water 25°C for five minutes. The samples for evaluating the effects of moisture damaged were conditioned in water at room temperature for 6-days. They were also tested under water at 25C for five minutes. All samples were dried in the oven at 85°C for 24 hours after testing. The weights of all samples were recorded before and after testing. The difference in the two weights was used as the response parameter for evaluating raveling. The response parameter, percent aggregate loss was calculated using Equation 5.

$$Aggregate\ Loss = \left[\frac{Wt_b - Wt_a}{Wt_b}\right] \times 100 \times 1.33 \qquad [5]$$

Where:

Wt_b = specimen dry weight before testing,

Wt_a = Specimen dry weight after testing, and

Both the rubber hose of the WTAT and rubber wheels of the CAT do not cover the entire area of the sample during the test. The ASTM D7000 recommends using a correction factor of 1.33 when using a Hobart A120 Mixer used in this study.

3.3.2.2 Experimental Plan Early Raveling

The WTAT was selected as the candidate test for evaluating resistance to early raveling of slurry surfacing treatment. The objective of this task was to establish this testing procedure for evaluating early raveling with the WTAT, and determine if the test is sensitive to factors know to affect early raveling. The experimental plan formulated to achieve these objectives is presented in Table 16. These factors were selected based on what is reported in the literature as significant factors affecting the curing characteristic of slurry systems (Deneuvillers and Samonos 2000, Fugro 2004, Johannes, Mahmoud and Bahia 2011).

Table 16. Experimental Plan for Early Raveling

Factors	**Levels**	**Description**
Curing Time (hrs.)	4	1, 6, 12,24
Curing Temp (ºC)	2	25 and 45
Emulsion Type	2	SS-1H, CSS-1HP
Cement Content (%)	2	0 and 3
Replicates	3	N/A
Total	96	

Samples were prepared to conform to a standard thickness of the WTAT of 6.5 mm. Samples were prepared at an emulsion content that conform to an 8 micron film thickness as per Surface Area method (ISSA TB 113) and optimum water content required for optimum workability.

Samples were prepared according to ISSA TB 100, with the only difference being that samples were tested dry without soaking them in water for a total testing time of one minute. All samples for this section were prepared with granite aggregate using the fine gradation. The response variable measured was percent aggregate loss using Equation 5 aggregate loss at a given curing time. ANOVA analysis was employed to determine if the WTAT is sensitive to factors affecting the early raveling of slurry systems.

3.3.2.3 Experimental Plan for Developing an Accelerated Moisture Damage Procedure

This task was accomplished in three steps. In the first step, the need for a moisture condition test was investigate by testing both dry and six days moisture conditioned samples.

The experimental plan given in Table 17 was formulated to accomplish this task. Asphalt emulsions were selected as the parameter for controlling which samples meet the requirements of a slurry seal and which samples meet the requirements of a micro-surfacing.

Table 17. Experimental Plan for Evaluating the Need for Moisture Conditioning

Factors	Levels	Description
Emulsion Type	3	CSS-1h, CSSh-1HP, SS-1H
Aggregate Type	2	Granite and Slag
Testing Conditions	6	Dry & 6-day soak
Replicates	3	N/A
Total	36	

Once it was shown that there is a need to evaluate moisture damage. The second step focused on developing an accelerated moisture damage tests, to replace or supplement the current 6-days soak test. This was accomplished by conditioning samples in water at different temperatures for different conditioning time, and comparing the test results to those from the current six days soak procedure. The experimental plan followed is given in Table 18. A t.test was performed on the results and the condition giving results similar to the 6-days soak was identified.

Table 18. Experimental Plan for Identifying Moisture Conditioning Procedure with Similar Results as the six days soak test

Factors	Levels	Description
Emulsion Type	2	CSS-1h, SS-1H
Testing Conditions	3	Wet-24hrs (40C), Wet-48hrs(60C) and Wet 6-days (25C)
Replicates	3	N/A
Total	18	

Once the condition was identified, an exhaustive testing was carried using the two conditions to establish if indeed the two procedures give similar results. The experimental plan given in Table 19 was formulated to achieve the objectives of this task.

Table 19. Experimental Plan for Developing and Accelerated Moisture Damage Test

Factors	**Levels**	**Description**
Emulsion Type	3	CSS-1h, CSSh-1HP, SS-1H
Aggregate Type	2	Granite and Slag
Testing Conditions	2	6-day soak, 48hrs @ 60C
Replicates	3	N/A
Total	36	

An ANOVA analysis was performed on the results to establish if the two conditioning procedures give similar results, and also to identify factors affecting moisture induced raveling. The last step involved evaluating the ability of the WTAT to determine the impacts of mineral filler on the resistance to moisture of slurry surfacing, i.e. asphalt –filler compatibility.

The experimental plan for emulsion-filler compatibility is presented in Table 20.

Table 20. Experimental Plan for Compatibility

Factors	**Levels**	**Description**
Emulsion Type	3	CSS-1H, CSS-1HP, SS-1H
Filler Type	2	Limestone & Baghouse fine
Replicates	3	N/A
Total	18	

All samples were prepared and tested according to ISSA TB 100, with the only exception being that samples cured at non-standard conditions were allowed to cool to 25 ºC before testing. All samples were prepared at a fixed emulsion content that gives a film thickness of 8 micron and at minimum water contents required for optimum workability. Aggregate loss was used as response parameter and was calculated using Equation 5.

3.3.3 Testing Plan for Evaluating Resistance to Bleeding

Two candidate test methods for evaluating bleeding were identified for evaluation. The two methods selected where the Stationary Laser Profilomer (SLP) and volumetric properties of Marshall compacted samples. Each of these methods is discussed in subsequent sections.

3.3.3.1 Testing Plan for Using the Stationary Laser Profilometer (SLP).

The Stationary Laser Profilometer (SLP) was used to measure surface texture of slurry surfacing samples. The performance parameter measured was the mead profile depth (MPD). The MPD was selected because it is the performance parameter currently used in the field to measure bleeding. Figure 21 graphical illustration about how the MPD is measured using Equation 6.

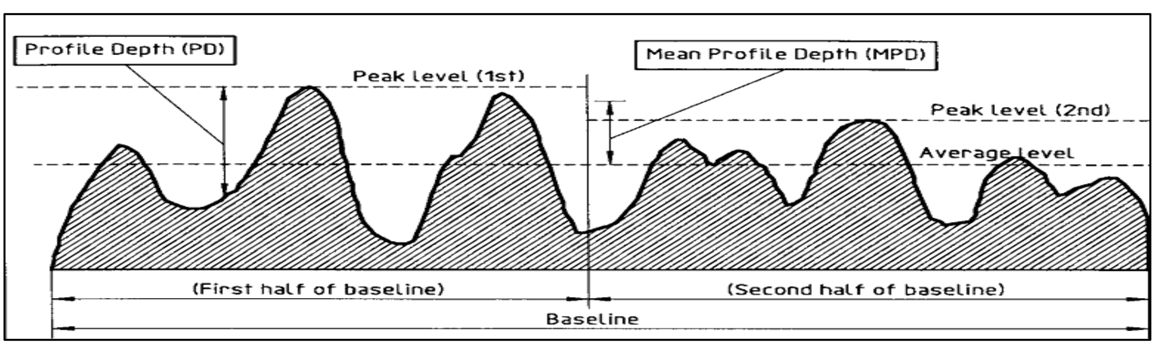


Figure 21. Diagram. Illustration of mean profile depth (Transit New Zealand 2005)

$$Mean\ Proflie\ Depth = \frac{Peak\ Level\ (1st) + Peak\ Level\ (2nd)}{2} - Average\ Level\ [6]$$

The laser measurements were taken on the surface of Loaded Wheel Test (LWT) samples. The LWT test samples were prepared in accordance with ISSA TB 109 to a thickness of 6.5 mm. The samples were prepared at different asphalt contents corresponding for various asphalt film thickness. The asphalt contents for different gradation were the surface area method (ISSA TB 118) using Equations [1]-[4] systems prepared at different residual emulsion content. The samples were cured in the oven at 60ºC for 24 hours to obtain fully cured sample. The samples were then allowed acclimate to room temperature for at least two hours. Three profiles were marked on the samples along their longitudinal length (along the travelled direction of the loaded wheel), one at the center, and there two five millimeters on each side of the center. The MPD was calculated from these profiles. One profile was also marked at the center in the horizontal direction of the sample; it was used to calculate the vertical and horizontal deformation of the samples. The profiles of the samples were measured before and after subjecting the samples to 1000 cycles at room temperature the LWT. Two replicates will be tested for each combination. The experimental plan presented Table 21 was formulated to meet the objectives of this research.

Table 21. Experimental Plan for Evaluating Bleeding with the SLP

Factors	**Levels**	**Description**
Emulsion Type	3	SS-1H, CSS-1H, CSS-1HL
Residual Asphalt content (FT)	3	8, 12 and 16 microns
Gradation	2	Coarse and Fine
Replicates	2	N/A
Total	36	

3.3.3.2 Experimental Plan Measuring Volumetric Properties to Evaluate Bleeding

Another method considered for evaluating bleeding was the volumetric approach, which uses the volumetric parameter percent void filled asphalt (%VFA) of Marshall (ASTM D1559) compacted samples to quantify bleeding. The Marshall procedure in its currently state is not ready applicable to slurry surfacing systems. As part of this study a sample preparation procedure that allows compacted samples of slurry surfacing treatments to be fabricated. The general Marshall Design Procedure involves compacting asphalt mixture at different asphalt contents, compaction effort and temperature in a 101.6 mm diameter by 76.2 mm in thickness Marshall mold. Compaction is carried with a Marshall Hammer that weighs 4.54 kg, and has 98.4 mm diameter foot. The hammer is dropped from height of 457 mm. Samples are compacted for a certain number of blows on each side determined based on the expected traffic level. Compacted samples are allowed to cool to room temperature before evaluated for density (bulk specific gravity and Rice Specific Gravity), volumetrics (% Air Voids (VTM); Voids in Mineral Aggregate (VMA); Voids Filled With Asphalt (VFA)) and for Marshall Stability and Flow values. Specification limit exists for using these parameters to select optimum asphalt content that will result in maximum durability and stability.

This procedure is not readily applicable to surfacing mixture as noted earlier, due to presence of the water in the mixture before curing. Also slurry surfacing are generally not exposed to temperature above 100ºC similar to those used for standard HMA mixtures, or in currently available methods for preparing slurry surfacing compacted samples. A new sample preparation procedure is described below:

- Mix about 1100g of dry aggregate with predetermined desired water for optimum workability, filler amount and emulsions content selected emulsions contents in a suitable mixing bowl.
- Pour the homogenous mixture into a 280 ± 5 mm diameter, 9.5 mm high Wet Track Abrasion mold. The mold should be centered on top of an asphalt impregnated felt paper, which must also be covered with a non-stick paper. The mixture must be levelled with a glass rod to a thickness of approximately 9.5 mm.
- Mark all samples with the asphalt content and cure the samples in a forced draft oven at 60ºC for 24hrs.
- Peel the samples from the non-stick paper, and place them in a pan marked with sample information. Manually break down the sample into a loosed mix. This should be accomplished while the sample is still at 60ºC to allow for ease of separation.
- Place the loose mixture back in the oven and condition it at a compaction temperature of 100ºC for 1 hour and 30 minutes. The Marshall molds are also heated to 100ºC for the same amount of time. At the end of the curing condition, the temperature of the mix is checked again.
- Place a paper disk is placed in the mold and adds about 500g of the loose mixture. The mixture is spaded 15 times around the edge and 10 times at the center with a hot spatula.

- Compact the samples with the desired number of blows on each side with a Marshall hammer and the samples to cool down at room temperature for 24 hours. Samples for the Rice Density are prepared following the same procedure, except that they are subjected to any compaction.

Samples are tested for bulk specific density and maximum density respectively and their volumetrics calculated using Equations [7]-[11].

$$VTM = \left[1 - \frac{G_{mb}}{G_{mm}}\right] 100 \quad [7]$$

$$VMA = \left[1 - \frac{G_{mb}(1-P_b}{G_{sb}}\right] 100 \quad [8]$$

$$VFA = \left[\frac{VMA-VTM}{VMA}\right] 100 \quad [9]$$

$$G_{se} = \left[\frac{1-P_b}{\frac{1}{G_{mm}} - \frac{P_b}{G_b}}\right] \quad [10]$$

$$G_{mm} = \left[\frac{1}{\frac{1-P_b}{G_{se}} - \frac{P_b}{G_b}}\right] \quad [11]$$

Where:

G_{mb} = Bulk specific gravity of compacted mixture

G_{sb} = Bulk specific gravity of aggregate

G_b = specific gravity of asphalt cement

G_{mm} = Maximum Theoretical gravity of mixture

G_{se} = Effective specific gravity of aggregate

P_b = Asphalt cement, percent by weight of mix

VMA= Voids in Mineral Aggregate

VTM= % air voids

VFA= Voids Filled with Asphalt

The experimental plan presented in Table 22 was formulated to meet the objectives of this. It is should be noted that the emulsions used for this section were obtained from different suppliers, although the names are the same. In addition to the emulsions shown, two more emulsions were tested, a SS-1H and CSS-1H from other suppliers to increase the sample size data corrected. However, these emulsions were not sufficient to give samples enough for both gradations.

Table 22. Experimental Plan Evaluating Bleeding based on volumetrics

Factors	**Levels**	**Description**
Emulsion Type	2	CSS-1H and CSS-1HP
Gradation	2	Fine and Coarse
Residual Emulsion Content (FT in μm)	4	8, 10, 12 and 14
Compaction Levels	2	35 and 50 blows
Replicates	2	
Total	64	

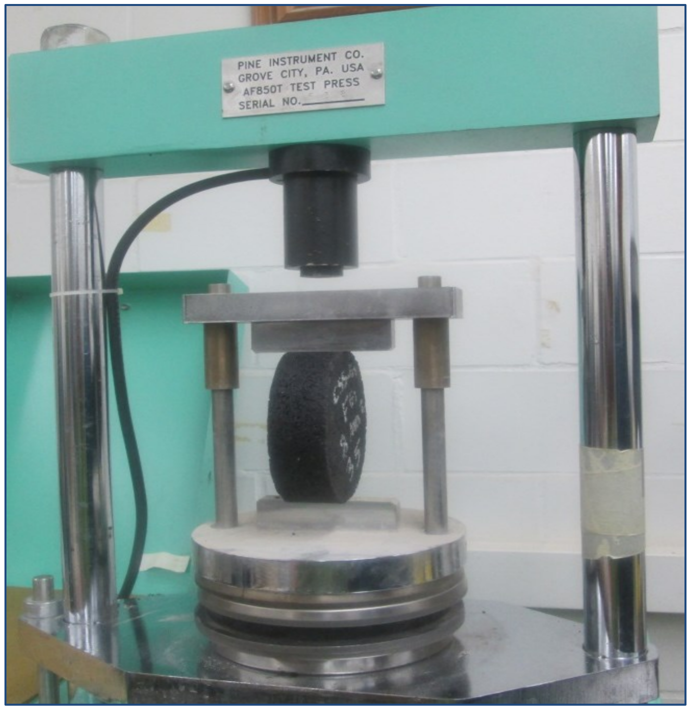


Figure 22. Example of Slurry surfacing samples being tested for IDT strength

Their results were only included in the graphical analysis of the data, but not in the statistical analysis of the results. After tested for density, samples were tested for Indirect Tensile Strength in accordance with ASTM D3610. Figure 22 show an example of a slurry surfacing sample being for the IDT strength. The peak load and strain at the peak load were used to calculate the IDT strength and failure strain respectively using Equations [12] and [13].These two parameters were further used to compute the IDT stiffness index, which was calculated using Equation [14].

$$S_t = \frac{2000 \times P}{\pi \times t \times d} \qquad [12]$$

$$\varepsilon_f = 12.7X_t \qquad [13]$$

$$IDT_Q = \frac{S_t}{\varepsilon_f} \qquad [14]$$

Where:

S_t = IDT strength, kPa	*D* = specimen diameter, mm
P = maximum load, N	ε_f = strain at maximum load,mm
t = specimen height immediately before test, mm	X_t = horizontal deformation at failure, mm
	IDT_Q = IDT stiffness index, kPa/mm

3.4 Laboratory Verification of the Proposed Improved Mixture Design Framework

Limited verification of the improved mixture design developed from the findings of this study was carried out. Materials from three micro-surface projects constructed around the country were collected. The job mix formulas used on the respective projects were also obtained. A mixture design was performed for each project using the improved mixture design procedure, and the mixture proportions established were compared to those used for construction in the field. The materials used on the three projects are presented below.

3.4.1 Field Project Materials

All aggregate and emulsions procured were representative of the materials used in construction in the field, and all met the specification given by ISSA TB 147 (2010). All three projects used a CSS-1HP emulsion formulated to meet the requirements of AASHTO M-208.

The emulsions for two projects were supplied by Ergon and Asphalt and Emulsion, while one was supplied by Paragon Technical Services as indicated in Table 23. Different aggregate types and aggregate gradation were used for each project. The gradation for the Waco, TX project was a Texas Grade II, and used aggregates from Delta-Capital Aggregate quarry. The Vicksburg, MS project meets the gradation of ISSA Type I, and used the Vulcan Calera 821's aggregate. The York, PA projected also used an ISSA Type II gradation, with Martin Type A aggregate.

Table 23. Description of Materials for the Field Projects

Location	Aggregate	Asphalt Emulsion	Mineral Filler
Waco, TX	Texas Grade II coarse graded surface aggregate	Ergon Asphalt and Emulsion CSS-1hP	Portland Cement Type I
Vicksburg, MS	Vulcan Calera 821's	Paragon Technical Services CSS-1hP	Portland Cement Type I
York, PA	Martin Type A	Ergon Asphalt and Emulsion CSS-1hP	Portland Cement Type I

The mineral filler specified by the emulsions supplier was a non-air entrained, lump free Portland cement meeting the specifications of AASHTO M-85. Distilled water was used in the preparation of the samples. No set retarding additives were used. The gradations of the three projects are shown in Figure 23, while the properties if the aggregate and asphalt emulsions used are given in Table 24. These results were supplied by the contractor, with the exception of the aggregate specific gravities and absorptions that determined by the researchers because the emulsions supplier did not have this information available. The aggregate dried over at 120ºC to remove all residual water, and then sieved and batched according the gradation of each project for each test procedure.

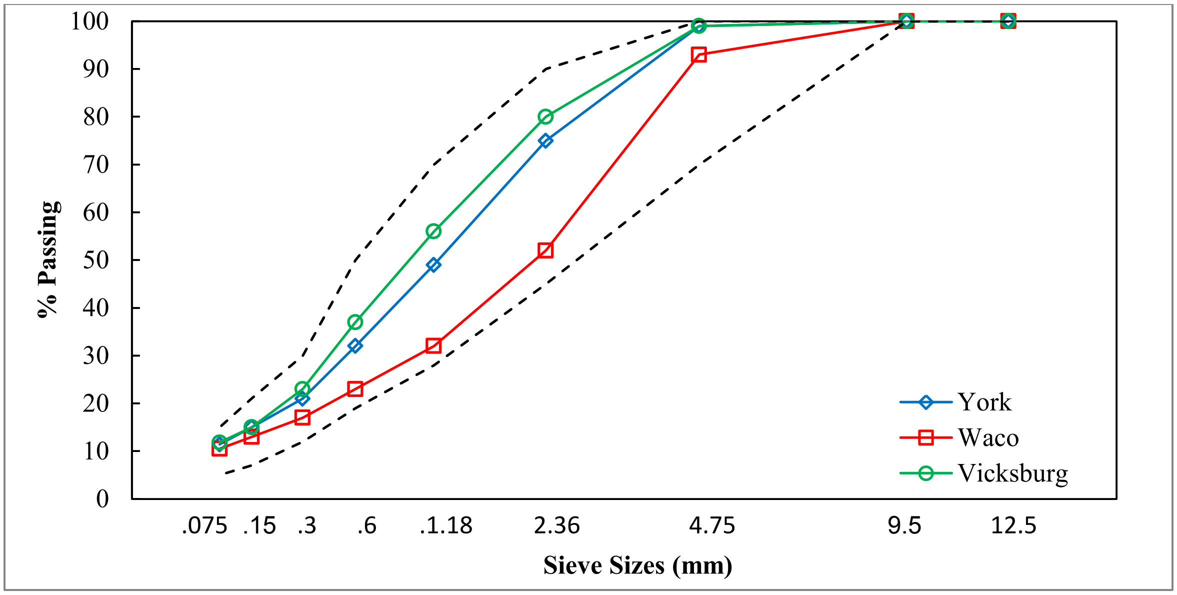


Figure 23. Gradations for field projects

Table 24. Material Properties

Aggregate					
Quality Test	**Method**	**Specification**	**Waco**	**York**	**Vicksburg**
Sand Equivalent	ASTM D2419	65 Min.	71	72	67
Methylene Blue	ISSA TB A147	None	6	4ml	4ml
Methlylene Blue Factor Alpha Labs	AASHTO T19	None	64	46	48
Aggregate Bulk Specific Gravity (G_{sb})	ASTM C125	N/A	2.424	2.806	2.735
Aggregate Apparent Specific Gravity (G_{sa})	ASTM C125	N/A	2.666	2.821	2.789
Aggregate Absorption (%)	ASTM C125	N/A	3.76	0.652	0.719
Asphalt Emulsion					
Residual Asphalt	ASTM D244	60 min	63.1	64.6	63.6

4. Laboratory Evaluation of Promising Test Methods

4.1 Slurry System Workability Test (SSWT)

4.1.1 Introduction

The main mixture parameter affecting construction of slurry surfacing is workability. Workability is divided into two components: (1) mixing stability (also referred to as mixing time) and (2) consistency. Mixing time is the length time that a mixture can be continually worked without breaking (Chang 1979). Consistency on the other hand, measures the flow properties of a mixture that has adequate mixing time (Chang 1979). For given asphalt content, workability is mainly controlled by varying the amount of mixing water content.

This study tested the hypothesis that an automated mixing device can be used to establish optimum water for workability of slurry surfacing systems (slurry seals and micro-surfacing). As such, the objectives of this task were, to identify a candidate automated mixing device, establish a testing and data analysis procedure, determine if the device can be used to select optimum water content for workability of mixtures made with different emulsion types and aggregate gradations. The results are presented in the subsequent sections.

4.1.2 Development of the Experimental Testing Procedure

An IKA EUROSTAR Power Control-Vic mixing device and software that allows the equipment to be controlled by a computer was selected based on previous work by others (Fugro 2004). This device will be referred to as the Slurry Surfacing Workability Test (SSWT) in this study. The SSWT is based on the concept of measuring the torque required to rotate a mixing paddle, which is immersed in the fresh slurry mixture at a constant speed for a specified period of time. As the viscosity of the fresh slurry mixture changes due the breaking and setting process of the asphalt emulsion, it is also reflected in the measurement of the torque value with time. The principles of the SSWT and it various components are described in details in Section 3.2. The test was carried out on 350 grams of dried aggregate sample sizes and at a testing speed of 50 RPM throughout based on the previous work of others (Fugro 2004). All samples were prepared at a fixed emulsion content of 8 microns film thickness determined by the surface area method using equations presented in Section 3.2. Mixing water content was added using the amount of water required to reach the saturated surface dry (SSD) of the project aggregate as the reference point. The steps taken in establishing the testing procedure used in this study is presented in the following sections.

4.1.2.1 Step 1: Establishing the Appropriate Clearance Distance

Sufficient clearance, or gap height, between the mixing paddle and bottom of the mixing bowl is required to ensure that torque measurements are not influenced by interactions between the coarse aggregate and sample container. The maximum aggregate size used in slurry surfacing systems ranges from 2.36 mm to 4.75 mm for fine and coarse gradations of ISSA specification respectively. Trial gap heights of 6.5 mm and 13 mm were selected as these distances provide clearance distance that is larger than the maximum aggregate size of the coarse gradation by factors of 1.4 and 2.7 respectively. The effect of gap height on torque measurements was investigated using sample mixtures made with of a CSS-1H emulsion, slag aggregate, coarse gradation and a mixing water content of 8SSD condition of the aggregate. The results are presented in

Figure 24, and demonstrate that variability is significantly reduced at a gap setting of 13 mm. This gap setting was selected for further device evaluation.

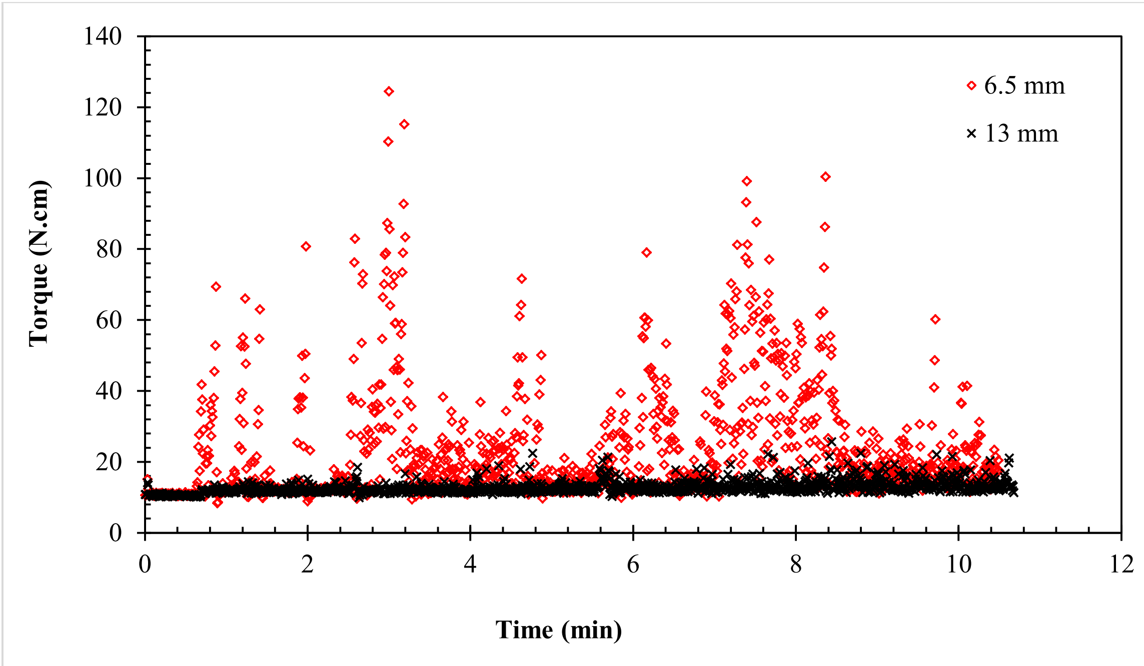


Figure 24. Effect of the gap setting (CSS-1H, Slag aggregate, 8SSD and coarse gradation)

4.1.2.2 Step 2: Selection of Mixing the Paddle Geometry

Two mixing paddles with different geometries were evaluated. Paddle A is a velp scientific stirring shaft propeller with 3 stainless steel blades, oriented at the bottom of the shaft 60 mm, shaft 400 x 7mm. It was selected based on the recommendation of Fugro (Fugro 2004) who has studied workability of slurry surfacing mixtures. Paddle B was also stainless, and was fabricated in this researcher to match the geometry of a paddle used in study for workability of HMA by Gudimettla et al. (Gudimettla, Cooley and Brown 2003), except that the dimensions were smaller. Paddle B had the following geometries: the bottom blade is at 45° to the direction of rotation to lift mix from the bottom of the container. The middle blade is at 90° to the direction of rotation of the shaft, but curved slightly to prevent segregation. The top blade is at 45° to the direction of rotation of the shaft to force the mix downward. The three blades have a length of 50 mm and thickness of 2 mm. The diameter of the shaft is 10 mm. Figure 25 present pictures of the two mixing paddles evaluated.

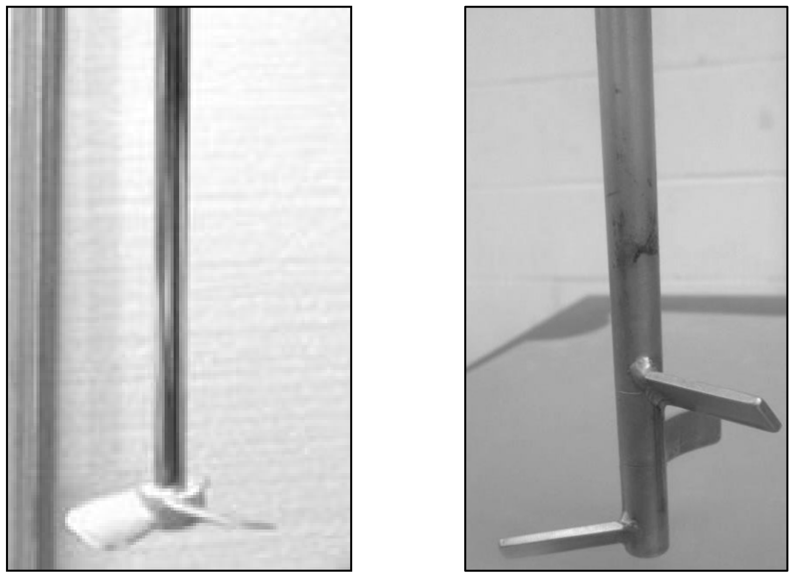


Figure 25. Pictures of the two mixing paddle evaluated: left-Paddle A and Paddle B on the right

Sensitivity to mixing water content was chosen as the criteria to select the appropriate paddle geometry, as this is the mixture design factor that controls the workability. Samples were prepared with two levels water contents (4SSD and 8SSD), coarse gradation, slag aggregate and a CSS-1H emulsion. The results are shown in Figure 26 and Figure 27 for Paddle A and Paddle B respectively. The results show negligible differences between the two-water contents for Paddle A, while clear difference between the two water contents can be observed in the results of Paddle B. A closer examination of the interaction between Paddle A and the mixture revealed that the paddle was creating a shear wall slip in the sample as it rotates (Gudimettla, Cooley and Brown 2003).

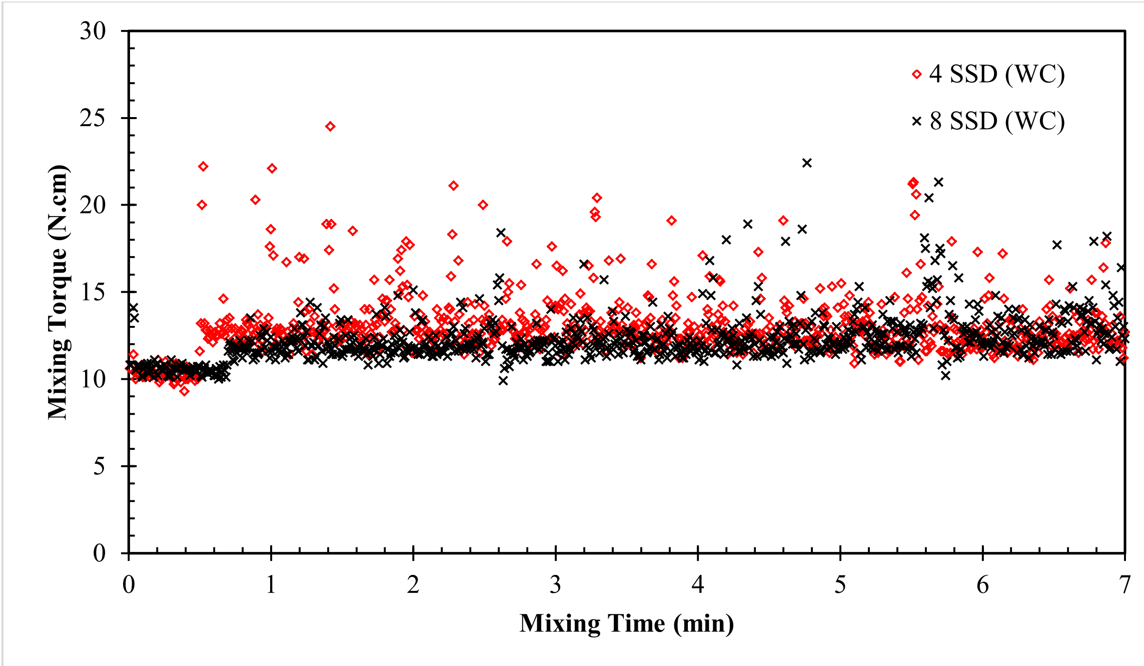


Figure 26. Effects of water content on the mixing torque vs. time for mixing Paddle A

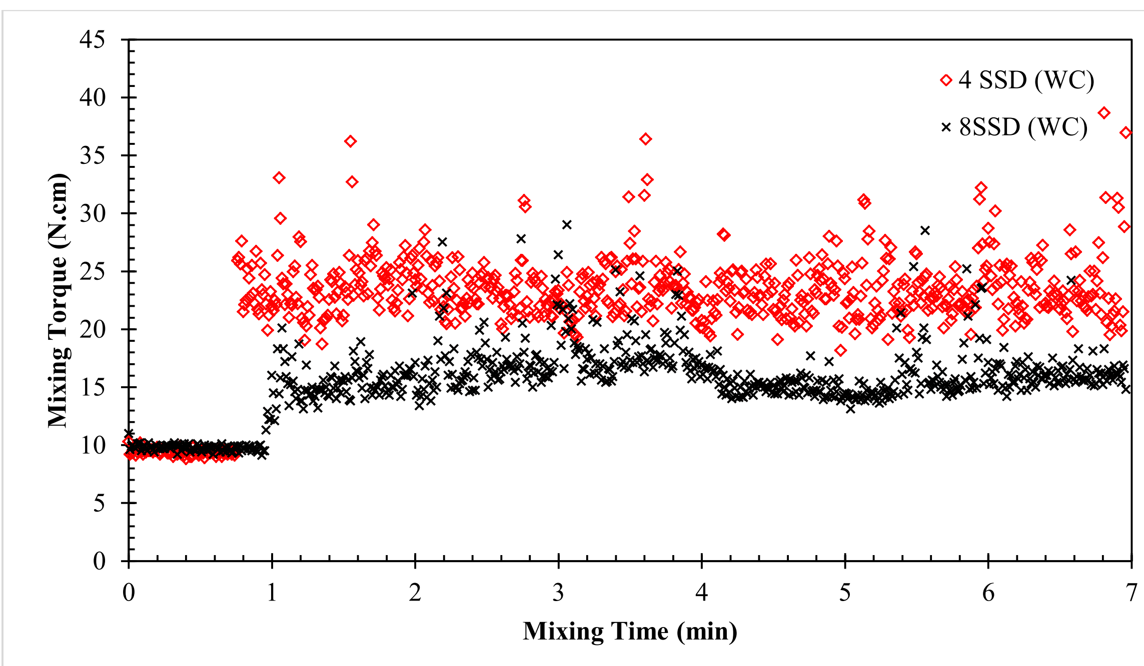


Figure 27. Effects of water content on the mixing torque vs. time for mixing Paddle B

This phenomenon causes the water in the mixture to migrate to the center of the container while most of the aggregate remained on the wall of the mixing bowl, as is shown in Figure 28. Paddle A was abandoned as a result, and the rest of the testing process was carried out with Paddle B.

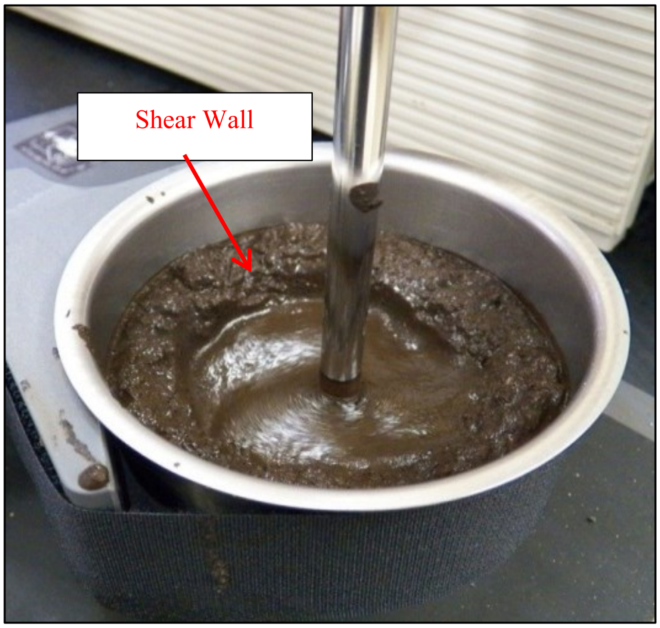


Figure 28. Example of a shear wall created by the Paddle A during testing

4.1.2.3 Sample Testing Procedure and Data Filtering

The procedure for testing the samples was established as follow: first, the SSWT is allowed to run for one minute with no sample in the mixing bowl to establish a zero point. Aggregate are premixed with water by hand and added into the mixing bowl without stopping the test. The test is further allowed to run for two minutes until the torque level reaches a constant value. The emulsion is quickly added to the mixture and the equipment allowed running for a total test time of 10 minutes. This time was deem sufficient based on current practice that requires workability to be evaluated for a period of 2 minutes for modified emulsions and 3 minutes for unmodified emulsions. This testing procedure established is given in Figure 29. The result shows how the torque changes when different mixture components are added at different stages. The results also show that the equipment has a torque value of 10 N.cm when no material is present. The equipment manufacturer did not include calibration information. The values of 10 N.cm was taken as the zero point, was subtracted from all results that were later measured to obtain the true torque value.

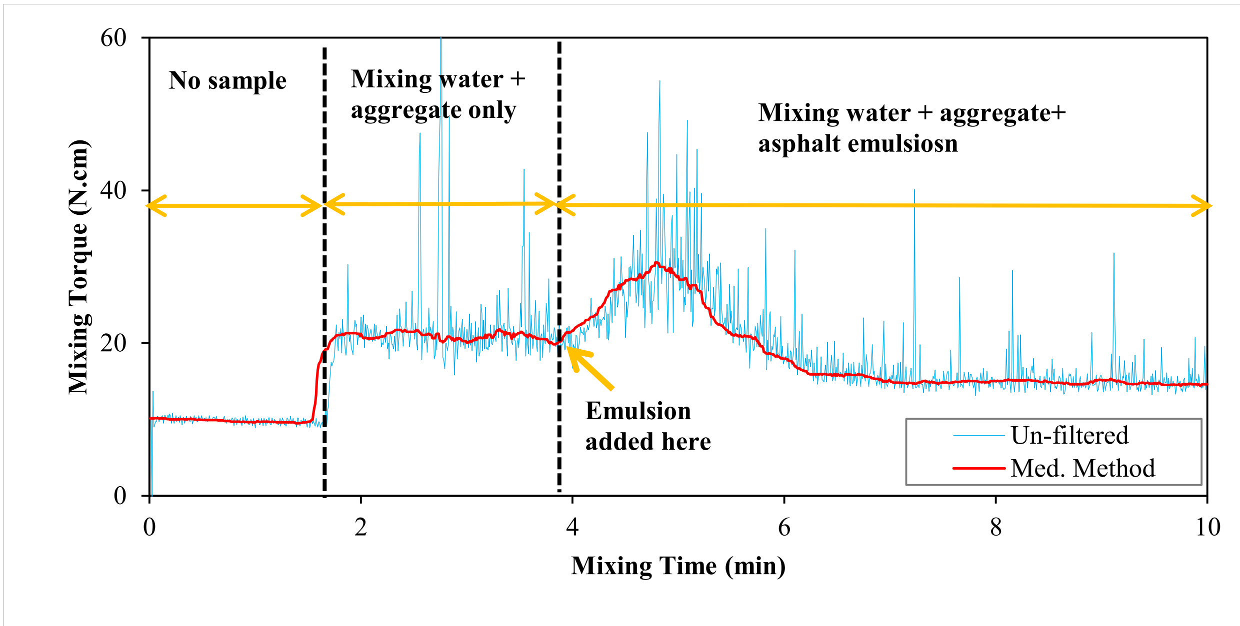


Figure 29. Schematic of the testing procedure used and examples of the filtered vs. filtered results

The median filtering method (MFM) described in Orfanidis (Orfanidis 1996) was applied to the results to remove the scatter. This method is based on the concept of replacing the signal value at each point by the median value of a group of surrounding points, and is suitable for data with localized peaks (Orfanidis 1996) . Figure 29 also show an example of raw data before and after filtering, and it is clear that the scatter is significantly reduced after the filtering method was is applied. Figure 30 show the results of three replicates from test, and the result show that the SSWT gave repeatable results by visual examination.

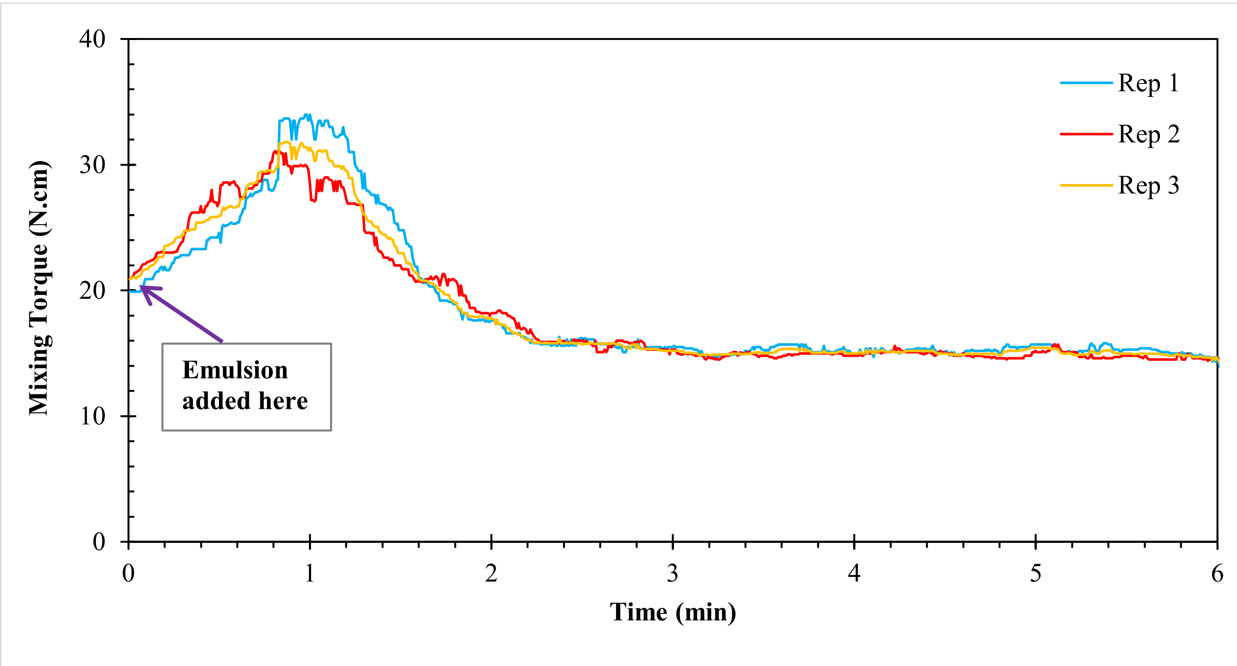


Figure 30. Examples of the results of three replicates

4.1.3 Effects of Mixture Components on Workability

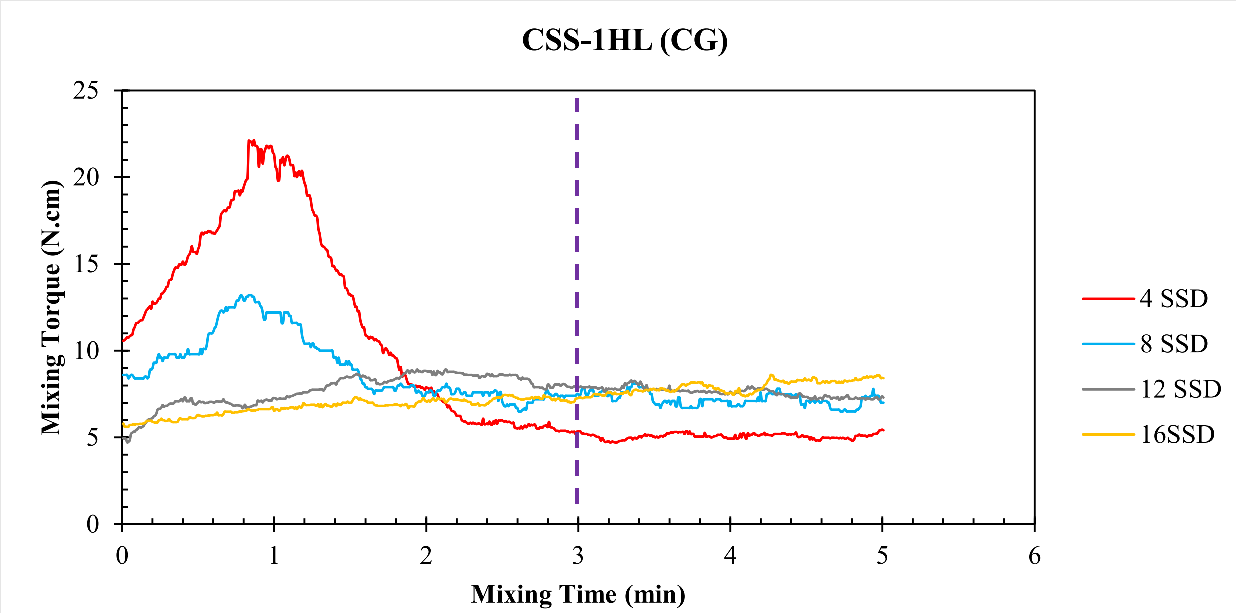
The experimental plan presented in Table 14 was used to evaluate the ability of SSWT to differentiate between different factors know to affect workability. It was necessary to establish a reference point for evaluating the results of the SSWT. This was accomplished by performing the Hand Mixing Test (ISSA TB 113) and Segregation test (ISSA TB 111) on the factors presented in Table 14 to establish minimum (insufficient mixing time) and maximum water content (with segregation above 15%) that will be allowed by current ISSA specifications. These results are given in Table 25. They represented the allowable mixing water range that will give a mixing time greater than three minutes and will not exhibit severe segregation.

Table 25. Results of the Minimum and Maximum Allowable Water Contents Established from the Hand Mixing Test and Segregation Test (ISS TB 111) respectively

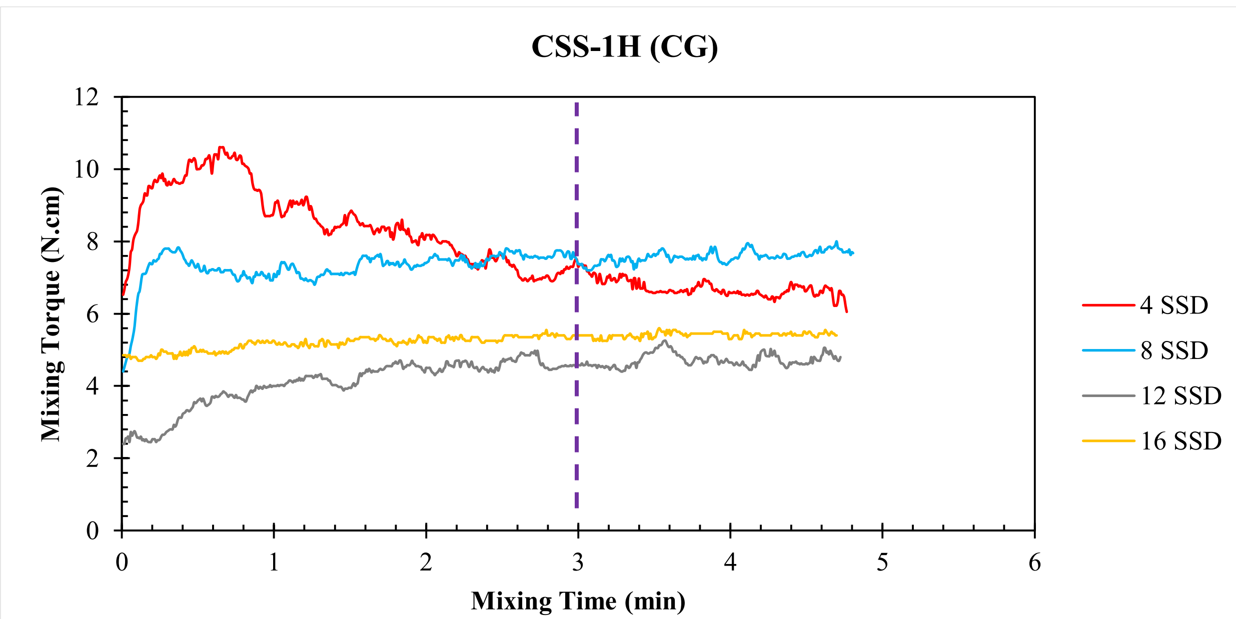
Emulsion Type	Aggregate Gradation	Min. Mixing Water (×SSD)	Max. Water (×SSD)
CSS-1HL	Coarse	8	11
CSS-1H	Coarse	7	11
SS-1H	Coarse	5	10
CSS-1H	Fine	8	11
SS-1H	Fine	6	10

Testing was carried out with the SSWT after the reference water contents were established. The results of the mixing torque versus mixing time for the coarse gradation are given in Figure 31 (a) for the cationic latex modified CSS-1HL, cationic unmodified CSS-1H (b) and anionic unmodified SS-1H (c). The dotted line shown indicate the mixing time of three minutes, currently used as the base for identifying mixtures with insufficient mixing time. Overall, the results show that the SSWT is sensitive to mixing water content as differences can be noted between different water levels for a given emulsion type. The test can also differentiate between emulsion types because different magnitude of torque values are observed for the same water contents and mixing time. The challenge, however, lies in how the data presented can be used to establish mixture with different workability given the unique trends for different emulsions or water contents.

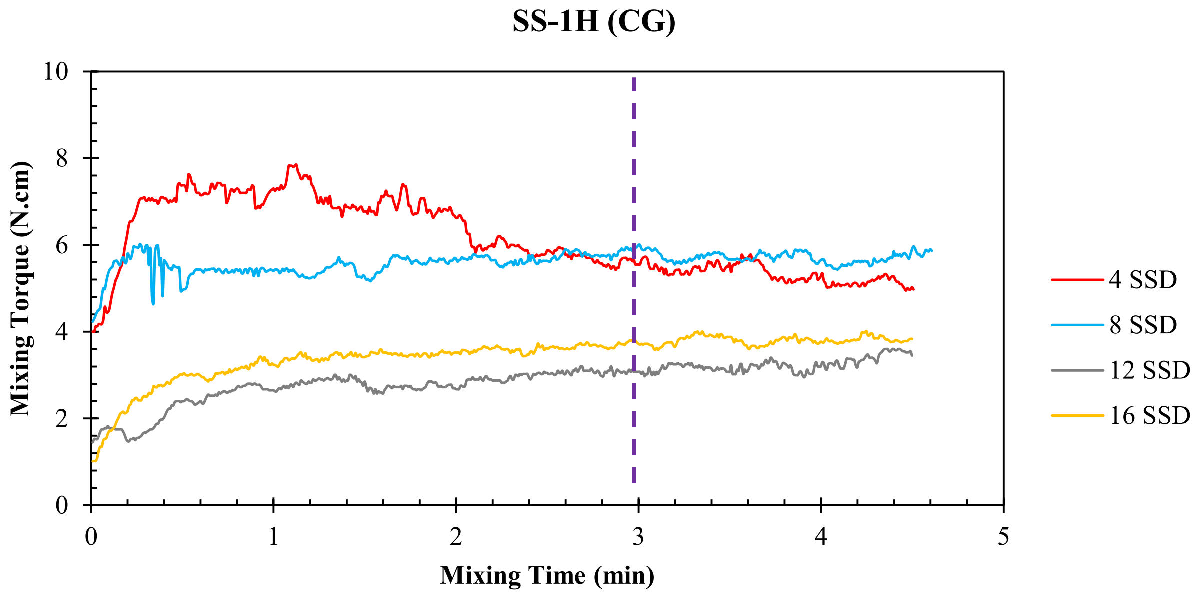
All mixtures prepared at a water content of 4SSD were found not to have sufficient mixing time in the Hand Mixing Test (See results Table 25) for all three emulsions.


CSS-1HL (CG)
Mixing Torque (N.cm)
0
5
10
15
20
25
0
1
2
3
4
5
6
Mixing Time (min)
4 SSD
8 SSD
12 SSD
16SSD

(a)


CSS-1H (CG)
Mixing Torque (N.cm)
0
2
4
6
8
10
12
0
1
2
3
4
5
6
Mixing Time (min)
4 SSD
8 SSD
12 SSD
16 SSD

(b)



(c)

Figure 31.Effects of water content on the mixing torque of CSS-1HL (a), CSS-1H (b) and SS-1H (c) for coarse gradation

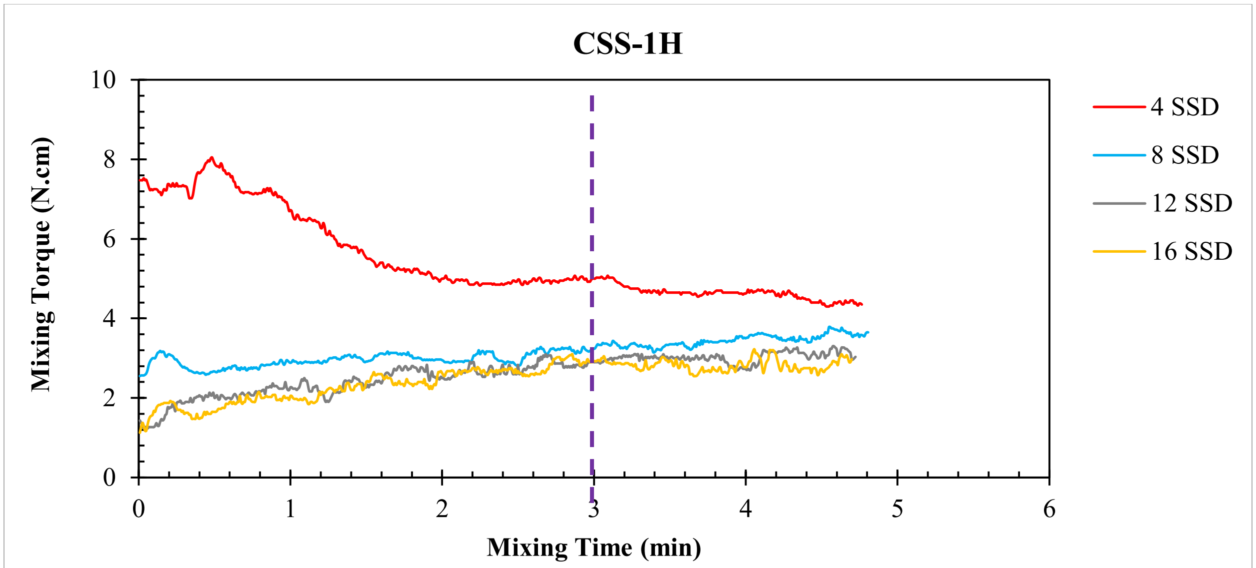
This means that at this water content, none of the mixture evaluated remained workable up to three minutes as currently required by ISSA/ASTM guidelines. These mixes were expected to show the highest torque values for all emulsions throughout the testing period. When evaluated with the SSWT, mixture prepared with 4SSD water content show graphs with a pronounced increase in torque value for the first minute, and then a drop afterward and eventually flattens out. The increase in torque value can be attributed to breaking of the emulsion, while the point where the curve where peaks indicates that the mixture has reached a setting point. The set point is a stage where all the emulsion has been adsorbed on the surface of the mineral aggregate, and the water initially in the emulsion has been freed into the mixture (ISSA 2010). The additional “free” water from the emulsion causes the additional lubrication of the mixture and hence a decrease in the torque value is noted. The results presented show significant effects of the chemistry of the emulsion used. The peak values for the CSS-1HL is 23 N.cm and it occurred after one minute, 13 N.cm for CSS-1H at 0.6 minute and 7.4 N.cm at 0.8 minute for the SS-1H emulsion at 4SSD water content. At three minutes, the torque value for the CSS-1HL is 5 N.cm, 7 N.cm for the CSS-1H and about 5.3 N.cm for the SS-1H emulsion, again just for mixtures prepared at 4SSD water content. This observation indicate that it is not sufficient to use the torque value as a criteria for identifying mixture that have insufficient mixing time, as has been suggested by others (Fugro 2004). The results obtained from the SSWT in its current form cannot be used to identify mixture with insufficient mixing time without using subjective judgment of the person performing the testing.

All mixtures that were prepared at water content of 12SSD exhibited significant amount of segregation based on the result of the segregation test as presented in Table 25. The results presented in Figure 31, show the curves of mixtures prepared at 12SSD and 16SSD do not have peaks and remained fairly constant throughout the testing procedure. Their torque value a low than that of mixtures prepared at 8 and 4SSD respectively almost in the first two minutes. However, a lower torque value alone cannot be used to identify mixtures exhibiting segregation for several reasons. One, the torque value of 12 SSD is lower that the torque value for 16SSD, indicating a mixture with high water content has better workability that a mixture with low water content. The switch in trend can be attributed to the interaction between the mixing paddles the particles that have segregated out of the mixture are piling up at the bottom of the mixing container.

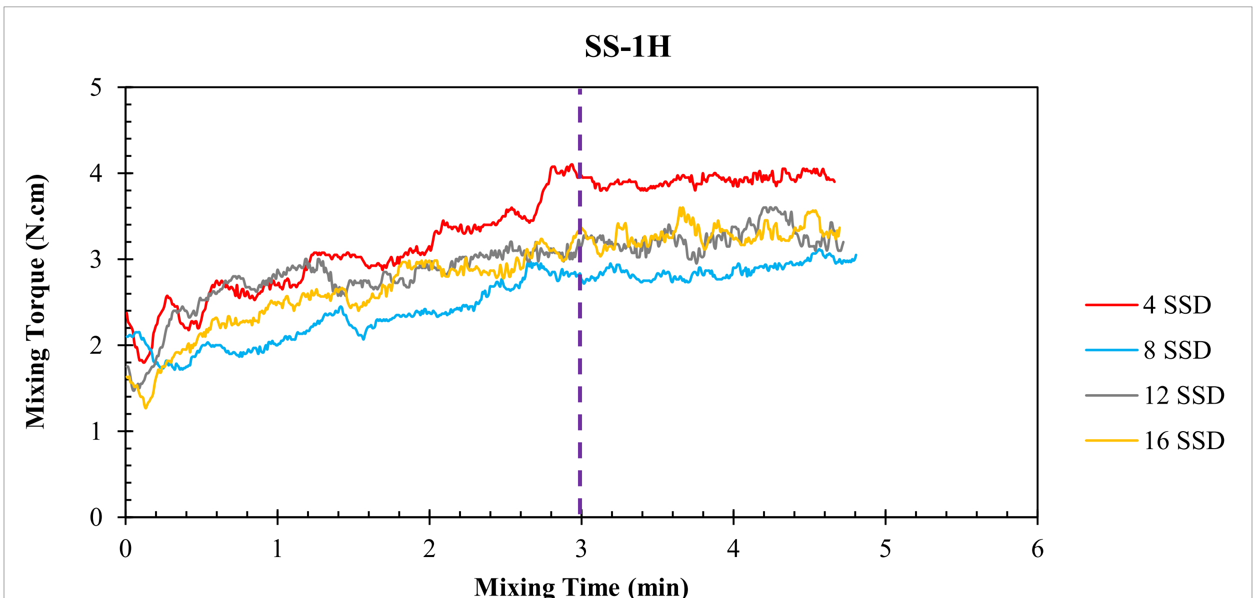
Another important point to make is that, mixtures that have undergone breaking and setting point experience decrease in torque value with additional mixing. As observed in the case of the CSS-1HL emulsion, the mixture prepared at 4SSD ended up having the lowest torque value after 3 minutes. Using a criteria of a lower torque value as a mean of identify mixes that exhibit segregation will false identify the mixture at 4SSD at exhibiting segregation for the CSS-1HL emulsion, while for the SS-1H and CSS-1H mixture at 12SSD will be deemed to results in more segregation that mixture prepared at 16 SSD.

Mixtures that prepared at 8SSD and were expected to have sufficient mixing time, and exhibits not segregation based on the results given in Table 25. However, there is no objective way of determining that mixture prepared with water content have sufficient workability based on the results obtained. Different torque values are obtained for different emulsions, and the shape of the curve obtain are unique to each emulsion. This make it difficult to use the results obtained to establish optimum water content for workability.

The results mixture prepared with the fine gradations presented in Figure 32 (a) for the CSS-1H emulsion and (b) for the SS-1H respectively. The results presented in Figure 32 show that the SSWT is sensitive to aggregate gradation when compared for those in Figure 31 for the same emulsions. However, although mixture prepared at 4SSD were identified to exhibit premature breaking in the hand mixing test, shape of the curves in Figure 32 are somewhat different from those observed with the coarse gradation. The torque at 4SSD water content remains above that those of mixture prepared at higher water content, unlike what was observed with the coarse gradation. For the CSS-1H emulsion, no clear difference can be noted between the 8, 12 and 16 SSD, and this make it hard to identify mixture with segregation. For the SS-1H, the mixing torque value for mixtures at all four water levels appears to be increasing with time. For the 4SSD water content the noted increase in mixing torque value could be that the mixture is breaking, but has not reached the set point yet. The mixing torque for the 8 SSD is lower than that of the 12 and 16 SSD water contents respectively.



(a)



(b)

Figure 32. Effects of water content on the mixing torque of CSS-1H (a) and SS-1H (b) for fine gradation

This indicates that severe segregation occurred in mixture prepared with both 12 and 16SSD water contents. This observation is in line with the results presented in Table 14, which indicated that water content above 10SSD with result in segregation. The results for mixtures prepared with fine gradation collaborated with those of mixture prepared with the coarse gradation, that it is not possible to use the SSWT to identify mixture with insufficient mixing time severe segregation without using subjective judgment.

4.1.4 Summary

The objective of this task was to test the hypothesis that an automated mixing device, referred to in here as the slurry surfacing workability test (SSWT) evaluated in this study can be used to establish optimum water content for workability of slurry surfacing systems. This test will be a better alternative to current the current Hand Mixing test, Split-Cup test and Consistency test currently used which are highly depended on the experience of the operator. The results presented in this research showed the test to be promising in differentiating between water contents, emulsion types, and gradation. However, the results of the test are heavily depended on the chemistry of the emulsions used. Very complex results that proved challenging to interpret were noted. Different emulsions exhibited significantly different torque versus time curves at different water content, making it challenging to establish a comprehensive criterion for evaluating workability and selecting optimum water content for construction. While the results helped to understand the complex behavior of slurry seals in the fresh state, the test however, is not recommended for use it is current state as further research is required to understand how to interpret the results.

4.2 Evaluation of Resistance to Raveling

4.2.1 Introduction

Raveling is a common distress that can occur in the early or late service life of slurry surfacing treatments. It is a process by which excessive loss of the cover aggregate occurs when subjected to traffic loading. Raveling can lead to loss of skid resistance thus compromising the safety of the traveling public, and can also exasperate the loss of structural capacity of underlying layers by allowing moisture and air into the underlying pavement layers. It is therefore important to confirm that a slurry seal system will demonstrate acceptable resistance to both late and early raveling during the laboratory mixture design procedure.

This study was divided into two phases to evaluate raveling. In Phase 1, candidate laboratory test methods were evaluated in order to select a test method for the proposed mixture design procedure. Selection was based on the ability of the test method to provide repeatable results and to demonstrate sensitivity to mixture design and environmental factors known to affect raveling. Phase 2 involved application of the selected test method to study and understand factors contributing to both early and late raveling.

4.2.2 Evaluation of Candidate Test Methods for Raveling

Two test methods for evaluating raveling were identified from the literature. The test methods are the Wet Tract Abrasion Test (ISSA TB 100) and the Cohesion Abrasion Test developed by Deneuvillers and Samonos (Deneuvillers and Samonos 2000) and advanced by Fugro (Fugro 2004). Both tests are run with the same equipment, a Hobart A120 mixer, and involve similar steps for sample preparation and conditioning. The main difference between the test methods is the testing geometry used to abrade the slurry seal surface. The WTAT uses a fixture head equipped with a rubber hose, whereas the CAT uses a fixture head with two rubber wheels. Both geometries are intended to simulate abrasion caused by traffic loading. Pictures of the Hobart mixer with the two different fixtures are attached are shown in Figure 33. As an artifact of using the same testing apparatus with two different geometries, test methods also differ in the how samples are supported during the test procedure. The modified Hobart mixer was developed for the WTAT test and includes an internal locking mechanism that ensures contact with the slurry seal surface at a constant pressure.

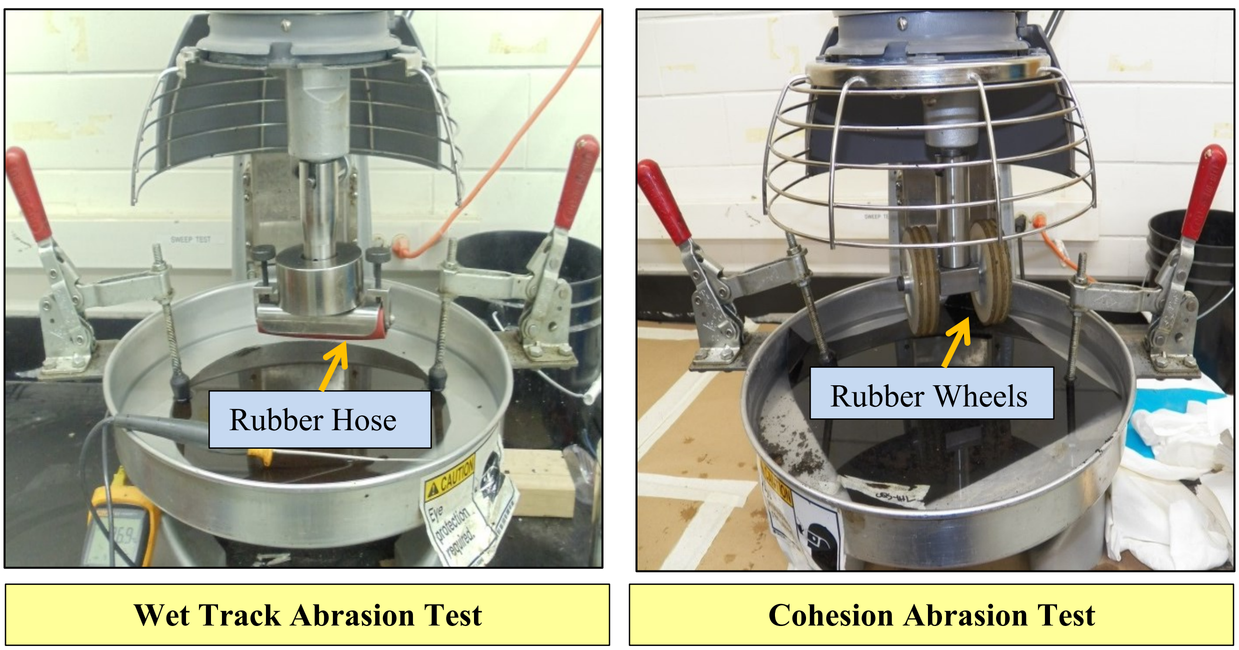


Figure 33. Photo of the WTAT (left) and CAT (Right)

Due to the increased height of the CAT geometry, use of this internal locking mechanism is not possible, thus requiring support of the sample from the bottom of the sample by using a wooden block.

The experiment plan in Table 15 was used to evaluate the two test methods. The results for the sample tested in dry conditions are presented in Figure 34. The solid bars represent the results of the WTAT while the results for the CAT are shown by the hatched bars. Three replicates were tested for all combinations; the standard deviation between replicates is presented as error bars in the figures. The results presented show both methods giving very low percent aggregate loss of almost below two percent, preventing assessment of the sensitivity to each candidate test method to changes in materials. To better differentiate between materials the tests were conducted on samples conditioned in water for 6 days at room temperature.

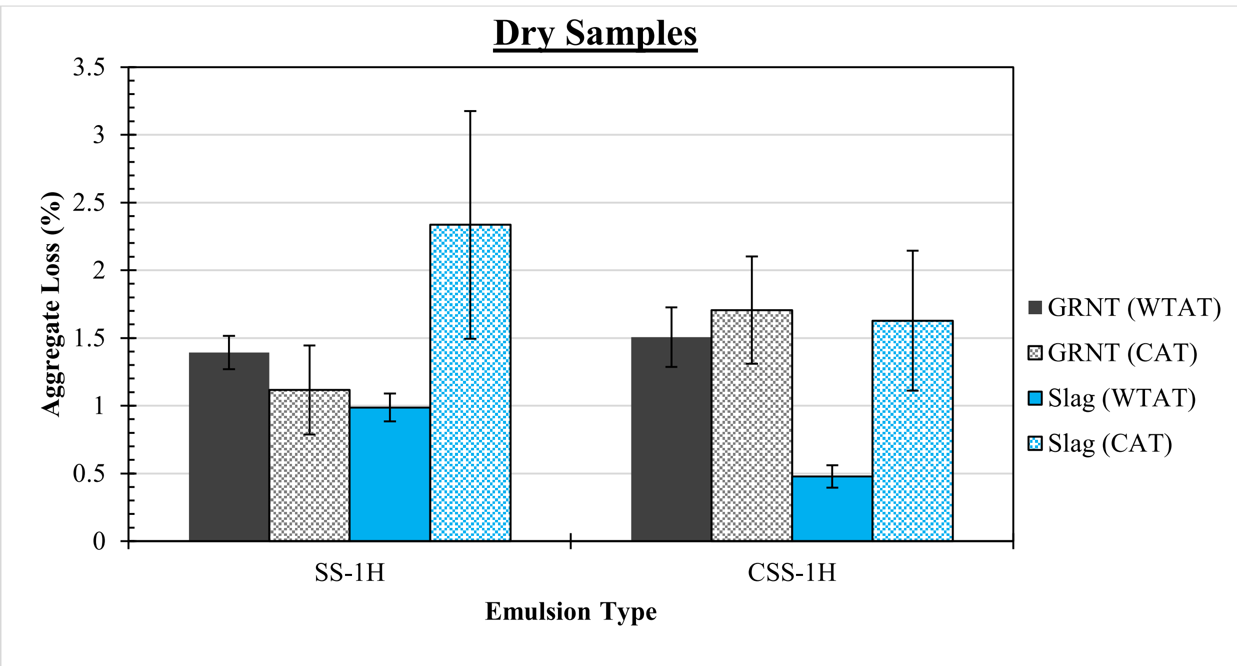


Figure 34. Raveling results of dry samples for the WTAT vs. CAT

Results are presented in Figure 35. It can be observed that moisture conditioning increased the range of percent aggregate loss values observed and was able to identify both moisture resistant and moisture sensitive materials combinations. The WTAT results indicate that the treatment prepared with the granite aggregate is more moisture sensitive than those prepared with slag as the percent aggregate loss parameter increases by a factor of three regardless of the emulsion chemistry used. The WTAT also demonstrates sensitivity to changes in emulsion type as lower values of percent aggregate loss were observed for the CSS-1H emulsion relative to the results of the SS-1H. The trend shown by the results of the WTAT with regards to both emulsion types and aggregate types is consistent with what been widely reported in the literature (Benedict 1978, Gates 1986, Alan 1986). Similar ranking is observed for tests conducted with the CAT geometry. However, due to the high variability observed in the results, the CAT is not as successful in identifying the impacts of changing materials on performance.

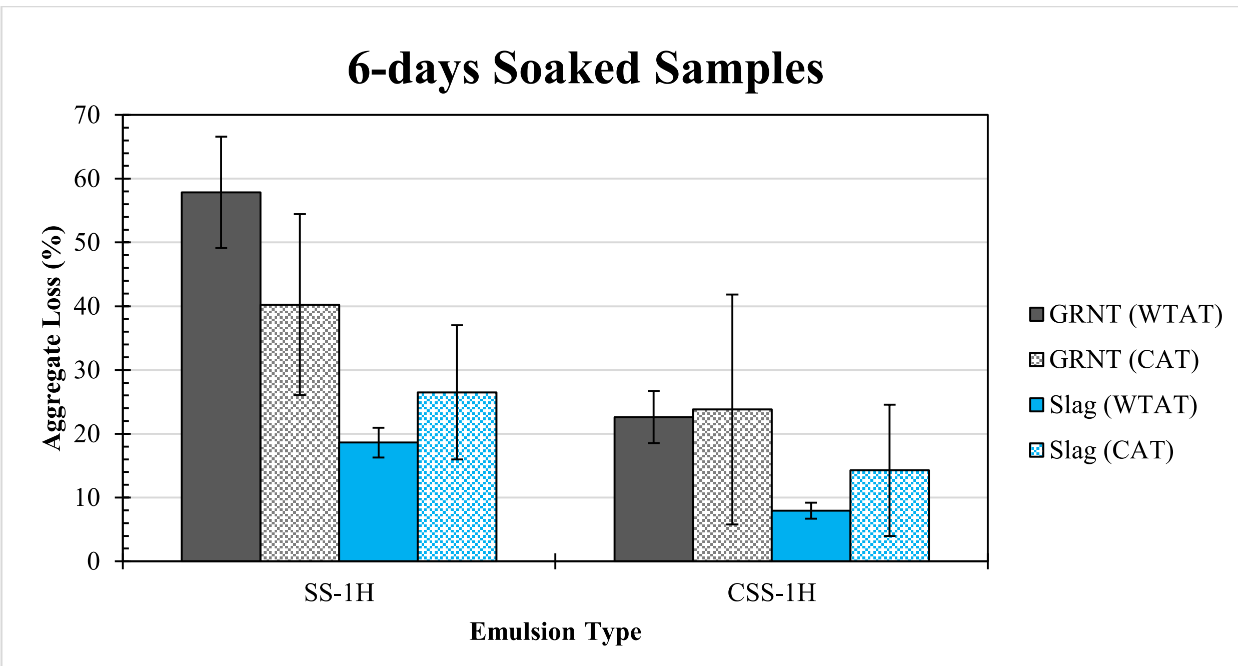
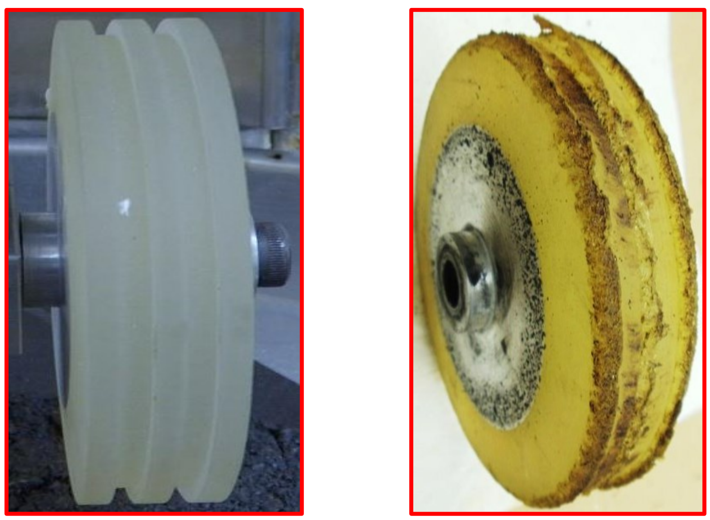


Figure 35. Raveling results of 6-days water conditioned samples for the WTAT vs. CAT

Two potential factors contributing the increased variability in the results of the CAT were identified. One was the wear of the CAT wheels during the test. As shown in Figure 36, the wheel geometry used in the CAT test experienced significant wear after testing a limited amount (i.e. 10) of samples. The wearing of the wheels results in non-uniform loading of the samples, as well high stress concentrations associated with surface irregularities on the sample. Additional review of the literature found that the CAT geometry had only been applied to assess early raveling of samples cured for less than five hours. In this condition the slurry seal surface does not have sufficient strength to cause the wearing of the wheel surface observed in this study when testing on fully cured samples (Deneuvillers and Samonos 2000) (Fugro 2004). The only solution identified to address wheel wear was to discard the testing geometry after each test. This alternative was deemed impractical and cost prohibitive as the cost of each CAT geometry is approximately $500. The second factor contributing to increased variability is use of the wooden block support underneath the sample pan to support the sample during testing.

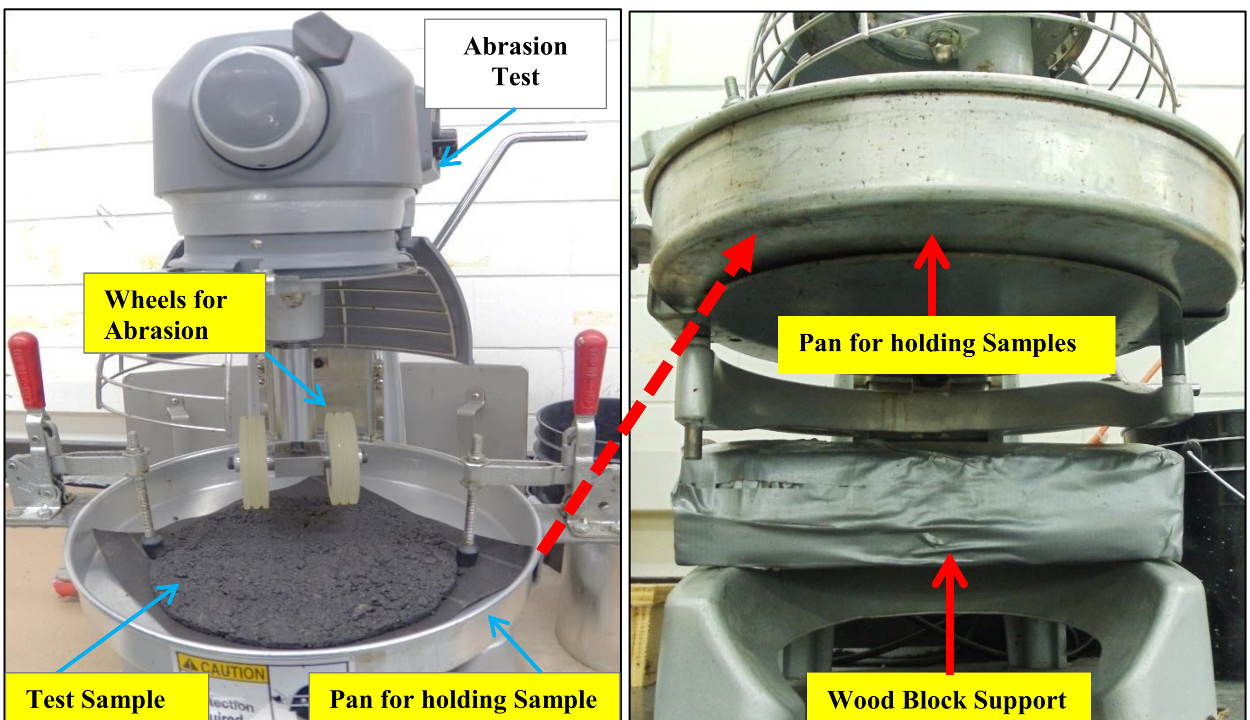


CAT Wheel before test

CAT Wheel after testing 5 samples

Figure 36. Picture of the CAT wheel when new (left) and after testing 36 samples (right)

In the test, the location of this support directly relates to the contact pressure applied to the surface of the sample. An example of the block support used is provided in Figure 37 As shown in Figure 37, placement of the wooden block support is arbitrary and left to the experience of the user, therefore there is no verification that a consistent contact pressure is applied to the sample for testing of replicates. The issue of varying support conditions is further exasperated by the fact that the height of the wheel is changing due to wear. Addressing this issue was decided to be cost prohibitive and impractical as it would require additional instrumentation and mechanical modification of the machine to ensure that consistent contact pressure was applied to all samples. Conversely, a system to control contact pressure through the internal locking mechanism is present in the current testing device when the WTAT geometry is used.



A: Front View of the CAT Equipment

B: Front View of the CAT Equipment From Under the Pan

Figure 37. Left picture shows the front view of CAT Machine. The picture on the right shows the same view from the support pan downward

Based on the aforementioned factors contributing to the increased variability of the CAT geometry, it was deemed unacceptable for application to fully cured slurry seal systems. As a result the WTAT testing geometry was selected for use in subsequent raveling resistance tests conducted in this study.

4.2.3 Evaluation of Resistance to Early Raveling

After construction, slurry surfacing treatments require additional curing time prior to opening to traffic, to allow for development of cohesive strength and shear resistance. If the slurry seal system is opened prematurely, significant raveling may occur and the service lives of both the treatment and of existing pavement maybe be compromised. The decision on when to open the slurry seal to traffic is currently a balance between reducing user delay and minimizing performance risks associated with premature opening. This task evaluated the hypothesis that a raveling based test like WTAT test can be used to evaluate early raveling of slurry surfacing treatments. The results are presented in the following tests.

4.2.3.1 Sample Preparation and Testing Procedure Used

Samples were prepared following the procedure outlined in ISSA TB 100 as described in Section 3.3.2. The samples were cured in a force draft oven at various curing times and temperatures to evaluate the effects of climactic conditions on rate of curing as evaluated by the raveling vs. curing time relationship. After the prescribed conditioning the samples were cooled to 25ºC for 25 minutes, and tested in the WTAT equipment at 25ºC for one minute without soaking.

4.2.3.2 Evaluation of Curing Time versus Raveling Relationships

The experimental plan presented in Table 16 was used to define the percentage raveling vs. curing time relationship and to identify the influence of changes in materials or curing temperature. The results for the SS-1H emulsion for all conditions tested are presented in Figure 38, while those of the CSS-1HP are given in Figure 39. The raw data are given in Appendix A.

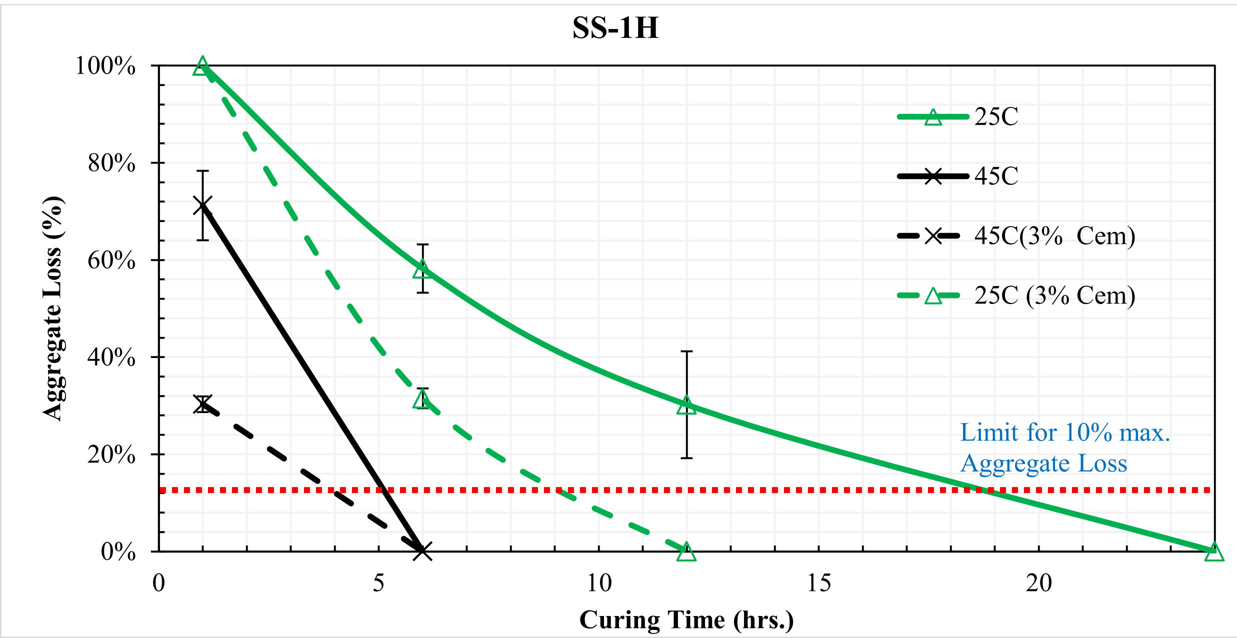


Figure 38. Effects of temperature and cement on raveling vs. curing time relationship for the SS-1H emulsion.

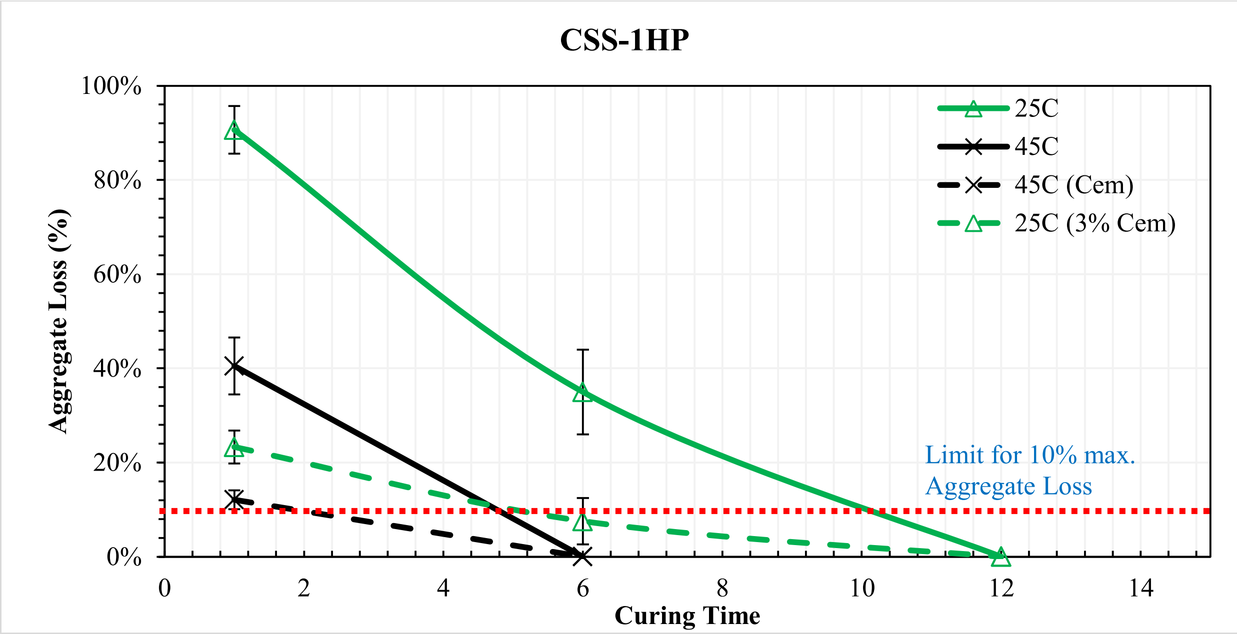


Figure 39. Effects of temperature and cement on raveling vs. curing time relationship for the CSS-1HP emulsion

The solid lines represent samples prepared without adding cement, while the dotted lines represent samples with 3 percent cement content. For a given emulsion type, the results presented demonstrate that the raveling vs. curing time relationship is sensitive to both curing temperature and the presence of cement. This indicates that to minimize time to trafficking, the surface treatment should be placed when pavement temperatures are high, and the design should include cement. In comparing results in Figure 38 and Figure 39 the effect of emulsion type is also evident, particularly for a curing temperature of 25°C, where the CSS-1HP emulsion reduces the time to 10% raveling by a factor of two relative the SS-1H emulsion. Experimental results are consistent with the main factors reported in the literature to have significantly affected early raveling resistance of slurry surfacing treatments (Bennedict 1985a, Alan 1986, Gransberg 2010).

Currently the ASTM D7000 recommended opening the road to traffic at the time when less than 10 percent aggregate loss is observed for chip seal treatments. The time required to reach less 10 percent aggregate loss for the factor combinations presented in Figure 38 and Figure 39 are presented in Figure 40. The results demonstrate that it takes less than five hours to reach less than 10 percent aggregate loss at 45ºC irrespective of emulsion type and cement content. At 25ºC, it can take between 6 to 24 hours of curing to reach less 10 percent aggregate losses, depending on emulsion type and percent of cement added. Hence, during cold climate, the amount of time a road is closed off after re-surfacing with can be reduced by specifying emulsions with less time the reach less than 10 percent aggregate loss in the WTAT or specify adding cement, provided that other performance parameter are not compromised.

The results presented in Figure 40 were further analyzed by ANOVA determine if the difference observed in the mean of the factors evaluated were statistically significant at a 95 percent confidence interval. These results are presented in Table 26. Replicates were included as an additional factor in ANOVA to establish the repeatability of the test procedure. The results show that repeatability of the test is not a concern as the p-value of the replicate factor is high that 0.05.

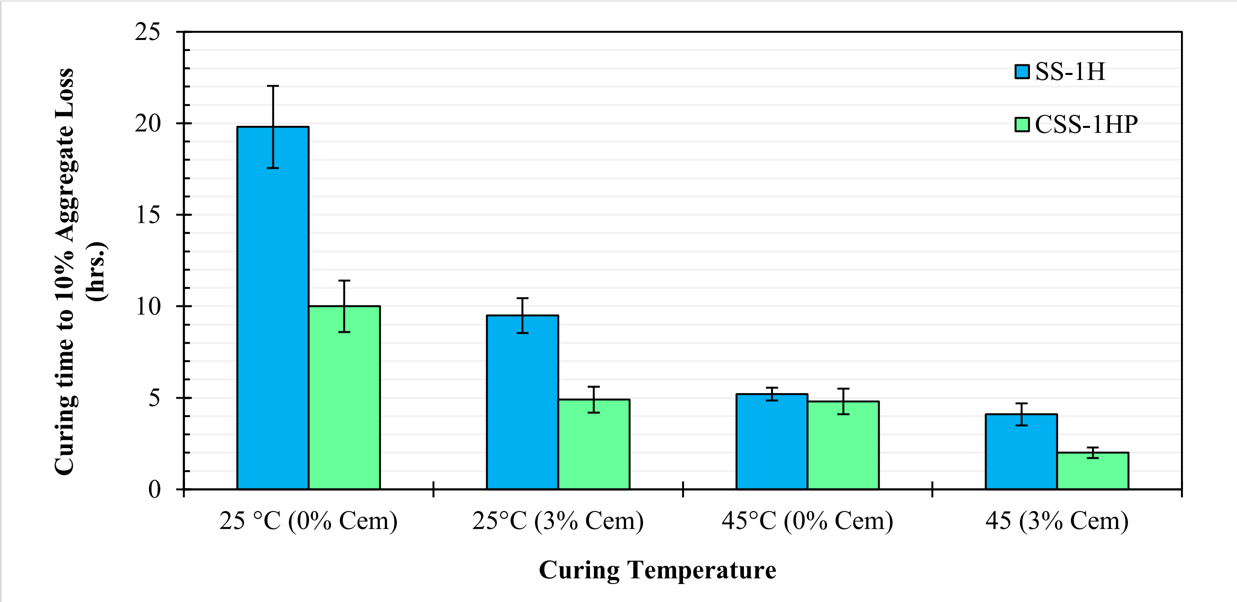


Figure 40. Curing time to reaching less than 10 percent aggregate loss for different factor combinations

Table 26. ANOVA Results for Factors Affecting Curing Time to Reach less than 10 percent aggregate loss in the WTAT

Factors	Df	F-value	Pr(>F)	Significant Level
Replicates	2	0.4624	0.637946	
Temperature	1	119.222	7.98E-09	***
Cement	1	54.973	1.47E-06	***
Emulsion Type	1	43.608	6.07E-06	***
Temperature : Emulsion	1	22.532	0.000219	***
Temperature : Cement	1	20.827	0.000319	***
Residuals	16			
Pooled Standard Deviation	1.56			
Adujusted-R^2	91.73%			

At 95 percent confidence interval, the most important factor affecting the time required to reach less than 10 percent aggregate loss is curing temperature, followed cement content and then by emulsion type. The two-factor interaction between cement content and temperature as well as between temperature and emulsions are also significant. These results are well in support of the observations made in the graphs presented in Figure 38, Figure 39, and Figure 40. Together, the results presented indicate that SHAs have several approaches they could use to minimize the time the road is closed off when newly surfacing treatment has been placed (provided that there is correlation between lab and field observations): construction should be carried out in the summer during hot climate, allow cement to be added, or use polymer modified asphalt emulsion.

4.2.4 Evaluation of Resistance Long-term Raveling

4.2.4.1 Introduction

Raveling resulting from moisture exposure is one of the critical failures that can affect the service life of slurry surfacing treatment (TTI-1289-1 1995). Current ISSA and ASTM guidelines do not require moisture damage evaluation on slurry surface treatment meeting the requirements of a slurry seal (ISSA TB A105), but have an optional requirement for treatment meeting the requirements of a micro-surface (ISSA TB 147). Evidence in the literature show that moisture induced raveling occurs in all slurry surfacing treatments, irrespectively of their ISSA classification.

Current test procedure for evaluating moisture damage takes 9 days from sample preparation to obtaining the results. This time consuming procedure could become a practical barrier for the industry if moisture evaluation is included as a mandatory requirement in current design. This task tested the hypothesis that moisture damage is detrimental to all slurry surfacing systems irrespective of their classification. Another hypothesis evaluated that the current 6-days soak test can be replace with a conditioning period that uses high temperature. The findings are presented in the following sections.

4.2.4.2 Evaluation of the Need for a Moisture Damage Test Experimental

The experimental plan given in Table 17 was used to establish the need for a moisture damage evaluation in all slurry surfacing treatments. Samples were prepared according ISSA TB 100 for both dry and 6-dyas moisture conditioned samples. The results for the granite aggregate are shown in Figure 41 while those for slag aggregate are given in Figure 42 for both dry and moisture conditioned samples, while sample tested in dry condition give almost similar results. The effects of moisture on the aggregate loss for both granite and slag can be noted. For granite, moisture increased raveling by a factor 7 to 41, depending on the emulsion type used. For slag aggregate, moisture condition increase aggregate loss by a factor of 10 to 19 also depending on the type of emulsion used. Overall the samples prepared with the polymer modified CSS-1HP showed lower increase in aggregate loss compared to samples prepared with the CSS-1H and SS-1H Emulsions.

It is interesting to point out that current ISSA and ASTM specification do not require moisture damage evaluation for slurry surfacing treatment constructed with either an SS-1H or CSS-1H and all other unmodified emulsion type. And even in the case of modified emulsion, the test is only recommended when the amount of polymer added to emulsion is more than three percent by the weight of the residual asphalt content. The results presented demonstrate weakness in current ISSA and ASTM guidelines, by not having a mandatory moisture damage test as part of the specification.

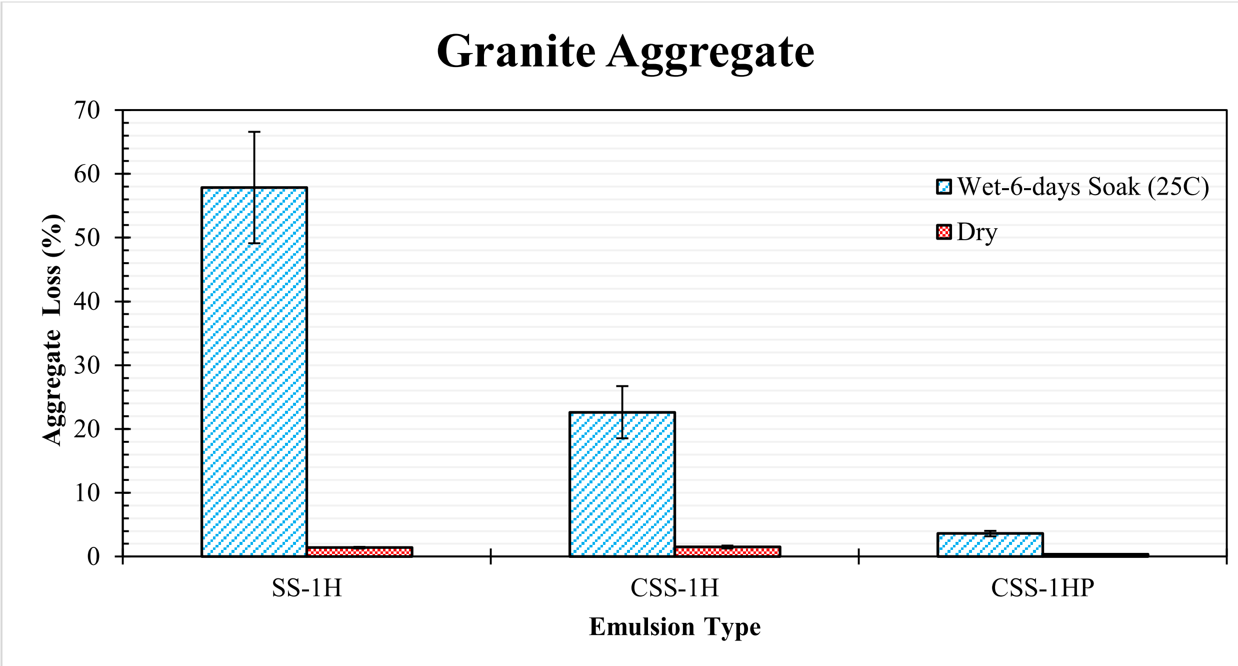


Figure 41. Effects of moisture conditioning on aggregate loss for the granite aggregate

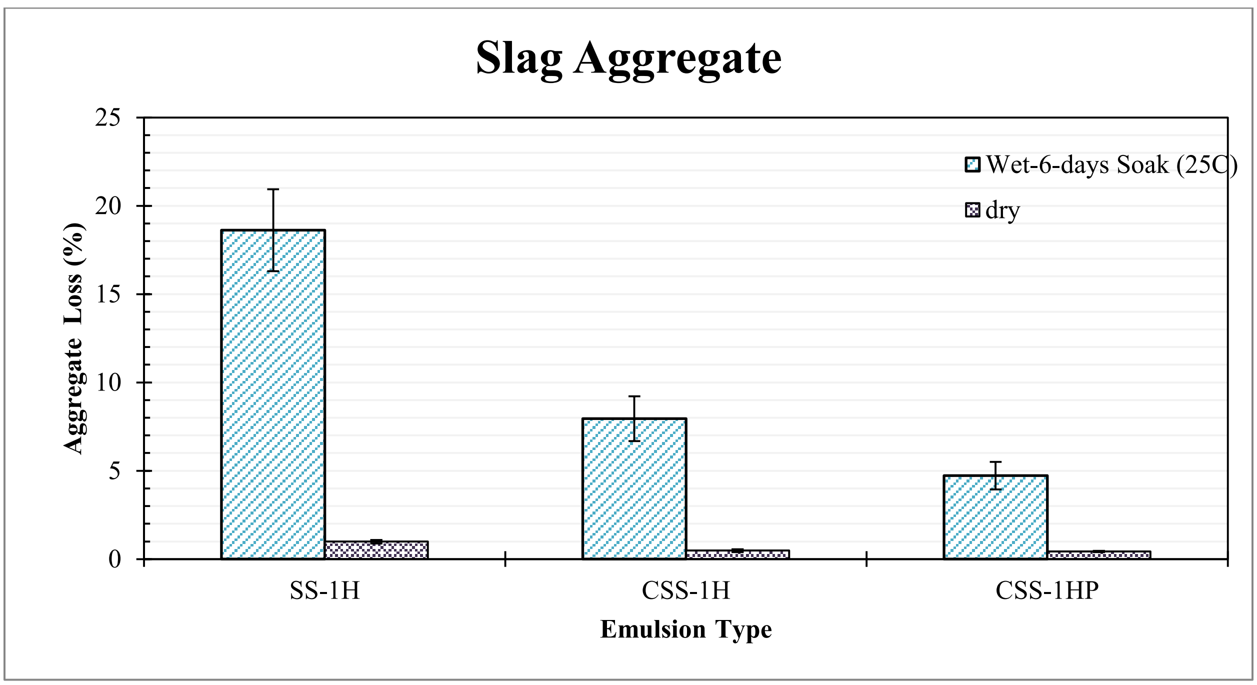


Figure 42. Effects of moisture conditioning on aggregate loss for the slag aggregate

As shown, the service life of some slurry surfacing, specifically those constructed with unmodified emulsions, could be serious compromised especially when used in climate with high rainfall. This finding confirm the recommendations of previous researcher (Raza 1994*a*, Andrew, et al. 1994) who have proposed that that moisture damage evaluation is necessary for all slurry seal systems and thus changes to current specifications is needed.

4.2.5 Development of Accelerated Moisture Damage Evaluation Procedure

The results presented in the previous section have demonstrated the need for moisture damage evaluation. This task addresses the practical concerns of the 6-days moisture damage testing requirements by investigating accelerated conditioning methods. This task was accomplished by first defining a new conditioning protocol (i.e. time and temperature) that results in damage similar to the current conditioning protocol, the accelerated conditioning procedure was then applied to various micro-surfacing and slurry seal systems and compared to the current system to confirm that both conditioning methods resulted in similar performance.

In the first stage, samples were prepared with two emulsion types (SS-1H and CSS-1H) and conditioned in water at three conditions. The three conditions evaluated were 24hours soaking at 40ºC, 48 hours soaking at 60ºC and 6-day soak at 25ºC (reference) as given by the experimental plan in Table 18. The temperatures were selected based on currently used conditioning temperatures for evaluating accelerated moisture damage in hot asphalt binders (AASHT TP-91) and hot asphalt mixtures (AASHTO T-283). For the accelerated moisture damage procedure, temperature was raised to increase the rate of diffusion of water through the asphalt film (due to a softening of the asphalt) and to increase the rates of the chemical reactions between the water, asphalt, and aggregate that govern moisture damage (DeVisscher 2008).

Results of the two emulsions at the different conditions investigated are presented in Figure 43. The results show that samples conditioned in water for 48 hours at 60ºC appear to show increase in aggregate loss close to those of the 6–days soak for both emulsions. Samples conditioned water at 40ºC for 24 hours only give similar results to the 6-days soak for the CSS-1H but not for the SS-1H emulsion

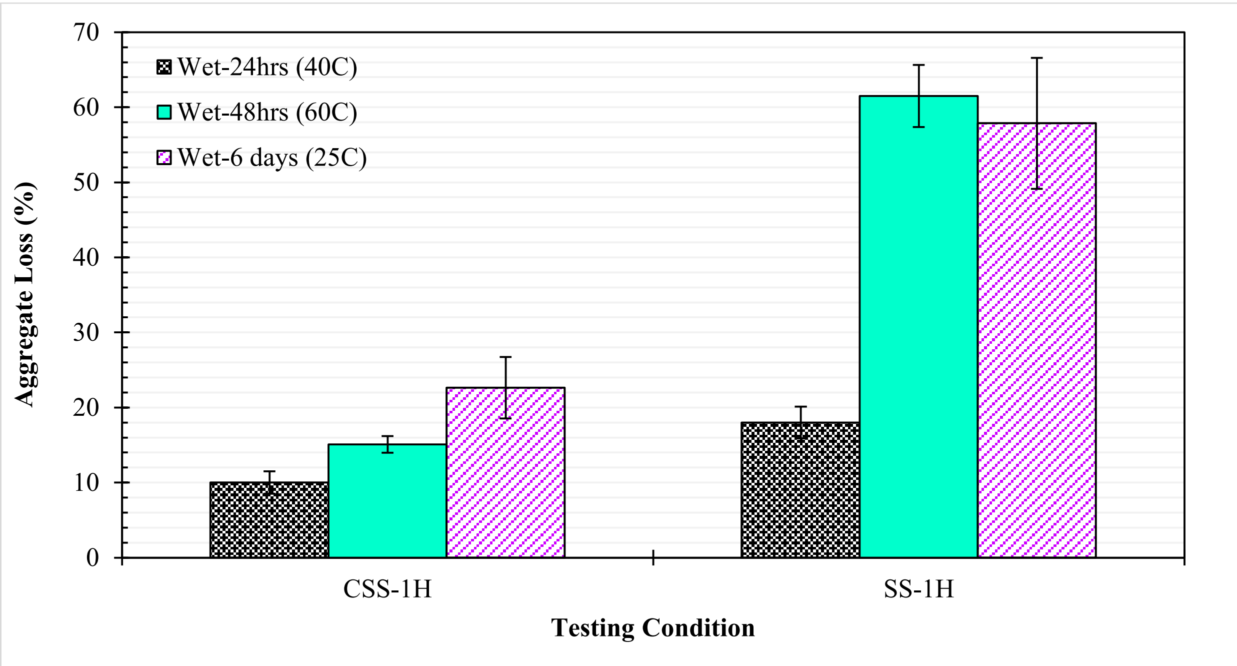


Figure 43. Moisture damage results for different conditioning times and temperatures

To validate that conditioning samples in water at 60ºC for 48 hours yield similar results as the 6-day soak test, more samples were further tested at the two conditions following the experimental plan presented in Table 19. The results for granite are presented in Figure 44 while those for slag are given in Figure 45, while the raw data are given in Appendix B. The results for granite show similar results for the SS-1H emulsion, while slight variations in the results of the two conditioning period for the CSS-1 and CSS-1HP emulsions can be noted.

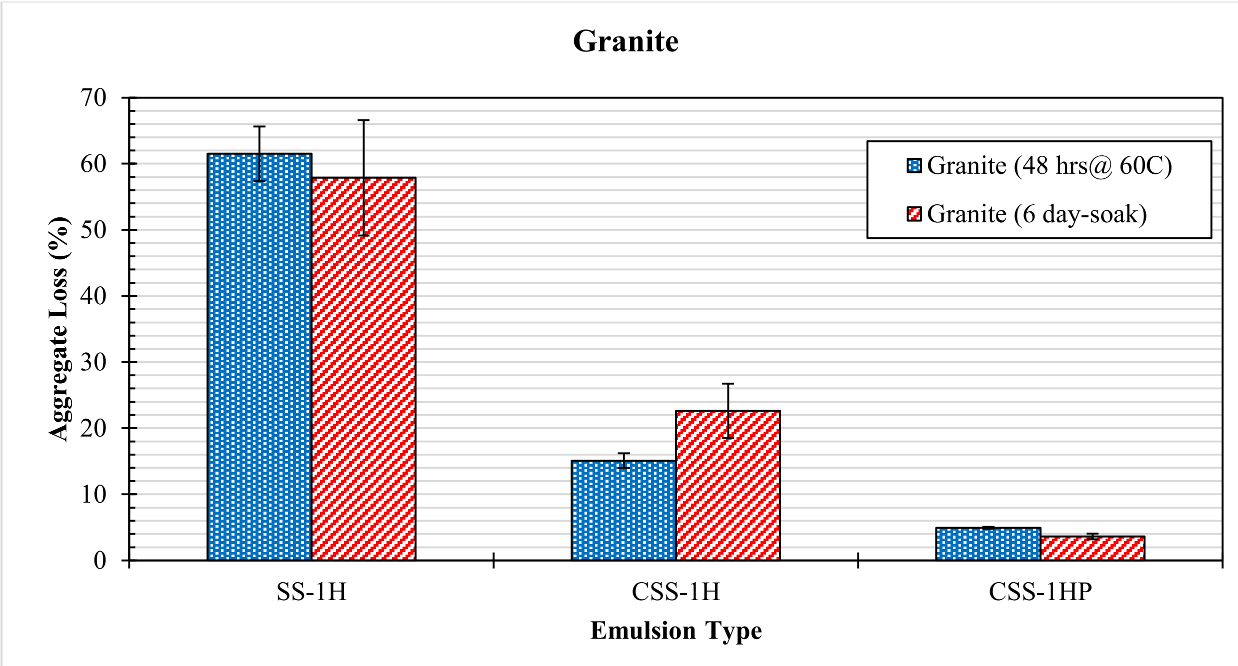


Figure 44. Moisture damage results for 48 hrs. at 60C versus 6-day soak test results for granite

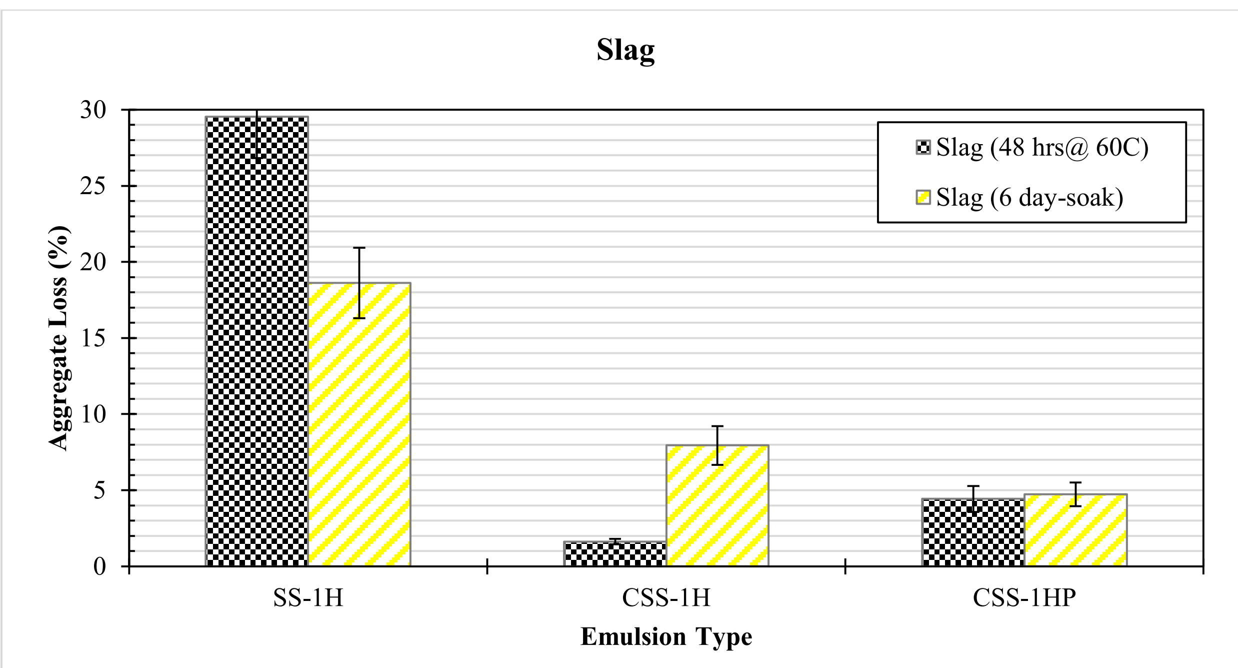


Figure 45. Moisture damage results for 48 hrs. at 60C versus 6-day soak test results for slag

The result for the CSS-1H appears to show the 48 hours at 60ºC procedure under predicting aggregate loss by six percent, while the results for the CSS-1HP emulsion are too low to make any concrete judgment. It appears the mechanisms causing moisture damage for the CSS-1H and granite aggregate are affected by the conditioning temperature. The results for slag show the two procedures giving similar results for the CSS-1H and CSS-1HP emulsions, but not for the SS-1H. The results for the 48 hours at 60ºC are about 33.3% higher than the results observed for the 6-day soak test. It appears the higher temperature could be too severe for the SS-1H emulsions when used with slag aggregate. However, it is encouraging to note the two procedures rank the performance of the three emulsions in the same order for both aggregate types. Overall, the SS-1H emulsion experienced the highest aggregate loss, followed by the CSS-1H; and then the polymer modified CSS-1HP with the lowest aggregate loss. It is worth to mention that the CSS-1HP showed lower aggregate loss possible due the addition of polymer.

The results for the two aggregate for the 48 hours at 60ºC conditioning are shown in Figure 46 to show the effects of aggregate type and emulsions type on resistance to moisture damage. The results show the granite to be more susceptible to moisture damage than the slag aggregate; however the moisture damage associated with use of granite can be offset by appropriate emulsion selection as shown by the similarity in results between the two aggregate types when used in combination with the CSS-1HP emulsion. The ability of polymer modification to improve moisture damage resistance observed in this study is consistent with effects noted in the literature for both polymer modified emulsion and modified hot asphalt binder (Harkness 1977, Moraes, Velasquez and and Bahia 2011).

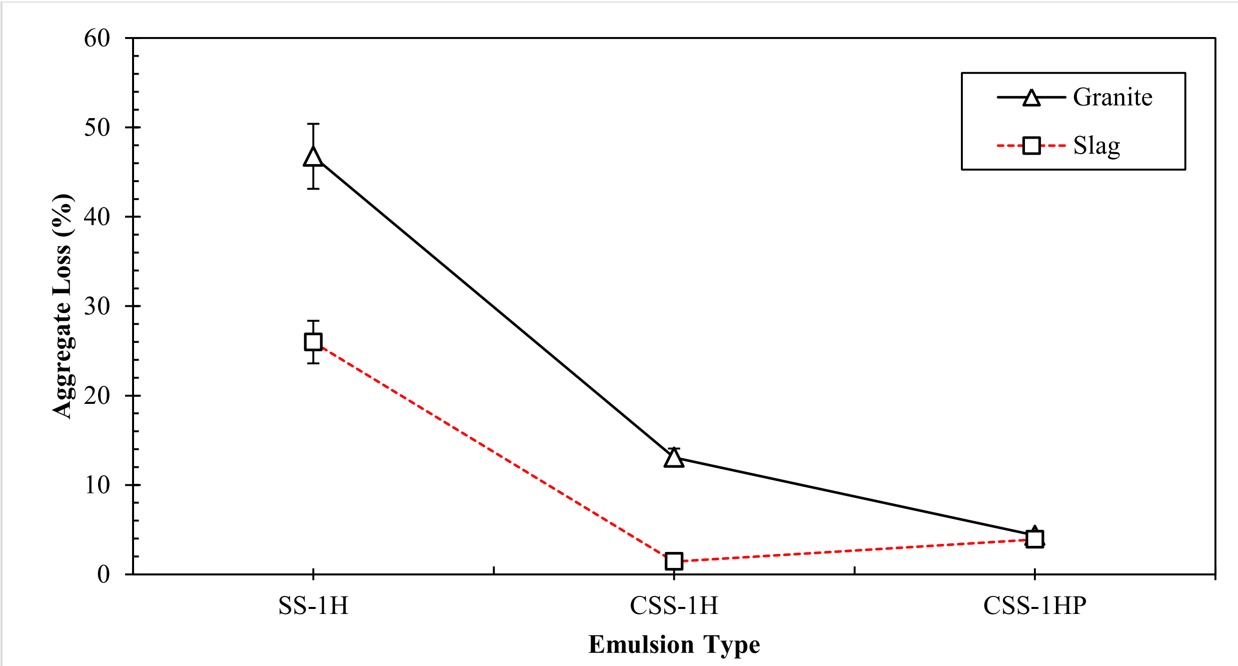


Figure 46. Effects of aggregate type of resistance to moisture damage

An ANOVA analysis was performed on the results presented above determine if the difference in means of the results for the two conditioning procedure was statistically significant, and as well as the identify factors significantly affecting resistance to moisture induced raveling. The results are given in Table 27, and were evaluated at a 95 % confidence interval.

Table 27. ANOVA Analysis Results for Factors Affecting Resistance to Moisture Damage

Source	**Df**	**F value**	**Pr(>F)**	**Sig. Level**
Emulsion Type	2	309.75	< 2.2e-16	***
Aggregate Type	1	168.51	7.20E-13	***
Conditioning Method	1	0.0003	0.987231	
Emulsion : Aggregate Type	2	54.238	5.28E-10	***
Emulsion Type: Conditioning Method	2	2.424	0.108262	
Aggregate type :Conditioning Method	1	8.920	0.006077	**
Residuals	26			

The result show that the two conditioning procedure give statistically similar results for the aggregate type and emulsion type tested as indicated by p-value of the conditioning methods higher than 0.05. The most statistically significant factors are aggregate type, emulsions type, their two-way interaction factor and a two-way interaction factor between emulsions type and conditioning method. This finding is in agreement with the results presented in prior sections. Moisture susceptibility in slurry surfacing can be reduced by careful selection of aggregate or asphalt emulsion, and the 48hrs @ 60C procedure presented here can be used to perform this selection.

4.2.6 Evaluation Emulsion-Filler Compatibility by the Wet Track Abrasion Test

4.2.6.1 Introduction

In current practice, it is common to add mineral filler to slurry surfacing mixes to either improve workability, accelerate trafficking time, or to improve in-service mixture performance characteristics. For this technique to be effective it is imperative that the mineral filler added is compatible with the asphalt emulsions used in the mix design to prevent premature failure due to raveling.

Current practice uses the Ruck & Puck test (ISSA TB144) described in Section 2.51 to evaluate emulsion-filler compatibility. However, the Ruck & Puck test has been reported to be subjective, operator depended and does not measure a performance parameter (aggregate loss) similar to distresses observed in the field when there is no compatibility between the asphalt emulsions mineral filler added (Andrew, et al. 1994, TTI-1289-1 1995, Robati 2012). Some researcher has questioned meaning of the results obtained from the Ruck & Puck test in relation to failures observed in the field, and whether the high cost of procuring the test equipment is really justifiable (Andrew, et al. 1994, Raza 1994b, TTI-1289-1 1995). This task evaluated the hypothesis that the WTAT can be used to identify asphalt emulsion-filler incompatibility. Result for Asphalt Emulsion-Filler-Compatibility

The experimental design given in Table 20 was used to evaluate emulsion-filler compatibility. Granite aggregate were used to carry out the test, and to evaluate the effect of mineral filler type on performance, the P200 material was replaced with the fillers tested. All other mix design components were held constant. The results for the three mineral filler and emulsions types are presented in Figure 47.

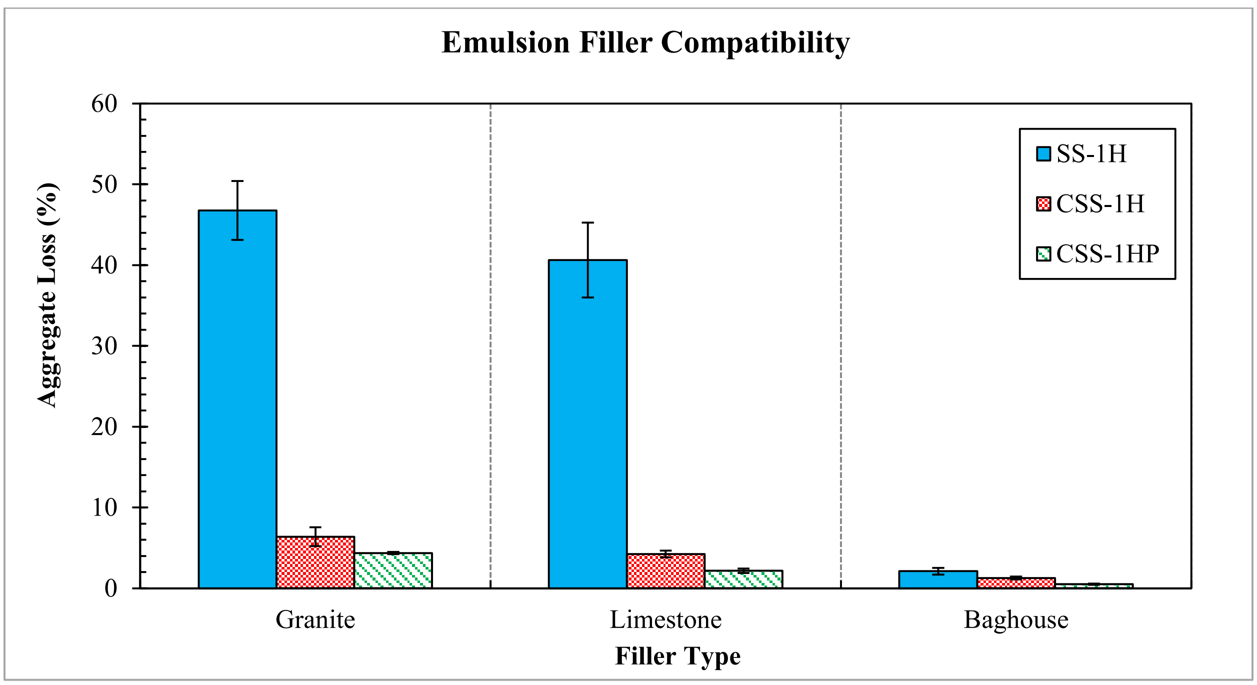


Figure 47. Effects of emulsion-filler compatibility on resistance to moisture induced raveling

Results presented in Figure 47 indicate that the WTAT test is successful in identifying emulsion-filler combinations that are incompatible. Similar results of aggregate loss are obtained for all three emulsions when the mineral filler used is either granite or limestone. Also, clear difference between emulsion type can be noted when granite or limestone fillers are used, with the SS-1H emulsion having aggregate loss almost 6 time that of the CSS-1H and CSS-1hP, whose aggregate loss is about five percent or lower. The percent aggregate loss is reduced to almost zero percent for all three emulsion types the mineral filler obtained from the baghouse of an HMA production facility (Granite + Natural Sand) is used to replace P200 materials.

Although the data presented in this research are limited, the most important thing is that the WTAT is able to identify emulsion/filler combinations that are susceptible to moisture damage. The results also emphasize the importance of including moisture damage resistance for all slurry seal treatments in mix design specifications, as a measure to ensure that the correct materials are used and the emulsion selected is compatible with the project filler. The WTAT test is a promising candidate as it addresses both emulsion-filler compatibility and overall mixture quality through use of a parameter that relates to distresses experience in the field.

4.2.7 Summary

This study evaluated two methods found in the literature for evaluating raveling of slurry surfacing treatments. The results identified the wet track abrasion test (WTAT) as a better test compared to the cohesion abrasion test (CAT) in terms of repeatability, sensitivity to materials type, and from the economic point of view. The WTAT was further used to determine if moisture condition significantly affects resistance to raveling for both emulsions for slurry seal and micro-surfacing per current specification of ISSA TB A 105 and A147. The result showed that mixes that are not currently required to be evaluated with a moisture damage test exhibited to highest aggregate loss after moisture conditioning. This finding indicate that performance of all slurry surfacing treatments can be improved by incorporation a mandatory moisture damage test that uses aggregate loss as a performance criteria. Another task covered in this section the establishment of an alternative moisture damage test that yield results in the short time than 6-days conditioning procedure. The results showed promise in conditioning samples in water at 60ºC for 48 hours. Results presented show that aggregate type, emulsion type and their two way factor interaction as significant factors affecting resistance to moisture damage with the proposed new conditioning methods. Lastly, the possibility of using a raveling based test to identify emulsion-filler compatibility was explored. Sample conditioned with different filler and conditioned in water using the new conditioning method and evaluated with WTAT. The results showed that the WTAT and new conditioning test can distinguish the impact of different filler types on aggregate loss.

4.3 Evaluation of Potential Test Methods for Bleeding

4.3.1 Introduction

Slurry surface treatments are applied as wearing courses, the top layer on which the travelling public directly drive one. As such, they should possess sufficient skid resistance during both wet and dry season to provide adequate surface friction needed safe breaking and stopping. Many researchers (Bennedict 1985a, Bennedict 1989b, Benedict 1991a, Raza 1994a, Andrew, et al. 1994) have reported deficiencies in the sand adhesion test (ISSA TB 109) currently used to evaluate bleeding. Based on this short-coming, this section presents the results of alternative test methods for evaluating bleeding identified from the literature. Similar to previous sections, candidate test methods were evaluated based on repeatability and sensitivity to mix design factors known to influence bleeding.

4.3.2 Evaluation of Bleeding by Surface Texture with the Stationary Laser Profilometer (SLP)

One approach for measuring bleeding considered was using surface texture as performance criteria through measurement of the Mean Profile Depth (MPD). The MPD was measured with a Stationary Laser Profilometer (SLP) equipment and analysis procedure developed by Miller et.al (Miller, et al. 2012). The MPD was selected as a surface texture measurement due to its use in current practice by agencies to evaluate the skid resistance of in-service pavements. Measurements were made on samples on Loaded Wheel Test (ISSA TB 109) before and after testing. Two replicates were prepared, and three profiles were measured in the wheel to give a total six replicates. Testing was conducted on the experimental plan presented in Table 21 was used to establish the repeatability of the measurements as well as to establish if the MPD measured was sensitive to factors known to affect bleeding. The results of the different factors investigated are presented in subsequent sections.

2.1.1.1. Effects of emulsions Types on the Mean Profile Depth (MPD)

The results of the MPD for three emulsions tested are presented in Figure 48 for the medium gradation. The results presented demonstrate the general trend of MPD decreasing with increasing asphalt content (film thickness) for all the three emulsion types, with the magnitude of the change emulsion dependent. This observation is in line with what has been generally observed in the field. A lower value of MPD indicated potential for bleeding, and generally high values of the MPD are desired. However, two out of three emulsions tested show no significant sensitivity to change in asphalt emulsions content due to the high variability in the MPD values observed.

The results presented also show that the effect of emulsion type is not significant at the lower film thickness of 8 microns. At the film thickness of 12 and 14 microns, slight differences can be noted only between the CSS-1HL and CSS-1H. A picture of the samples for the CSS-1H emulsions at the three residual asphalt film thicknesses is shown in Figure 49. The presence of bleeding can be clearly seen present in the sample for the 14 micron residuals asphalt film thickness, but the system use to measure surface texture was not capable of detecting these differences due to the high variability of the test procedure.

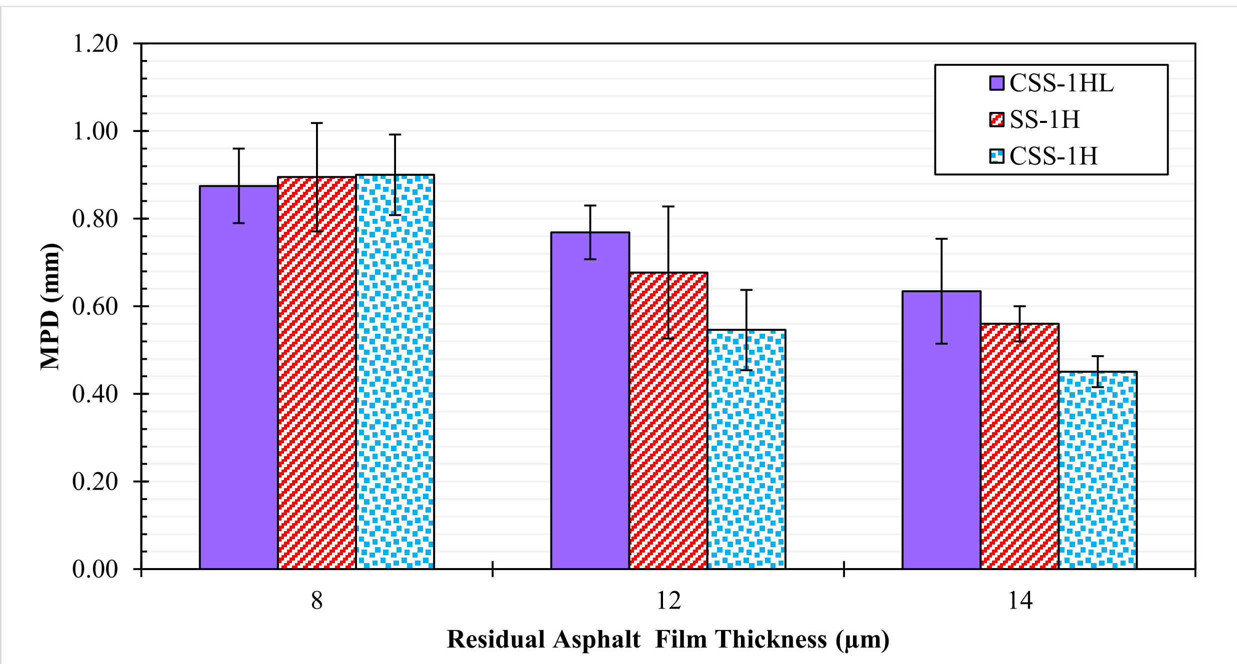
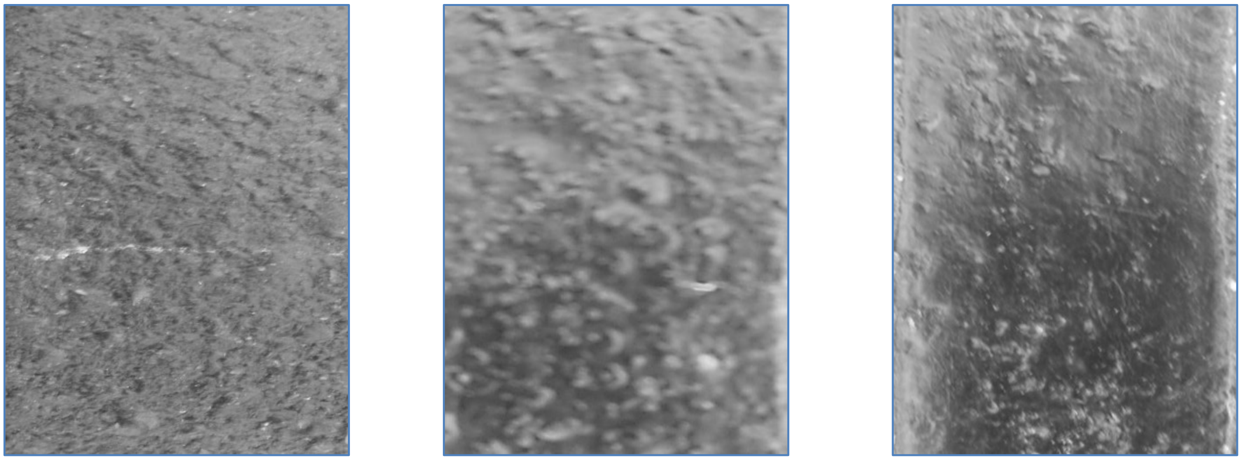


Figure 48. Effects of emulsion type on the MPD (@1000 cycles in LWT)



CSS-1H (FG) 8µm FT | CSS-1H (FG) 12µm | CSS-1H (FG) 14µm

Figure 49. Pictures of the CSS-1H emulsion samples at different emulsions content after subjected to 1000Cycles in the LWT

2.1.1.2 Effects of Aggregate Gradation

Sensitivity to gradation was evaluated with two emulsions type using the medium and fine gradations. The results are given in Figure 50. Both the coarse and fine gradations show decrease in the MPD value with increase in residual asphalt film thickness. The results show effects of gradation on the MPD values at high residual asphalt contents. The effect of gradation is more prevalent at higher asphalt contents, and also with the SS-1h emulsions. Again, there variability in the data is higher, and this inhibits any concrete observation regarding the effects of gradations to be made.

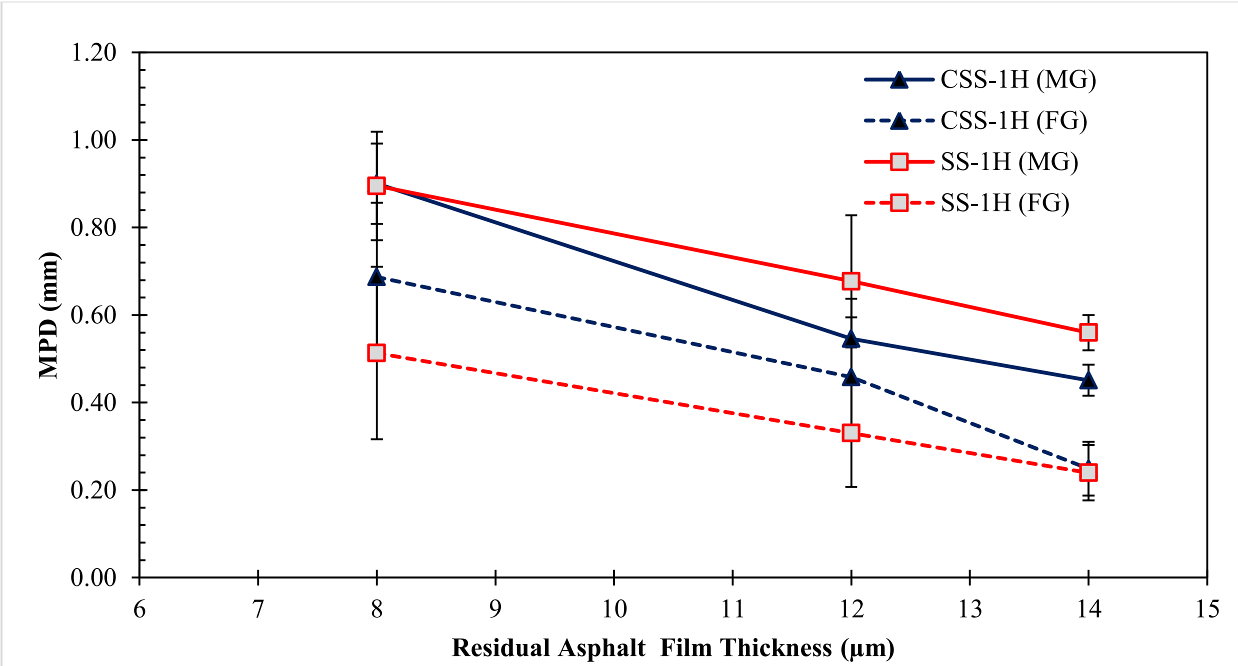


Figure 50. Effects of aggregate gradation on the MPD (@1000 cycles in the LWT)

2.1.1.3 Effects of Traffic Volume on the MPD

Slurry surfacing constructed in areas with high traffic volume are more prone to bleeding due to the increased cycles of traffic loading. The effect of traffic volume on the MPD was investigated for one emulsion, the SS-1H. The results are given in Figure 51 for the 1000 and 2000 loading cycles for the two gradations. The solid bars indicate the results at 1000 cycles, while the hatched bars indicate the results for the 2000 loading cycles. The results for the fine gradation show an unexpected trend as no logical relationship between the number of loading cycles and the MPD value is present for both gradations. Four out of six combinations evaluated show no sensitivity to traffic loading, and while the remaining two appear to show the MPD increasing with the number loading cycle.

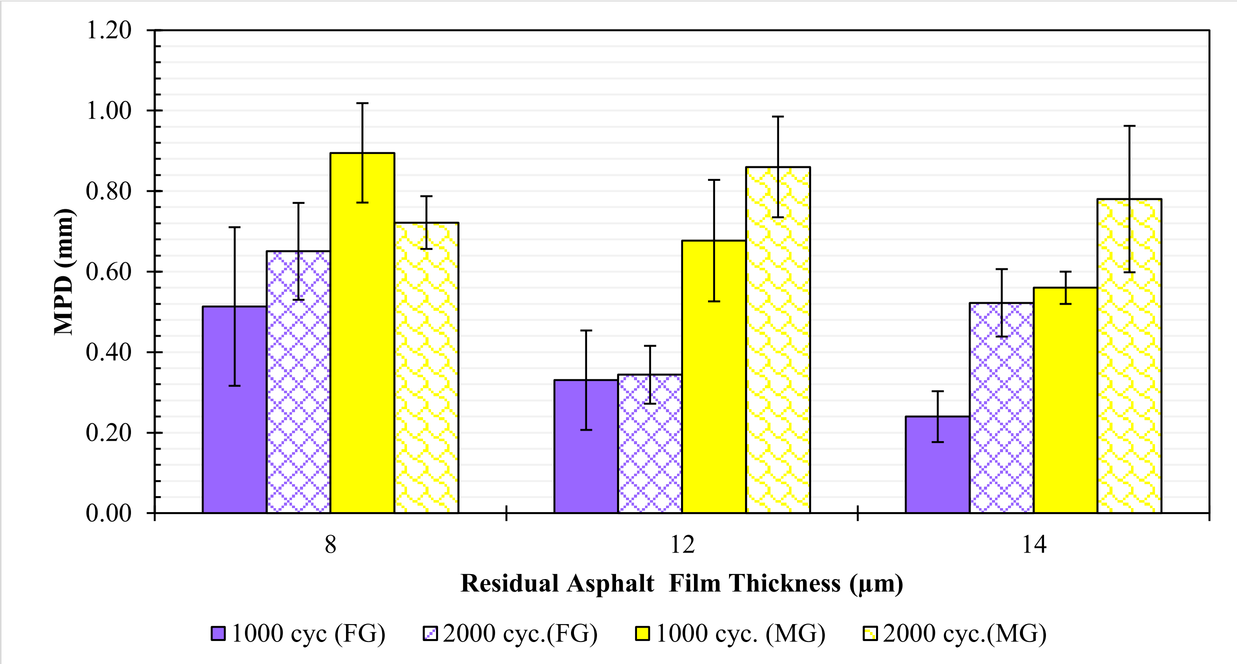


Figure 51. Effects of Traffic level on the MPD of the SS-1H emulsion

All the results presented in the previous sections on the MPD were analyzed using ANOVA to determine the repeatability of the test, as well as to identify significant factors affecting the MPD. Separate ANOVA analyses were carried out for emulsion type, gradation and loading cycle, and the results are presented in Table 28.

The results from the effects of emulsion type identified asphalt film thickness as the only factors with significant effects on the MPD at a confidence interval of 95 %. Replicates and emulsion types were found to be insignificant. However, the Adjusted R-squared observed for the model fitted to the data is 44%. The Adjusted R-squared measures the proportion of variation in the MPD that is accounted for by the independent variables measure, and it takes into account the numbers of independent variables included in the model. The low value of Adjusted R-squared observed indicate that much of the variation observed in the data is not random, and hence the results need to be used with caution.

Table 28. ANOVA Results for the MPD

Source	Df	F - value	Pr(>F)	Sig. Level
Effects of Emulsions Type				
Emulsion Type	2	1.1443	0.3329	
Film Thickness	2	14.7783	4.16E-05	***
Replicates	3	0.867	0.4698	
Residuals	28			
Standard Error	0.1915			
Adjusted R-Square	44%			
Effects of Gradation				
Emulsion Type	1	0.9048	0.34736	
Gradation	1	46.905	3.46E-08	***
Film Thickness	2	35.7953	1.49E-09	***
Replicates	3	0.5757	0.63442	
Emulsion Type: Gradation	1	4.1388	0.04875	*
Residuals	39			
Standard Error	0.1205			
Adjusted R-Square	71%			
Effects of Loading Cycles				
# of Loading Cycles	1	4.5807	0.03833	*
Film Thickness	2	2.2993	0.11313	
Replicates	3	0.3928	0.75882	
Residuals	41			
Standard Error	0.2124			
Adjusted R-Square	8%			

The main factor suspected to behind the inconsistency of the results presented is the samples size used. The LWT is tested on samples that are 6.5mm in thickness, and thick possible caused some end effects on the samples which is reflected in the results. A visual examination of the samples after testing showed that larger aggregate particles were more exposed after high number of loading cycle (2000 cycles) for both gradations. An example is shown in the images in Figure 52 for medium gradation, and larger particle sizes can be seen more exposed after 2000 cycles.

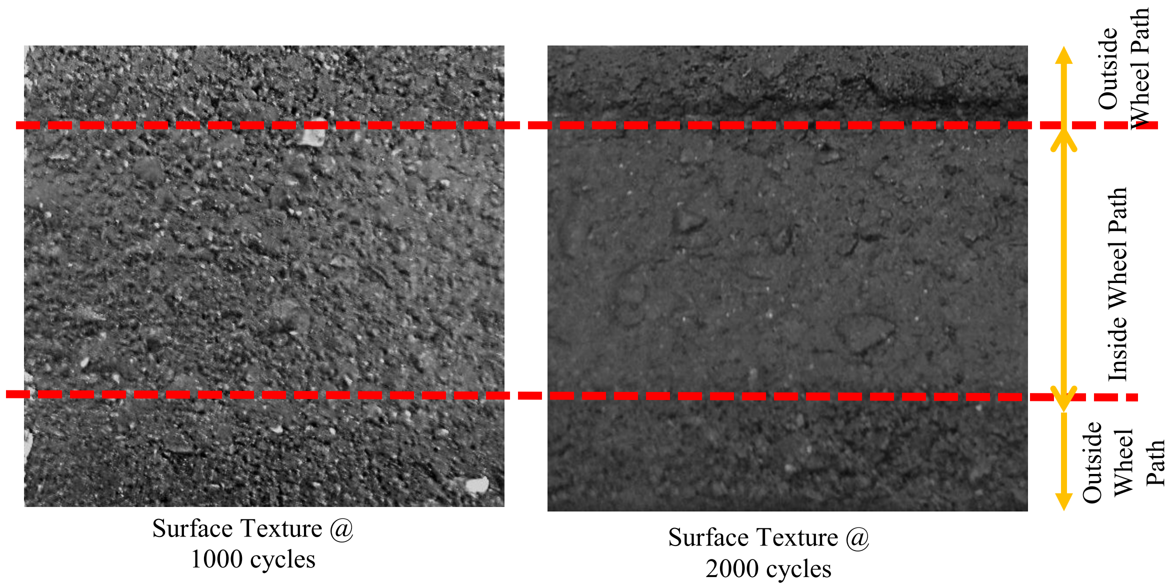


Figure 52. Picture show how the surface texture increases with number of loading cycles

The exposed particles were included in the results as a false positive increase in the MPD. It is possible that the combined effects of aggregate getting exposed with loading cycles and sensitivity of the laser equipment resulted the inconsistent results obtained and the high variations noted in the data as well. At this moment, other methods of evaluating bleeding are therefore recommend over the MPD measured with the SLP explored in this study, until a better method of preparing samples with uniform surface texture is established.

4.3.3 Evaluation of the Resistance to Bleeding and Rutting on Marshall Compacted Samples

4.3.3.1 Introduction

The second candidate method identified for evaluation of bleeding potential was volumetric analysis of samples prepared using the Marshall compaction and mix design method (ASTM D1559). Several researchers (Reinke, et al. 1989, Kramer and Doyle 1989, Labuschagne, Louw and Gerrie 2012) have already made attempts to use the Marshall Method to evaluate volumetric and strength properties of slurry surfacing. The Marshall method used by these researchers, however, the sample size and compaction temperature used by these researchers is not representative of field conditions (ISSA 2010).

The objectives of this task were to (1) develop a sample preparation procedure for slurry surfacing systems by Marshall Method, and (2) compare laboratory compacted densities those reported from field samples, and (3) lastly to evaluate the repeatability and sensitivity of the volumetric parameters to factors known to affect bleeding.

4.3.3.2 Sample Preparation Procedure Developed

A new sample preparation procedure was developed from which loose slurry mixture was acquired and used to prepare Marshall compacted samples. Sample are prepared and cured following the procedure for the WTAT described in ISSA TB 100. The only difference being the thickness of the mold used was 9.5 mm and that the asphalt felt disk were covered with a non-stick paper to allow for both enough materials to be recovered, and also for easy to removal. After curing the samples in the oven for 24 hours at 60ºC, the losses mixture was put in pans marked with sample information, broken up into losses mixture while still hot, covered and put back in the oven at 100ºC together with Marshall.

After 2 hours, 500 grams of loose mixture is compacted with the Marshall hammer with the desired number of blows of both sides. This procedure yield samples that are approximately 25 mm in heights, which is relatively close to the thicknesses used in the field. Samples were cooled at room temperature for 24 hours before evaluated for density in accordance with ASTM D2726 and tested for Indirect Tensile Strength in accordance with ASTM D6931. Rice samples were obtained from the WAT samples, broken up into a loose mixture, and tested from maximum theoretical density in accordance with AASHT T209. This procedure is described more in detail in Section 3.3.3.2, and also presented graphically shown Figure 53.

The experimental Plan presented in Table 22 was formulated to meet the objectives of this sub-task. The results are presented in subsequent sections.

4.3.3.3 Laboratory versus Field Density

The first step in assessing the viability of application of the Marshall method was to compare the laboratory measured densities to densities reported from field samples. This was important because previous researchers (Reinke, et al. 1989) have reported that current laboratory methods yield samples with densities much higher than those measured on field samples. Field densities of micro-surfacing samples have been reported to be around 2100 Kg/m^3 or to have bulk specific gravity of compacted mixture of 2.10 after 5 years (Reinke, et al. 1989). Unfortunately, only one study was found in the literature that has done actual field measurement of micro-surfacing and all other researcher seem to quote results of this study. The ISSA TB 147 for evaluating resistance rutting of slurry surfacing treatments also recommended that samples whose bulk specific gravity exceed 2.10 after trafficking with a 1000 cycles to be rejected. Using these resources as guidelines, the results of the bulk specific gravity of 106 samples compacted in this study are given in Figure 54.



1. Apply Non-stick Paper to Felt **2. Cast Mixture in WTAT Molds** **3. Cure in Oven for 24hrs@ 60ºC**



4. Remove from Paper and Felt **5. Break Mixture While at 60ºC** **6. Mixture After Breaking**


6. Compaction in the Marshall Hammer **7. Compacted Samples**

Figure 53. Sample reparation procedure for Marshall Compacted Samples

The range of the residual asphalt film thickness used cover the range reported to be used in the field. The results shown represent all three ISSA gradations, commonly used asphalt emulsions as well as compaction effort representing both high (50 blows per side) and low (35 blows per side) traffic volume. The mean of the data presented is 2.105 and the standard deviation was 0.054. This show that the results obtained from the sample preparation procedure developed gives densities well within those reported in the literature from field samples.

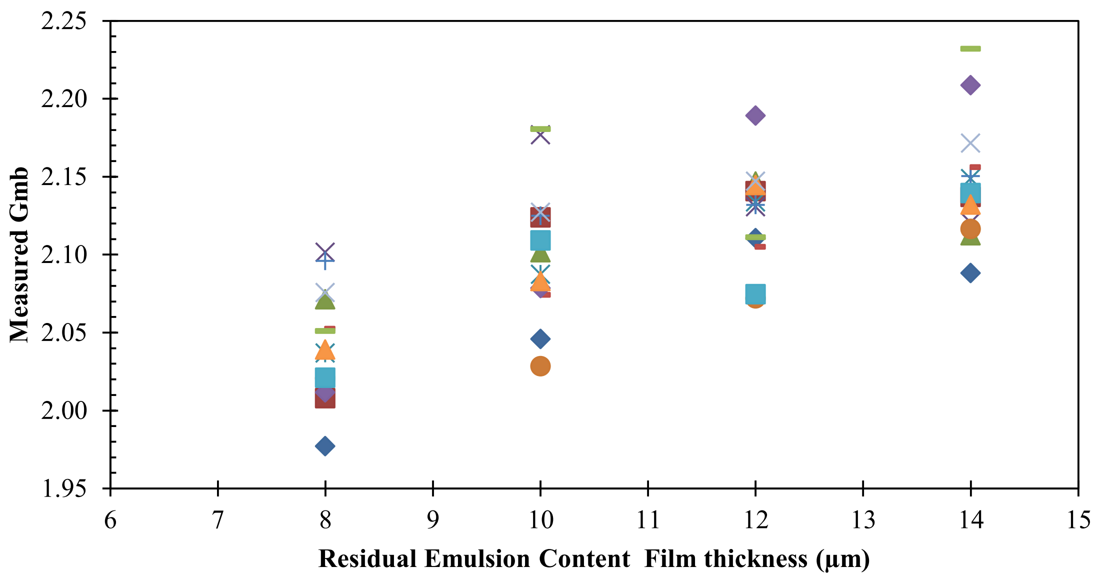


Figure 54. Bulk Specific Gravity of Laboratory Compacted Samples

4.3.3.4 Evaluation for Bleeding Using the Volumetric Parameter % Voids Filled with Asphalt (%VFA)

Bleeding caused by excessive asphalt content occurs because the volume of voids between the aggregate particles of given gradation becomes saturated with the asphalt binder by traffic compaction. In relation to volumetric analysis, this condition is evaluated by the voids filled with asphalt (% VFA) parameter. To minimize the risk of bleeding, a maximum %VFA limit is proposed to ensure that available voids are not filled with asphalt. To address the effects of traffic volume, different levels of compaction are proposed.

The results of % VFA for three emulsions types used are presented in Figure 55 for the coarse gradation. The raw data are given in Appendix C. The solid bar graph represent the results of samples compacted with 35 blows to represent low traffic volume, while the corresponding hatched bar graph represent the results of samples compacted with 50 blows preside to represent high traffic. The dotted line shown indicates the recommended maximum % VFA by SABITA (Labuschagne, Louw and Gerrie 2012) to prevent bleeding in slurry surfacing treatments. Robert et al. (Robberts, et al. 1996) have also reported that when the % VFA exceed approximately 80% to 85%, the asphalt mixture typically becomes unstable and rutting is likely to occur.

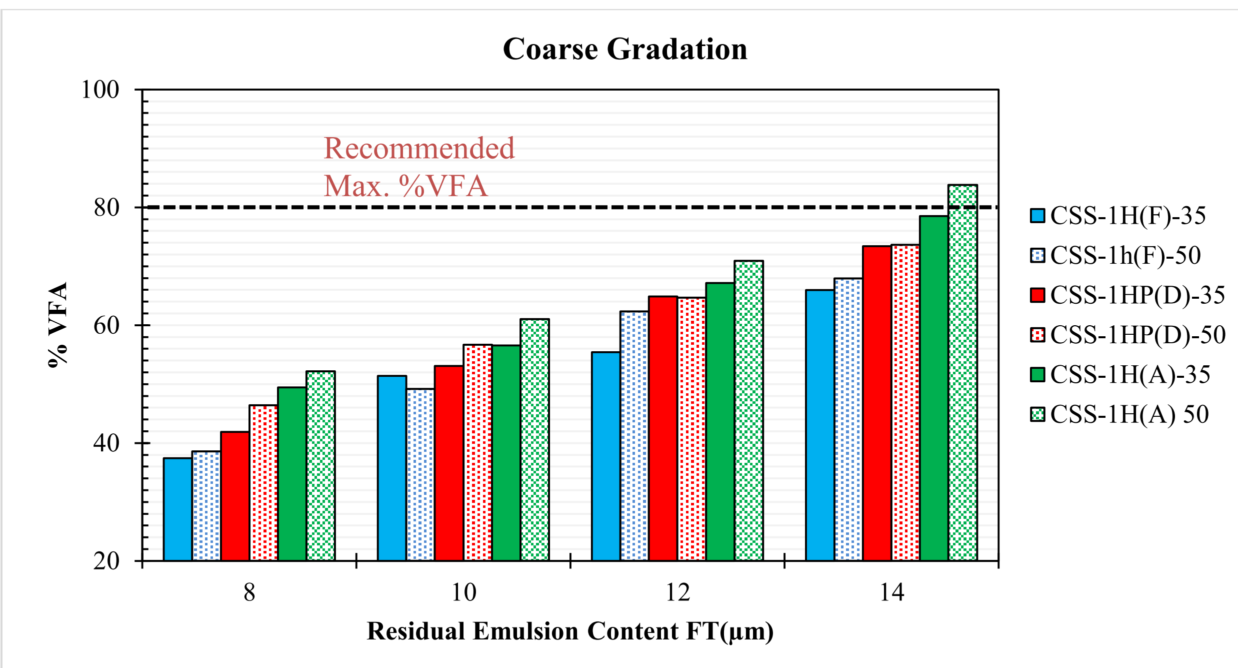


Figure 55. Effects of Emulsion Type and Compaction Effort on % VFA (Coarse gradation)

The results exhibit a consistent trend with % VFA increasing with increases in asphalt content for all emulsion types and both levels of compaction effort. This trend is consistent with the relationship between %VFA and asphalt content observed in standard mix design procedures for HMA. The results also show the parameter % VFA to be somewhat sensitive to emulsion type for the coarse gradation. Two types of CSS-1H emulsions from different suppliers were evaluated and together with a polymer modified CSS-1HP also from a different suppliers. The results show that the polymer modified CSS-1HP show relatively lower % VFA than the CSS-1H (A), but not lower than the value of the CSS-1H (F). This observation emphasizes the importance of developing performance based specification for different materials, as not all modified emulsion perform better than unmodified emulsions in terms of resistance to bleeding. Overall, most samples compacted with 50 blows showed high %VFA than samples compacted with 35 blows, depending on the emulsion type. The %VFA for almost all asphalt content evaluated is below the recommended 80% maximum, except only for the CSS-1H (A) at 50 blows.

The results for fine gradation was carried out with an SS-1H emulsions, CSS-1H (A) and CCS-1HP (D) and are presented in Figure 56. The results presented show a different trend from that of the coarse gradation. Sensitivity to emulsion type is barely noticeable, while the effects of traffic appear to be present only at lower asphalt contents. All three emulsions showed %VFA above 80% at the film thickness of 12 microns and above.

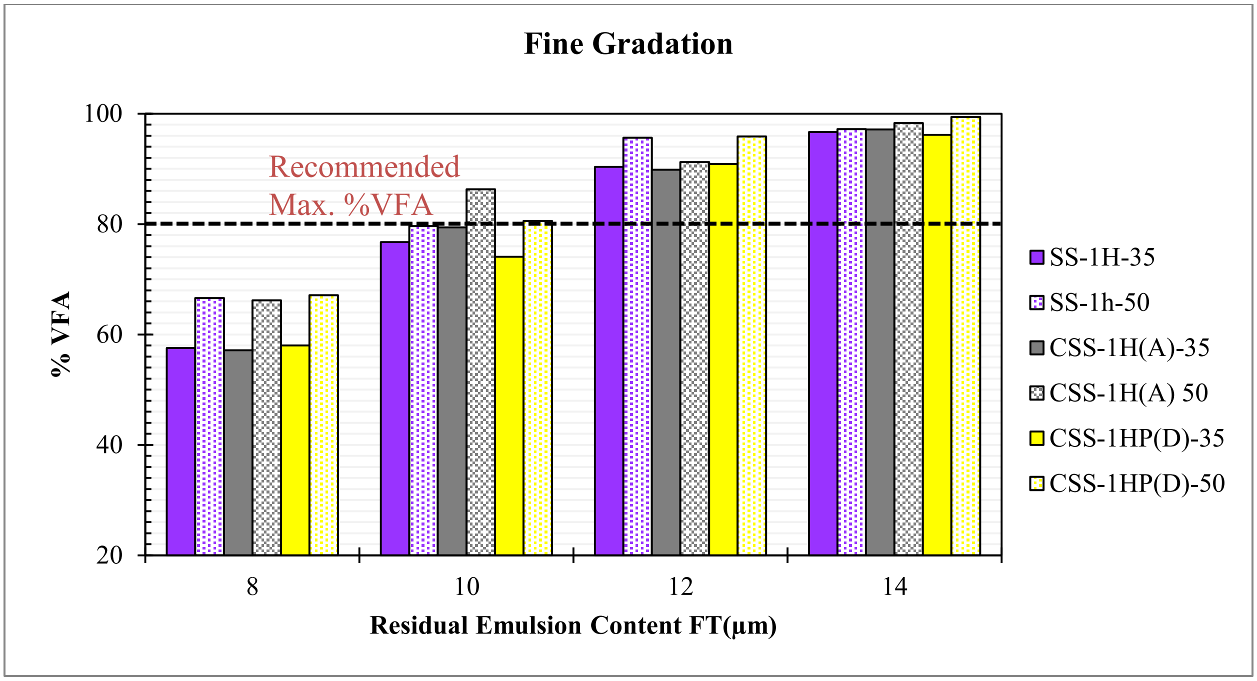


Figure 56. Effects of Compaction Effort on % VFA (Medium gradation)

At a film thickness of 10 microns, the SS-1H emulsion and CSS-1HP(D) approach the 80% mark for samples compacted at 50 blows, while the CSS-1H(A) is above the recommended limit. The results shown indicate that bleeding is more likely to occur when the fine gradations are used than with the coarse gradations given in ISSA TB A105 & A147. This appear to indicate that residual asphalt content below 10 microns film thickness must be used when fine gradations are used to prevent premature failure associated with bleeding.

It is possible that the driving factor behind high % VFA for the fine gradation is the surface area method (ISSA TB 118) used to calculate the required asphalt content to give a certain film thickness. The surface area method (ISS TB118) is greatly dependent on the gradation, and it yield very high asphalt contents for fine gradations than for coarse gradations. Table 29 present the residual emulsion contents used to achieve the four film thicknesses selected for each gradation. The ratios of the residual asphalt contented used for the fine gradation divided by that of coarse gradation is presented in the last column.

Table 29. Film Thicknesses used Corresponding % Residual Asphalt Content

Film Thickness (μm)	Residual Asphalt Content (%)		Residual Asphalt Content Ratio (Fine/Coarse)
	Fine Gradation	Coarse Gradation	
8	9.3	5.7	1.63
10	11.4	6.9	1.65
12	13.6	8.2	1.66
14	15.7	9.4	1.67

As can be seen, the fine gradation contained about 39% to 40 % more residual asphalt content than the coarse gradation for the same film thickness. Current ISSA guidelines recommend a maximum of 13.5% residual asphalt content when using unmodified emulsions and 10.5% when using polymer modified cationic emulsions for the fine gradation used in this study. While these ISSA limit appear to justify the high % VFA of the polymer modified CSS-1HP (D) at a film thickness of 10 microns, they do not give accurate limits for the unmodified emulsion. According to current ISSA guidelines the 12 micron film thickness will not result in bleeding for the fine gradation, conversely laboratory results indicate that regardless of materials or compactive effort the %VFA observed exceeded 90%. Additional investigation is needed to verify the finding of this study, and if verified, ISSA guidelines on allowable maximum asphalt content may need to be revised.

The results presented were evaluated by ANOVA for each asphalt film thickness to establish the effects of gradation, compaction effort, and emulsion on % VFA, and also to evaluate the repeatability of the procedure developed. The results are presented in Table 30 for all four film thicknesses used. In all cases, two-factor interactions that were found significant at

95% confidence are also given, while those that were not significant were removed from the model using the Backward Elimination Method (Chatterjee 2006).

Repeatability was evaluated by including replicates as factor in the analysis, looking at standard error, and also by the Adjusted R-squared. The results show good repeatability as the factor replicate have a p-value much great then 0.05, standard error below 2.7 and an adjusted R-squared above 93% for all four film thicknesses. All three main factors (emulsion, traffic and gradation) were found significant at film thicknesses of 8 and 10 microns, but only emulsion type and gradation are significant at film thicknesses of 8 and 10 microns. This means that bleeding can be control by changing any of the three main factors evaluated when using asphalt contents below 10 microns. But as the asphalt emulsion content exceed10 microns, bleeding are can only be controlled changing emulsion type and gradation. Three two-way factor interactions were found significant at a film thickness of 8 microns but only one interaction factor was significant at other three emulsion film thickness. This bleeding maybe control by avoiding certain main factor combination when lower levels of asphalt emulsion are, used, however, as the asphalt emulsion content increases on most factor combination becomes insignificant.

Table 30. ANOVA Results for % VFA at Different Asphalt Film Thicknesses

Factors	DF	F-value	Pr(>F)	Sig. level
Film thickness: 8 microns				
Emulsion Type	3	192.9865	2.04E-10	***
Gradation	1	377.6648	1.95E-10	***
Traffic Volume (#of blows)	1	93.3176	5.20E-07	***
Replicates	1	0.405	0.536445	
Emulsion: Traffic Volume	3	4.9796	0.017998	*
Emulsion: Gradation	1	24.9706	0.000311	***
Gradation: Traffic Volume	1	12.9981	0.003611	**
Residuals	12			
Standard Error	1.505			
Adjusted R-squared (%)	97.9			
Film thickness: 10microns				
Emulsion Type	3	142.1288	1.02E-10	***
Gradation	1	530.3254	1.58E-12	***
Traffic Volume (#of blows)	1	20.058	0.00052	***
Replicates	1	0.0083	0.92868	
Emulsion: Traffic Volume	3	3.9035	0.032221	*
Residuals	14			
Standard Error	2.019			
Adjusted R-squared (%)	97.7			
Film thickness: 12 microns				
Emulsion Type	3	64.8379	1.88E-08	***
Gradation	1	359.0912	2.23E-11	***
Traffic Volume (#of blows)	1	3.5481	0.08055	.
Replicates	1	0.185	0.67368	
Emulsion: Gradation	1	7.2556	0.01747	*
Residuals	14			
Standard Error	2.645			
Adjusted R-squared (%)	93.37			
Film thickness: 14 microns				
Emulsion Type	3	105.6439	9.29E-11	***
Gradation	1	273.8112	1.74E-11	***
Traffic Volume (#of blows)	1	2.8882	0.108588	
Replicates	1	0.0226	0.882352	
Emulsion: Gradation	1	9.732	0.006603	**
Residuals	16			
Standard Error	2.466			
Adjusted R-squared (%)	96.37			

4.3.4 Evaluation of Test Method for Rutting

Slurry surface treatments that meet the requirements of a micro-surfacing are sometime applied in multi-layers or used for rut filling application. Stability and resistance to permanent deformation under the action of traffic loads, especially at high temperature is an extra factor that needs to be taken into account during the mixture design. In current practice, rutting potential is evaluated by measuring the vertical deformation, lateral deformation, and specific gravity of the sample of LWT sample at a specified number of cycles in accordance with ISSA TB147. Although the industry appears to be satisfied with the existing criteria for evaluating rutting using the LWT (Fugro 2004, Gransberg 2010), some concern with the procedure has been raised. They included, use of non-representative test temperature, unstable load-supporting mechanism, subjectivity of the specific gravity as only part of the sample is subjected to loading, and problems related to end effects noted in this study (Raza 1994a, Bennedict 1985b).

Alternative testing methods for evaluating rutting that uses engineering failure parameters to evaluated rutting were evaluated in an effort to supplement the LWT in ISSA TB 147. The test evaluated was the Indirect Tensile strength test described in ASTM D 6931. It addition to actual mixture failure parameter measured by the IDT test, the test is performed on Marshall compacted samples on which physical properties for determining volumetrics are measured, and hence no new sample are required. The results are presented in the following section.

4.3.4.1 Experimental Results

4.3.4.1.1 Indirect Tensile Strength

The results for the IDT strength are presented in Figure 57 for the coarse gradation and in Figure 58 for the fine gradation. On each graph, the solid line represent samples compacted with 50 blows while the dotted line represent samples compacted with 35 blows. A high number of IDT typically indicate that good performance in term resistance to rutting could be expected while a low number typically indicate high for rutting (Robberts, et al. 1996). The results presented show the IDT varying with emulsion content. There appears to be an optimum emulsion content at which the IDT is highest for a given emulsion type, traffic level (# of blows) and aggregate gradation.

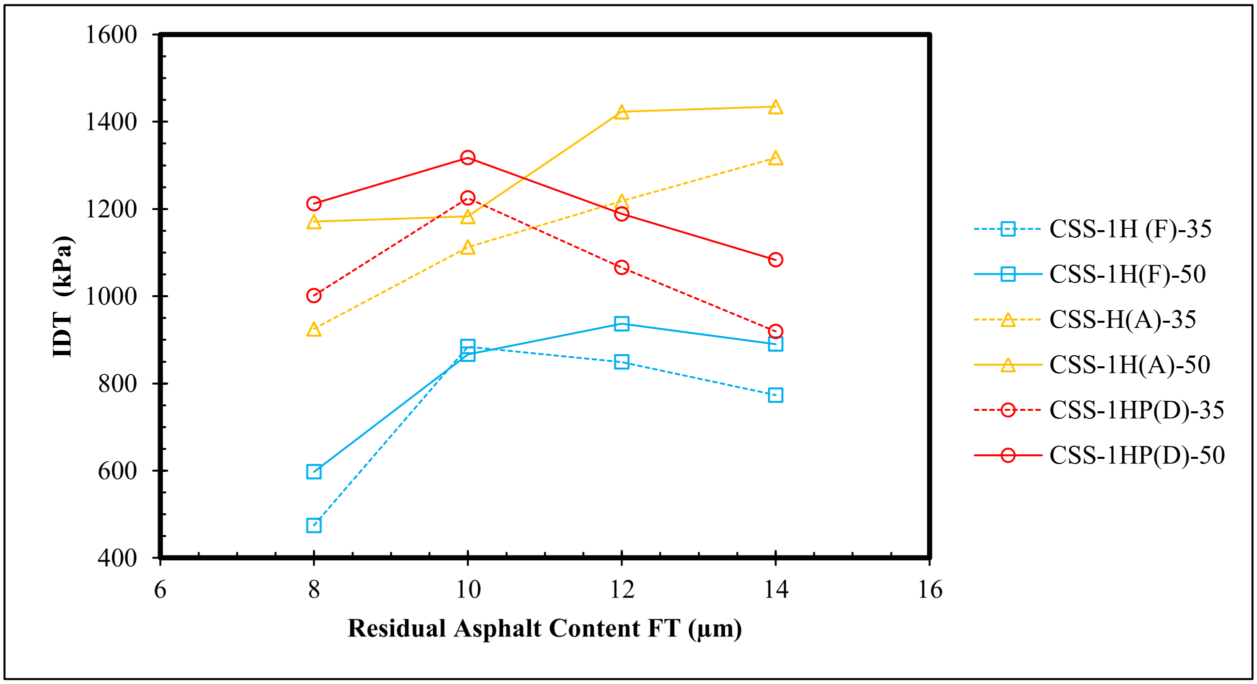


Figure 57. Effects of residual asphalt content and emulsion type on DT strength for the coarse gradation

These results shows the potential for using the IDT to select the asphalt content that will results in the most stable mixture in the field when evaluated in the ranges that will not result in bleeding. The results also show logical trend for the most part in relation to compaction effort. For the most part samples compacted with 50 blows per side (high traffic) have higher IDT values than samples compacted with 35 blows (low traffic), especially so for the results of the coarse gradation than for fine gradation.

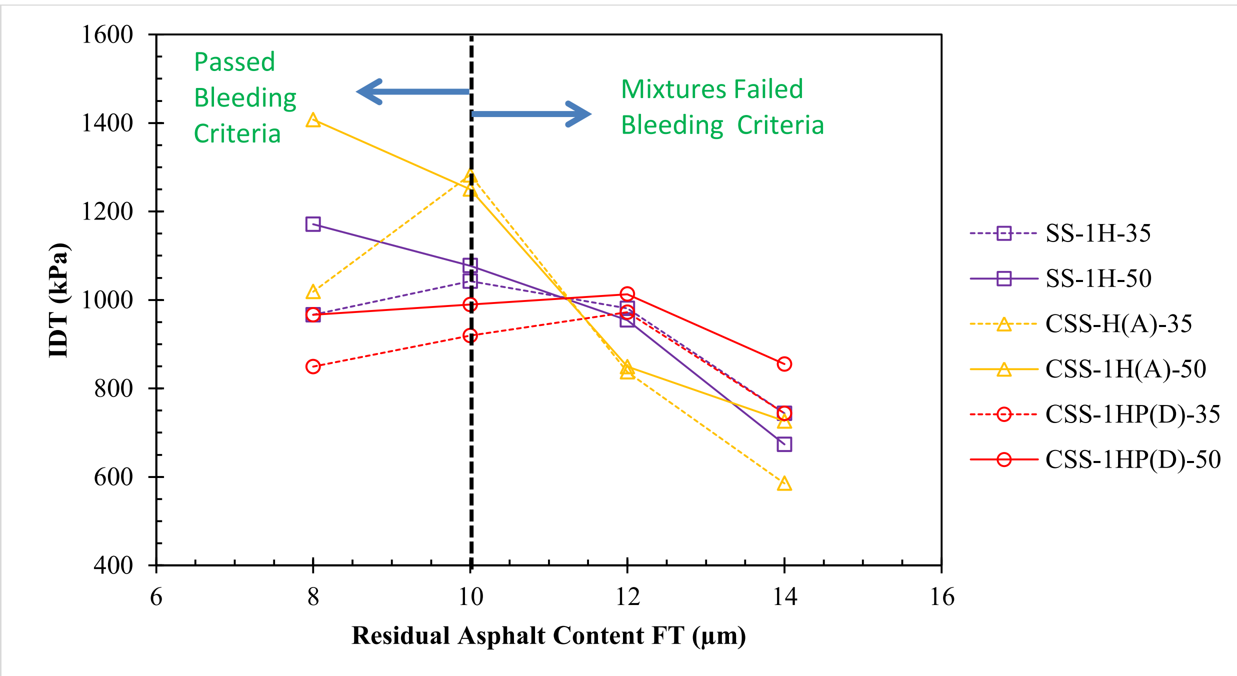


Figure 58. Effects of residual asphalt content and emulsion type on Marshall Stability for the fine gradation

The results presented also show the effects of emulsion type, and show the different levels of asphalt content at which each emulsion give the most stable mixture. For the fine gradation, asphalt contents which failed the bleeding criteria are marked on the graph. There appears to be no defined relationship between mixtures that experienced bleeding and IDT values, meaning that one parameter cannot be used to predict the other. For the two emulsions that were tested both with the fine and coarse gradation, there appears not significant difference between the values of the IDT, except at asphalt contents that did not pass the bleeding criteria, where the fine gradation has lower IDT values.

4.3.4.2 Evaluation by Failure Strain

The tensile strain at failure has been reported to be a potential indicator for cracking potential of hot asphalt mixture (Robati 2012). High failure tensile strain values indicate an asphalt mixture that has plastic behaviours, and may have potential for permanent deformation such as rutting and shoving under loading. Low failure strain value indicates a mixture that may have insufficient binder which may lead to durability problems with the pavement (Levin 2003). Low flow values may also indicate a mixture with a binder so stiff, that a pavement experience low temperature or fatigue cracking.

The results of the IDT test were analyzed by the tensile strain at failure criteria calculated with Equation 13 for a 12.5 mm loading strip. The results are presented in Figure 59 for samples compacted with 35 blows and in Figure 60 samples compacted with 50 blows. The hatched bar represent results for the fine gradation while the solid bars are for the coarse gradation. The results presented show minor changes in failure tensile strain values with change in asphalt content, except for the CSS-1H (A), fine gradation, compacted at 50 blows, which shows significant increase in failure strain values with increase in asphalt content. The effects of emulsion type appears also to be noticeable especially at low and high asphalt content, indicating that this testing criteria could be used to identify asphalt emulsion both rutting and durability potential. Minor effects of gradation and compaction efforts are also present, especially with for

CSS-1H (A) emulsion at high asphalt content. The coarse gradation appear to show high failure strain values for samples compacted with 35 blows, while the opposite is observed for samples compacted with 50 blows.

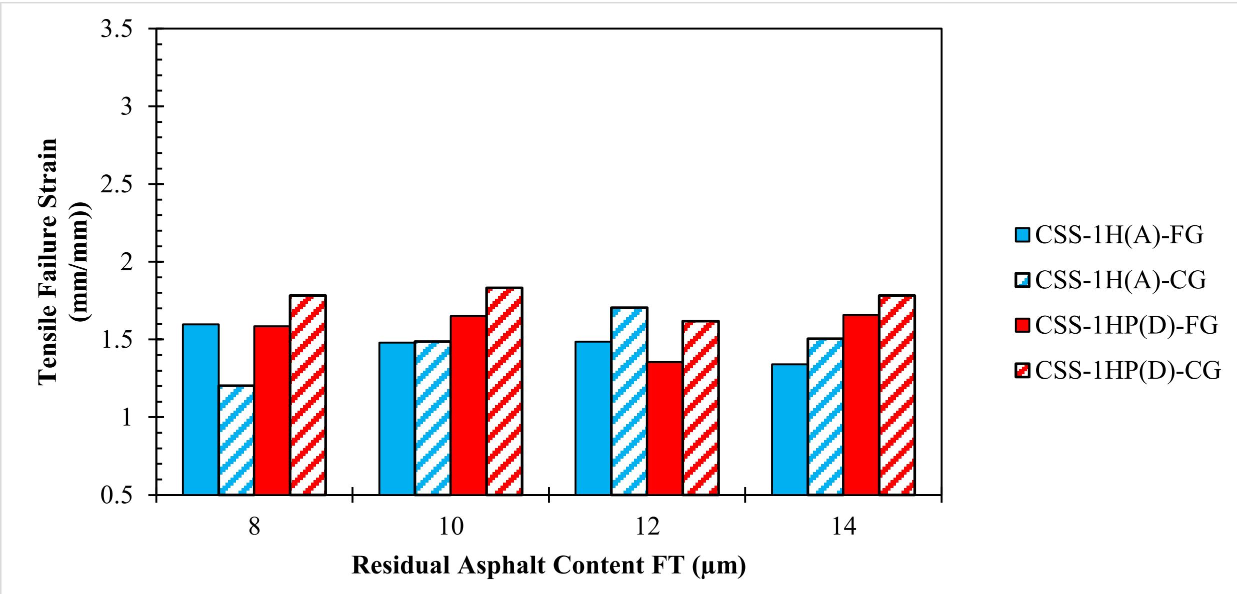


Figure 59. Strain at Maximum Load for Mixture Compacted with 35 Blows (Low Traffic)

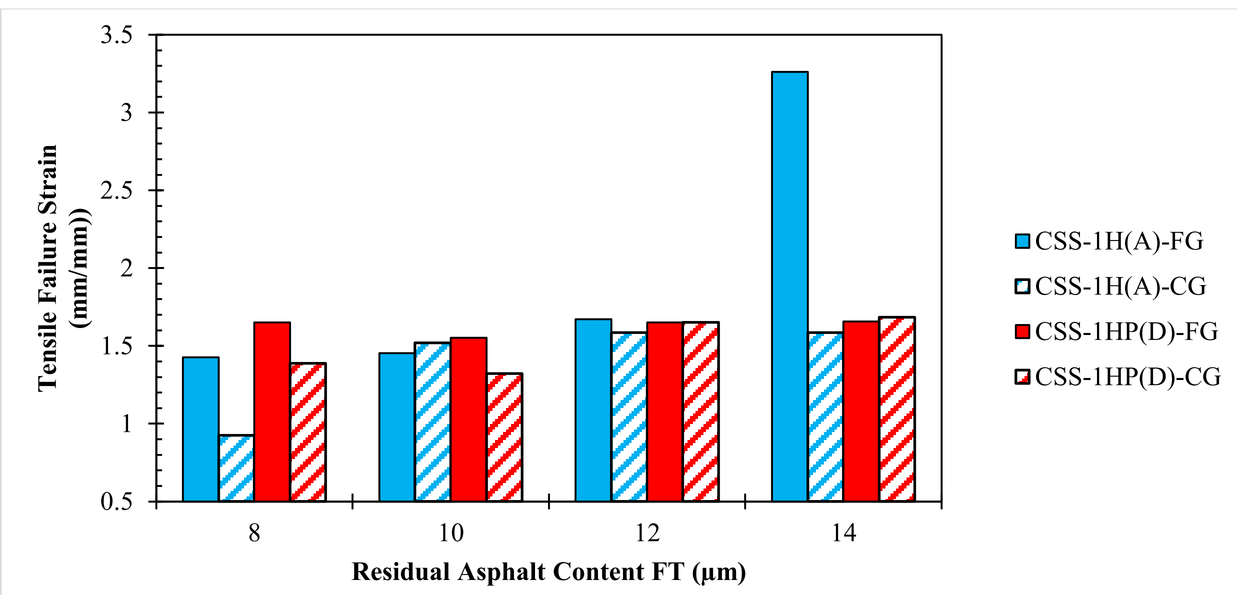


Figure 60. Strain at Maximum Load for Mixture Compacted with 50 Blows (High Traffic)

4.3.4.3 IDT Strength Quotient

Another evaluation criteria considered for the results obtained from the IDT strength test results was the IDT strength Quotient (IDTQ). This was calculated as the ration of the IDT strength to the failure strain. It is similar to the Marshall Quotient (Asphalt Institute 1984) that is used as a general indication of the mixture stiffness of hot asphalt mixes. A higher ratio indicate a stiffer mixture, and maybe suitable for higher traffic volume roads. Figure 61 present IDTQ results for sample compacted with 35 blows, while the results for 50 blows are presented in Figure 62. The raw data are given in Appendix D. The hatched bar represent results for the fine gradation while the solid bars are for the coarse gradation. The results show the IDTQ to be sensitive to asphalt content in the mixture as different values are observed at different asphalt contents. The results also show sensitivity to emulsion type, aggregate gradation and compaction effort.

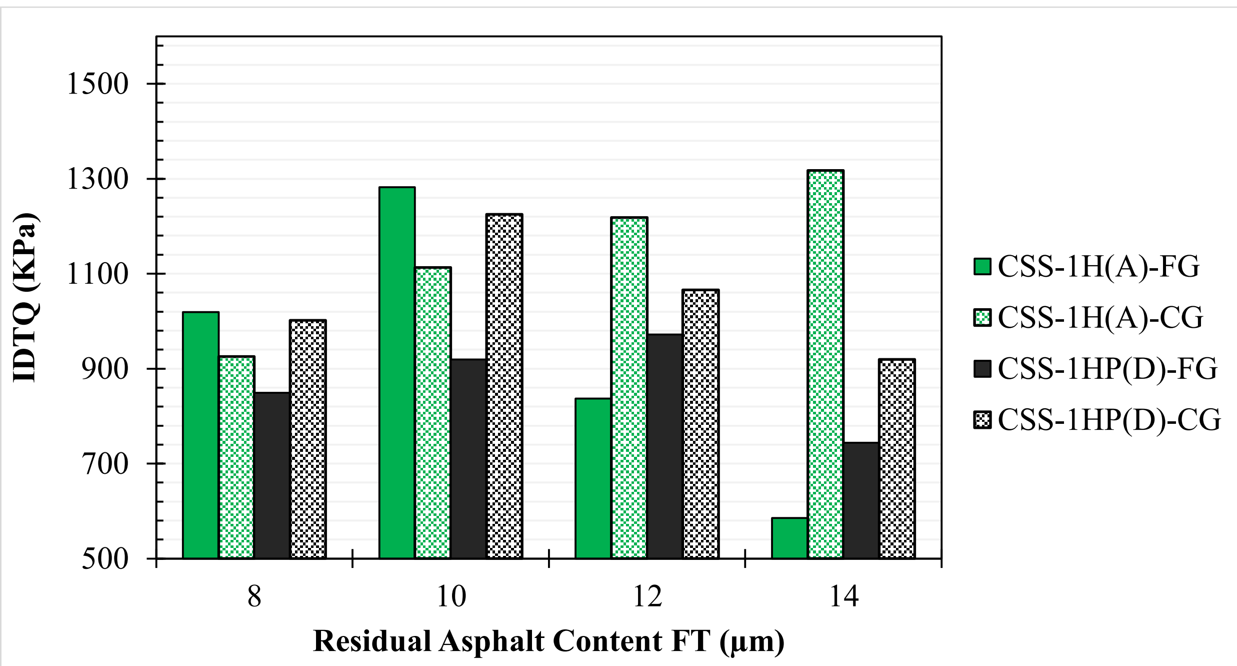


Figure 61. IDTQ of samples compacted with 50 blows

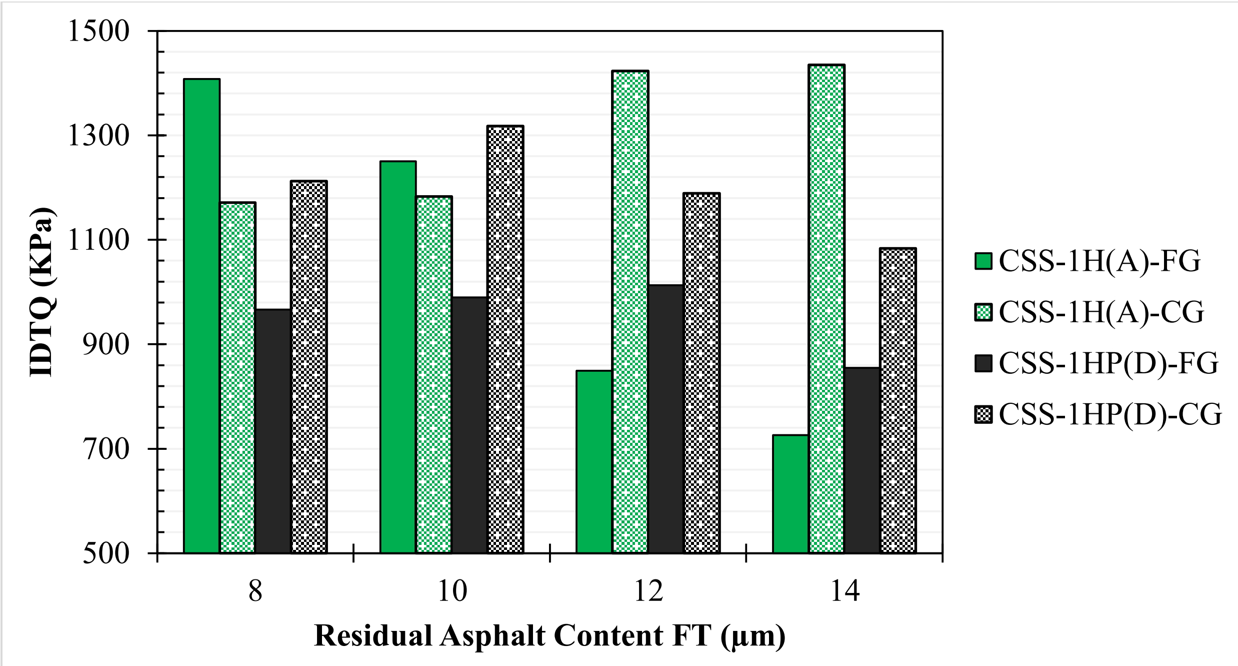


Figure 62. IDT Quotient for Samples compacted with 50 blows

Overall, the CSS-1H (A) emulsion has high values of IDTQ than the CSS-1HP (D) emulsion when the asphalt content is 8 to 10 micron film thickness, but the opposite is observed at 12 and 14 microns film thickness for both compaction efforts. The effects of gradation are both emulsion and asphalt content dependent. The fine gradation give high values of IDTQ than the coarse gradation at 8 to 10 micron film thickness when used with the CSS-1H (A) Emulsion, but a reverse trend is observed at asphalt content of 12 microns and high film thickness. For the CSS-1HP (D) emulsion, the coarse gradation has higher IDTQ values than the fine gradation for a given asphalt content or compaction effort used. Samples compacted with 50 blows appear to have higher IDTQ values than those for 35 blows compaction efforts. These observation shows that the IDTQ is a promising parameter that could be used to characterize the performance of different slurry surfacing mixtures, and could be useful designing high performing slurry surfacing systems.

4.3.4.4 Summary of Findings

This objective of this task was to identify, evaluate and recommended an alternative test method for evaluating bleeding. This method will be used as an alternative to the current sand adhesion test (ISSA TB 109). The two tests evaluated were the MPD measure with the SLP on LWT samples. The results showed that the MPD is sensitive to emulsion content, gradation and emulsions type, but the results of showed high variability, and did not give a meaningful trend when the effect of traffic was evaluated. The statistical analysis (ANOVA) of the results shows that this approach did not give repeatable results, and low values of adjusted-R-squared (as low as 8%) were obtained from the model fitted to the data. This inconsistency in the results was attributed to the edge effects arising from the small sample thickness used for LWT test samples, in combination with the way in the MPD is calculated. It conclude that this approach, although, promising, is not appropriate for evaluating bleeding or establishing maximum allowable asphalt content in slurry surfacing mixtures. The second method considered was the use of the volumetric parameter %VFA measured on Marshall compacted samples. A method for preparing Marshall compacted samples was developed and used to produce samples. The %VFA was determined on the results, it showed sensitivity to asphalt content, gradation, compaction effort and emulsion type. The ANOVA result collaborated this observation and it also show that the procedure yielded samples with better repeatability compared to that of the MPD. The compacted Marshall samples from which the % VFA was measured were further tested for IDT strength and the results used to calculate three mixture parameters: IDT strength, failure strain, and IDTQ, the ration of the IDT to the failure strain. The results showed the IDT strength and IDTQ parameters more sensitive to asphalt content, emulsion type, gradation and number of compaction effort. The failure strain showed the least sensitivity to factors evaluated. The results presented show that the current ISSA TB 147 for evaluating resistance to rutting could be supplemented with testing methodology that measure failure engineering parameters like the IDT strength and IDTQ presented in this study. This may better enhance the performance of slurry surfacing mixes.

5. Proposed Modifications to Current ISSA TB A105 and A147 Mixture Design Framework for Slurry Seal Systems

The objective of a mix design procedure is to determine the optimum amount of water, filler, and emulsions content that will mix and coat the project aggregate to give final product with desired performance characteristics for a given traffic and climate. In identifying areas of opportunity where current ISSA design guidelines could be improved, certain important factors considered. It is generally desired that a mixture design procedure use a performance based approach, whereby performance based tests for the mixture components and for the mixture its self are specified, rather than specifying the materials to be used and proportions of these in the mix. In addition testing should be carried out under climatic and traffic conditions similar to those expected in the field. Following are desired characteristics of the test methods used the evaluate mixture characteristics:

- Relate to field performance
- Repeatable
- Easy to use at of temperature/humidity conditions that may occur during placement and long term performance in the field
- Require less time and less equipment
- Affordable

It is important to note that all slurry surfacing are applied with the objectives of improving safety (increase surface texture), reduced permeability to moisture and air into the underlying layers, fill ruts and improve ridability by eliminating minor surface irregularities.

5.1 Proposed Unified Modified Mixture Design Procedure

The first modification proposed is that there should be one unified mixture design for both slurry seals and micro-surfacing with different performance specification limits for different traffic levels and climatic condition instead. This will help eliminate many terminology problems and confusion associated these treatments currently experienced in the in practice. This view is shared by other researchers (Fugro 2004) and the California Department of Transportation is in the process of developing a unified mixture design for slurry seals and micro-surfacing. It will allow state agencies to only specified desired performance criteria, instead of specifying materials and test to be run. The rest of the medications proposed are focused on the procedure for performing job mix formula are described in detailed in the following sections. No modification to the procedure for selecting individual material components was evaluated in this study, and hence will it no be discussed further.

5.2 Modified Mixture Design Framework (Job Mix Formula)

5.2.1 Selection of Initial Residual Asphalt content

Current practice recommends using the Surface Area method (ISSA TB 118) to select trial asphalt contents. There is sufficient evidence in the literature, caution notes given in the ISSATB 118, and the results for bleeding evaluated in this study that show that the Surface Area Method yield excessive asphalt contents that could lead to premature failure by bleeding, rutting or shoving in slurry surface treatments. Both ISSAT TB A105 and A147 contain ranges of residual asphalt contents for different gradation for which good performance has been observed in the field. This range is general between 5.5 and 11% residual asphalt content. It proposed that these ranges should be used as a starting point for selecting trial residual asphalt contents for performing a mixture design for selecting field application rates.

5.2.2 Establishing Minimum Asphalt Content

In current practice, the minimum residual asphalt content is determining based on raveling results of fully cured dry-conditioned samples. This is especial common practice for all treatments meeting the requirements of the slurry surfacing. However, the results presented in the this study showed that most mixtures show less aggregate loss when evaluated in the dry condition, but aggregate loss could increase by tens of magnitude when exposed to moisture. Also, mixtures meeting the criteria of slurry surfacing for which moisture damage evaluation is currently not required showed the highest increase in aggregate loss after conditioned in water than samples prepared with emulsions meeting the criteria for micro-surfacing. This observation show fundamental short fall in current approach for selecting the minimum asphalt content. As a result, it is proposed that the minimum residual asphalt content be determined based on the results of the moisture conditioned samples for all slurry surfacing. This will ensure that premature failure arising from the effects of moisture is addressed in the mixture design. An alternative procedure that allows for the effects of moisture to be determined in a much shorter time of two days than the current procedure for six days used was established in this study. The allowable total aggregate loss based on current ISSA/STM specification is about 5% after moisture conditioning. This same performance criterion can still be used to select the minimum allowed asphalt content.

5.2.3 Establishing of Maximum Allowed Residual Asphalt Content

The maximum allowed residual asphalt content is currently determined from the results of the sand adhesion test in accordance with ISSA TB 109. Serious problems of repeatability, operator dependency, and insensitivity to factors know to affect bleeding in the results of tested has been raised through the literature since the early 1980s (Bennedict 1985, Bennedict 1989, Andrew, et al. 1994, Robati 2012). A procedure for evaluating bleeding using the volumetric parameter % VFA measured on Marshall compacted samples were developed in this study. Promising results were observed in the results presented. Specifically, samples prepared at asphalt content higher than the 11 % residual asphalt content, the maximum currently recommended by ISSAT TB A105 and A147 showed %VFA value above 80%. While more research is needed to verify the results presented in this study, it appear promising to use % VFA as better criteria for establishing the maximum allowed asphalt content. The maximum limit of 80% person is recommended as an initial value, as this value has also been proposed by others to prevent potential for bleeding, rutting and shoving (Robberts, et al. 1996, Labuschagne, Louw and Gerrie 2012).

5.2.4 Criteria for Evaluating Rutting

Resistance for rutting is evaluated based on the results of the LWT in accordance with ISSA TB 147. A 2004 survey by Fugro (Fugro 2004) showed that most contractors, asphalt emulsion manufactures and state highway agencies are content with test in evaluating rutting. However some problems associated with the LWT test to evaluated rutting have also been raised by other others (Bennedict 1989a, Raza 1994b), including also those presented in this study. This study proposes adding a mechanistic failure criteria measured on engineering properties of the mixture to supplement or replace the current criteria for evaluating rutting. Of the parameters evaluated in this study, the Indirect Direct Tensile Quotient developed in this study was found to be more sensitive to factors know to affect potential for rutting than other parameters considered. It is the ratio of the maximum tensile strength of the mixture at failure divided by the failure strain at failure tested on Marshall compacted samples in accordance with ASTM D6931. A procedure for preparing Marshall compacted samples for slurry surfacing system was developed in this study and the results for density measure are well within field's densities values reported in the literature. It is not possible to recommend initial values for at the moment as more emulsions specifically modified emulsions needs to be tested need to be tested for any limits to be established.

5.2.5 Criteria for Evaluating Asphalt Filler Compatibility

Asphalt-emulsion filler compatibility is currently evaluated using the Ruck & Puck Test contained in ISSA TB 115. While test maybe useful for asphalt emulsion manufacturer in formulating their products, it does not appear to have relation to field performance from the mixture performance point of view. This study recommend using a raveling based test on moisture conditioning samples to evaluate material compatibility, because the primary distress observed in the field as a results of material incompatibility is raveling. The results presented in this study has shown the WTAT performed on sample conditioned in water at 60ºC for 2 days could identify emulsion-filler combination with high potential for raveling. Evaluating compatibility with the WTAT will reduce the number of testing equipment required to perform a slurry surfacing mixture design; better control of many variables currently associated with using many test equipment requiring different sample geometries. The time required to batch samples of different geometry required to get repeatable results will be significantly reduced.

5.2.6 Criteria for Establishing Trafficking Time

A criteria for establishing time required to open a newly surfaced pavement to traffic based on evaluation of early raveling is also proposed to be added to current ISSA/ASTM guidelines. The main distress observed in field when a slurry surface is trafficked prematurely is early raveling. The result presented in this study showed that the WTAT can differentiate between samples cured at different times, temperature or have different amounts of cements, making it the best candidate for determining traffic time. Pioneering countries of micro-surfacing like France use the WTAT equipped with rubber wheels to establish trafficking time (Deneuvillers and Samonos 2000), and this equipped is the process of being adapted by many in the United States. However, the results of this study showed that while the WTAT equipped with rubber wheels (CAT) as referred to in this maybe suitable for evaluating early raveling, it does not give repeatable results when used on fully cured samples. The wheel experience significant wear, and require to be changed for almost every four samples to get repeatable results as described in detail in this report.

This study recommended using the WTAT to evaluate not only early raveling, dry and wet raveling as well. The test is not only cost effective, in addition to being sensitive to factors know to affect raveling, but will again reduce the number of equipment required to perform a mixture design. Initial limits of 10% maximum aggregate loss in the WTAT are recommended. That is, the time for opening to traffic should be the taken to correspond the curing time at which less than 10% aggregate loss is obtained.

5.3 Modified Mixture Design Criteria

The mixture design criteria for selecting the optimum mixture component using the modifications proposed in this study is presented in Table 31. Please note that these are initial specification limits proposed based on the limited results of this study as discussed elsewhere.

Table 31. Proposed Modified Mixture Design Criteria

Mixture Parameter Measured	Test Method	Parameter Measured	Specification Limit	
			Low Traffic	High Traffic
Performance Parameters for Constructability				
Mixing Time	Hand Mixing Test ISSA TB	Time mixture remains workable by hand (min)	3	
Consistency	Consistency Test ISSA TB	Horizontal slump (cm)	2-3	
Coating	Boiling Test ISSA TB	% Coating (min)	90%	
Performance Parameters for Early Performance				
Early Raveling	Modified WTAT (ISSA TB 100)	%Aggregate Loss, max (1 min)	10	
Performance Parameters for Common Distressed at Intermediate Temperature				
Dry Raveling	WAT (ISSA TB100)	%Aggregate Loss, max (5 min)	3%	
Moisture Damage (Raveling)		%Aggregate Loss, max (5 min)	5%	
Performance Parameters for Common Distressed at High Intermediate Temperature				
Bleeding	Marshall Compacted Samples	% VFA, max	80%	
Permanent Deformation	IDT ASTM D6931	IDTQ, max.	TBD	TBD
	LWT (ISSA TB 147)	Lateral Displacement & Gsb. (max)	N/A	5% & 2.1

5.4 Modified Mixture Design Framework

The mixture design framework with proposed modification incorporated is presented in Figure 63. The different steps required to be performed at each step are described in details in the next sections.

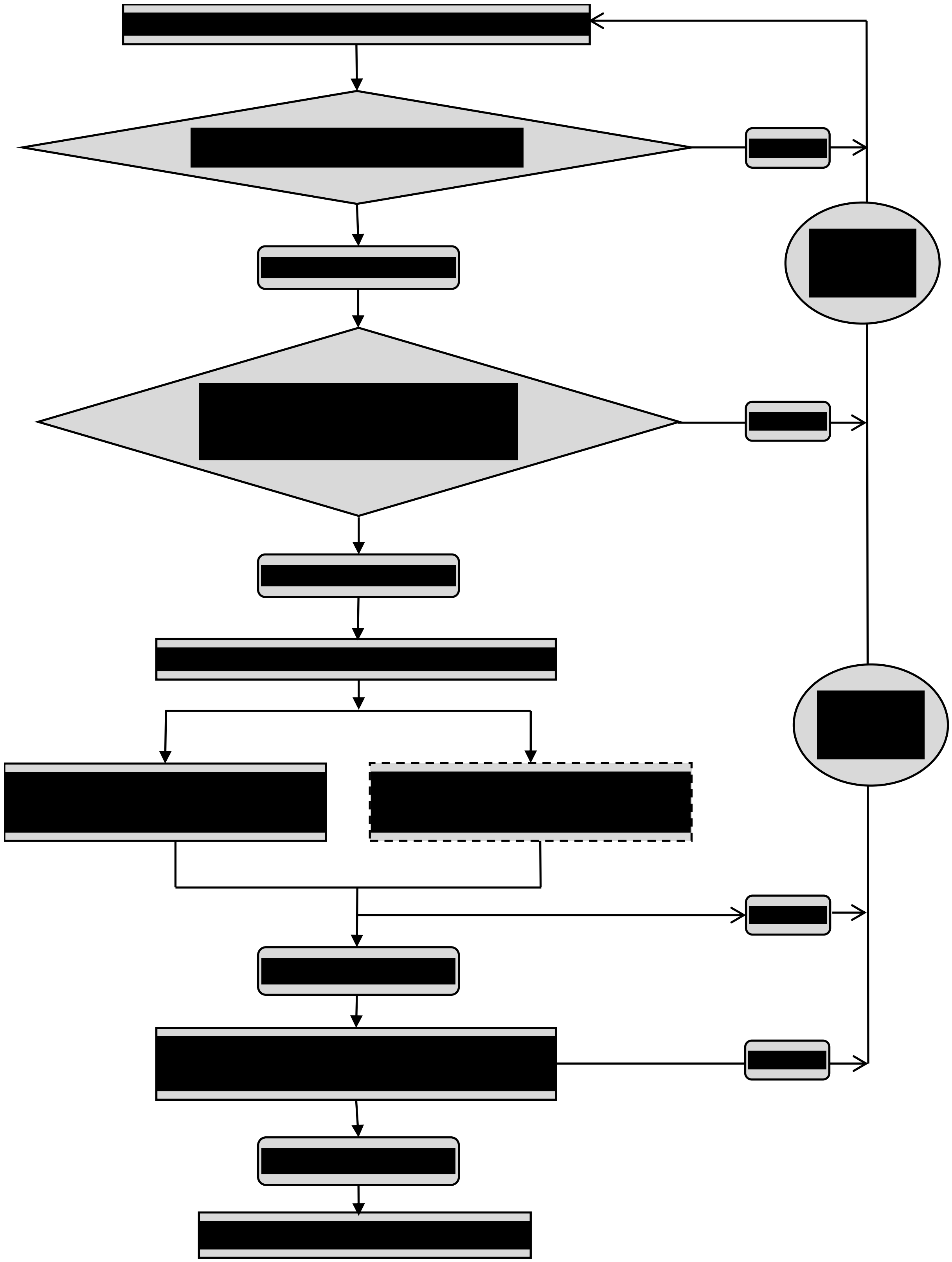


Figure 63. Proposed modified mixture design flow chart

5.4.1 Step 1: Material Selection

Materials will be selected following current ISSA guidelines as follows:

- Selection of aggregate: The acceptability of the aggregate for use in slurry systems will be evaluated using quality tests specified by ISSA TB A105 and A143.
- If the aggregate are accepted, only then that other required tests such as gradations, specific gravity and absorptions can be performed.
- Selection of aggregate gradation: Aggregate gradation will be selected based on the intended use of the surfacing, and shall be within one of the three gradation bands specified by the ISSA TB A105 or as specified by a local state highway agency.
- Selection of the asphalt emulsion: The base binder used in the emulsification process should be selected following the SuperPave PG system (consider climatic conditions under which the emulsions will be applied). The asphalt emulsion itself shall meet the specification of the ASTM D977 (anionic emulsion), ASTM D2397 (cationic emulsion), and supplementary specification for modified asphalt emulsions specified in ISSA TB A143.
- Selection of mixing water: mixing water shall be portable and free from ions and other dissolved matter that could results in problems with insufficient mixing time.
- Selection of mineral filler: Mineral filler such as Portland cement, hydrated lime or other mineral filler that meets specifications may be used.
- Selection of breaking and or curing agents: additive that controls the workability and or traffic time shall be used following the recommendations of the emulsion manufacture when necessary.

- Selection trial emulsion contents: Four trial asphalt emulsions content shall be selected either based on agency experience or following ISSA guidelines recommended residual asphalt content values. The ISSA guidelines recommend the following range of optimum residual asphalt content for its three gradations:
    - Type I: 10-16 % residual asphalt content by weight of the dry aggregate
    - Type II: 7.5-13.5% residual asphalt content by weight of the dry aggregate
    - Type III: 6.5-12% residual asphalt content by weight of the dry aggregate

5.4.2 Step 2: Preparation of the Mixture Samples to Establish Optimum Water Content for Workability

Optimum water for workability will be established per current ISSA guidelines using the Hand Mixing Test (ISSA TB113) and Consistency Test (ISSA TB116). Optimum water content is determined for every emulsion contents selected for evaluation.

5.4.3 Step 3: Preparation of the Mixture Samples to Determine Minimum Required Residual Emulsion Content

This step establishes the minimum required residual asphalt emulsion content to be used in the field. It involved evaluating resistance to raveling of moisture conditioned samples of the selected residuals emulsion content conditioned under the procedure developed in this study. The sample shall be prepared at the optimum mixing water content as determined in Step 2. The WTAT samples shall be prepared using representative gradations including materials retained on sieve No. 4.75. Larger aggregate sizes have significant effect on the amount air voids available on the mixture sample. It is possible that by removing larger particles the results of for moisture damage could be affected. Sample be prepared at a thickness representative of field conditions. If this no known a thickness of 9.5 mm is recommended (Gransberg 2010). This shall be used in combination with a WTAT abrasion horse with a smaller diameter should be used when using gradation with particles retained on sieve No.4.75mm or larger.

The samples shall be fully cured in the oven at 60ºC for 24 hours before conditioned in the water bath at 60ºC for 48 hours. Samples shall be tested under water at 25ºC in the WTAT following current ISSA TB 100. The recommended optimum binder content will be selected by evaluating aggregate loss in the WTAT and using 5% maximum aggregate loss to select the minimum allowable residual asphalt content.

5.4.4 Step 4: Establish the Optimum Residual Emulsion Content

Step 4 established the optimum residual asphalt content (ORAC). It will involve preparing compacted Marshall Samples and rice samples following the sample preparation procedure developed in this study at three residual asphalt contents: MRRAC, MRRAC +1% and MRRAC + 2%. The Marshall compacted samples shall be tested for density for determining mixture volumetric, and for Marshall Stability. The parameter %VFA will be used establish maximum allowed residual asphalt content to prevent bleeding. For mixture not intended for rut filling of application in multi-layers, the optimum residual content will be taken as the mid-point between the minimum allowed and maximum allowed.

For mixture required for rut filling applications, the sample at residual asphalt contents between the minimum and maximum allowed shall be tested for the IDTQ and LWT to select optimum residual asphalt content. The asphalt content with the highest IDTQ and lowest vertical deformation is taken as the optimum asphalt content.

5.4.5 Step 5: Establishment Time to opening to Traffic to Prevent Early Raveling

This step established the time required to open the newly placed slurry surfacing system to traffic. It will involve preparing Wet Track Abrasion Samples at the optimum asphalt emulsion content as determined from prior steps. The sample will be cured at the expected climatic field condition at test in the WTAT for one minute without soaking to establish curing time required to give the minimum aggregate loss.

6. Verification of Modified ISSA Procedure through Comparison with Field Mixture Design

The modified mixture design framework developed in this study was used to determine design parameters of three field projects of micro-surfacing. The field projects were constructed with design parameters established based on select laboratory testing and the experience of the emulsions suppliers with micro-surfacing. The objective was determine if the procedure developed in the study yield design quantity similar to those established based on the emulsion supplier's years of experience and subsequently used by the contractors in the field.

Field aggregates and emulsions and the corresponding contractors' mixture design were acquired. The projects were constructed in Waco, TX, Visksburg, MS, and York, PA. Information on material properties, aggregate gradation, materials suppliers, and sample preparation methods are presented in Section 3.4.1. The results are presented in the next sections.

6.1 Optimum Water Content for Workability

Current recommended range of residual asphalt content in ISSA TB A147 guideline for micro-surfacing were used in selecting initial trial residual asphalt contents. Four trials residual asphalt emulsions content of 5, 7, 9 and 11 percent of dry aggregate were selected weight for each project. Optimum water content was determined for all four emulsion contents in accordance to ISSA TB 113 for 200 gram samples. A total of three replicates were prepared per emulsion content. The of optimum water content selected are presented in Figure 64.

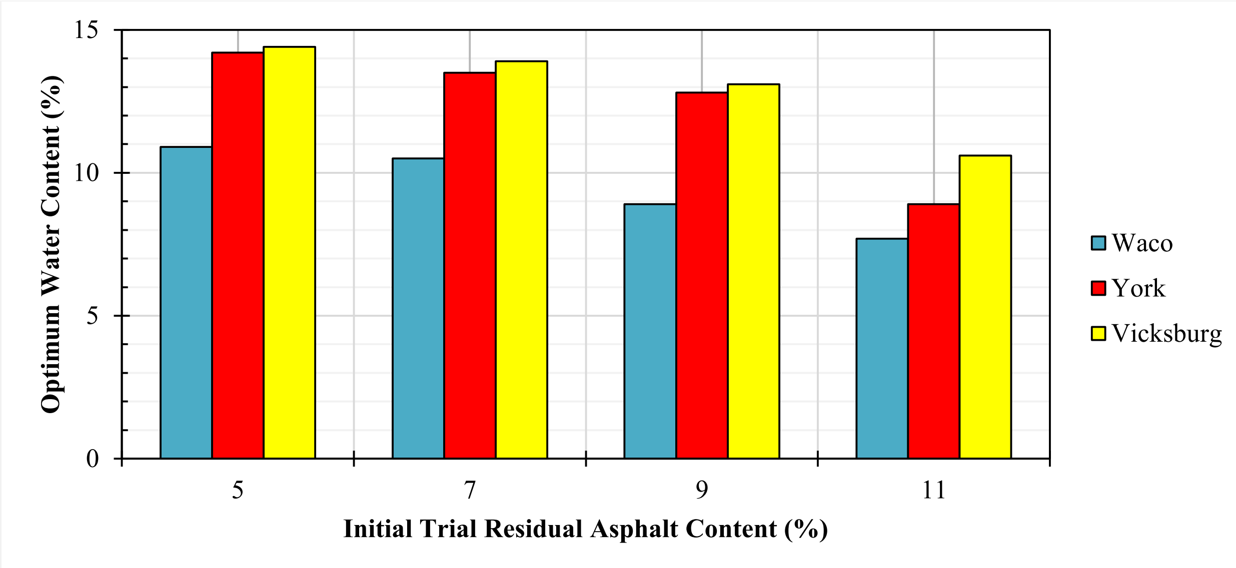


Figure 64. Optimum water content for workability

6.2 Minimum Required Asphalt Content

The minimum required asphalt content was determined from the results of raveling for moisture conditioned samples of WTAT. Samples prepared according to ISSA TB 100, with the exception that representation gradations were, and conditioned in water for 2 days at 60ºC. A sample thickness of 6.5mm was utilized for the Vicksburg and York projects which were Type II, while a thickness of 9.5mm was used to prepared samples for the Waco project which was a Type III. The diameter of the rubber hose used for the Waco projects was 12.5 mm. Three replicates were prepared for each emulsion content. The results are presented in Figure 65 for all three projects. The minimum required residual asphalt content for the three projects was determined as follow: Vicksburg, 7.4%, York, 7.0% and Waco, 6.7%. This was determined using the 5% maximum aggregate loss criteria which what ISSA TB 147 currently recommends for moisture damage.

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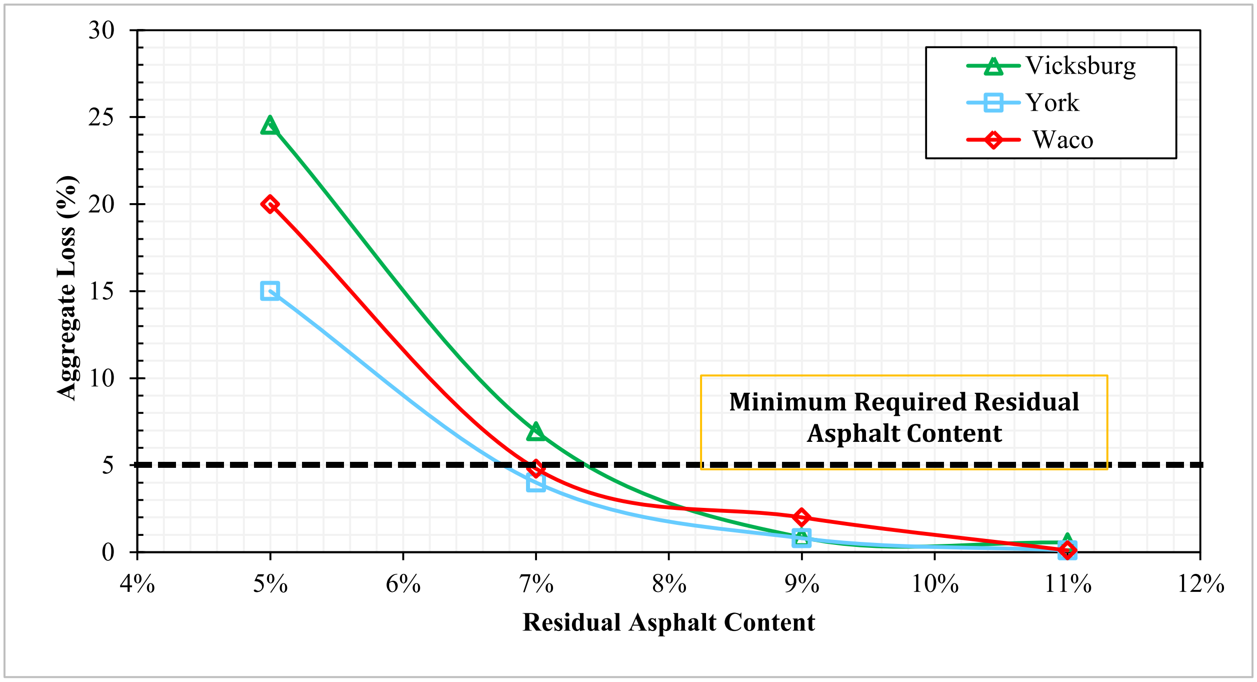

Figure 65.WTAT results for the 48 hours water conditioning at 60ºC

6.3 Establishment of the Optimum Emulsion Content

Marshall Samples were prepared at minimum required residual asphalt content (MRRAC), MRRAC +1% and MRRAC +2% following the procedure developed in this study. The optimum water content for workability was established for each asphalt content in accordance with ISSA TB 113. All samples were compacted with 50 blows on each side following the criteria for high traffic volume. After cooling to room temperature at for 24 hours, the bulk specific gravity of the and the maximum theoretical specific gravity of the samples were measured, and used the calculated mixture volumetrics. The Marshall compacted samples were further tested for their IDT strength and failure strain in accordance to ASTM D6931. The results of the IDT strength and failure stain at maximum load were used to calculate the IDT Quotient.

The results for % VFA are presented in Figure 66. As can be observed none of the emulsion contents used resulted in a % VFA above 80. The results for the IDTQ are presented in Figure 67. The optimum residual emulsion content was taken as the asphalt content at which the IDTQ is highest. The optimum residual emulsion contents were established as follows: Waco, TX, 7.0%; York, PA, 7.7 % and Vicksburg, MS, 8.4 %.

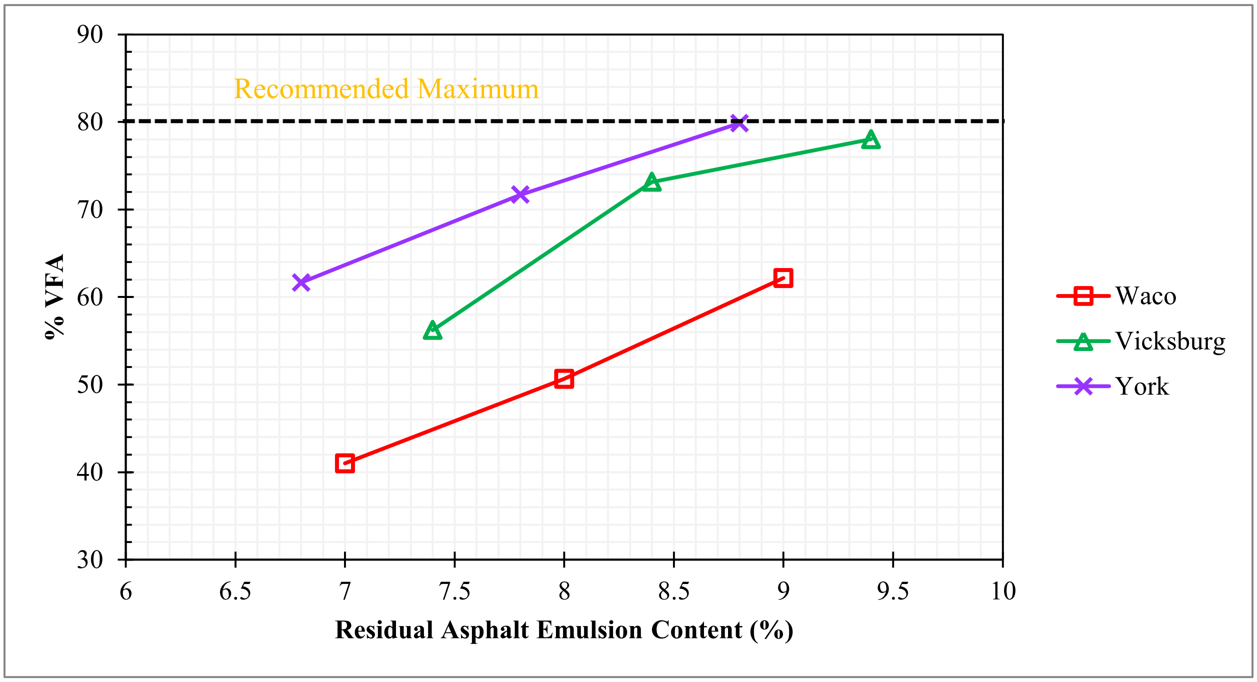

Figure 66. Results for % VFA

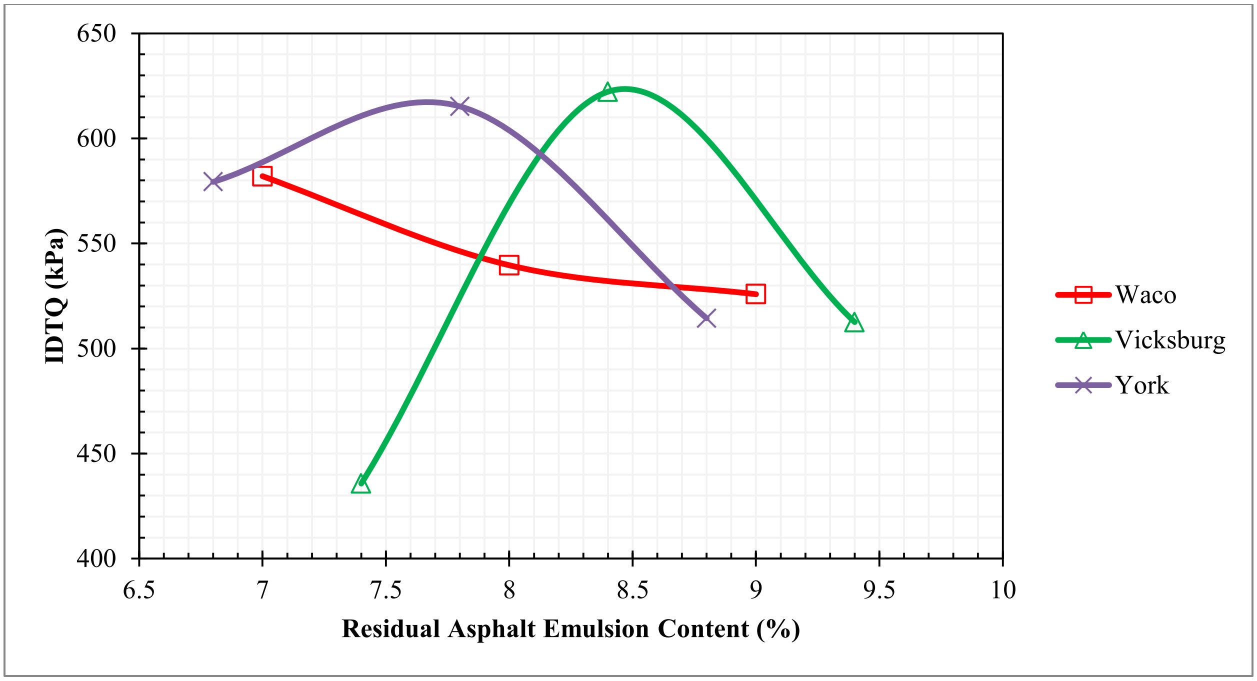

Figure 67. Results for IDTQ @ 25ºC

6.4 Establishment of Traffic Time

The time to opening to traffic was determined from WTAT samples prepared at the optimum asphalt contents and optimum water content for workability. The samples were cured at 25ºC and test in the WTAT for 1 minute at 1, 5, 12 and 24 hours curing time. Three replicates were evaluated for each curing time. The results are presented in Figure 68. Time to open to traffic was taken as the curing time required reaching a maximum aggregate loss of 10%. The opening time of 7, 10 and 11 hours were established for Vickburg, Waco and York projects respectively.

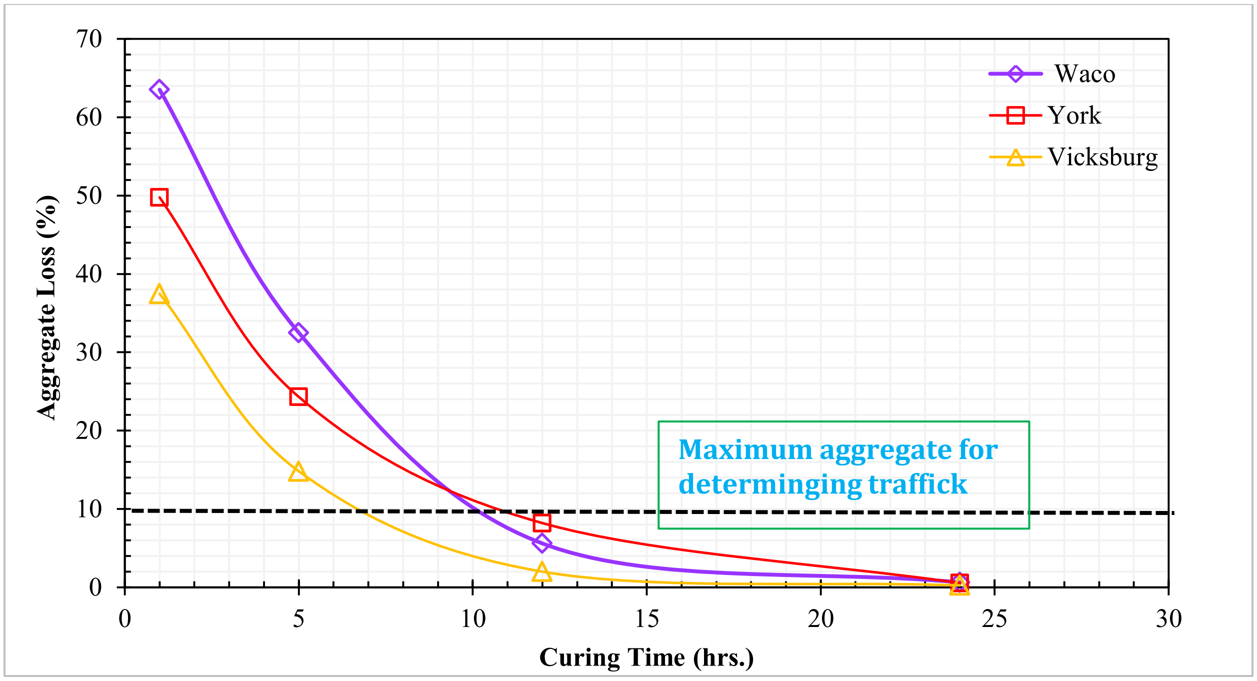

Figure 68. WTAT resistance to early raveling

6.5 Comparison of Design Parameters

The results for the design parameters from the procedure and those used by the contractor in the in the field are presented in Table 32. The results of the optimum asphalt content as established by the two procedures are graphically presented in Figure 69. A tolerance limit of 0.3% residual asphalt content was recommended for field construction. This value was used as a standard deviation and is indicated by the error bars.

Table 32. Results of 25 mm Marshall Samples Compacted at 100°C(50 blows/side)

Field Project	Mixture Method	Cem. Content (%)	% WC	%RAC	Traffic Time (hours)
Waco	Modified ISSA	1	14.3	7.0 ± 0.3	10
	Contractors	1	5 to15	7.6 ± 0.3	N/A
York	Modified ISSA	1	12.1	7.8 ± 0.3	11
	Contractors	1	4 to 14	7.4 ± 0.3	N/A
Vicksburg	Modified ISSA	1	13.2	8.4 ± 0.3	7
	Contractors	1	2 to 12	7.92 ± 0.3	N/A

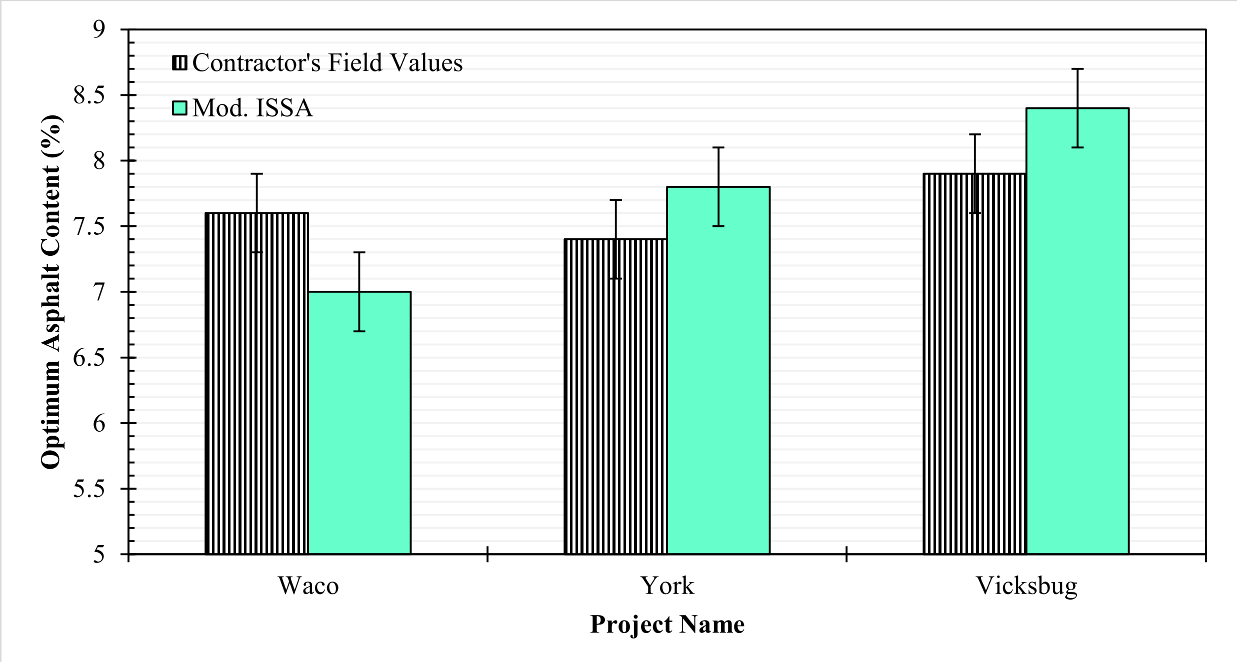

Figure 69. Comparison of the Optimum Asphalt Content from the Modified ISSA Procedure to Contractors' Values Used on Field Projects

The results shown are encouraging as the residual asphalt content obtained from the modified ISSA is 100% within the 0.3% residual asphalt content margin specified by the contractor. This finding is very promising because there is currently no known mixture design procedure (including ISSA guidelines) that yield results similar to those known to work well by the contractor as of the writing of this manuscript (March 2014). Evidence in the literature (Andrew, et al. 1994, Benedict 1991, Baumgardner 1991, TTI-1289-1 1995, Deneuvillers and Samonos 2000, Fugro 2004, Belkahia 2012, Robati 2012) show that current ISSA/ASTM guidelines do not yield design values similar to those commonly used or recommended by the contractor/emulsion supplier for field construction. Hence, the modified procedure developed in the study is significant improvement to current practice.

The amount of water content for workability are also well with the contractors' recommended range. No information was provided regarding the time when the different projects where opened to traffic, and hence it was not possible to evaluate the accuracy of the results of the WTAT when used to evaluate early raveling.

7. Summary of Findings and Conclusions

7.1 Conclusions

Beside the wide spread use of slurry seals and micro-surfacing, there still no standardized mixture design. Problems associated with current mixture design in accordance to the International Slurry Surfacing Association's guidelines (TB A105 & TB A147) and American Society for Testing and Materials guidelines, (D3610 &D6272) are well documented in the literature. The main objective of this study was to develop an improved rational mixture design procedure for slurry surfacing systems (Slurry seals and micro-surfacing). This was achieved by conducting a detailed literature review to identify common distresses occurring in the field, mixture parameters related to these distresses, and laboratory test methods for measuring the identified performance related mixture parameters. Candidate laboratory test methods for evaluating critical mixture parameters related to field failure were identified and evaluated. Repeatability, sensitivity to factor known to affect performance, ease of use, operator dependency, availability, and cost were used as a criterion in the selection of candidate test methods. Special consideration was made to minimize the number of devices and methods required to perform the mixture design. Efforts were placed on test methods that can evaluate similar distresses observed at different times in the life of a slurry surfacing systems. A comprehensive mixture design framework was developed using candidate test method and the philosophy of selecting the minimum asphalt content based on moisture damage evaluation.

Based on the results and analysis of this dissertation the findings can be summarized as follows:

- Workability of slurry surfacing mixtures evaluated with an automated mixing device, he Slurry Surfacing Workability Test (SSWT) used in this study is mainly influenced by the chemistry of the asphalt emulsions, mixing water content, and aggregate gradation. Mixtures prepared with different emulsions chemistries exhibited unique mixing torque versus time curves at the same mixing water content, besides being classified in the same category by the Hand Mixing Test (ISSA TB 113) and Segregation Test (ISSA TB 111). In addition, the results as from the SSWT showed no defined trend with time or water content, making it difficult to establish a criterion for assessing workability. As a result, the SSWT was deemed an insufficient test for selecting optimum water content for slurry surfacing systems in its current form.

- The Wet Tract Abrasion Test (WTAT) specified in ISSA TB 100, was found to give better results in terms of repeatability, sensitivity to factors affecting raveling and affordability than the Cohesion Abrasion Test (CAT) for evaluating long-term raveling slurry surfacing systems. The CAT experienced considerable wear during testing which caused high variation in the results. Testing each sample with a new set of rubber wheels in the CAT is not economically viable.
- Early raveling could be evaluated with the WTAT run for one minute without soaking. The results showed that curing time, emulsion type, cement content, and curing temperature, influences early raveling. Hence, the WTAT has potential in assessing damage of new slurry surfacing systems arising from premature trafficking of the treatment before the mixture has developed sufficient cohesion strength to withstand traffic stresses. Using the WTAT to evaluate early raveling can eliminate the need forth the Cohesion test (ISSA TB 139), which will not only reduce the number of test device needed, but can also results in a $2,500 saving in cost equipment.

- Establishing the minimum allowed asphalt content based on the results of dry samples alone can seriously undermine the durability of the slurry surfacing systems when exposed to moisture. The results in this dissertation showed that samples meeting criteria of a slurry seals and micro-surfacing experienced up 55% increased raveling after water conditioning.
- A new 2-day moisture damage conditioning procedure developed in this study rank different mixtures similar to those conditioned in water for 6 days at room temperature. This procedure effectively reduces the testing time for evaluating moisture damage evaluation from 9 to 4 days. The new procedure can also identify asphalt-filler incompatibility, and could potentially be used to eliminate the need for the $13,000 asphalt-filler compatibility test (ISSA TB 144) currently used. The current asphalt-filler compatibility test (ISSA TB 144) does not measure parameter related to distresses observed in the field when compatibility is an issue. Additionally, the test is operator depended, and has repeatability problems.
- The mean profile depth (MPD) measured by a stationary laser profilometer (SLP) on Loaded Wheel Test (LWT) was found ineffective in characterizing bleeding, and hence, in establishing the maximum allowed residual asphalt content in a mixture. The testing results were neither repeatable nor sensitive to factors investigated known to affect bleeding. Main issues with this procedure are related to the end effects of LWT samples, and inherent variable procedure for calculating the MPD.
- Bleeding can be evaluated by using a volumetric parameter %Void Filled with Asphalt (VFA) on Marshall compacted samples following the procedure developed in this study, and hence it can also be used to establish maximum allowed residual asphalt content. This

procedure showed sensitivity to asphalt content, emulsion type, aggregate gradation and compaction effort, and as such could be used to identify mixture with potential for bleeding.

- The criteria for evaluating stability of slurry surfacing mixtures by the IDT strength ratio, showed sensitivity to emulsion type, aggregate gradation, compaction effort and asphalt content. This approach can be used to supplement the current criteria for evaluating potential for rutting on slurry surfacing mixture intended for filling ruts, or to be applied in the multi-layers.
- The modified mixture design procedure developed in this study is simple, and provides similar design asphalt contents and water contents similar to those used by contractors in the field, established based on many years of experience. Based on the extensive experimental evidence presented in dissertation, the proposed mixture design procedure is a significant improvement to the current empirical methods available.

7.2 Recommendations for Future Work

1. The modified mixture design procedure and mixture design verification method developed in this dissertation should be adopted as a basis for establishing a standardized mixture design framework for slurry surfacing systems. However, additional testing with different materials used in slurry surfacing systems is required to ensure that the modified procedure works for a wide variety of conditions and materials available in the pavement industry.
2. Extensive field evaluation is needed to compare the mix design to laboratory data to help determine the relative value of the proposed performance-based to modify or adjust them when required. Field evaluation can assist also in establishing rational performance limits.

- There is a need to standardize the testing equipment including assessment of ruggedness and precision. This will facilitate certification of mix design laboratories.

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Appendix A: Raw Data for Early Raveling

SS-1H							CSS-1HP					
Emulsion	**Curing Time**	**Cure. Temp**	**Filler (%)**	**Average**	**St.Dev**		**Emulsion**	**Curing Time**	**Cure. Temp**	**Filler (%)**	**Average**	**St.Dev**
SS-1H	1	25	0	100%	0%		CSS-1HP	1	25	0	91%	5%
SS-1H	6	25	0	58%	5%		CSS-1HP	6	25	0	35%	9%
SS-1H	12	25	0	30%	11%		CSS-1HP	12	25	0	0%	0%
SS-1H	24	25	0	0	0							
SS-1H	1	25	3	100%	0%		CSS-1HP	1	25	3	23.31%	3.51%
SS-1H	6	25	3	31%	2%		CSS-1HP	6	25	3	7.56%	4.95%
SS-1H	12	25	3	0%	0%		CSS-1HP	12	25	3	0.00%	0.00%
SS-1H	1	45	0	71%	7%		CSS-1HP	1	45	0	41%	6%
SS-1H	6	45	0	0%	0%		CSS-1HP	6	45	0	0%	0%
SS-1H	1	45	3	30%	2%		CSS-1HP	1	45	3	12%	2%
SS-1H	6	45	3	0	0		CSS-1HP	6	45	3	0	0

Appendix B: Raw Date for Late Raveling

Aggregate	Condition	Emulsion Type	Average	Std. Dev
Granite	Dry	SS-1H	1.393	0.123
		CSS-1H	1.507	0.220
		CSS-1HP	0.369	0.027
	48hrs	SS-1H	61.500	4.124
		CSS-1H	15.080	1.114
		CSS-1HP	4.948	0.151
	6-days (RT)	SS-1H	57.868	8.733
		CSS-1H	22.619	4.100
		CSS-1HP	3.604	0.435
Slag	Dry	SS-1H	0.987	0.103
		CSS-1H	0.477	0.082
		CSS-1HP	0.431	0.037
	48hrs	SS-1H	29.529	2.707
		CSS-1H	1.623	0.172
		CSS-1HP	4.429	0.855
	6-days (RT)	SS-1H	18.615	2.323
		CSS-1H	7.943	1.273
		CSS-1HP	4.728	0.781

1. Appendix C: Raw Volumetric Data for The Modified Marshal Method

Emulsion Type	Resid.Asphalt FT(μm)	%VFA		%AV		Gradation
		35 blows	50 blows	35 blows	50 blows	
CSS-1H(F)	8	37.4	38.6	18.4	17.7	CG
	10	51.4	49.2	13.3	14.3	
	12	55.4	62.3	13.1	10.2	
	14	66.0	67.9	9.9	9.1	
CSS-1H(A)	8	49.4	52.2	14.9	13.5	
	10	56.5	61.0	13.1	11.1	
	12	67.2	70.9	9.7	8.3	
	14	78.5	83.8	6.2	4.5	
CSS-1HP(D)	8	41.9	46.4	16.8	14.3	
	10	53.1	56.7	13.2	11.6	
	12	64.9	64.7	9.6	9.7	
	14	73.4	73.6	7.4	7.3	
CSS-1H(F)	8	46.8	58.6	17.2	11.5	MG
	10	63.1	74.0	11.7	7.4	
	12	76.7	76.6	7.6	7.6	
	14	88.5	87.4	3.9	4.2	
CSS-1H(A)	8	57.2	66.2	13.9	9.9	FG
	10	79.4	86.3	6.2	3.9	
	12	89.8	91.2	3.2	2.8	
	14	97.1	98.3	1.0	0.6	
CSS-1HP(D)	8	58.0	67.1	14.1	10.0	
	10	74.1	80.6	8.5	6.0	
	12	90.9	95.9	3.0	1.3	
	14	96.2	99.4	1.3	0.2	

Appendix D: Raw Data for the Indirect Tensile Strength Test

Emulsion Type	Resid.Asphalt T(μm)	IDT Stiffness Ratio	
		35 Blows	50 Blows
CSS-1H(F)	8	474.3	597.3
	10	884.2	866.6
	12	849.1	936.9
	14	772.9	890.0
CSS-1H(A)	8	925.2	1171.1
	10	1112.5	1182.8
	12	1217.9	1422.9
	14	1317.5	1434.6
CSS-1HP(D)	8	1001.3	1212.1
	10	1225.0	1317.5
	12	1065.7	1188.7
	14	919.3	1083.3
CSS-1H(A)	8	1018.9	1407.7
	10	1282.4	1250.2
	12	837.3	849.1
	14	585.6	726.1
CSS-1HP(D)	8	966.2	1171.1
	10	1042.3	1077.4
	12	980.8	954.5
	14	743.7	673.4
SS-1H	8	849.1	966.2
	10	919.3	989.6
	12	972.0	1013.0
	14	743.7	855.0