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EVALUATION AND IMPROVEMENT OF MICRO-SURFACING MIX DESIGN METHOD AND MODELLING OF ASPHALT EMULSION MASTIC IN TERMS OF FILLER-EMULSION INTERACTION

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ABSTRACT

This Doctorate program focuses on the evaluation and improving the rutting resistance of micro-surfacing mixtures. There are many research problems related to the rutting resistance of micro-surfacing mixtures that still require further research to be solved. The main objective of this Ph.D. program is to experimentally and analytically study and improve rutting resistance of micro-surfacing mixtures. During this Ph.D. program major aspects related to the rutting resistance of micro-surfacing mixtures are investigated and presented as follow: 1) evaluation of a modification of current micro-surfacing mix design procedures: On the basis of this effort, a new mix design procedure is proposed for type III micro-surfacing mixtures as rut-fill materials on the road surface. Unlike the current mix design guidelines and specification, the new mix design is capable of selecting the optimum mix proportions for micro-surfacing mixtures; 2) evaluation of test methods and selection of aggregate grading for type III application of micro-surfacing: Within the term of this study, a new specification for selection of aggregate grading for type III application of micro-surfacing is proposed; 3) evaluation of repeatability and reproducibility of micro-surfacing mixture design tests: In this study, limits for repeatability and reproducibility of micro-surfacing mix design tests are presented; 4) a new conceptual model for filler stiffening effect on asphalt mastic of micro-surfacing: A new model is proposed, which is able to establish limits for minimum and maximum filler concentrations in the micro-surfacing mixture base on only the filler important physical and chemical properties; 5) incorporation of reclaimed asphalt pavement and post-fabrication asphalt shingles in micro-surfacing mixture: The effectiveness of newly developed mix design procedure for micro-surfacing mixtures is further validated using recycled materials. The results present the limits for the use of RAP and RAS amount in micro-surfacing mixtures; 6) new colored micro-surfacing formulations with improved durability and performance: The significant improvement of around 45% in rutting resistance of colored and conventional micro-surfacing mixtures is achieved through employing low penetration grade bitumen polymer modified asphalt emulsion stabilized using nanoparticles.

Keyword: Micro-surfacing, Mix design, Rutting, Mastic modelling, RAP & RAS, nanoparticles

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Résumé

Ce programme de doctorat ce concentre sur l'évaluation et l'amélioration de la résistance à l'orniérage des enrobés coulés à froid (ECF). Il y a plusieurs problématiques en lien avec la résistance à l'orniérage des ECF qui demandent encore du travail. L'objectif principal de ce doctorat est d'étudier et d'améliorer, autant expérimentalement que de manière théorique, la résistance à l'orniérage des ECF. Pour ce programme de recherche, plusieurs aspects en lien avec la résistance à l'orniérage des ECF sont étudiés et présentés comme suit. 1) L'évaluation et la modification de la méthode actuelle de formulation des ECF. Pour cette partie des travaux, une nouvelle méthode de formulation pour les ECF de type III est présenté. Contrairement à la méthode actuelle, la méthode proposée permet d'optimisé la proportion de granulats dans les ECF. 2) L'évaluation des méthodes d'essais et sélection de la granulométrie pour les ECF de type III. Dans cette partie, des limites au niveau de la granulométrie sont proposés. 3) L'évaluation de la répétabilité et de la reproductibilité a été effectuée afin de mieux cerner les limites au niveau des différents essais. 4) La modélisation de l'effet rigidifiant du filler sur le mastic bitumineux des ECF a été effectué à l'aide d'un nouvel modèle développé dans le cadre de cette recherche. 5) L'efficacité de la nouvelle méthode de formulation des ECF a été vérifiée en utilisant des enrobés recyclés et des bardeaux d'asphaltes recyclés dans les mélanges en remplacement des granulats vierges. Il a été démontré que la nouvelle méthode fonctionne bien et qu'il est possible d'utiliser des matériaux recyclés en grande quantité dans les ECF. 6) Le développement d'un ECF coloré avec des performances mécaniques améliorées. L'augmentation de la résistance à l'orniérage de 45% est obtenue grâce à l'utilisation de bitume dur modifié avec un polymère et stabilisé avec nanoparticules.

Mots clés : enrobé coulé à froid, formulation, orniérage, modélisation, mastic bitumineux, enrobés recyclés (RAP), bardeaux d'asphaltes recyclés (RAS), nanoparticules

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INTRODUCTION

Pavement preservation is defined as a program employing a network-level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety, and meet motorist expectations (FHWA, 2005). Actions used for pavement preservation include routine maintenance, preventive maintenance (PM), and corrective maintenance (Uzarowski and Bashir, 2007). Transportation agencies use chip seal, slurry seal, micro-surfacing, cape seal, fog seal, etc.

Micro-surfacing was developed in an attempt to form a thicker slurry seal that could be used in wheel paths and ruts in order to avoid long rehabilitation work on high traffic roads. To do this, high quality aggregates and emulsions were incorporated in order to reach a stable product which is applied in multi-stone thickness and provide rutting resistance. Micro-surfacing, as an asphalt emulsion treated material, was the result of combining selected aggregates and bitumen, and then incorporating polymers and emulsifiers that allowed the product to remain stable even when applied in multi-stone thicknesses.

The area of asphalt emulsion treated materials for road surface treatment has been one of the fastest growing areas within civil engineering in the last decade. Much focus and research efforts have been placed on understanding the field performance of asphalt emulsion treated materials, as well as the asphalt emulsion technology. However, a review of research studies on micro-surfacing mixtures reveals that experimental investigations are still needed to encompass many aspects such as mix design procedure and specification, use of recycled materials, the effect of filler, specific properties of the asphalt emulsion, and rutting resistance of mixture. This manuscript based PhD thesis aims to address those shortcomings.

CHAPTER 1

RESEARCH FOCUS AND OBJECTIVES

1.1 Research Problems

Rutting, which is a surface depression in the wheel-paths, is one of the most important degradation found on bituminous pavement. Two types of rutting exist: mix rutting and subgrade rutting. Micro-surfacing can be applied on the road surface to fill either type of rut deformation. Micro-surfacing is a polymer modified quick setting slurry system that mainly consists of asphalt emulsion, aggregates, cement and water. According to International Slurry Surfacing Association (ISSA), there are three types of slurry surfacing according to their gradation. Type I, which is a slurry surfacing mixture used on residential streets, as a maximum nominal aggregate size of 2.36 mm. Type II and III are micro-surfacing mixtures that can be laid down in multilayers and have maximum nominal aggregate size of 4.75 mm (ISSA, 2010). Micro-surfacing mixture as a rut fill material (Type III) must be stiff enough to resist against heavy traffic loading. Improving the stiffness of micro-surfacing materials can be achieved through:

1. Employing an accurate mix design method and specification to select optimum mix proportions and aggregate gradation;

2. Improving the stiffness of mastic by selecting the optimum filler concentration;

3. Incorporating low penetration (hard) polymer modified asphalt emulsions as the binder for micro-surfacing mixtures.

It is well known that, one of the primary reasons for the insufficient rutting resistance of bituminous materials is the inaccurate mix design method to select the optimum mix proportion (Muzaffar khan, 2012). For a micro-surfacing mixture to resist against rutting

deformation, the mix proportion such as asphalt emulsion content, aggregates type, gradation, water and cement contents must be selected accurately. As of now, there have been no accurate mix design standards and specifications to accurately select type III micro-surfacing mixture proportion to ensure the performance of such materials against rutting deformation. Therefore, it is needed to study and determine the right mix proportions for type III application of micro-surfacing through a new mix design standard and specification, which consider rutting resistance as the most important property of these materials. Such a new mix design procedure should include mix design tests with high level of repeatability, and reproducibility, while being applicable to a wide range of materials from virgin aggregates to recycled materials such as reclaimed asphalt pavement (RAP), and recycled asphalt shingles (RAS).

Moreover, the resistance of type III micro-surfacing materials against rutting is dependent of the mastic stiffness, that consists mainly of mineral filler including the portion of material passing the No. 200 (0.075 millimetre) sieve, and bitumen (Asphalt Institute, 2007). By now, there have been no specifications and standards to suggest amount and type of incorporated filler in micro-surfacing mixtures with regard to the type of added bitumen emulsion in order to reach the optimum resistance of mix against rutting. Consequently, it is needed to study and determine the effect of filler and bitumen properties on stiffness of mastic in micro-surfacing mixtures.

In addition, the quick setting asphalt emulsion used in micro-surfacing mixture is predominantly made of moderate to high penetration grade bitumen, which normally, forms low stiff mastic in the mix, and thus having less resistance against rutting. Therefore, there is also a need to produce asphalt emulsion from low penetration (hard) grade bitumen to form stiffer bitumen in the mastic of micro-surfacing mixtures. In order to produce hard asphalt emulsions for micro-surfacing application, researchers are often faced with finding the right balance between workability and storage stability of the emulsion on the one hand and breaking characteristics and material properties on the other. Micro-surfacing application demands the asphalt emulsion that have excellent storage stability and which break rapidly. This can be achieved through using the right type of stabilizer at the right dosage. Therefore,

it is required to study and determine the right type and concentration of stabilizer to increase the storage stability of asphalt emulsion materials consist of hard bitumen, and thus improving rutting resistance of micro-surfacing mixtures.

Furthermore, the micro-surfacing mixture can be polymer modified for improving against rutting resistance. Technically, it is done through modification of asphalt emulsion using certain polymers. In polymer modified bitumen, the polymer phase includes inorganic material that tends to get separated from organic bitumen phase under loading at different temperatures and frequencies (Asphalt academy, 2007). Thus, it is needed to study and determine the right type of polymer to modify the base binder of bitumen emulsion, and so improving the final rutting resistance of micro-surfacing mixtures.

1.2 Research subproblems

The above defined research problems are broken down into following research sub-problems:

1. To analyze and determine the effect of asphalt emulsion, water, and cement content on properties and performance of micro-surfacing mixtures, and discover their distinctive effects on rutting resistance of mixture;

2. To study and evaluate additional mix design tests that can be used to select optimum mix proportions for micro-surfacing mixtures;

3. To analyze and determine repeatability and reproducibility of micro-surfacing mix design tests, and discover the source of variation in testing results;

4. To analyze and determine the effect of filler properties on the stiffness of mastic in micro-surfacing mixture, and discover minimum and maximum filler concentration with regard to the rutting resistance of micro-surfacing mixtures;

5. To analyze and determine the effect of asphalt emulsion properties on the stiffness of mastic, and discover their distinctive effects on mastic stiffening rate;

6. To study and determine the combined effect of filler and asphalt emulsion on the stiffness of mastic;

7. To study the effect of recycled pavement materials such as RAP and RAS into micro-surfacing mixtures, and discover their distinctive effects on mixture properties;

8. To determine the effect of different amounts of RAP and RAS materials on properties of micro-surfacing mixtures;

9. To Study and determine the effect of specific nanoparticle as stabilizer on the storage stability of cationic quick setting asphalt emulsions;

10. To evaluate the effect of low penetration asphalt emulsion on rutting resistance of micro-surfacing mixtures;

11. To study and determine the effect of Styrene–butadiene–styrene (SBS), Styrene–butadiene–rubber (SBR) latex, and Ethylene vinyl acetate (EVA) on the rutting resistance of micro-surfacing mixtures, and stiffness of bitumen residue;

1.3 Research Objectives

The main objective of this Ph.D. program is to experimentally and analytically study and improve rutting resistance of micro-surfacing mixtures. Each above mentioned sub-problems is related to a specific objective as listed below:

1. To develop a new mix design procedure for type III micro-surfacing to maximize rutting resistance;

2. To select the micro-surfacing mix design tests that can be utilized in order to find the optimum asphalt emulsion content for maximum rutting resistance;

3. To establish limits in which the micro-surfacing testing results are repeatable and reproducible;
4. To identify filler properties that can be used to model the increase in complex shear modulus (|G*|) of micro-surfacing mastic as a function of filler concentration, and establish minimum and maximum limits for the amount of filler with regard to the mastic and mixture properties;

5. To identify asphalt emulsion properties that can be used to model the increase in complex shear modulus (|G*|) of micro-surfacing mixture;

6. To model micro-surfacing mastic stiffness in terms of filler-bitumen interaction;

7. To evaluate the feasibility of using recycled materials into micro-surfacing mixture using new developed mix design procedure, and producing more environmental friendly products;

8. To establish limits for the maximum amount of allowable RAP and RAS materials into micro-surfacing mixtures with regard to the predominant properties of mixture such as rutting resistance;

9. To identify the effect of nanoparticles on the viscosity of asphalt emulsion and improving the storage stability of cationic quick setting emulsion using nanoparticles;

10. To evaluate the feasibility of formulating micro-surfacing mixtures using low penetration grade asphalt emulsion, and improving the rutting resistance of micro-surfacing mixtures by using this new asphalt emulsions;

11. To identify the effect of SBS, SBR latex, and EVA polymers on stiffness of bitumen residue, and improving rutting resistance of micro-surfacing mixtures using the appropriate polymer.

1.4 Research scope and significance

The research effort presented in this Ph.D. thesis deals with evaluating and improving rutting resistance of micro-surfacing mixtures against heavy traffic loading. For the first and second parts of this research program, a new mix design procedure and specification for type III micro-surfacing as rut-fill materials was developed that accurately select the optimum mix proportions such as aggregate gradation, asphalt emulsion, water, and cement contents. The new mix design procedure and specification, is able to select the optimum asphalt emulsion and aggregate gradation for micro-surfacing mixtures. However, the existing mix design procedures for micro-surfacing report the mix proportions with a large tolerance that results in low consistency of testing results. The findings in first and second parts of this Ph.D. program were respectively submitted to the Canadian Journal of Civil Engineering and, published in the International Journal of Pavement Engineering and Asphalt Technology.

Moreover, the micro-surfacing mix design tests are very operator dependent, which may lead to a significant variation in results between operators and laboratories. In the third part of this research program, the new developed mix design procedure were run with different operators and laboratories using same materials in order to establish the repeatability and reproducibility limits for each mix design tests. This helped with improving the accuracy of testing results when using the new mix design procedure. The findings were published in the Australian Journal of Civil Engineering.

The filler part of the aggregates (material smaller than 75 micron) is critical to control the reaction rate in micro-surfacing and thus rutting resistance. It was decided to study the stiffening effect of filler on asphalt mastic of micro-surfacing. Normally, stiffer mastic results in better rutting resistance of asphalt mixtures. For the fourth part of this doctorate program,

a successful model to predict the true behavior of the mastic stiffness in micro-surfacing mixtures was developed. The model is capable of predicting the minimum and maximum filler concentrations in micro-surfacing mixtures using filler and asphalt emulsion predominant properties. Besides, a better understanding of the mechanism in which the filler gives stiffness to the mastic of micro-surfacing mixtures is provided. A correlation between mastic stiffness as a function filler concentration and cohesion of micro-surfacing mixtures is reported as well. The findings are accepted to be published in the Journal of Materials in Civil Engineering.

Using the findings in previous parts of study that made us able to accurately select the quality and quantity of materials for micro-surfacing mixtures, it was decided to expand the developed design method and specification to other types of materials. For the fifth part of this doctorate program, RAP and RAS materials were added to the micro-surfacing mixtures with the aim of verifying the new mix design procedure to be employed for a wide range of materials. The new mix design procedure successfully formulated micro-surfacing mixtures using 100% recycled materials. RAS was added to micro-surfacing mixtures for the first time to show the potential of such materials to be incorporated into road surface treatment materials. Also, the limits for the amount of added RAP and RAS materials into micro-surfacing mixtures were established. The results were published in the conference proceeding of the 58th Annual Meeting of the Canadian Technical Asphalt Association.

For the sixth part of this Ph.D. program, the significant improvement in rutting resistance of micro-surfacing mixtures was achieved through employing low penetration grade bitumen polymer modified asphalt emulsion stabilized using nanoparticles. Further, the improvement in rutting resistance was achieved through less asphalt cement content comparing the conventional micro-surfacing mixes. Colored micro-surfacing mixtures were also successfully formulated with superior durability and performance compared to conventional mixes. This further show the potential of low penetration asphalt emulsions to form cold mix asphalt with the same stiffness or even stiffer, compared the hot mix asphalt mixes. However, more research is still required to develop such cold asphalt mixes. The results of this part of

study are published in 13th International Conference on Pavement Engineering and Infrastructure in UK.

1.5 Outline of thesis

The research work presented in this Ph.D. thesis is divided into eight chapters:

- chapter 1 provides research problems, sub-problems, objectives, research scope and significance;

- chapter 2 provides a literature review related to the current work;

- chapter 3 presents the first published article of this Ph.D. program. The article is titled: "Evaluation of a modification of current micro-surfacing mix design procedures", and proposes a new mix design method to select the optimum mix proportions for type III micro-surfacing mixtures;

- chapter 4 titled: "Evaluation of test methods and selection of aggregate grading for type III application of micro-surfacing" presents the second published paper about the new specification proposed to select the optimum aggregate gradation to improve the resistance of micro-surfacing mixture against rutting;

- chapter 5 presents the third article published during this Ph.D. program. The article is titled: "Evaluation of repeatability and reproducibility of micro-surfacing mixture design tests and the effect of total aggregates surface areas on the test responses", and presents the limits for repeatability and reproducibility of micro-surfacing mix design tests;

- chapter 6 titled: "A new conceptual model for filler stiffening effect on asphalt mastic of micro-surfacing", presents the fifth submitted article about a new conceptual model for the stiffening rate of filler to the mastic. The model is also able to establish limits for minimum and maximum filler concentrations in the micro-surfacing mixture;

- chapter 7 titled: “Incorporation of reclaimed asphalt pavement and post-fabrication asphalt shingles in micro-surfacing mixture”. The paper presents the limits for the use of RAP and RAS in micro-surfacing mixtures;

- chapter 8 presents the sixth paper published during this Ph.D. program. The article is titled: “New Colored Micro-surfacing formulations with improved durability and performance”. The paper discusses the potential of low penetration asphalt emulsion to significantly improve rutting resistance of micro-surfacing mixtures.

Finally, conclusions and recommendations for future work are provided.

Each paper presented in this thesis, chapter 3 to 8, present the results of different part of the research program that were performed in order to achieve the main goal of the thesis. Four papers are on mix design. It is complicated to really understand which factors of the mix do affect rutting resistance if the mix design is not accurate, repeatable and usable with wide range of materials, such as recycled asphalt pavement or recycled asphalt shingles. Because of this, it was decided to first work on the mix design.

Subsequently, it was observed that the mastic of micro-surfacing has a dominant effect on rutting resistance of micro-surfacing mixtures. Therefore, the effect of mastic stiffness on rutting resistance of micro-surfacing mixtures was studied and a conceptual model was proposed.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Micro-Surfacing Mix Design Procedures and material specifications

One of the critical components to ensure the success of a micro-surfacing project includes a comprehensive mix design process (Kazmierowski, 1995). Quality of the materials and the use of a knowledgeable and experienced contractor are among the other key factors (Kazmierowski, 1995). Schilling et al. reported that the filler part of aggregates (material smaller than 75 micron) is critical to control the reaction rate in micro-surfacing (Schilling et al., 2002).

Hicks et al. concluded that the due to the fast-set of asphalt emulsion in micro-surfacing, aggregate characteristics influence the quality of mixture much more than in conventional slurry seals (Hicks et al., 1997). However, if the materials and proportions are selected precisely, micro-surfacing can significantly improve the rutting resistance and friction characteristics of the road surface (Hixon et al., 1993). Hixon et al. also reported a 40% reduction in the amount of original rutting and substantial increases in the friction characteristics of the pavement (Hixon et al., 1993).

Among all mix design guidelines, ISSA and ASTM guidelines are the most accepted and practiced around the world. ISSA developed A105 guideline for Slurry Seal mix design (ISSA, 2005) and A143 guideline for Micro-surfacing (ISSA, 2005). ASTM suggested D3910 guideline for Slurry Seal (ASTM, 1998), and D6372 for Micro-surfacing (ASTM, 1999). Despite the differences between Slurry Seal and Micro-Surfacing (i.e., polymer modification, application thickness, traffic volume, and curing mechanisms), both ISSA and ASTM suggested similar test methods and design procedure to evaluate Slurry Seal and Micro-surfacing.

In fact these procedures do not make any distinction between Slurry Seal and Micro-surfacing mix design and consider same test methods for both systems. Texas Transport

Institute (TTI) studies documented the problems associated with using the existing methods for micro-surfacing and suggested the development of a comprehensive mix design especially for Micro-surfacing (TTI, 1995). California Department of Transportation (Caltrans) has also studied both systems of Slurry Seal and Micro-surfacing together in order to provide a rational mix design procedure (Caltrans, 2004). The minister de transport Quebec (MTQ) has developed its own specification for micro-surfacing (Robati et al., 2012).

The European Union has a similar set of standards and norms to design Slurry Seal and Micro-surfacing. Other countries such as Germany, France, United Kingdom, and South Africa have had experience with Slurry Seal and Micro-surfacing systems, and have developed specific guidelines for their specific use. However, among all these guidelines, ISSA and ASTM are commonly used worldwide.

Repeatability and reproducibility of micro-surfacing mix design tests have also been subjected to the focus of researchers. Andrews et al. studied the repeatability and reproducibility of micro-surfacing mix design tests (Andrews et al., 1995). In their report, the repeatability of micro-surfacing tests using materials falling within current micro-surfacing specifications was obtained. Material compositions were the only variation in their study, and the test responses were evaluated to determine repeatability and reproducibility of the tests. Different types and amounts of asphalt emulsion, and various types of aggregates with same gradation were used to prepare micro-surfacing mixtures in their study. The mix design tests were performed at one laboratory by a same technician for all micro-surfacing mixtures. The effects of different amounts of Portland cement additive in micro-surfacing mixtures were studied in their report as well. They reported improved properties of micro-surfacing mixtures with same aggregate gradation but different amounts of Portland cement. According to their results, the consistency of the wet track abrasion tests and loaded wheel test is poor (Andrews et al., 1995).

2.2 Effect of filler on rheological properties of bitumen-filler mastics

Many studies have continuously reported the effect of mineral fillers on various properties of bitumen-filler mastics. Schilling reported that the filler part of aggregates (material smaller than 75 micron) is critical to control the reaction rate in micro-surfacing (Schilling, 2002). Anderson addressed the effect of filler on moisture damage, stiffness, oxidation, rutting, cracking behavior, workability and compaction characteristics in asphalt pavements (Anderson, 1987). Anderson (1987) showed that the viscosity of the binder-filler mastic rises almost exponentially as the filler portion increases.

One of the earliest studies to postulate the effect of filler on asphaltic materials is the work of Clifford Richardson in the beginning of 20th century (Richardson, 1914). He reported that certain types of fillers such as silica, limestone dust, and Portland cement adsorb relatively thicker film of asphalt. In 1912, for the first time, Einstein reported the stiffness effect of fillers on a composite matrix. He developed coefficient of Einstein as the indicator of the rate of increase in stiffness of the matrix by incorporation of filler particles (Einstein, 1956).

Following the study conducted by Einstein, the stiffening effect of filler to the asphaltic materials had been the focus of many specialists in the asphalt field. In 1930, Traxler reported the important parameters in fillers with regard to their potential for stiffening the asphaltic materials. According to his study, size and size distribution of filler particles are the fundamental filler parameters as they affect the void content of filler. He also considered the surface area of filler particles and their shape as the influential parameters governing the stiffening effect of filler to the asphaltic materials (Traxler, 1961).

In 1947, P. J. Rigden developed a new theory named the “fractional voids concept”. He considered the asphalt required to fill the voids in a dry compacted bed as “fixed asphalt,” while asphalt in excess of that amount was defined as “free asphalt”. According to Rigden theory, the only factor affecting the viscosity of the filler-asphalt system is the fractional voids in filler. He was reported that other characteristics of fillers, and also asphalt properties are of less significant with regard to the viscosity of filler-asphalt system (Rigden, 1947).

In 1962, Tunnicliff described the importance of filler particle size distribution as the main properties of filler affecting the filler-asphalt system. He reported that there is a gradient of stiffening effect, which has a bigger value at the surface of the particle size, and becomes weaker with distance from the surface (Tunnicliff, 1962). In 1973, Anderson and Goetz concluded that the type of filler affect the stiffening effect of filler to the filler-asphalt system (Anderson and Goetz, 1973). They explained that the stiffening effect could be due to "the presence of some sort of physico-chemical interaction" between filler and asphalt.

In 1999, Shenoy et al. reported the bitumen-filler mastic as a suspension system where mineral filler particles are suspended in bitumen. This suspension system constitutes dilute and concentrated regions. In diluted region, there is no any interaction between filler particles due to the large distance between particles. However, in concentrated region, there exists an interaction between filler particles, and thus affecting the rheological properties of the mastic (Shenoy et al., 1999).

In 2005, Little and Petersen have reported the potential of hydrated lime filler to decrease the phase angle (δ), and thus improving resistance of mastic against loading. In this research, bitumen with different ageing condition was mixed with limestone and hydrated lime filler at the fixed concentration of 20%. Rheological results shown a significant increase in resistance to loading for mastics prepared with aged bitumen and hydrated lime (Little and Petersen, 2005).

Many other studies have also been performed to better understand the linear viscoelastic analysis of bituminous binders using a rheometer (Delaporte et al., 2007; Yusoff et al., 2011). However, in 2010, Faheem and Bahia introduced a conceptual model for the filler stiffening effect on mastic. They postulated that the filler stiffening effect varies depending on the filler mineralogy and the concentration in the mastic (Faheem and Bahia, 2010). According to their study, the change in stiffness (G*) as a function of the increase in filler concentration can be divided into two regions: diluted and concentrated regions.

2.3 Effect of polymer nanocomposites on rheological properties of asphalt emulsion

Processes of asphalt modification involving natural and synthetic polymers were patented as early as 1843 (Thompson DC, 1979). SBS, SBR, and EVA polymers as the bitumen modifier are the most studied polymers (Bates R, 1987; Becker Y, 2001; Wegan V, 2001; Chen JS, 2002; Roque R, 2004; Shukla RS, 2003; and Kim MG, 1999). However, nanoparticles can also provide nano-reinforcement to the polymer network in the bitumen, and thus improve different properties. Basically, polymer nanocomposites consist of a blend of one (or more) polymer(s) with various nanomaterials such as nanoclays, carbon nanotubes, etc. (Gupta RK, 2005; and Alexander M, 2000). As it is clear from the name, polymer nanocomposites are polymer-matrix composites containing materials which have at least one dimension below about 100 nm, (seven carbon atoms side by side would describe a length of approximately 1 nanometer). This small size offers some level of controllable performance and properties to the polymers. Specific nanoparticles, such as Clay, Carbon montmorillonite, Carbon black, Silica (SiO_2), Zinc oxide (TiO_2), Talc, and Aluminium oxide (AlO_2) are the most studied nanoparticles in the bituminous materials. In 2009, Baochang Z. et al. studied the effect of montmorillonite clay modification of SBR polymer in order to improve rutting resistance of bituminous materials (Goh, S.W., 2011). They have shown that the SBR polymer network in the bitumen is modified by the montmorillonite clay, and thus increasing the stiffness of bitumen, while decreasing the phase angle (δ), which is ideal rheological condition for the bitumen to resist well against shear loading. Other researchers have also studied the effect of nanoclay to increase different properties of polymer modified bitumen (SureshkumarM. S., 2010; and PolaccoG., 2008). Amirkhanian et al., in 2010, have investigated the rheological properties of binders containing different percentages of carbon nanoparticles after a short-term aging process of the bitumen materials (Amirkhanian et al., 2011). They have shown that the addition of nanoparticles was helpful to increase complex modulus and also, the rutting resistance of the RTFO binder. In 2012, Ghasemi et al. have shown that nano-SiO_2 can improve the viscosity, storage stability, adhesion, cohesion, and stiffness of SBS modified bitumen and asphalt mixture (Ghasemi et al., 2012).

Moreover, nanocomposite technology has advanced considerably in recent years and excellent engineering properties have been achieved in numerous systems. In multiphase materials the improvement of properties relies heavily on the nature at the interphase region between polymer domains and nanoparticle reinforcements. Strong adhesion between the phases provides excellent load-transfer and good mechanical elastic modulus and strength, whereas weak interaction contributes to crack deflection mechanisms and toughness. Polymer molecules are large and the presence of comparably sized filler particles affects chain gyration, which in turn influences the conformation of the polymer and the properties of the composite system (Fischer, 2003).

Effect of clay nanoparticles on rheological properties of bituminous binders, such as penetration, viscosity, softening point, hardness, storage stability, stiffness, and viscoelastic behaviour was the focus of researchers. Clay minerals are classified into different minerals including kaolinite, illite, smectite (montmorillonite), chlorite, halloysite, and the vermiculite group. However, the most important commercial clay minerals are kaolinite and montmorillonite. Chunfa Ouyang et al. investigated the effect of SBS/kaolinite clay (KC) on the mechanical properties of bituminous binder (Chunfa Ouyang et al., 2004). KC, with an average particle size of 0.044 mm, non-calcined type was used in this study. They studied the effect of different SBS/KC ratio on mechanical properties of bitumen. The temperature at which SBR and KC were mixed together was shown to be the source of variation in test results. AH-9- paving asphalt from China were selected as a base binder. Different properties of asphalt such as rheological characteristics, and high temperature storage stability, were significantly improved. Moreover, some properties of SBS/KC compound like molecular weight distribution, tensile strength, ultimate elongation, modulus, and hardness were reported as the influential parameters on rheological properties of bitumen.

Montmorillonite Clay has also been the focus of many researchers to modify the bitumen properties. Generally, Montmorillonite Clay is a similar type of clay to Kaolinite type, but, differs in its structure, and its silicate surface. In 2009, Jahromi et al., shown that small amount of nanoclay can significantly improve the properties of polymer modified bitumen.

Ghafarpour et al. performed Dynamic Shear Rheometer (DSR) test on the hot asphalt mixtures to investigate the effect of the amount and type of Montmorillonite nanoclay on the rheological properties of bitumen binder (Jahromi et al., 2009). They prepared asphalt mixture consisting of 60/70 penetration grade bitumen as the base asphalt binder, which is one of the most widely used in Iranian mixing plant operations, and modified the binder by different amounts and types of Montmorillonite nanoclay. The purpose of this research was to investigate the effect of nanoclay modification of bitumen binder on rheological properties such as stiffness, phase angle, penetration, softening point, ductility, rutting, fatigue, and aging properties of the hot mix asphalt. Two types of commercially available Montmorillonite nanoclay with different organic modifiers, which are Cloisite-15A nanoclay, and Nanofill-15 nanoclay were studied. Nanofil-15 had no effect on penetration of 60/70 penetration binder, but, softening point increases from 54 to 61 °C. Influence of nanoclay modification on stiffness and elastic properties of bituminous binder have been studied by DSR measurements over a wide range of temperature varying between -15 and 100 °C. However, it is not practical to perform tests over the entire temperature and frequency ranges. In the dynamic shear modulus test, an oscillatory stress is applied and the resulting strain is measured. The viscoelastic response of the material under sinusoidal loading conditions are described by the dynamic (complex) shear modulus (G*), and phase angle (δ). Complex shear modulus (G*) is an indicator of the stiffness of the mix and is the absolute value of the peak-to-peak stress delivered divided by the peak-to-peak recoverable strain under sinusoidal loading. The phase angle is the degree to which the mix behaves elastic or viscous material. In the purely elastic materials, the applied stress and resulting strain response occur with each other, thus, these material have the phase angle of zero degree. Perfectly viscous materials have a 90 degrees lag in phase angle between the applied sinusoidal stress and the resulting strain. Asphalt is characterized as a viscoelastic material with phase angle in between zero and 90 degrees. It is well-known that, the complex modulus (G*) increases by decreasing temperature and/or increasing frequency. Two types of nanoclay (Cloisite-15A, and Nanofil-15) were selected, and DSR test were performed on specific temperatures (Jahromi et al., 2009). To predict complex shear modulus (G*), and phase angle (δ) over a wide range of

temperatures, master curve were developed using the well-known Williams-Landel-Ferry (WLF) theory with using equation 2.1:

$$\log a_T = -\frac{C_1(T - T_{\mathrm{re}})}{C^2 + T - T_{\mathrm{re}}} \quad (2.1)$$

Where a_T, is the shift factor value, C_1 and C_2 are constants, T is temperature measurement and T_{re} is reference temperature (20 °C).

Figure 2.1 and 2.2 show the stiffness (G*), and phase angle (δ) values versus wide ranges of frequency for unmodified and nanofil-modified bitumen at unaged and short-term aged conditions. It is well-known that, when the binder gets older (aged), the stiffness value increases, while the phase angle values decreases. This is due to oxidation effect. An ideal binder has low temperature sensitivity, which means that the stiffness and phase angle do not change much over time. Figure 2.1 shows that the nanofil modification of unaged binder increases its stiffness at low to medium frequency. Data analysis of stiffness, after short-term aging, also shows that the rate of increase in stiffness is reduced with time. As the nanofil modified binder get older, its stiffness value hardly increase compared to unmodified binder, especially at the frequencies ranges between 10^{-3} and 100 Hz (low to medium frequency).

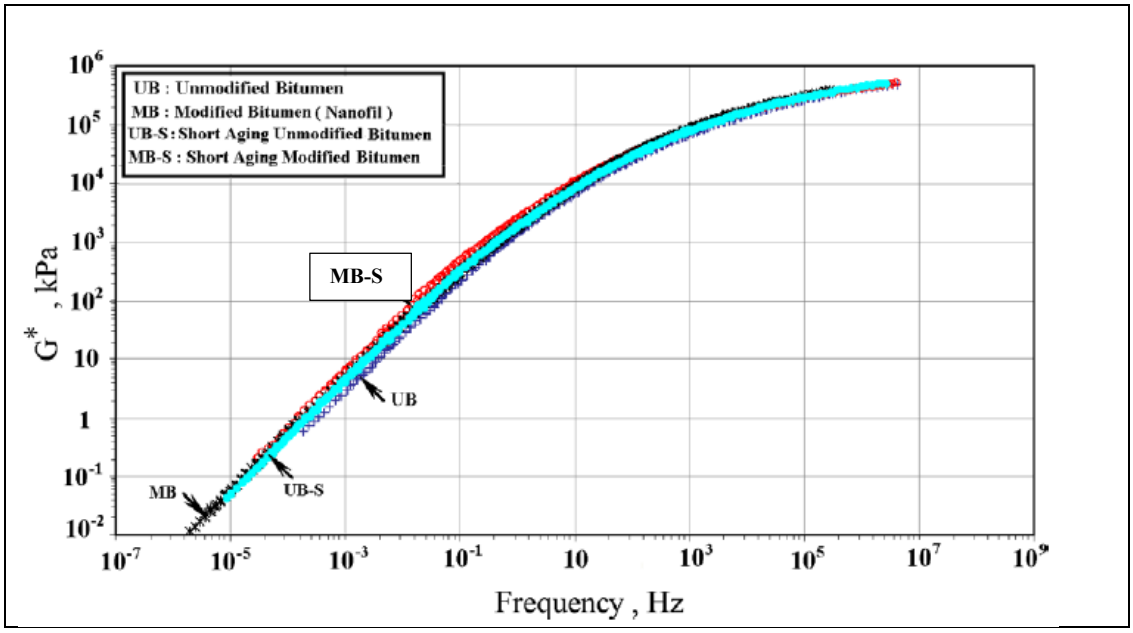

Figure 2.1 Master curve of stiffness for
nanofil modified and unmodified bitumen
Extracted from Jahromi (2009, p. 2901)

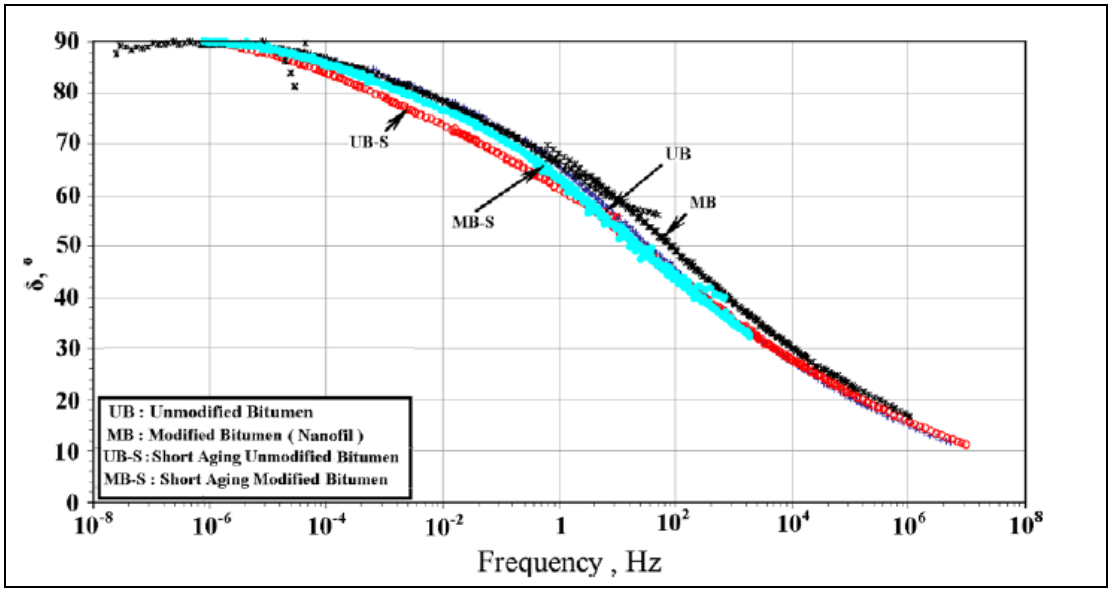

Figure 2.2 Master curve of phase angle for nanofil
modified and unmodified bitumen, short term aged
Extracted from Jahromi (2009, p. 2901)

Figure 2.2 shows that, the nanofil modification of unaged binder decrease its phase angle at high frequency. Based on the analysis of phase angle after short-term aging, it can be concluded that the nanofil modification helps in reducing the rate of decrease of phase angle due to ageing effect at the frequencies ranges between 10^{-3} and 1 Hz (low to medium frequency).

Effect of nanoclay modification on rutting and fatigue properties of binder has also been studied (Ghafarpour, 2009). DSR test responds were presented as G* divided by sin δ (G*/ sin δ), and G* multiple by sin δ (G*. sin δ), to find the effect of amount of added nanoclay, and type of nanoclay on rutting and fatigue behavior of hot asphalt mixtures at respectively high and low temperature. A higher G*/ sin δ and G*. sin δ values reflect more resistance to rutting and fatigue respectively. A sinusoidal loading with constant loading time and frequency of 0.1 sec and 10 rad/s were applied in all DSR tests in this part of research. 85% in RCAT short-term and long-term ageing were applied on modified and unmodified binder to evaluate effect of nanoclay on rutting and fatigue properties of aged and unaged binder. 60/70 penetration bituminous binder, three levels of cloisite nanoclay (0, 4, and 7%), and two levels of nanofil-15 nanoclay (0, and 7%) were selected to analyses the effect of amount and type of nanoclay on fundamental rheological properties of virgin binder such as rutting and fatigue at high and low ranges of temperature respectively. Temperatures range between 40 to 80 °C were selected to evaluate the parameter of rutting at high temperature, while, temperatures from 0 to 20 °C were selected to measure the parameter of fatigue at low temperature. Figure 2.3 and 2.4 are typical graphs of physical data derived from this part of study. As it can be seen from Figure 2.3, when the amount of cloisite nanoclay increases in binder from 0 to 7%, rutting resistance at high temperature improves because the measure parameter of $G^*/\sin\delta$ increase. This increase is around 1.6% at temperature between 40 to 50 °C. Also, the increment (percentage wise) is somewhat lower or equal in short and long-term aging conditions. Same trend was observed with the addition of nanofil nanoclay in virgin binder. However, the effect of cloisite nanoclay on rutting resistance of binder is more than that of binder modified by cloisite. Figure 2.5 and 2.6 show the measured parameter of $G^* \sin\delta$ versus temperature ranges between 0 to 20 °C. As it can be seen from these figures, the measured parameter of G* sin δ for both nanofil and cloisite nanoclay modified binder

increase as the amount of nanoclay increase in binder, thus, indicating improve in fatigue resistance of binder.

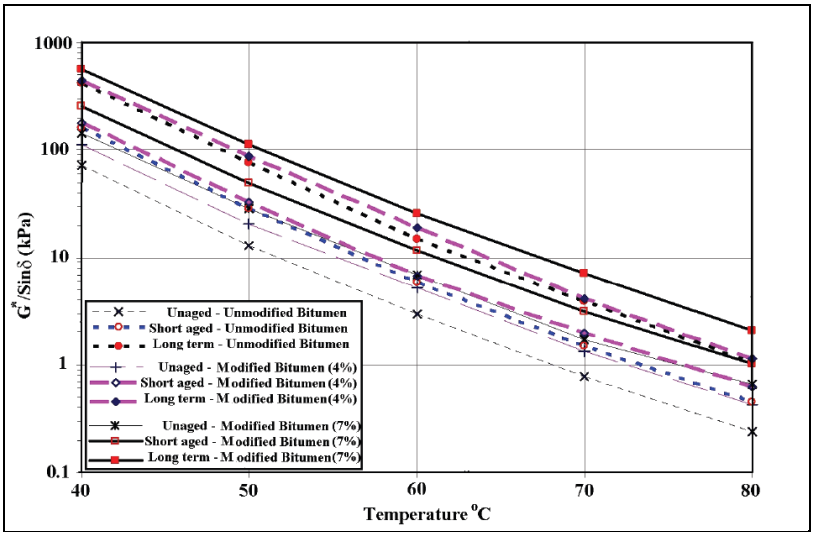

Figure 2.3 Comparison of G*/Sinδ of unmodified and cloisite modified Bitumen
Extracted from Jahromi (2011, p. 279)

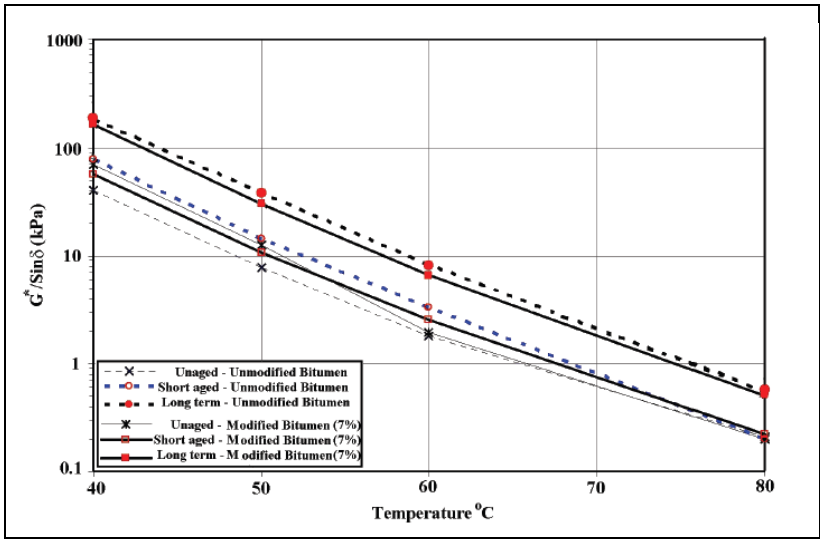

Figure 2.4 Comparison of G*/Sinδ of unmodified and nanofill modified bitumen
Extracted from Jahromi (2011, p. 279)

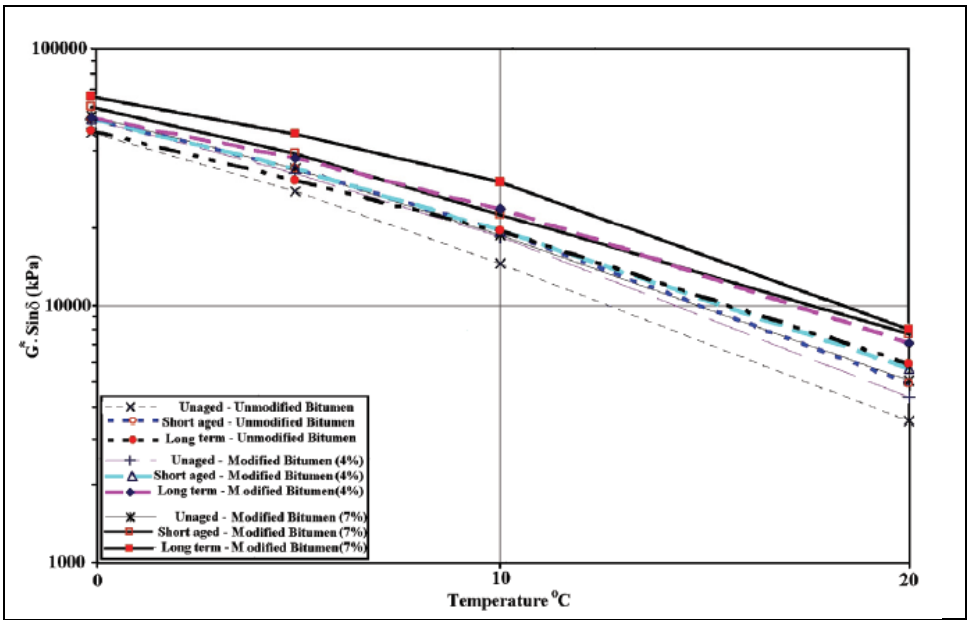

Figure 2.5 Comparison of G*.Sinδ of
unmodified and cloisite modified bitumen
Extracted from Jahromi (2011, p. 280)

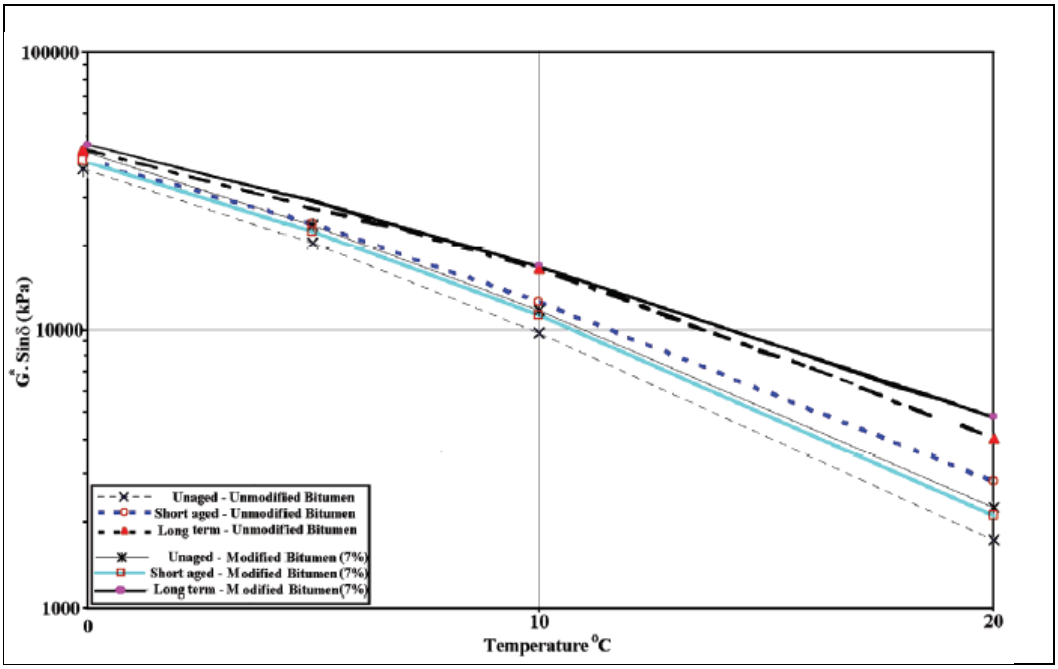

Figure 2.6 Comparison of G*.Sinδ of
unmodified and nanofill modified bitumen
Extracted from Jahromi (2011, p. 280)

In 2011, Sadeghpour Galooyak et al. studied the effect of nanoclay on rheological properties and storage stability of SBS-modified bitumen. They prepared asphalt mixture consist of 85/100 penetration grade bitumen as the base asphalt binder, which was obtained from an Iranian petroleum refinery. This base binder was modified with two types of conventional SBS polymers labeled A (a linear type-SBS), and B (a branched-type SBS). The resulted bitumen is called a triple nanocomposite (OMMT/SBS-modified bitumen) material in this study. When binder was modified with SBS type-A, the amount of added nanofil to further modify the binder were 0, 35, 50, and 65% by weight of SBS polymer in bitumen. While, in the case of modification of binder with SBS type-B, the amount of added nanofil to the binder were 0, and 50 by weight of SBS polymer in bitumen. Totally six mixtures were prepared, and tested in this study. The purpose of this research was to investigate the effect of SBS copolymer on the characteristics of base binder. However, limited experimental studies have been conducted to evaluate the effect of nanoclay reinforced polymer (polymer nanocomposites) on the properties of bitumen. To do this, nanoclay modification of SBS-modified bitumen binder were performed and different rheological properties such as penetration, softening point, ductility, elastic recovery, rotational viscosity, stiffness, phase angle, high-temperature storage stability, and aging characteristics were evaluated. Figure 2.7 shows SBS type-A modified bitumen, and nanoclay/SBS modified binder, before and after one hour storage at 163 °C. The morphology of SBS-modified bitumen changes quickly with time, and after one hour, coarser particles of SBS polymer are formed in the case of SBS modified binder. However, those coarser particles of SBS were not formed in the images numbering (d), thus indicating more storage ability of triple nanocomposite compare to SBS modified binder. The phase separation can be seen from figure (a) to (b), while, there is no phase separation in figure (c) to (d).

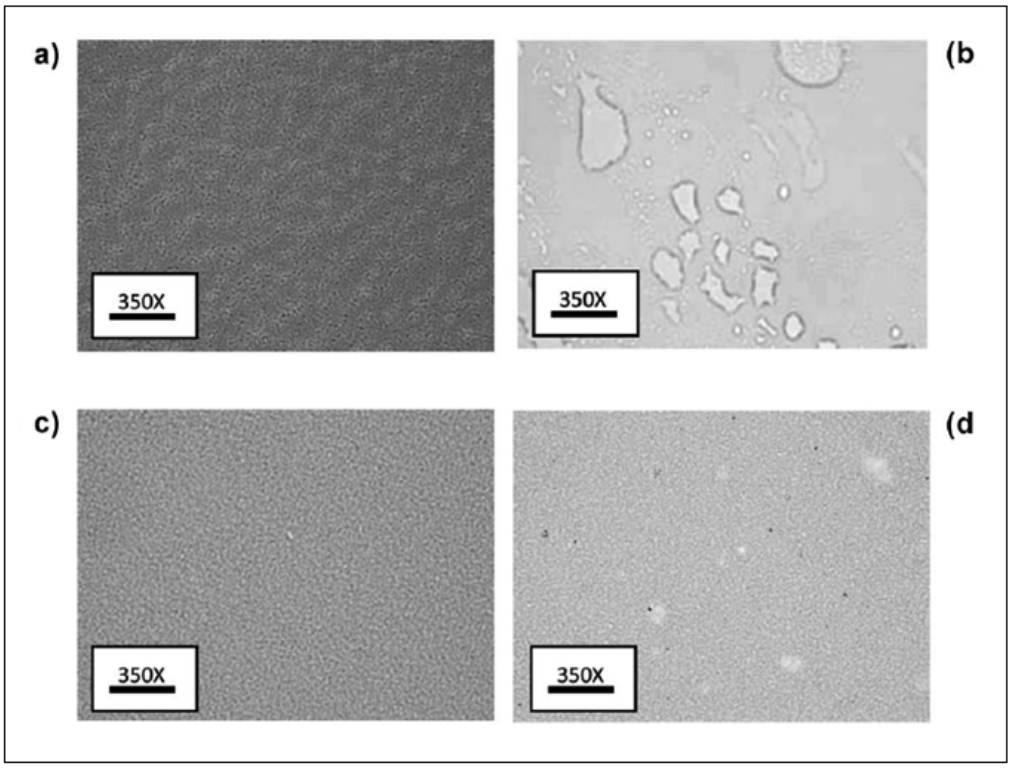

Figure 2.7 Morphology of SBS A- modified bitumen before and after adding nanoclay at 163 °C: a) SBS A- modified bitumen at 0 min b) SBS A- modified bitumen after 1 hr storage c) triple nanocomposite at 0 min, and d) triple nanocomposite after 1 hr storage
Extracted from Sadeghpour (2011, p. 857)

CHAPTER 3

EVALUATION OF A MODIFICATION OF CURRENT MICRO-SURFACING MIX DESIGN PROCEDURES

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3.1 Abstract

Although Micro-surfacing is widely used, current tests and mix design methods mostly rely on laboratory conditions and the correlation between laboratory results and field performance is poor. Therefore, there is a need to develop new mix design procedures, specifications, and guidelines for Micro-surfacing mixtures. The research described in this paper intended to suggest modifications to the actual International Slurry Seal Association (ISSA) mix design procedure for micro-surfacing. The first part of study reports the findings of a detailed laboratory investigation concerning the effect of asphalt emulsion, added water content, and Portland cement on the design parameters and properties of micro-surfacing mixtures. A multilevel factorial design is used to assess the effect of different mixture proportions on the test responses. For this, one aggregate type, one asphalt emulsion type/grade, and one aggregate gradation were used in the study. This part of study consisted mainly of establishing a method for preparing and testing micro-surfacing mixture using four main mixture design tests proposed by the ISSA (TB 139, TB 113, TB 100, and TB 109). The results obtained with ISSA TB 109 and ISSA TB 100 mixture design tests were found highly variable and not precise enough to suggest optimum mix design. For the second part of this study, different tests were also studied in order to refine the current mix design procedure.

The results have shown that ISSA TB 139 can be used to define the optimum water content at which samples should be tested, and that ISSA TB 147 mix design test should be used to define the optimum asphalt emulsion content.

3.2 Background

Micro-surfacing was developed in an attempt to form a thicker slurry seal that could be used in wheel paths and ruts in order to avoid long rehabilitation work on high traffic roads. To do this, high quality aggregates and advanced emulsions were incorporated in order to reach a stable product which is applied in multi-stone thickness and provide rutting resistance. Micro-surfacing was pioneered also in Germany, in the late 1960's and early 1970's (International Slurry Surfacing Association, 2011). Micro-surfacing is the result of combining highly selected aggregates and bitumen, and then incorporating special polymers and emulsifiers that allowed the product to remain stable even when applied in multi-stone thicknesses. Micro-surfacing was introduced in the United States in 1980, as a cost-effective way to treat the surface wheel-rutting problem and a variety of other road surface problems (International Slurry Surfacing Association, 2011). Micro-surfacing can be applied in double layer for addressing surface irregularities. Moreover, micro-surfacing has variety of applications where quick opening for traffic is important.

Among all mix design guidelines, ISSA and ASTM guidelines are the most accepted and practiced around the world. ISSA developed A143 guideline for Micro-surfacing (ISSA, 2005a), and ASTM suggested D6372 for Micro-surfacing (ASTM, 1999a). Despite the differences between Slurry Seal and Micro-Surfacing (i.e., application thickness, traffic volume, and curing mechanisms), both ISSA and ASTM suggested similar test methods and design procedure to evaluate Slurry Seal and Micro-surfacing. In fact these procedures do not make any distinction between Slurry Seal and Micro-surfacing mix design and consider same test methods for both systems, while Texas Transport Institute (TTI) documented the problems associated with using the existing methods for micro-surfacing and suggested the development of a comprehensive mix design especially for Micro-surfacing (TTI, 1995). California Department of Transportation (Caltrans) has also studied both systems of Slurry

Seal and Micro-surfacing together in order to provide a rational mix design procedure (Caltrans, 2004). Quebec department of transportation (MTQ, 2011) has developed its own specification for micro-surfacing based on ISSA, and the European Union, as well as South Africa has similar sets of standards and norms to design Slurry Seal and Micro-surfacing. However, among all these guidelines, ISSA and ASTM are commonly used worldwide.

3.2.1 Optimum Mix Design Procedures for Micro-surfacing

ISSA TB 111 presents a different method of design procedure for Slurry Seal. This design procedure suggests ranges of variation for the input design variables and provides a method to choose the optimum design. ISSA TB 111 was developed from papers presented by Huffman et al. in 1977 (ISSA, 2005b). The method has two parts. Part I is about primary design considerations. The objectives of the design can be improving skid resistance of surface, crack filling, or rut correction. At the end of part I suitable aggregate type, gradation and asphalt emulsion materials are selected. Part II is about developing a job mix formula for the selected materials in part I. Firstly, theoretical bitumen requirement (BR) is obtained by adding the percent bitumen required for an 8µm coating and the percent required for absorption. Percent bitumen required for an 8µm coating is determined by Surface Area Method. The water content for each BR level that results in a 2.5 cm flow is reported as optimum water content for each BR level. At this time, designers have three levels of Pure Asphalt Requirements (PAR), and the optimum water content for each PAR. Finally, optimum BR is selected. In order to do this, three mix formulations, which met the requirements of two already described compatibility tests, are selected for further testing using wet track abrasion (WTAT) and loaded wheel tests (LWT). The results of WTAT and LWT according to different level of asphalt cement are drawn on the same graph for a given amount of water, as well as maximum values of 807 g/m² for WTAT, and 538 g/m² for LWT (Figure 3.1). As it can be seen from Figure 3.1, the minimum asphalt emulsion is determined by wet track abrasion test. Then, loaded wheel test is used to establish maximum required asphalt emulsion for mixture, and the optimum asphalt content is the amount at the middle of those limits.

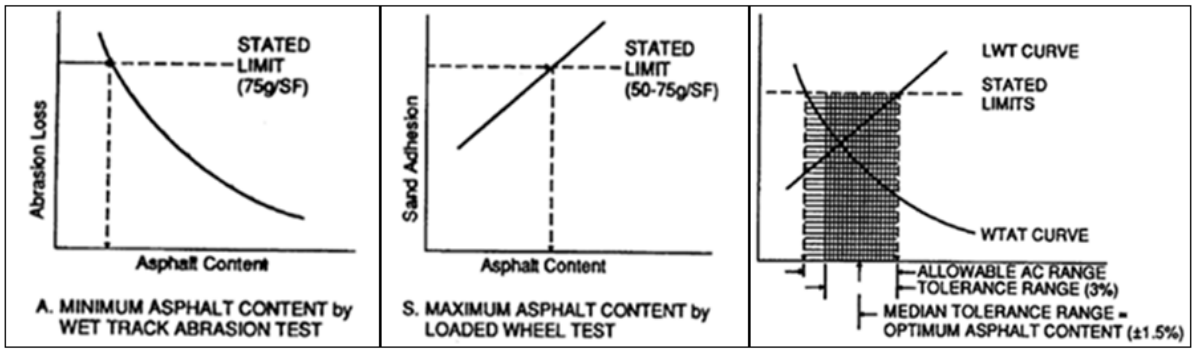

Figure 3.1 Graphical Determination of Optimum Asphalt Content
Extracted from ISSA (2004, p. 13)

ISSA A143 guidelines and specifications also use the above mentioned procedure to select the optimum amount of required bitumen for micro-surfacing mixtures. This time, however, mixing time test is run to determine the optimum water content at which mixture can be mixed at room temperature (77ºF or 25ºC) for at least 120 seconds.

Following a study on quality of micro-surfacing with the ISSA mix design procedure for micro-surfacing, Texas Transportation Institute (TTI) developed a new mix design procedure which is somewhat different from ISSA and ASTM mix design procedures (TTI, 1995). TTI mix design procedure for micro-surfacing recommends to only use of wet track abrasion test to select optimum bitumen content for mixture. Wet track abrasion test is performed for all emulsion/cement/water combinations to select the minimum bitumen content at which aggregate loss of sample is less than 807 g/m² (75g/ft²) for 6-day soaked samples (TTI, 2005). Then, the optimum asphalt content is determined at minimum bitumen content plus 0.5%. This 0.5% is to account for variability. TTI mix design procedure recommends that the modified cup flow test be performed for micro-surfacing mixtures to select the amount of added water content at which the separation of fluids and solids in mixture is greater than 5mm (0.2 in). Modified cohesion test is recommended by TTI to select optimum amount of Portland cement to obtain a cohesion torque greater than 12 kg-cm at 30 minutes and 20 kg-cm at 60 minutes.

3.3 Research Approach

It is reasonable to assume that the final properties of micro-surfacing is affected by mix proportions such as asphalt emulsion content, aggregates type, gradation, water and cement content. The amount of asphalt emulsion residue, added water, and cement content in the mixture greatly influences the magnitude of the test response for all the tests using to design micro-surfacing mixture. If the mix proportions are assumed to be selected perfectly, then the properties of mixture are not affected by mix proportions. Therefore, there is a need to develop the optimum mix design procedures, specifications, and guidelines for Micro-surfacing to improve the final properties of mixture by selecting the optimum amount of mix proportions.

The overall goal of this study is to improve the performance of micro-surfacing mixtures through the development of a rational mix design procedure, guidelines, and specifications. The purpose of the testing program of this study is first to validate the hypothesis that there is the optimum amount of mix proportions at which the mixture shows its excellent mix properties. This overall goal should be achieved with the use of micro-surfacing equipment with the following specific objectives:

1. To map the influence of asphalt emulsion, water, and cement contents on the properties and performance of micro-surfacing mixtures especially used in Quebec;

2. To evaluate some additional mix design tests to select optimum mix proportions for micro-surfacing mixtures.

3.4 Experimental Program

The first part of this study reports the findings of a detailed laboratory investigation concerning the effect of asphalt emulsion and added water content and the use of additives (1% Portland cement) on the design parameters and properties of micro-surfacing mixtures. For this, one aggregate type (Ray car), one asphalt emulsion type/grade (CQS-1HP), and one

gradation, were used in the study. The term CQS-1HP is the standard name for micro-surfacing emulsions used in the industry and it conforms to all ISSA specifications. CQS-1HP emulsion used in this project had 65.1% residual asphalt content. Other properties of CQS-1HP asphalt emulsions are listed in Table 3.1. This part of the study consisted mainly in establishing a method for preparing and testing micro-surfacing mixture using four mixture design tests proposed by the ISSA, which are ISSA TB 139 (ISSA, 2005c), ISSA TB 113 (ISSA, 2005d), ISSA TB 100 (ISSA, 2005e), ISSA TB 109 (ISSA, 2005f).

Table 3.1 Test Results on CQS-1HP asphalt emulsion ISSA Specifications

Tests	**Results**	**ISSA Specifications**	
		min	max
Viscosity @ 25°, SSF	28.0	20	100
Sieve,%	0.04	-	0.10
Coating Test,%	90.0	80.0	-
Residue by Distillation to 204.4°,% mass	65.1	62.0	-
Particle Charge	Positive	Positive	
Settlement, 5 day,%	0.9	-	5
Tests on Residue			
Softening Point by R 7 B, °C	63	57	-
Kinematic Viscosity @ 135°C, mm²/sec	1825	650	-
Penetration @ 25°C, 100 g, 5 sec	75	40	90
Ductility @ 25 °C, cm	110+	40	-

The second part of this study was about a modification to ISSA A-143 design procedure for micro-surfacing. With regard to the detailed laboratory findings obtained from the first part of study, the optimum mix design procedure for micro-surfacing was presented. The ISSA A-143 mix design procedure for micro-surfacing contains two parts, which are preliminary design consideration and job mix formula.

Modifications were conducted to the job mix formula, and preliminary design considerations remain unchanged. For this purpose, the ISSA TB 147 (ISSA, 2005g) mix design test was proposed to measure the resistance of mix against rutting deformation under heavy loading traffic.

The third part of study documented the validity of the new mix design procedure for three types of aggregates. Ray car, Graham Pitt, and rive-sud aggregates obtained in Quebec, were used in this part of study.

Mid-range type III aggregate gradation was selected, and 1% of Portland cement was used in all mixture specimens. Based on the modified job mix formula procedure suggested for micro-surfacing, mixture proportions were selected.

3.4.1 Dependent and Controlled Variables

Table 3.2 summarizes the matrix of experiment used in this study. A multilevel factorial design was selected. The aggregate type's materials were treated as qualitative factor while the other remaining factors were quantitative. The detailed results are presented in Robati 2011 (Robati, 2011).

Three asphalt emulsion and four added water content levels were used in the study. Three replicates for each asphalt emulsion-water combination were used in the study. As it was decided to use sieve analysis of aggregates in each sample, the repeatability of tests was perfect.

Table 3.2 Factor levels used in Design of experiment (DOE)

Factors	Levels of Factors			
	1	2	3	4
A: Emulsion Residue (%)	7.6	8.1	8.6	-
B: Added Water (%)	7	8	9	10
C: Cement (%)	0	1	-	-
D: Aggregate Type	Ray-Car	Rive-sud	Graham Pitt	-
Responses	Test			ISSA TB
	wet track abrasion loss, 1-Hour & 6-Day soaked			100
	cohesion at 30 minute and 60 minutes			139
	vertical deformation by Load Wheel Test			147-A
	sand adhesion by loaded wheel tester (LWT)			109
	remained coated area Wet Stripping Test			114
	Mixing Time Test			113
	percent Moisture retained in samples			-

3.5 Results and Discussion

Analysis of results was conducted using Analysis of Variance (ANOVA) by STAT Graphic software (version 10). Output of ANOVA is a model including independent variables (Factors) and dependent variable (Responses). The complete results are presented in appendix I.

In this model, those independent variables effect on dependent variables are determined by ANOVA at a specified confidence level. ANOVA uses R-square (R^2) to predict the future outcomes of the model on the basis of other related information.

Outputs of ANOVA used in this study are ANOVA table, standardized Pareto chart, main effect plot, and estimated response. ANOVA table show the statistical calculation of R-square, sum of square, mean of square, and F-value. Standardized Pareto charts show standardized effect of each effect group on the results.

The red line on standardized Pareto chart represents the estimated critical F-value. Main effect plot and estimated responses tabulate the actual effect of factors involved in study on the results.

3.5.1 Direct effects of factors on the responses

Figure 3.2 and 3.3 show the effect of asphalt emulsion on the responses. As it can be seen from Figure 3.2a asphalt emulsion residue and the amount of water in the mixture have profound influence on the sand adhesion test results. By changing only the quantity of water in the mixtures with the same quantity of emulsion, the amount of sand adhered increased or decreased. It appears that the amount of sand adhered to the sample is sensitive not only to the amount of asphalt emulsion, but also sensitive to the amount of added water in the mixture.

The primary purpose of LWT is to determine maximum limit for adding asphalt emulsion in the mixture and is used in ISSA TB 111 and ISSA TB 143 mix design procedures for slurry seal and micro-surfacing to determine optimum binder content. In these guidelines, the WTAT will be performed at 1-hour and 6-day soak periods followed by tests using the LWT to determine the excess asphalt at the temperature that corresponds to the proposed traffic conditions (i.e., heavy at 35°C, moderate at 25°C, and low at 15°C).

Finally, the optimum binder content is selected by evaluating the abrasion loss in the WTAT and the binder content versus pick up from the loaded wheel tester. Designer should prepare trial mixtures with different amount of asphalt emulsion and added water contents to perform loaded wheel test, while, the results of this test are significantly influenced by different amount of water in those trial mixes. Thus the consistency for the loaded wheel test is poor which implies that the test method is vague and permits a wide range of interpretation.

Figure 3.2b and 3.2c show the effect of asphalt emulsion and added water content on the Wet Track Abrasion test results (1-Hour and 6-Day Soaked Samples). By increasing in asphalt emulsion residue and added water content, aggregate loss decreases.

As it also can be seen from these figures the amount of water in the mixture has a profound influence on the aggregate loss of samples for both 1-Hour and 6-Day soaked tests. Thus the consistency for wet track abrasion test is poor, which may lead to inaccurate selection of

optimum binder content using ISSA TB 111 and ISSA TB 143 mix design procedures for slurry seal and micro-surfacing.

Figure 3.2d and 3.3a show the effect of asphalt emulsion and added water contents on the results of Relative Moisture Retained in Samples of LWT and WTAT. The results showed that the relative percent retained moisture after 24 hours curing, expressed as percent by weight of the initial available moisture (initial added moisture + water portion of asphalt emulsion) ranges between 1.11 and 2.5% for LWT samples, and 0.88 and 1.42% for WTAT samples. Also, for a specific amount of asphalt residue, the relative percent retained moisture in LWT samples after 24 hours curing increased as added water content increased. It has been mentioned that, for a specific amount of asphalt residue, when amount of added water content increased, sample adhere more sand and result of loaded wheel Test significantly increased. Primary reason for inconsistency of loaded wheel test (Sand Adhesion) results is increasing in moisture retained in sample by adding more water. However, it seems that the galvanized steel materials used in fabricating specimen mounting plates in loaded wheel test prevent moisture evaporation from mixture during cure process of specimen. Retained moisture in loaded wheel Test specimens was higher than that of retained moisture in Wet Track abrasion Test specimens, which uses saturated roofing felt materials.

Figure 3.3b shows the effect of asphalt emulsion and added water contents on the 30-min cohesion test results. Modified cohesion test results at 30 minutes shows that there was a specific asphalt emulsion residue content at which when the added water content increased, there observed an optimum amount of 30-min and 60-min cohesion, which is the maximum cohesion of the mixture.

However, for other asphalt emulsion residue content used in this study, as the water increased, the 30-min and 60-min cohesion of mixture decreased. For the aggregate gradation using in modified cohesion experiment, this asphalt emulsion residue content is equal to 8.1%. For the mixture with 8.1% asphalt residue and 8% water, mean cohesion of mixture at 30 minutes with 5 replicates is 16 kg-cm. As added water content increases to 9%, mean cohesion of mixture increases to 18 kg-cm. If added water content increases to 10%, mean cohesion of mixture at 30 minutes decrease to 16 kg-cm. Thus, it can be concluded that the

optimum water content is dependent of mixture cohesion. Maximum cohesion was occurred at 8% added water content and after that by increasing water content, cohesion decreases.

Figure 3.3c shows the effect of asphalt emulsion and added water content on the Vertical Displacement test. As it can be seen from this figure, there is an optimum amount of asphalt emulsion residue in which mixture shows its maximum resistance against vertical displacement (rutting).

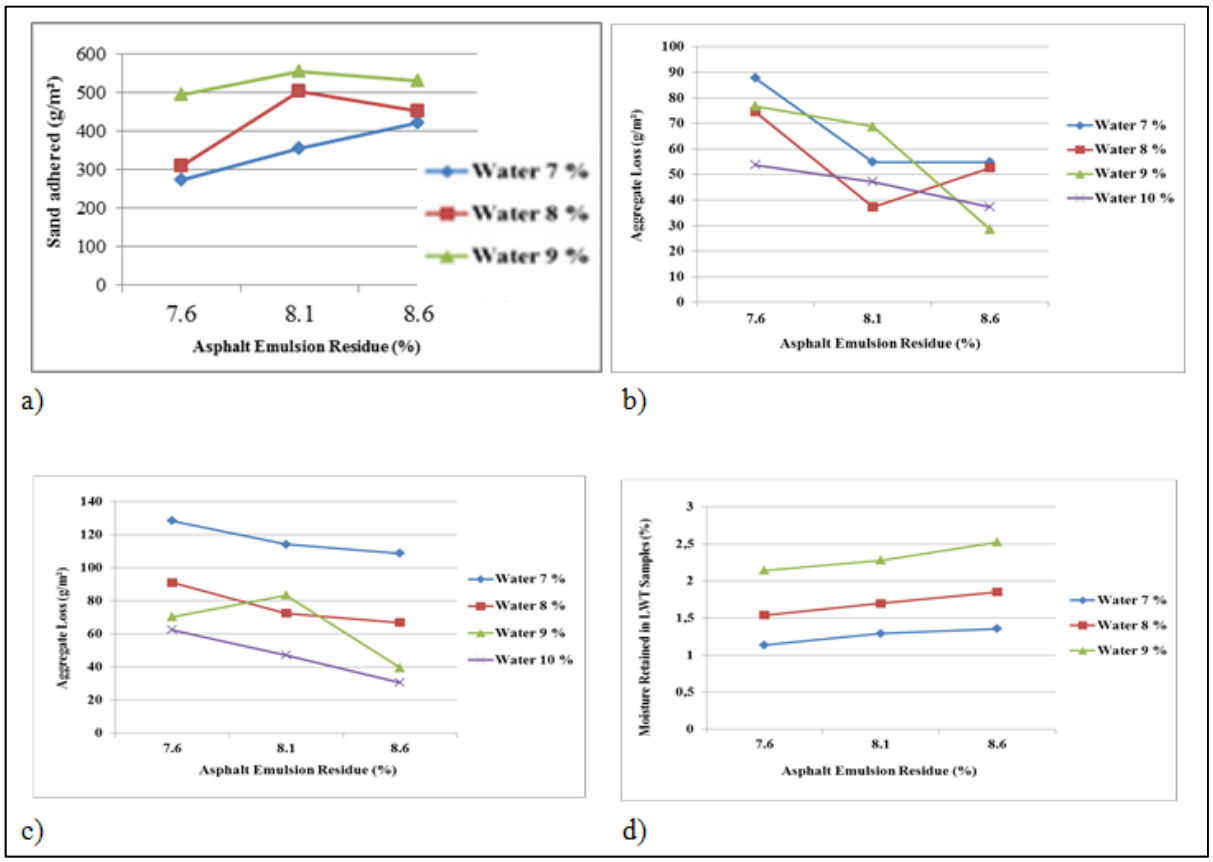

Figure 3.2 Effect of asphalt emulsion and water contents on a) sand adhered (Loaded Wheel Test), b) aggregate loss (WTAT 1-Hour Soaked), c) aggregate loss (WTAT 6-Day Soaked), d) retained moisture (Loaded Wheel test samples)

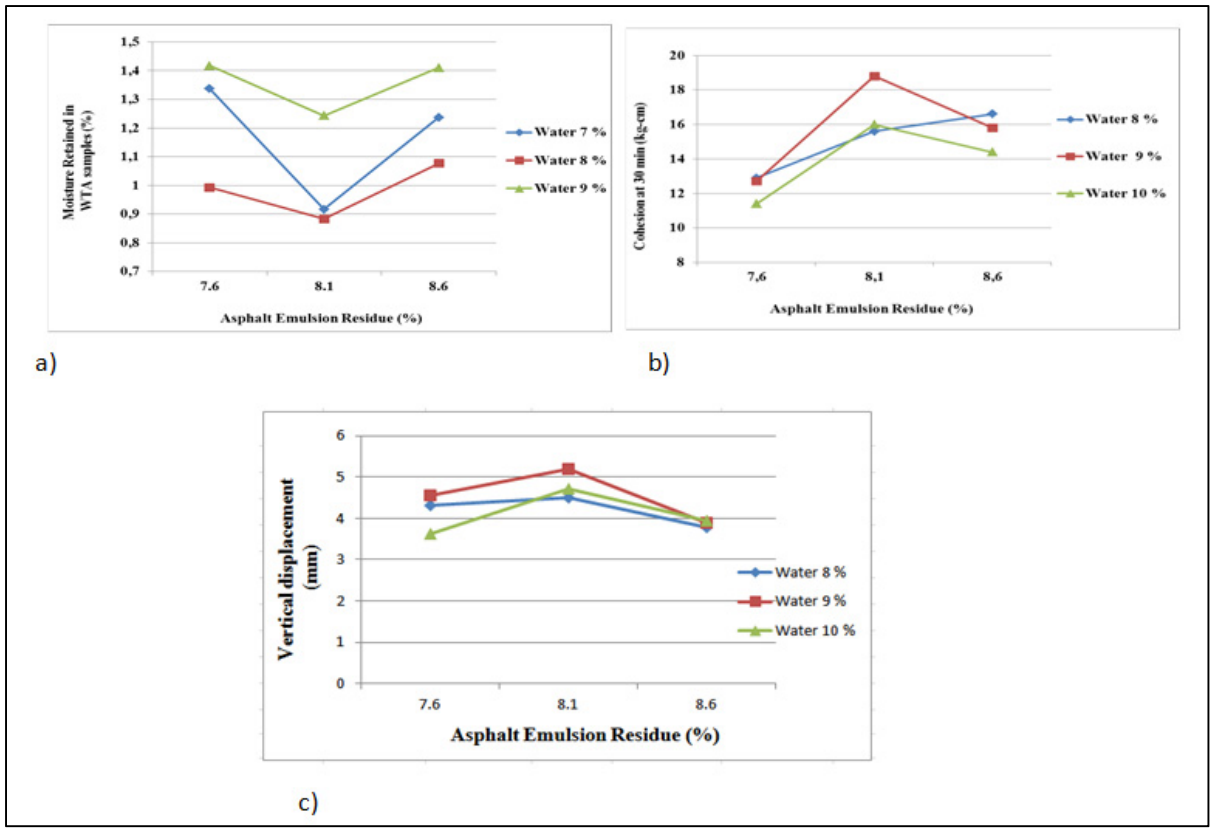

Figure 3.3 Effect of asphalt emulsion and water contents on: a) retained moisture (WTAT samples), b) Cohesion test at 30 min, and c) vertical displacement test

3.6 Analysis by mixture materials

Analysis by materials was performed in order to capture the standardized effect of asphalt emulsion and water on the test responses. This can help to check the sensitivity of testing results to change in asphalt emulsion and added water contents. Moreover, those mix design tests that can be used during the mix design procedure to select optimum mix proportions are identified. When analysis all the data together, it came that the asphalt emulsion and added water contents have major influences on the test responses (Table 3.3).

Results presented on the Table 3.3 show that the effects of asphalt emulsion and added water contents are significant on the testing results of LWT and WTAT. LWT and WTAT tests are used together to find optimum mix design proportions in ISSA standard. However, the results of these tests are sensitive not only to the asphalt emulsion content, but also, to the added

water content. This leads to a significant error to find the optimum mix proportions using the results of LWT and WTAT. Therefore, it is recommended to use alternative mix design tests to find the optimum amount of asphalt emulsion and water for micro-surfacing mixtures.
Table 3.3 shows that both asphalt and added water contents have high influence on the retained moisture in the mix. However, the effect of added water content on the LWT results is greater. The reason for that is the galvanized steel material used in fabricating specimen mounting plates in loaded wheel test, which prevent moisture evaporation from mixture during cure process of specimen. Thus, the retained moisture increases in the specimen as the added water content increase, and the risk of bleeding as a common distress in micro-surfacing mixtures increases.

Table 3.3 shows that how much the effect of added water content is well beyond of the critical F-value, and how much this effect is greater than the effect of asphalt emulsion residue on results of relative moisture retained in loaded wheel test samples.

Estimated F-value for the effects of asphalt emulsion residue content and its square amount are more than estimated critical F-value, which shows their significant effect on 30-min and 60-min cohesion of micro-surfacing mixtures. Effect of asphalt is higher than that of water, but, the effect of water on cohesion of mix, itself, is considerable. As it was already observed, there is an optimum amount of asphalt emulsion residue in which the mix shows its maximum resistance against vertical displacement, and the results shows minimum sensitivity to change in water content of mix, therefore, this test is suggested to be performed in order to select the optimum asphalt emulsion residue in the mix. While, the results of cohesion test can be used to select the optimum water content in the mix, because, it was already shown that there is optimum water content in the mix where mixture shows its maximum cohesion.

Table 3.3 Analysis of Variance

Loaded Wheel Test				
Source	**DDL**	**Mean Square**	**F-Ratio**	**P-Value**
A: Asphalt	1	53947.9	11.89	0.0087
B: Water	1	39662.8	8.74	0.0183
AB	1	9384.11	2.07	0.1884
Total error	8	4538.76		
Wet Track Abrasion Test (1-Hour Soaked)				
Source	**DDL**	**Mean Square**	**F-Ratio**	**P-Value**
A: Asphalt	1	1657.44	13.54	0.0051
B: Water	1	613.249	5.01	0.052
Total error	9	122.413		
Wet Track Abrasion Test (6-Day Soaked)				
Source	**DDL**	**Mean Square**	**F-Ratio**	**P-Value**
A: Asphalt	1	1657.44	12.88	0.0058
B: Water	1	6719.78	52.23	0.0000
Total error	9	128.656		
Retained Moisture in loaded wheel test samples				
Source	**DDL**	**Mean Square**	**F-Ratio**	**P-Value**
A: Asphalt	1	0.135	45.04	0.0005
B: Water	1	1.69602	565.86	0.0000
Total error	6	0.002997		
Retained Moisture in wet track abrasion test samples				
Source	**DDL**	**Mean Square**	**F-Ratio**	**P-Value**
A: Asphalt	1	0.00201667	0.2	0.6756
B: Water	1	0.0450667	4.54	0.1001
AA	1	0.113606	11.44	0.0277
BB	1	0.172089	17.33	0.0141
Total error	4	0.00992778		
Modifted Cohesion test at 30-min				
Source	**DDL**	**Mean Square**	**F-Ratio**	**P-Value**
A: Asphalt	1	15.0417	12.89	0.0229
B: Water	1	2.04167	1.75	0.2564
AA	1	15.125	12.96	0.0227
BB	1	3.125	2.68	0.1770
Total error	4	1.16667		
Modifted Cohesion test at 60-min				
Source	**DDL**	**Mean Square**	**F-Ratio**	**P-Value**
A: Asphalt	1	12.0417	11.26	0.0284
B: Water	1	0.375	0.35	0.5856
AA	1	17.0139	15.91	0.0163
BB	4	4.01389	3.75	0.1248
Total error	8	1.06944		
Mixing Time test				
Source	**DDL**	**Mean Square**	**F-Ratio**	**P-Value**
A: Asphalt	1	5890.67	84.52	0.0003
B: Water	1	15100.2	216.66	0.0000
AB	1	1560.25	22.39	0.0052
Total error	5	69.6944		

3.6.1 Results Summary

As it was just showed, the impact of the amount of asphalt residue and the amount of added water to micro-surfacing mixtures are quite important. A summary of the results presented in the previous sections is shown in table 3.4. Asphalt emulsion residue and added water content have a significant effect on the results of loaded wheel test, wet track abrasion test, mixing time test, and moisture retained in loaded wheel test.

Table 3.4 Results summary for all tests done on micro-surfacing shown in this chapter

Test	Significant effect of		Trend
	Added Water (W)	Asphalt Residue (A)	
Loaded wheel test	yes	yes	W ↑ : adhered sand ↑
			A ↑: adhered sand ↑
Wet track abrasion (1 hour soaked)	no	yes	W ↑: aggregates loss ↓
			A ↑: aggregates loss ↓
Wet track abrasion (6-day soaked)	yes	yes	W ↑: aggregates loss ↓
			A ↑: aggregates loss ↓
Mixing time	yes	yes	W ↑: mixing time ↑
			A ↑: mixing time ↑
Relative moisture retained (LWT samples)	yes	yes	W ↑ : moisture↑
			A ↑: moisture↑
Relative moisture retained (WTAT samples)	yes[1]	yes[2]	W ↑ : Presence of an optimum moisture content
			A ↑ : Presence of an optimum moisture content
Modified cohesion at 30 minutes (with or without cement)	no	yes[3]	W ↑ : cohesion ↓ (at 7,6 & 8,6 asphalt residue)
			W ↑: Presence of an optimum cohesion content (at 8,1 asphalt residue)
			A ↑ : Presence of an optimum cohesion
Modified cohesion at 60 minutes (with or without cement)	no	yes[4]	W ↑ : cohesion ↓ (at 7,6 & 8,6 asphalt residue)
			W ↑ : Presence of an optimum cohesion (at 8,1 asphalt residue)
			A ↑ : Presence of an optimum cohesion

[1] Significant effect of square amount of water
[2] Significant effect of square amount of asphalt emulsion residue
[3] Significant effect of asphalt emulsion and its square amount
[4] Significant effect of asphalt emulsion and its square amount

As for modified cohesion test (30-min and 60-min), asphalt emulsion residue and its square amount has a significant effect. For the moisture retained in wet track abrasion test samples, square amount of asphalt emulsion residue and added water content have a significant effect. It is important to note that those results are valid only for the different materials used in this study. If one uses another type of emulsion which reacts differently with another type of aggregates, the results may vary. The results are also only valid in the range of added water and asphalt emulsion used in this study. On the other hand, the different values that were used are commonly used amount and are the quantities that give overall optimum results.

3.6.2 Modification to ISSA A-143 Design Procedure

A Study of ISSA mix design tests for micro-surfacing was conducted to select optimum mix design procedure. The amount of asphalt emulsion residue and added water content in the mixture greatly influences the magnitude of the test response for all the tests investigated in this report. Mix design procedure for micro-surfacing suggested by ISSA to select optimum asphalt emulsion is based on loaded wheel test and wet track abrasion tests. In this method, the optimum asphalt emulsion is selected by evaluating the abrasion loss in the wet track abrasion tests versus pick up from the loaded wheel tester. Based on statistical analysis of detailed laboratory findings in this research, consistency for the loaded wheel test and wet track abrasion test is poor. The amount of water in the mixture had a profound influence on the sand adhered in sample of loaded wheel test, and aggregate loss in samples of wet track abrasion tests. However, the consistency for modified cohesion test is good, and the test can be used to select the optimum water content. The test should be performed at all asphalt emulsion/cement combinations used in the mixing test. The optimum water content for each of asphalt emulsion/cement combinations is selected at 30 minutes and 60 minutes cohesion. Those asphalt emulsion/cement/water combinations that show maximum cohesion at 30 and 60 minutes are selected for further testing following the mixing test to ensure minimum 120 seconds of mixing time at 25ºC (77ºF) for each of emulsion/cement/water combinations. As the main application of type III micro-surfacing is filling ruts in areas with heavy traffic, optimum asphalt emulsion content is selected for maximum rutting resistance. Following is

preliminary design considerations and suggested job mix formula procedures for micro-surfacing (see figure 3.4 and 3.5):

Preliminary design considerations

1. Describe the pavement to be treated: This includes providing information about surface condition, and climate conditions;

2. State objective of surface treatment: This mix design procedure is suggested for maximum rutting resistance in areas with heavy traffic;

3. Evaluate and select materials: The aggregate has to conform to grade III gradation suggested by ISSA mix design procedure. Mineral filler, and asphalt emulsion have to conform to specifications suggested by ISSA mix design procedure for micro-surfacing.

Job Mix Formula Procedures

1. Estimate Bitumen Requirement by surface area method for 8µm coating: Bitumen requirement can also be selected based on designer experience, for type III micro-surfacing. 12.5% asphalt emulsion (expressed by total weight of aggregates) is suggested;

2. Selection of three levels of asphalt emulsion content: These three levels of asphalt emulsion are bitumen requirement determined by surface area method ± 0.75%;

3. Estimate minimum water content: Filler/additives content is selected and added to aggregates. Mixing time test (ISSA TB 113) is run for each of mixtures with three different levels of asphalt emulsion to determine minimum added water content at which mixture can be mixed at room temperature (77ºF or 25ºC) for at least 120 seconds;

4. Conduct compatibility tests: Determination of aggregate filler-bitumen compatibility for each of three asphalt emulsion/filler/water combinations by Schulze-Breuer procedure or wet stripping tests;

5. Selection of optimum water content: The optimum water content for each of asphalt emulsion/filler combinations is selected at maximum 30 min and 60 min cohesion;

6. Selection of optimum asphalt emulsion: Test method for measurement of stability and resistance to compaction, vertical and lateral displacement of multilayered fine aggregate cold mixes (ISSA TB 147- Method A) is conducted for those asphalt emulsion/filler/water combinations having greater amount of 30-min and 60-min cohesion. Optimum emulsion content for rutting resistance can be determined at the minimum vertical and lateral displacements after 1000 cycle compactions of 56.7 kg load.

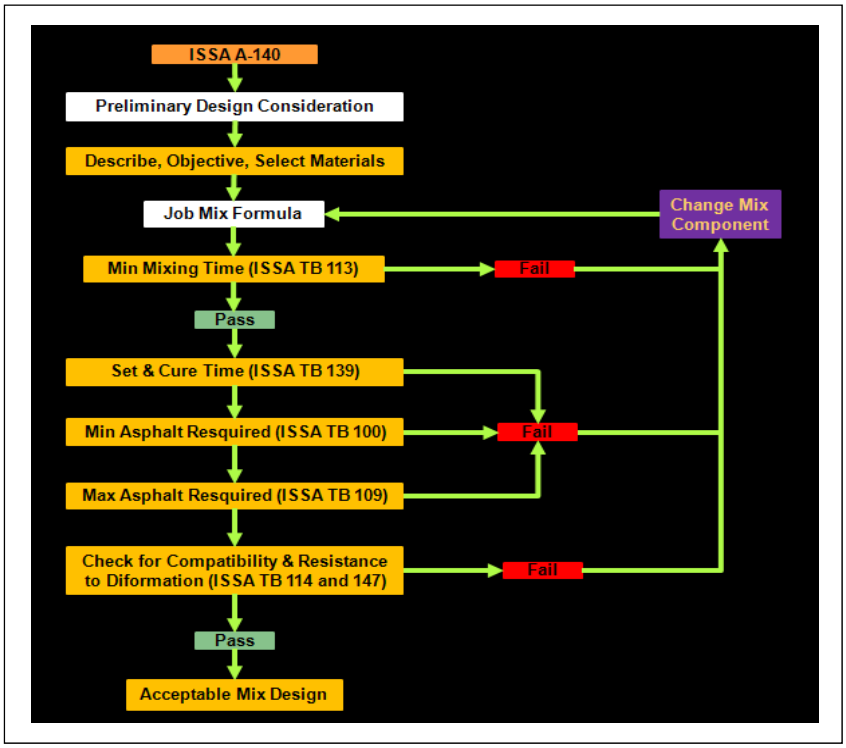

Figure 3.4 Flowchart of ISSA mix design procedure for micro-surfacing

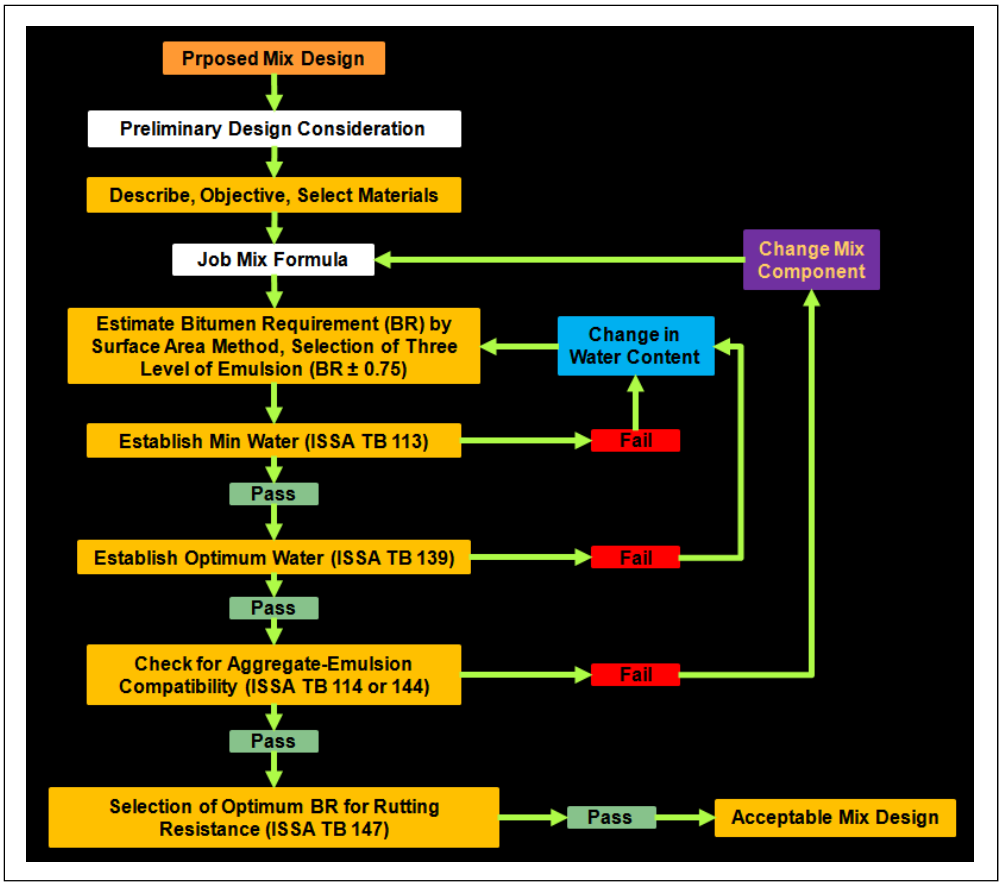

Figure 3.5 Flowchart of proposed mix design procedure for micro-surfacing

3.7 Validate Modification Design Procedure

Raycar, Graham Pitt, and rive-sud aggregates obtained from Quebec. Canada, were used in this part of study. Rive-sud aggregates were represented of limestone, while, Grahampitt and Raycar were granit types. Aggregate sizes range from 0-5 mm. Mid-range type III aggregate gradation was selected, and 1% of Portland cement was used in all mixture specimens. Based on job mix formula procedure suggested for micro-surfacing in section 4.5, mixture proportions were selected. Three levels of asphalt emulsion were bitumen requirement ± 0.75%. These three levels were 11.75, 12.5, and 13.25% (expressed by total weight of aggregates) asphalt emulsion. As CQS-1HP asphalt emulsion included 65% asphalt residue, these three levels of asphalt emulsion include 7.6, 8.1, and 8.6% asphalt emulsion residue

respectively. 1% cement was added to aggregates and mixing time test (ISSA TB 113) was run for each of mixtures to determine the minimum added water content at which a mixture can be mixed at room temperature (25ºC or 77ºF) for at least 120 seconds. Based on this test, Raycar aggregates required minimum of 9% water for each of 7.6, 8.1, and 8.6% asphalt residue content at which mixture can be mixed at room temperature (77ºF or 25ºC) for at least 120 seconds. The minimum added water content for Graham Pitt and rive-sud aggregates were 4 and 11% respectively.

Determination of aggregate filler-bitumen compatibility for each of three asphalt emulsion/filler/water combinations having mixing time greater than 120 seconds was conducted by wet stripping tests. This test is designed to help designer to select a compatible slurry system with a given aggregate. Wet stripping test results for raycar aggregates ranged from 95.5-97.5%. Graham Pitt ranged from 92.5-94%, and for rive-sud aggregates ranged from 90.5-93.5%, which are acceptable testing results based on ISSA mix design procedure for micro-surfacing.

All three levels of asphalt emulsion with 1% cement at minimum required water result in mixing time more than 120 seconds were compatible with raycar, Graham Pitt, and rive-sud aggregates, however, raycar aggregates were more compatible with three selected asphalt emulsion/water formulations.

The optimum water content for each of asphalt emulsion/filler combinations were selected at maximum 30 min and 60 min cohesion. 30-min cohesion of mixtures prepared using Raycar, Graham Pitt, and rive-sud aggregates ranged from 12.8 to 13.2 kg-cm at 7.6% asphalt emulsion residue and optimum added water content. However, cohesion of these mixtures at 8.1 and 8.6% asphalt emulsion residue and optimum added water content respectively ranged from 18-18.8 and 16.4 to 16.8 kg-cm. Thus. It can be concluded that for all three types of aggregates, mixtures with 8.1 and 8.6% asphalt emulsion residue had greater amount of 30-min and 60-min cohesion than mixtures with 7.6% asphalt emulsion residue. Therefore, optimum binder content should be selected between 8.1 and 8.6% asphalt emulsion residue for all three types of aggregates.

Test method for measurement of stability and resistance to compaction, vertical and lateral displacement of multilayered fine aggregate cold mixes (ISSA TB 147- Method A) were run for mixtures with 8.1 and 8.6% asphalt emulsion residue to select optimum binder. From the results obtained, it was observed that mixtures prepared using raycar aggregates show relatively better rutting resistance as compared with the mixtures prepared with Graham Pitt and rive-sud aggregates. Samples made with rive-sud aggregates show least rutting resistance. It may be because raycar aggregates are more compatible with CQS-1HP asphalt emulsion, while, rive-sud aggregates that contained lime stone filler were less compatible with CQS-1HP asphalt emulsion. Based on ISSA mix design procedure for micro-surfacing, for design to be accepted, lateral and vertical displacements at mid-length of specimen, after 1000 cycles of 56.7 kg load, must be less than 5% and 10% of original width and length at mid-length of specimen respectively. Lateral and vertical displacements at mid length of specimens prepared using Ray car aggregates were respectively equal to 5% and 10% of original width and thickness at mid-length of specimen as the number of cycles of 56.7 kg load approached to 3000 cycles. However, for Graham Pitt and rive-sud, lateral displacement were less than 5% and 10% of original width and thickness at mid-length of specimen as the number of cycles of 56.7 kg load approached to 2000 cycles.

Figure 3.6 shows vertical displacements at mid-length of specimens prepared using 8.1% and 8.6% asphalt emulsion residue. As it can be seen from this figure, vertical displacements of samples prepared with 8.1% asphalt emulsion residue were less than 5% and 10% of original width and thickness at mid-length of specimens made by raycar, Graham Pitt, and rive-sud aggregates.

For samples prepared with 8.6% asphalt emulsion residue, lateral and vertical displacements, after 1000 cycle compactions of 56.7 kg load, were beyond limits specified with ISSA TB 147 mix design test (Method A). It can be concluded that the amount of optimum binder content for micro-surfacing mixtures can be selected from the results of loaded wheel test.

Finally, optimum emulsion content for rutting resistance can be determined at the minimum vertical and lateral displacements after 1000 cycle compactions of 56.7 kg load. Therefore,

8.1% asphalt emulsion residue was selected as optimum asphalt emulsion residue content for maximum rutting resistance.

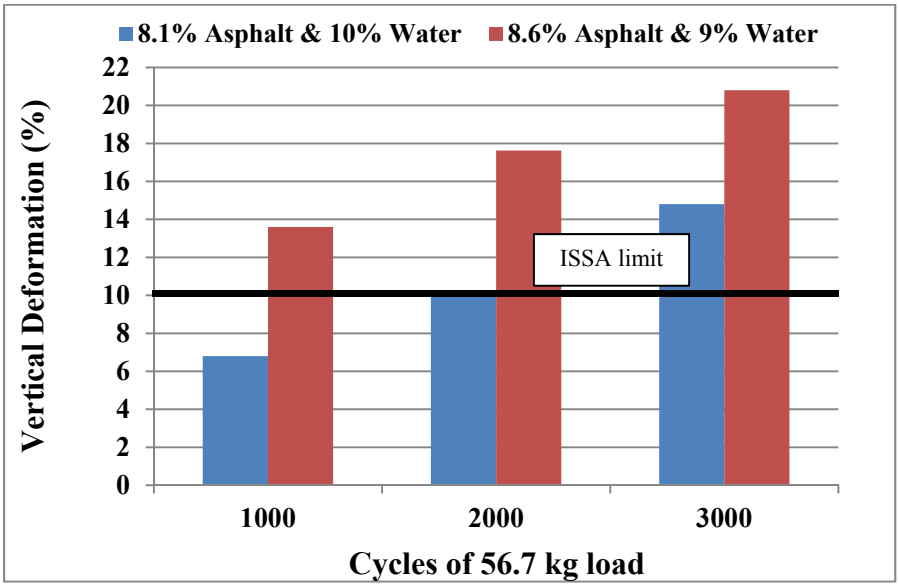

Figure 3.6 Vertical displacement test results, Ray car aggregates

3.8 Conclusion

The overall goal of this part of study was to improve the performance of micro-surfacing mixtures through the development of a rational mix design procedure, guidelines, and specifications. This was achieved thru a two parts experimental program. In the first part, the influence of different parameters was studied and the sensitivity of different tests was evaluated. Then, in the second part, modifications to ISSA mix design procedure for selecting optimum mix design proportions were suggested. Based on statistical analysis of the findings, the following conclusions are submitted:

1. Total amount of water in micro-surfacing mixtures appears to have a profound influence on the results of loaded wheel test and wet track abrasion tests (1-hour and 6-day soaked samples). The effect of added water content on 6-day wet track abrasion test results was much greater than the effect of asphalt emulsion residue. At the same amount of asphalt emulsion in mixtures, as the added water content increased, the amount of sand adhered

in loaded wheel test increases and the amount of aggregate loss in wet track abrasion test also increases. Selecting the optimum asphalt emulsion content by evaluating the abrasion loss in the wet track abrasion test versus pick up from the loaded wheel tester, is not precise enough;

2. The use of galvanized steel as specimen mounting plates in loaded wheel test do not allow water to evaporate through the curing process of mixture. Study of relative moisture retained in loaded wheel test samples after 24-hours curing show that as the asphalt emulsion and added water content increased, the retained moisture in samples was also increased and subsequently the amount of sand adhered in loaded wheel test increased. Results of relative moisture retained in wet track abrasion test after 24-hours curing evident that as the asphalt emulsion and added water content increases, there observed an optimum amount of relative moisture retained in WTAT samples;

3. Selection of optimum asphalt emulsion should be based on results obtained from test method for measurement of stability and resistance to compaction, vertical and lateral displacement of multilayered fine aggregate cold mixes (ISSA TB 147- Method A). Optimum emulsion content for rutting resistance can be determined at the minimum vertical and lateral displacements after 1000 cycle compactions of 56.7 kg load;

4. Selection of optimum water content for micro-surfacing mixtures should be based on results obtained from modified cohesion test (ISSA TB 139). The optimum water content for different asphalt emulsion/filler combinations should be selected at maximum 30 min and 60 min cohesion of mixture;

5. Regardless of the type of aggregates or filler that is used in preparing micro-surfacing mixtures, there is a specific asphalt emulsion residue content at which if the added water content increases, there will observe an optimum amount of 30-min and 60-min cohesion, which is the maximum cohesion of mixture. However, for other asphalt emulsion residue content, as the water increases, the 30-min and 60-min cohesion of mixture decreases.

This specific asphalt emulsion residue content seems to be the optimum emulsion content for mixture. There is other asphalt emulsion content at which 30-min and 60-min cohesion of mixture are also maximized. Optimum asphalt emulsion residue for mixture is selected based on maximum rutting resistance of the mixtures;

6. Mixtures prepared using Ray car aggregate, that may be more compatible with CQS-1HP asphalt emulsion rather than other aggregates types used in study, showed relatively better rutting resistance. Therefore, it can be concluded that compatibility between aggregates and asphalt emulsion does play an important role in micro-surfacing mixture design procedure and evaluation;

7. The 30-min and 60-min cohesion of micro-surfacing mixtures despite the types of aggregates used is maximized at a specific asphalt emulsion residue. It was observed that the 30-min and 60-min cohesion of micro-surfacing mixtures is not being affected by types of aggregates used in preparing mixture. Adding a little more or less asphalt emulsion than the optimum amount can be lead to cohesion loss.

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CHAPTER 4

EVALUATION OF TEST METHODS AND SELECTION OF AGGREGATES GRADING FOR TYPE III APPLICATION OF MICRO-SURFACING

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4.1 Abstract

Micro-Surfacing is a polymer modified, binder emulsion based, dense graded, cold mixed, and quick setting, asphalt resurfacing material. Type III application of micro-surfacing is used as the rut fill materials for highly trafficked roads. As of now, International Slurry Surfacing Association (ISSA) mix design guideline is the widely used standard to design micro-surfacing mixtures. The research described in this paper intended to suggest modifications to the actual ISSA mix design procedure to accurately select aggregate grading for type III micro-surfacing mixtures. To do this, a sensitivity analysis was performed in order to study the effect of aggregate gradation, and binder emulsion residue on five micro-surfacing mixture design tests, including Loaded wheel test (ISSA TB 109), Wet track abrasion test (ISSA TB 100), modified cohesion test (ISSA TB 139), vertical displacement test (ISS TB 109, Method-A), and Mixing time test (ISSA TB 113). The second part of study consisted mainly of establishing a limit for the aggregate gradation used in type III application of micro-surfacing, which gives higher resistance to rutting as it is the main property of type III micro-surfacing. In order to do this, the resistant of different micro-surfacing mixtures against rutting was evaluated, and modified specifications were suggested to select aggregate grading for type III micro-surfacing.

4.2 Introduction

Pavement preservation is defined as a program employing a network-level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety, and meet motorist expectations (FHWA, 2005). Actions used for pavement preservation include routine maintenance, preventive maintenance (PM), and corrective maintenance (Uzarowski et al, 2007). Transportation agencies use chip seal, slurry seal, micro-surfacing, cape seal, fog seal, etc.

Micro-surfacing was developed in an attempt to form a thicker slurry seal that could be used in wheel paths, and ruts in order to avoid long rehabilitation work on high traffic roads. To do this, high quality aggregates, and advanced binder emulsions were incorporated in order to reach a stable product, which is applied in multi-stone thickness, and provide rutting resistance. Micro-surfacing was also pioneered in Germany, in the late 1960s and early 1970s (International Slurry Surfacing Association, 2011). Micro-surfacing was the result of combining highly selected aggregates, and binder emulsion modified with incorporating special polymers. The binder emulsion also includes emulsifiers that allowed the aggregate-binder emulsion product to remain stable even when applied in multi-stone thicknesses.

Micro-surfacing was introduced in the United States in 1980, as a cost-effective way to treat the surface wheel-rutting problem and a variety of other road surface problems (International Slurry Surfacing Association, 2011). Micro-surfacing is applied in double layer for addressing surface irregularities. Moreover, micro-surfacing has variety of applications where fast traffic times are of concern. It also can apply on concrete bridge decks, airports runways and night works.

4.3 Background

Several mix design guidelines have already been developed to design micro-surfacing mixtures. International Slurry Surfacing Association (ISSA), Texas Transportation Institute (TTI), American Society for Testing and Materials (ASTM), and California Department of

Transport (Caltrans) developed their own mix design procedures for micro-surfacing. However, ISSA A-143 (ISSA A-143, 2005) guideline, and specification is the most widely used mix design procedure for micro-surfacing.

The components of the mixture are tested first. Based on this standard, aggregate gradation for the micro-surfacing mixture has to conform to one of the two gradations given in Table 4.1. It should be noted that Type III aggregate gradation is coarser, and more appropriate for application of micro-surfacing to fill rut on road areas with high traffic loading.

Table 4.1 ISSA Type II and III aggregate gradation for Micro-surfacing
Extracted from ISSA A-143 (2005, p. 13)

Sieve Size		Proportion Passing (% by mass)		Stockpile Tolerance,%
In	mm	Type II	Type III	
3/8	9.500	100	100	
No. 4	4.750	90-100	70-90	+/- 5
No. 8	2.360	65-90	45-70	+/- 5
No. 16	1.180	45-70	28-50	+/- 5
No. 30	0.600	30-50	19-34	+/- 5
No. 50	0.300	18-30	12-25	+/- 4
No. 100	0.150	10-21	7-18	+/- 3
No. 200	0.075	5-15	5-15	+/- 2

ASTM D 6372-99a (ASTM, 1999) is the most widely used procedure for the design of micro-surfacing. This mix design procedure recommends exactly the same aggregate grading with that of suggested by ISSA. Texas Transportation Institute (TTI) recommended a new mix design procedure for micro-surfacing in early 1994 (TTI, 2005).

Following a study on the reliability of determining mixture quality of micro-surfacing with the ISSA mix design procedure for micro-surfacing, they developed a new mix design procedure which is somewhat different from ISSA and ASTM mix design procedures.

Similar to other ISSA and ASTM procedures, the components of the mixture are tested first. The gradations proposed by TTI are shown in Table 4.2.

Table 4.2 TTI Type II and III aggregate gradation for Micro-surfacing
Extracted from TTI (2005, p. 50)

Sieve Size		**Proportion Passing (% by mass)**		**Stockpile Tolerance (%)**
In	**Mm**	**Type II**	**Type III**	
3/8	9.500	100	100	+/- 5
No. 4	4.750	98-100	99-100	+/- 5
No. 8	2.360	75-90	45-65	+/- 5
No. 16	1.180	50-75	25-46	+/- 5
No. 30	0.600	30-50	15-35	+/- 3
No. 50	0.300	18-35	10-25	+/- 3
No. 100	0.150	10-21	7-18	+/- 3
No. 200	0.075	5-15	5-15	+/- 2

It should be noted from Table 4.2 that the aggregate gradation recommended by TTI design procedure for micro-surfacing is different from the gradations recommended by ISSA and ASTM. These aggregate gradations are finer for sieve sizes 3/8 in to #16 than those used in ASTM and ISSA methods.

Caltrans developed a single mix design procedure for both slurry seal and micro-surfacing (CALTRANS, 2004). Caltrans research team considers that the procedures are the same for both slurry seal and micro-surfacing systems. Similar to other mix design procedures, the components of the mix are tested first.

Aggregate gradation, binder emulsion, and their chemical characteristics have to conform to ISSA specification for slurry seal and micro-surfacing. Other countries such as Germany, France, United Kingdom, and South Africa have had experience with Slurry Seal and Micro-

surfacing systems, and have developed specific guidelines for their specific use. Transport Quebec from Canada developed its own mix design procedure for micro-surfacing.

However, among all these guidelines, ISSA and ASTM are commonly used mix design guidelines worldwide.

4.4 Objectives

The first objective of this study was to examine the effect of aggregate gradation, and binder emulsion residue on the properties of micro-surfacing mixtures. Three different aggregate gradations and three levels of binder emulsion residues were used in the first part of this study to formulate different micro-surfacing mixtures.

The gradations were selected within the ISSA gradation size limit for type III micro-surfacing to fill rutting distresses on surface pavement of roads located at areas subjected to high traffic loading. The goal was to formulate, and evaluate a micro-surfacing mixture with maximum resistance to rut permanent deformation.

The second objective of this study was to recommend specification to select aggregate grading for type III micro-surfacing. The goal was to evaluate the effect of aggregate grading on properties of micro-surfacing mixtures, and to modify the existing ISSA specification to select aggregate gradation for type III micro-surfacing mixture as high quality rut filling materials.

4.5 Materials used in study

All the materials used in the sample preparation represent typical materials utilized for micro-surfacing projects in Quebec. The aggregates used in the study were Ray-Car (0-5 mm), obtained from Quebec, Canada, with same gradation satisfies type III requirements for aggregate gradation of ISSA mix design guideline.

Virgin aggregates was washed through sieve #200 to remove all their filler content and dried in an oven to a constant weight for a period of 24 hours. The temperature of oven was set at 60°C to dry virgin aggregates. Materials were then cooled at room temperature and screened through sieves number 3/8 (9.5 mm), 4 (4.75 mm), 8 (2.5 mm), 18 (1.25 mm), 16 (0.63 mm), 30 (0.6 mm), 50 (0.315), 100 (0.16 mm), and 200 (0.08 mm) respectively to obtain desired UG, MG, and LG gradations within the maximum and minimum aggregate gradation limits suggested by ISSA for type III Micro-surfacing application.

Filler were obtained from DJL Construction Company in Montreal, Quebec. In all micro-surfacing mixtures prepared in this study, desired amount of commercial filler were added to aggregates in order to obtain desire aggregate gradation.

All the mix components such as amount of added water, binder emulsion residue, aggregate, and Portland cement were selected based on a new mix design procedure developed by writer (Robati, 2011).

Figure 4.1 and Table 4.4 show the gradation curves, and ISSA standard for the aggregates used in this study. The first gradation, MG, follows the middle of maximum and minimum aggregate gradation limits suggested by ISSA for Type III Micro-surfacing application and is considered as mid-range aggregate gradation.

The second gradation, UG, follows the between the middle and upper limit of the type III gradation band for micro-surfacing. The third gradation, LG, was selected between the middle, and the lower limit of the type III gradation.

Using these three gradations, it was possible to provide better handling, and control of the micro-surfacing mixture properties. The total aggregate surface area was calculated using specific factors recommended by ISSA in Table 4.3.

Table 4.3 Factors Used in Calculating Surface Area of Slurry Seal Aggregate (ISSA TB 111, 2011)

Sieve No & Size		Surface Area Factors	
in	mm	ft^2/lb	m^2/kg
3/8	9.500	2	0.41
No. 4	4.750	2	0.41
No. 8	2.360	4	0.82
No. 16	1.180	8	1.64
No. 30	0.600	14	2.87
No. 50	0.300	30	6.14
No. 100	0.150	60	12.29
No.200	0.075	160	32.77

Table 4.4 Gradations of the aggregates used in this study

Sieve No & Size		% Passing by Weight				Stockpile Tolerance,%
in	mm	UG	MG	LG	Type III	
3/8	9.500	100	100	100	100	–
No. 4	4.750	91	88	84	70-90	+/- 5
No. 8	2.360	69	63	56	45-70	+/- 5
No. 16	1.180	49	44	38	28-50	+/- 5
No. 30	0.600	36	33	29	19-34	+/- 5
No. 50	0.300	26	23	19	12-25	+/- 4
No. 100	0.150	17	14	10	7-18	+/- 3
No.200	0.075	12.5	10	7.5	5-15	+/- 2
Total Aggregate Surface Area (m^2/kg)		11	9.2	7.4	–	–

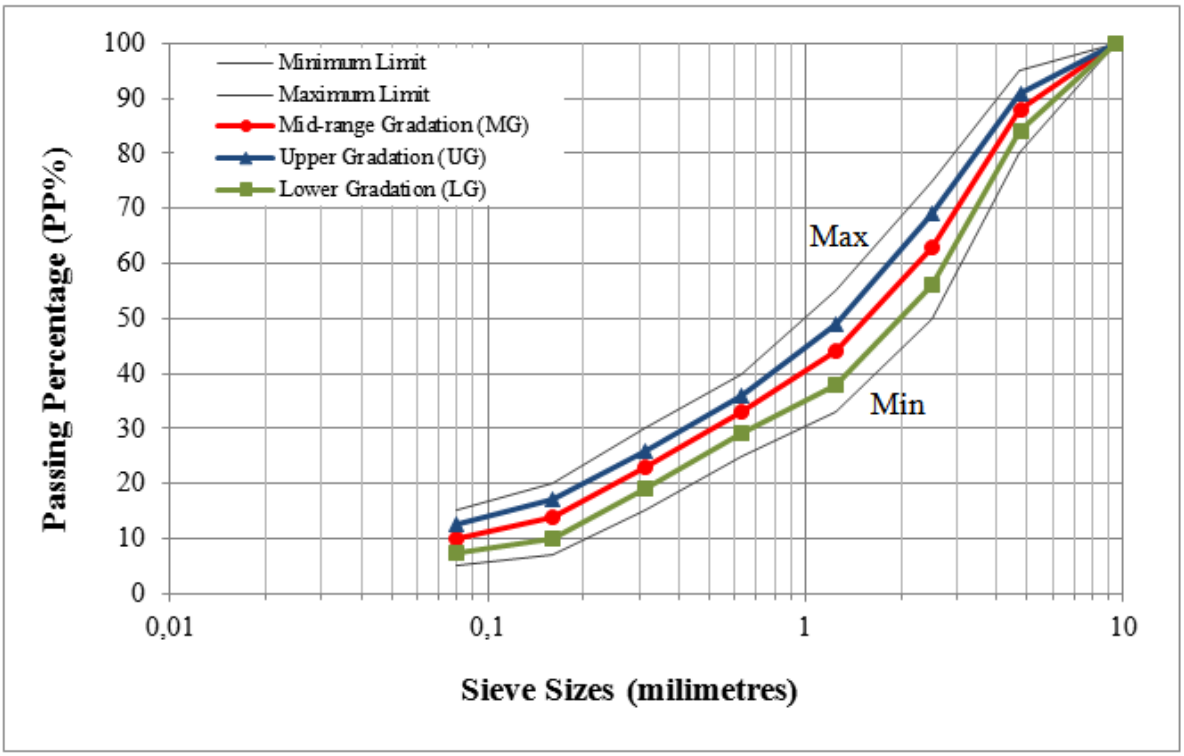

Figure 4.1 Upper, Lower, and Middle aggregate gradation curves (0-5 mm size)

The binder emulsion type used in all cases is a special cationic quick setting, low viscous binder emulsion, with a hard base binder, which is modified with styrene butadiene rubber (SBR) polymer in the form of latex liquid. CQS-lHP is the commercial name of this binder emulsion, which was bought from McAsphalt Industries Limited in Montreal.

In designing micro-surfacing mixtures base on ISSA specifications, the residual binder content of the emulsion must be more than 62.0%. CQS-1HP binder emulsion used in this study has 65.1% residual binder content, according to test results provided by McAsphalt Engineering Services. Other properties of CQS-1HP binder emulsion have been listed in Table 4.5.

As it can be seen from table 4.5, the binder emulsion used in this study is considered as a low viscous emulsion, which has high ability of coating the aggregates. This specially designed

binder emulsion break and set quickly in contact with aggregate surface area, so that, the road surface treated with micro-surfacing mixture can be open to the traffic in less than an hour after repair. The CQS-1HP binder emulsion can be used for slurry seal, Type II and III micro surfacing as the pavement preservation and surface treatment methods.

Table 4.5 CQS-1HP Binder Emulsion properties from supplier

Tests	**Results**	**ISSA Specifications**		
		min		**max**
Viscosity @ 25°, SSF	28.0	20		100
Sieve,%	0.04	-		0.10
Coating Test,%	90.0	80.0		-
Residue by Distiliation to 204.4°,% mass	65.1	62.0		-
Particle Charge	Positive	Positive		
Settlement, 5 day,%	0.9	-		5
Tests on Residue				
Softening Point by R 7 B, °C	63	57		-
Kinematic Viscosity @ 135°C, mm²/sec	1825	650		-
Penetration @ 25°C, 100 g, 5 sec	75	40		90
Ductility @ 25 °C, cm	110+	40		-

4.6 Experimental design (dependent and controlled variables)

The first part of this study reports the findings of a detailed laboratory investigation concerning the effect of aggregate gradation, and binder emulsion residue on the design parameters, and properties of micro-surfacing mixtures. To do this, one aggregate type, three different aggregate gradations (UG, MG, and LG), and three level of binder emulsion residue were involved in the study in order to formulate nine different micro-surfacing mixtures. Emulsified binder was kept constant to only investigate the effect of aggregate gradation, and binder emulsion on the properties of micro-surfacing mixtures. No Portland cement additives were used in mixtures.

The second part of study consisted mainly of establishing a limit for the aggregate gradation used in Type III micro-surfacing, which gives higher resistance to rutting. To do this, the resistant of prepared mixtures against rutting is evaluated. Table 4.6 and 4.7, show the experimental design used in phase one and two of this study. A multilevel factorial design was selected. The aggregate gradation's materials were treated as qualitative factor while the other remaining factors were quantitative.

Table 4.6 Design of Experiment (DOE), Factors involved in study

Factors	**Levels of Factors**		
	1	**2**	**3**
A: Aggregate gradation	UG	MG	LG
B: Binder Emulsion Residue (%)	7.6	8.1	8.6

Table 4.7 Design of Experiment (DOE), Responses involved in study

	Test	**ISSA TB**
Responses	Wet track abrasion loss, 1-hour & 6-day soaked	100
	Cohesion at 30 min and 60 min	139
	Vertical and lateral deformation by LWT	147-A
	Sand adhesion by loaded wheel tester (LWT)	109
	Percent moisture retained in samples	-
	Mix time	113

Table 4.8 shows, the proportions of each of 9 micro-surfacing mixture formulations used in first part of study. Table 4.9 represents a sample of mix design formulation used to prepare micro-surfacing mixture with MG gradation, and 12.5% binder emulsion.

Table 4.8 Mix design formulation used for different tests

Mixture No.	Aggregate Gradation	Binder Emulsion Residue (%)	Added Water Content (%)
1	MG	7.64	9
2	LG	7.64	9
3	UG	7.64	9
4	MG	8.13	9
5	LG	8.13	9
6	UG	8.13	9
7	MG	8.62	9
8	LG	8.62	9
9	UG	8.62	9

Table 4.9 A sample of mix design formulation used for micro-surfacing mixture prepared using MG gradation, and 12.5% binder emulsion

Mix components	Wet track abrasion test	Loaded Wheel Test	Modified cohesion test
Percentage (%)			
Aggregate	100	100	100
Binder emulsion	12.5	12.5	12.5
Portland Cement	0	0	0
Water	9	9	9
Weight (gr)			
Aggregate	700	500	300
Binder emulsion	87.5	62.5	37.5
Portland Cement	0	0	0
Water	63	45	27

4.7 Description of ISSA mixture design tests evaluated

The International Slurry Surfacing Association design technical bulletin A143 (ISSA A-143, 2005), published in May 2005, contains guidelines for the laboratory evaluation of micro-surfacing mixture designs. The tests examined in this study include ISSA TB 139, 100, 147 (Method A). Generally, apparatus, materials, sample preparation, and testing procedures are the same as those expressed in the International Slurry Surfacing Association design technical bulletin A143, published in May 2005.

4.7.1 Modified Cohesion Test

The cohesion test (ISSA TB 139, 2005) is used to classify micro-surfacing mixture to slow or fast setting systems. It also can be used to establish baseline formulations of binder emulsion, water, aggregate, and cement additives suitable for further testing.

In other words, suitable binder emulsion-water combination is selected based on results obtained after 30 and 60 min of curing at room temperature, 25°C (77°F). The minimum values required are 1.2 kilogram-meters for the 30 minutes test, 2 kg-m for 60 min.

Figure 2.a shows the modified cohesion tester used in this study. The 30-min modified cohesion test results is used to evaluate setting (flocculation) properties of micro-surfacing mixtures, while, the 60-min cohesion values can be considered as evaluation of traffic time (i.e., early rolling traffic time occurs at a torque level of 2 kg-m).

In this study, five identical specimens of each micro-surfacing formulation were mixed and casted in 10 mm x 60 mm diameters ring mold centered on the roofing felt squares and allowed to cure at room temperature. Torque measurement was made at suitable time intervals such as 30, 60, 90, 150, 210, and 270 minutes after casting. Figure 4.2-a shows the cohesion tester.

4.7.2 Wet Track Abrasion Test

Wet track abrasion test (WTAT) (ISSA TB 100, 2005) is a field simulation test to measure the wearing qualities of micro-surfacing mixture under wet abrasion conditions. Wet track abrasion test establishes the minimum binder emulsion content necessary to prevent excessive raveling of cured micro-surfacing mixture. This test was conducted after curing the samples at l40°F (60°C) for one day. The sample was then soaked in the water for 1 hour at ambient temperature. Figure 4.2.b shows the wet track abrasion machine used in this study. After completing the abrasion cycle, the specimen was removed from the pan and washed off debris with slow running water. The specimen was then placed in an oven at l40°F (60°C) to dry to a constant weight, and allowed to reach temperature and weighted. The difference between this new weight and the weight in grams obtained from before placing the sample in 77°F (25°C) water bath was reported as the abrasion loss of the specimen. Wet track abrasion test were performed on 1-hour soaked sample to determine susceptibility to moisture exposure. Figure 2-b shows the WTAT tester.

4.7.3 Loaded Wheel Test, Sand Adhesion

Loaded wheel test (ISSA TB 109, 2005) measures the resistance of mixture against flushing under heavy traffic. This test establishes the maximum binder emulsion content necessary to prevent flushing of cured micro-surfacing mixtures. The mixture is compacted by means of a loaded, rubber tired, reciprocating wheel. The measured parameter is the sand adhesion, which is an indirect measure of the amount of excess binder in the mix. Figure 4.2-c shows the loaded wheel test machine used in this study. The sample is prepared and oven dried at l40°F (60°C) for one day and allowed to be cold at room temperature for 1-hour. The sample was compacted using 1000 cycles of the 125 lb (56.7 kg) loaded wheel. The sample was weighed after compaction and the weight was recorded. Two hundred grams of fine Ottawa sand (ASTM Designation C-I09 graded standard) and metal strip were heated to 180°F (82.2°C) was uniformly spread over the sample surface, and sample was again compacted using the same load for 100 cycles. The specimen was removed from unit, and disassembled over a waste container and gently tapped to remove the un-adhered sand. The sample was

again weighted, and new weight recorded. The difference between this new weight and the weight in grams obtained from after completion of 1000 cycles of the 125 lb (56.7 kg) loaded wheel was reported as the sand that had adhered to the specimen, which is an indirect measure of the amount of excess binder in the mixture. The temperature at which the tests have been performed must be reports as well. This test was conducted at 25°C that correspond to moderate traffic. Figure 4.2-c shows the LWT tester.

4.7.4 Multilayer Loaded Wheel Test Vertical & Lateral Displacement

Multilayer Loaded Wheel test (Method A) (ISSA TB 147, 2005) measures the amount of compaction or displacement characteristics of micro-surfacing under simulated rolling traffic compaction. Because micro-surfacing can be used for filling ruts, it should have proper resistance against vertical and lateral deformations under heavy traffic. This test also establishes the minimum binder emulsion content necessary to prevent excessive deformation of micro-surfacing mixture. When a series of specimens, containing a different range of binder emulsion contents are tested, optimum emulsion content for rutting resistance can be determined at the minimum vertical and lateral displacements. The sample preparation and test procedure is exactly the same as for the loaded wheel test (sand adhesion). The only difference is the sample is room cured for 24 hours after the emulsion was broken at a temperature of l40°F (60°C). The mold specimen with nominal thickness of 12.7 mm was used in this study which represents the maximum limit for rutting on the road surface. The width and height of the specimen was measured (in the wheel path and at the mid-point of specimen length) before and after 1000 cycles of the 125 lb (56.7 kg) loaded wheel compaction. In this study, the width and height of the specimen were measured after 1000 cycles of the 125 lb (56.7 kg) loaded wheel compaction. It has been found that unconfined vertical deformation that exceeds 10% respectively is not satisfactory for compacted, multi-layer applications according to the recommendations of ISSA TB 147 (Method A). Multilayer Loaded Wheel Test Vertical & Lateral Displacement was conducted at 25°C.

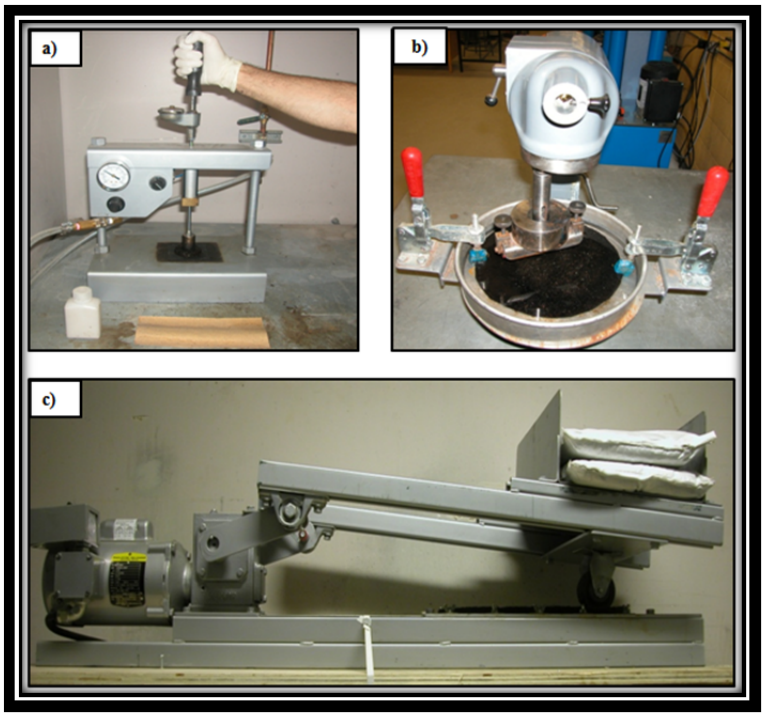

Figure 4.2 Micro-surfacing mix design tests
a) Modified cohesion tester b) Wet track
abrasion tester c) Loaded wheel tester

4.8 Results and discussion

Analysis of results was conducted using Analysis of Variance (ANOVA) by STAT Graphic software (version 10). Output of ANOVA is a model including independent variables (Factors), and dependent variable (Responses). In this model, those independent variables affecting the dependent variables are determined by ANOVA at a specified confidence level. ANOVA uses the correlation (R^2) to predict the future outcomes of the model on the basis of the other related information. Outputs of ANOVA used in this study are ANOVA table, standardized Pareto chart, main effect plot, and estimated response. ANOVA table show the statistical calculation of R^2, the sum of squares, the mean of squares, and the F-value.

Standardized Pareto chart evident the standardized effect of each effect group on the results. The red line on standardized Pareto chart represents the estimated critical F-value. The main

effect plot and the estimated response tabulate the actual effect of factors involved in study on the results.

4.8.1 Direct effects of binder and aggregate gradation on the test responses

Figure 4.3 to 4.9 show the plots of raw data for the effect of binder emulsion and aggregate gradation on the test responses. As can be seen from Figure 4.3 showing the change with binder emulsion residue, and the aggregate gradation in the mixture has a profound influence on the adhered sand to the sample. To take into account the effect of aggregate gradation, the total aggregate surface area of UG, MG, and LG gradations were already calculated (Table 4.3). The total aggregate surface area represents the only variation between UG, MG, and LG gradations. Figure 4.3 shows that, when the amount of binder emulsion residue increased in the mixes, more sand adhered tended to the sample, which inversely shows higher risk of a flushed surface (rich binder) for the micro-surfacing mixture. An inverse trend was observed when the total aggregate surface area was increased from 7.4 to 11 m²/kg, for the mixtures prepared using LG and UG aggregate gradations, respectively. As the total amount of aggregate surface area increased, the amount of adhered sand decreased, indicating lower risk of flushing for mix.

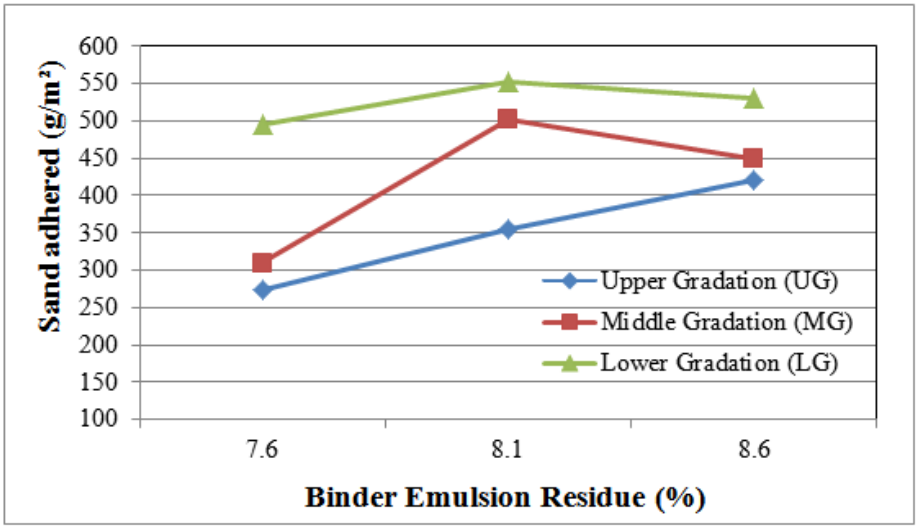

Figure 4.3 Plot of raw data for Loaded Wheel Test

Figure 4.4 shows the plot of raw data for Wet Track Abrasion test results (1-hour soaked samples). By increasing the amount of binder emulsion residue, aggregate loss decreased. As it also can be seen from this figure, when the amount of total aggregate surface area increased, the aggregate loss of sample also increased. In the case of mixes prepared using LG aggregate gradation, when the binder emulsion residue increased in the mix, the aggregate loss increased. This is due to presence of high amount of free binder emulsion in mix, which is not adsorbed by the surface of aggregates, and postponed the set and curing of the mix.

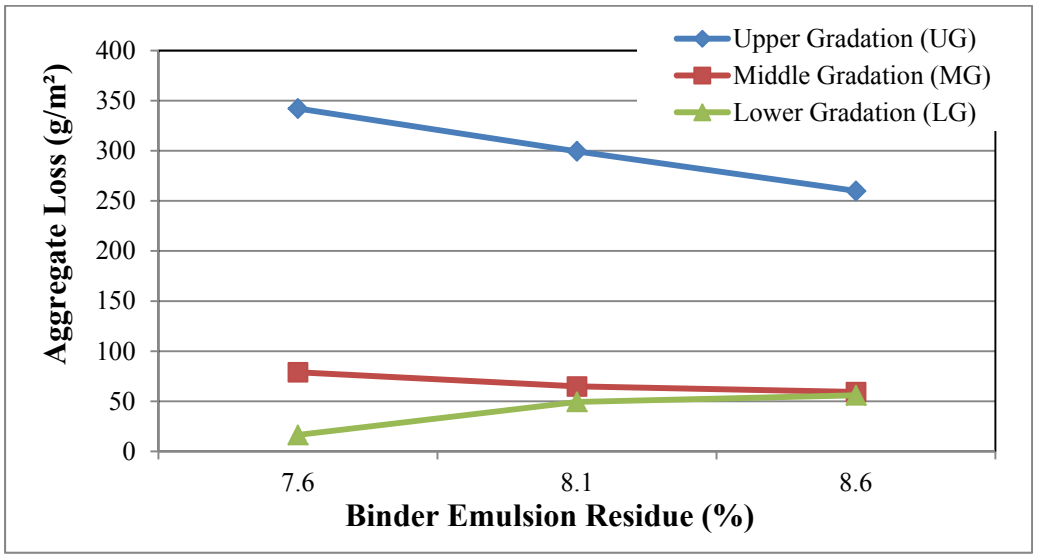

Figure 4.4 Plot of raw data for WTAT 1-Hour Soaked

The primary purpose of LWT and WTAT are to, respectively, determine maximum and minimum limit for adding binder emulsion in the mixture. LWT and WTAT are used in ISSA TB 111 (ISSA TB 111, 2005), and ISSA TB 143 (ISSA TB 143) mix design procedures for slurry seal and micro-surfacing in order to determine the optimum binder content for mix. In the above mentioned guidelines, the WTAT will be performed at 1-hour and 6-day soak periods followed by tests using the LWT to determine the excess binder at different temperatures. Finally, the optimum binder content is selected by evaluating the abrasion loss in the WTAT, and the binder content versus pick up from the loaded wheel tester.

However, when designer prepare trial mixtures with different amount of binder emulsion, the sensitivity of test results to the binder change is more in the case of LWT than that of WTAT. In other words, the consistency for wet track abrasion test results is poor, which may lead to inaccurate selection of optimum binder content using ISSA TB 111 and ISSA TB 143 mix design procedures.

Figure 4.5 and 4.6 show the plot of raw data for results of Relative Moisture Retained in samples of LWT and WTAT. The results showed that the relative proportion retained moisture after 24 hours curing, expressed as percent by weight of the initial available moisture (initial added moisture + water portion of binder emulsion) ranges between 1.96 and 3.16% for LWT samples, and 1.13 and 1.47% for WTAT samples. Also, in the case of micro-surfacing mixtures prepared using UG, MG, and LG aggregate gradations, the relative retained moisture in LWT samples after 24 hours curing increased as the amount of binder emulsion residue increased. This brings a big error in calculating the amount of optimum binder for micro-surfacing mixtures using LWT, because, the test results are not only sensitive to the changing of the binder, but also, are sensitive to the retained moisture in the sample.

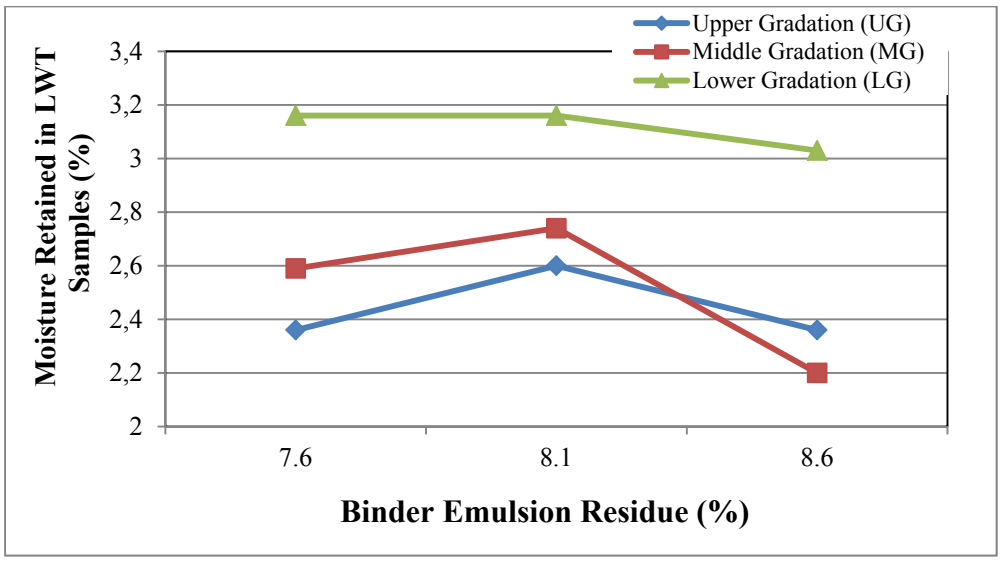

Figure 4.5 Plot of Raw data for Retained Moisture in LWT

Primary reason for the inconsistency of loaded wheel test (Sand Adhesion) results is the galvanized steel materials used in fabricating the specimen mounting plates in the loaded wheel test prevent moisture evaporation from mixture during the breaking process of the emulsion.

Retained moisture in loaded wheel Test specimens was higher than that of retained moisture in Wet Track abrasion Test specimens, which uses saturated roofing felt materials in fabricating the specimen mounting plates. It was also observed that, as the amount of binder emulsion residue increased in the mixtures, there is an optimum amount of moisture retained in the WTAT sample. While, by increasing the amount of binder emulsion residue, it was observed that the moisture content of system increased in the case of LWT sample.

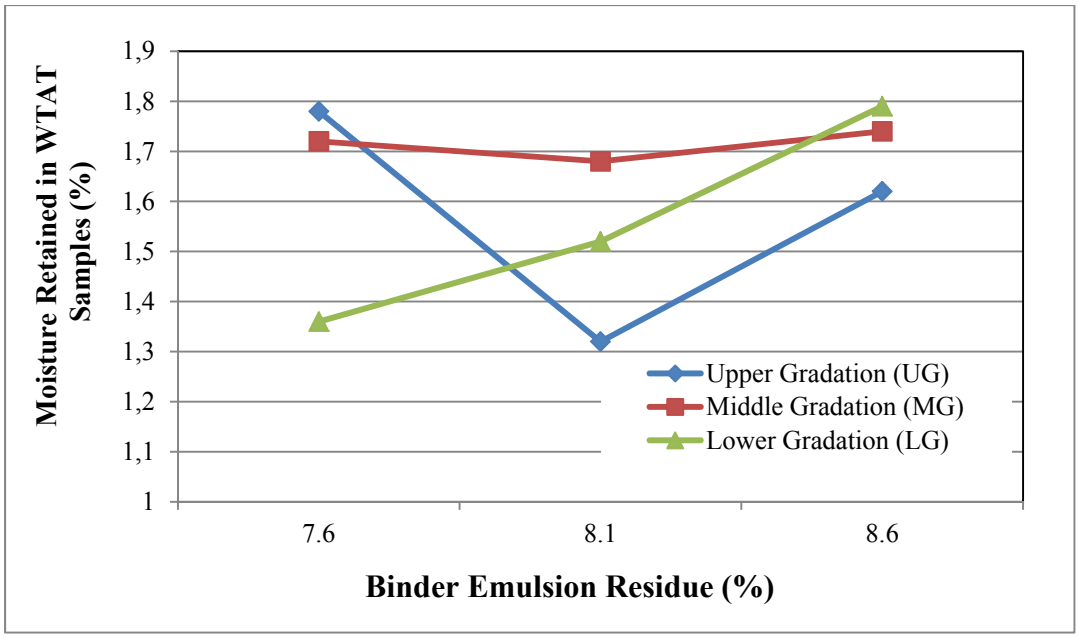

Figure 4.6 Plat of raw data for Retained Moisture in WTAT

Figure 4.7 and 4.8 show the plot of raw data for 30 and 60-min cohesion test results. Modified cohesion test results at 30 and 60 min show that, when the binder emulsion residue increased, there observed an optimum amount of 30-min and 60-min cohesions, for the mixes prepared using MG aggregate gradation. In the case of mixes made with UG aggregate gradation, when the binder emulsion residue increased, the cohesion increased.

For mixes made with LG aggregate gradation, when the amount of binder emulsion residue increased, the cohesion of mix slightly decreased. This is the reason why the aggregate loss increased, when the binder emulsion residue increased for the case of mixes prepared with UG aggregate gradation shown in Figure 4.4.

The cohesion of micro-surfacing mixtures is an important property that can be used to select different mix proportions. Normally, the micro-surfacing mix proportions are selected, so that, the 30 and 60 minutes' cohesions of mixture reach to the maximum amounts. For the design to be accepted, the amount of 30 and 60-min cohesion must be, respectively, higher than 1.2 and 2 kg-m.

In this study, the micro-surfacing mix prepared using MG aggregate gradation and 8.1% binder emulsion residue, plus that of prepared with UG aggregate gradation and 8.6% binder emulsion residue had maximum amount of 30-min and 60-min cohesion.

However, further testing was required to find the optimum mix proportions with regard to the rutting resistance, which is the main property, required of Type III micro-surfacing mixtures in areas with high traffic.

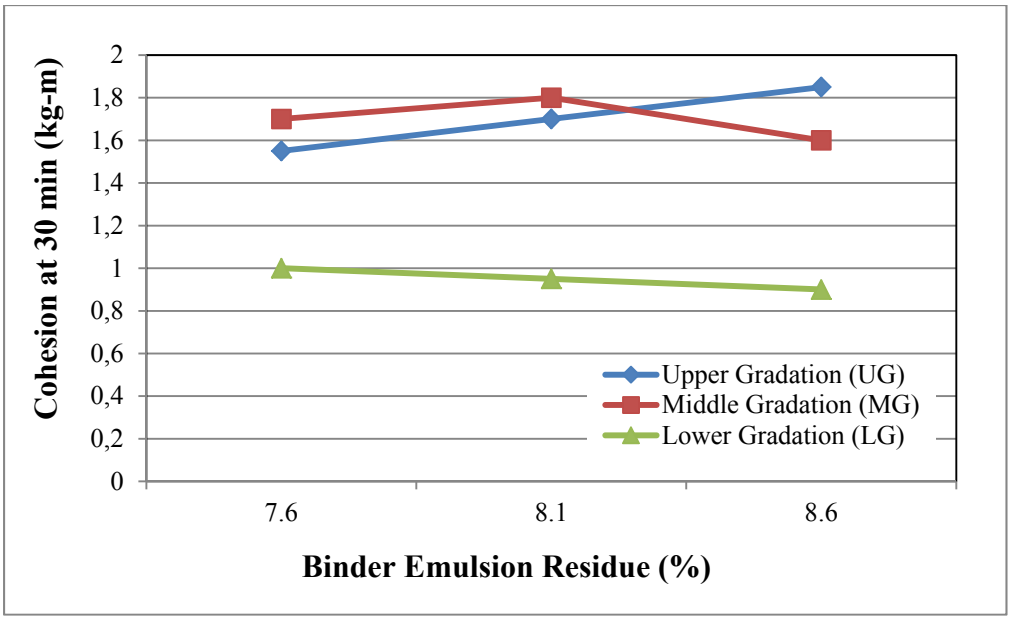

Figure 4.7 Plot of Raw data for Cohesion test at 30 min

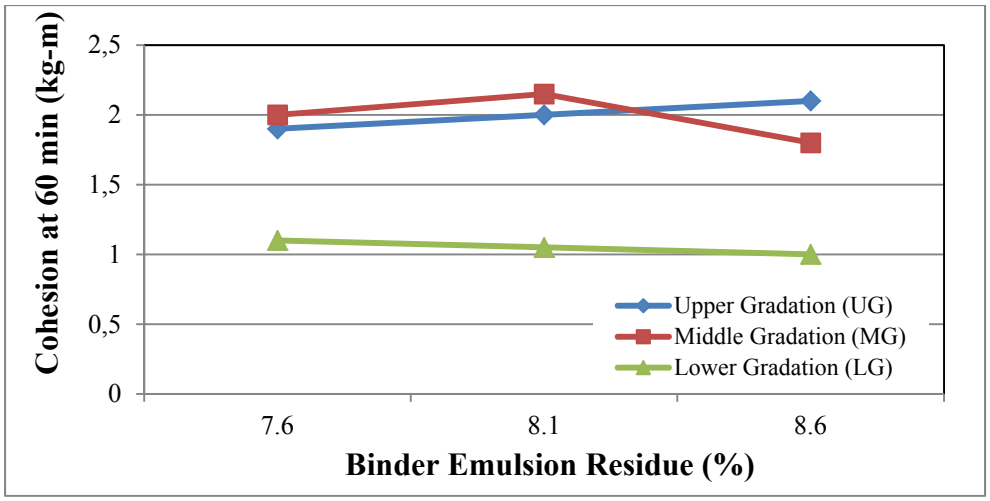

Figure 4.8 Plot of Raw data for Cohesion test at 60 min

Figure 4.9 shows the plot of raw data for mixing time test results. Mixing Time test results show that effect of aggregate gradation is more significant than that of binder residue effect. The result of mixing time ranges from 64 to 686 s. as it can be seen from figure 9, in the case of mixes prepared using LG aggregate gradation, mixing time increased more than other mixes.

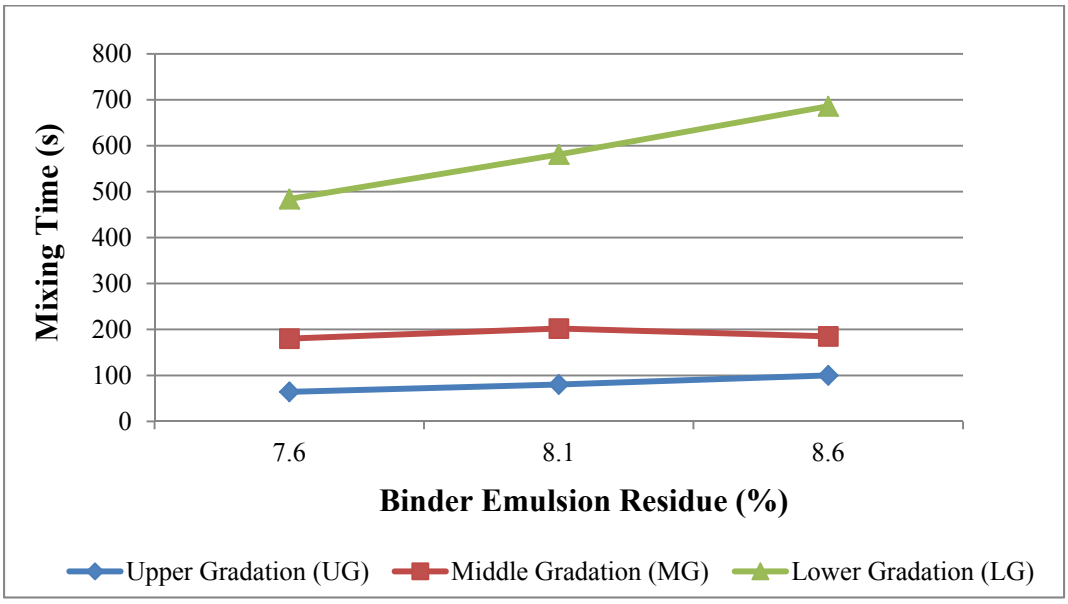

Figure 4.9 Plot of raw data for Mixing time test

Based on ISSA mix design guideline, for design to be accepted, mixing time of mixture must be more than 120 second (2 minutes).

It was observed that, mixes prepared with LG aggregate gradation provided long mixing time before the mixture broke. This is mainly due to very low aggregate surface area of mixes prepared with LG gradation.

4.8.2 Analysis by mixture materials

When analysis all the data together, it came that the binder emulsion and total aggregate surface area have high influences on the test responses (Figure 3 to 9).

The mixture materials such as binder emulsion residue and aggregate surface area are discontinuous factors; therefore, it was necessary to perform the analysis by materials to better investigate the effect of these two factors on the test responses.

Figures 4.10 to 4.15 show the significant effect of binder emulsion residue and aggregate surface area on the test results. The Letter “A” in the figures represent the effect of aggregate surface area on the test responses, while, the letter “B” represent the effect of binder emulsion residue.

If there is interaction between the effect of aggregate surface area and binder emulsion residue, the effect of this interaction on the test results is shown by the letter “AB”. The letters “AA” and “BB” represent, respectively, the squares of the effect of the aggregate surface area and binder emulsion residue on the test results.

Figure 4.10 to 4.13; show the significant effect of binder emulsion residue and total aggregate surface area on the result of loaded wheel test, wet track abrasion test, and retained moisture on both LWT and WTAT samples.

The interesting fact is that the effect of interaction between the effect of aggregate surface area and binder emulsion residue is also significant, which makes it difficult for the designer to select the optimum amount of binder emulsion residue using LWT and WTAT.

The other interesting fact is that the effect of aggregate surface area on the test results was observed to be higher than that of the effect of binder emulsion residue for all the mixture tests (Figure 4.10 to 4.15).

The reason for this is because of the interaction between binder emulsion and aggregate surface area in the micro-surfacing mixtures.

During the flocculation (setting) and coalescence (curing) of the binder emulsion, total aggregate surface area plays an important role. In the breaking of CQS-1HP grade binder emulsion, free emulsifier adsorbs onto the (oppositely charged) aggregate surface area, which neutralizes some charge on the surface of binder molecules, causing the binder molecules to eventually set on the aggregate surface area (Figure 4.16).

Too low aggregate surface area in relation to the binder emulsion molecules can actually reverse the charge on the minerals and so inhibit the setting of the emulsion.

Also too high aggregate surface area causes the charge on the emulsion droplets to be quickly destroyed by pH changes; then, the binder emulsion molecules very quickly set and curing of the system begins to occur at a slower rate.

Therefore, the aggregate surface area for a mixture like micro-surfacing should be selected carefully. The total amount of aggregate surface area is highly dependent of the filler content of the aggregates.

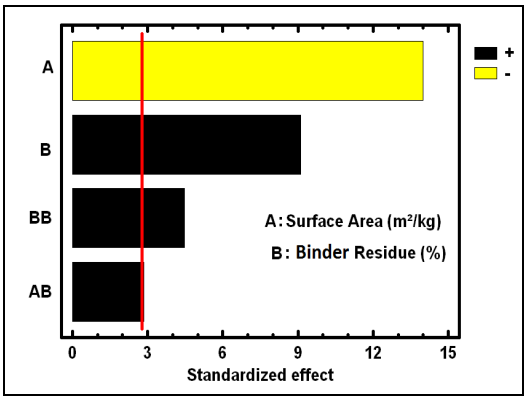

Figure 4.10. Pareto chart (Loaded Wheel Test)

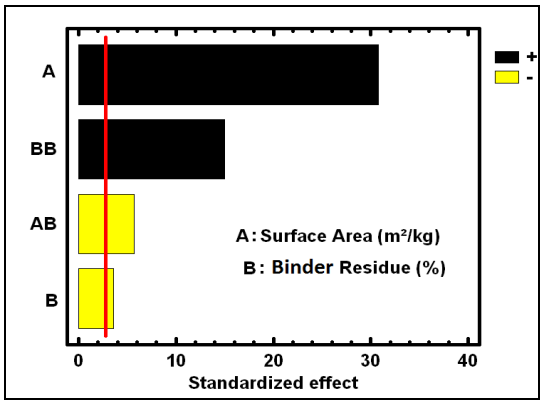

Figure 4.11. Pareto chart (Wet Track Abrasion 1-Hour soaked)

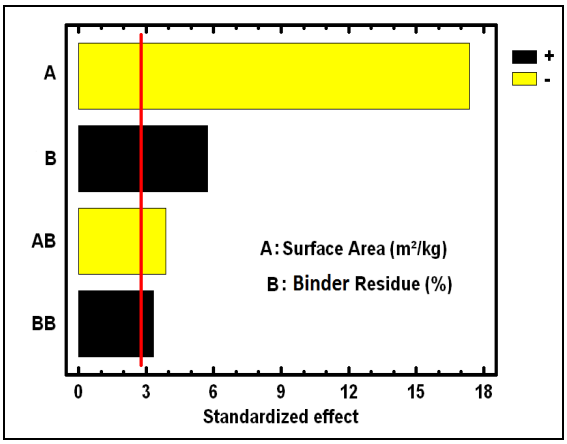

Figure 4.12. Retained Moisture (Loaded Wheel test samples)

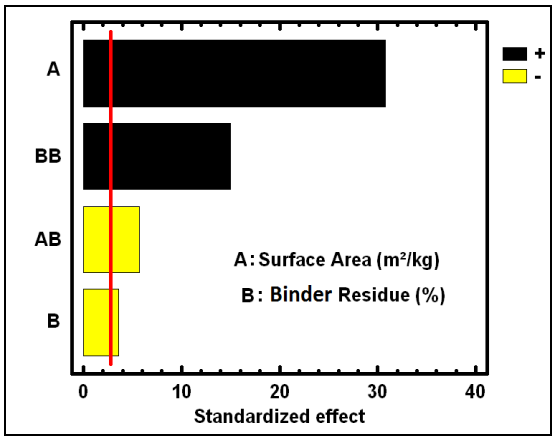

Figure 4.13. Pareto chart (Retained Moisture WTAT samples 1-Hour Soaked)

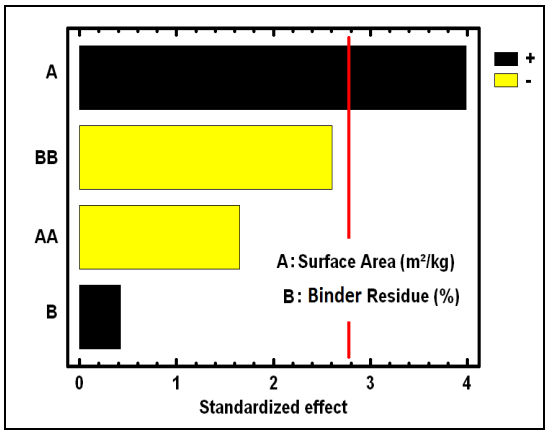

Figure 4.14. Pareto chart
(Cohesion test at 30 min)

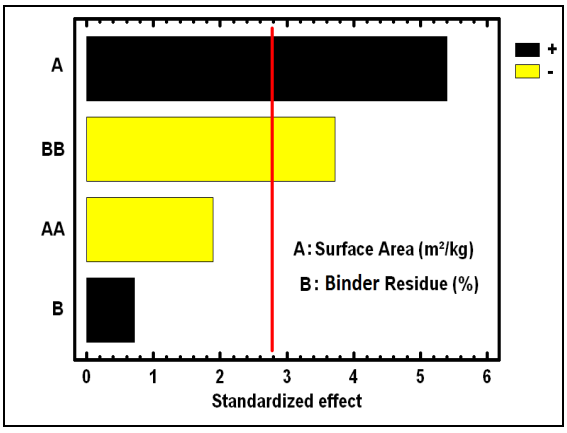

Figure 4.15. Pareto chart (Cohesion
test at 60 min)

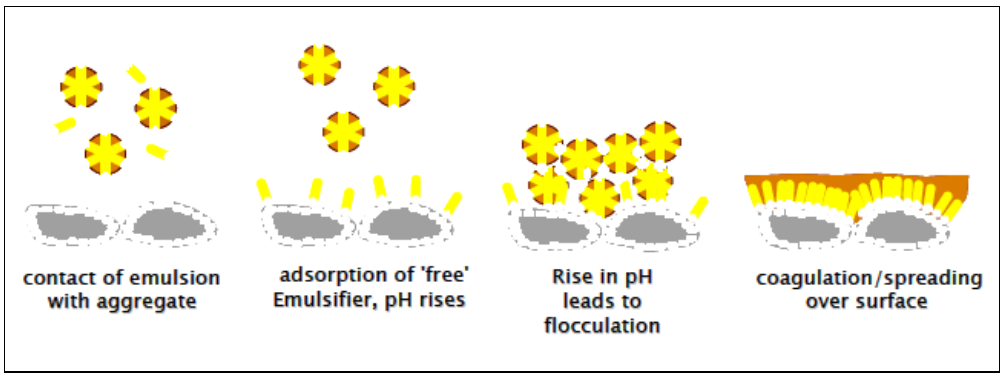

Figure 4.16 Possible stages in the
setting of a cationic emulsion
Extracted from Delmar (2013, p.40)

4.9 Result summary

As has been shown, the impact of the amount of binder emulsion residue, and the aggregate gradation to micro-surfacing mixture properties are quite important. A summary of the results presented in the previous sections is shown in table 4.10. Total aggregate surface area, and its square have a significant effect on the results of loaded wheel test, wet track abrasion

test, mixing time test, and moisture retained in LWT and WTAT. As for modified cohesion test (30-min and 60-min), binder emulsion residue has a significant effect on the test results.

It is important to note that those results are valid only for the different materials used in this study. If one uses another type of emulsion which reacts differently with another type of aggregates, the results may vary.

The results are also only valid in the range of added binder emulsion and aggregate gradation used in this study. On the other hand, the different values that were used are commonly used and are the quantities that give overall optimum results.

Table 4.10 Results summary for all tests done on micro-surfacing shown in this study

Test	Significant effect of		Trend
	Aggregate surface Area (A)	Binder Emulsion Residue (B)	
Loaded wheel test (LWT)	yes[1]	yes	B ↑ : adhered sand ↑
			A ↑: adhered sand ↓
Wet track abrasion (1 hour soaked)	yes[1]	yes	B ↑: aggregates loss ↓
			A ↑: aggregates loss ↑
Relative moisture retained (LWT samples)	yes[1]	yes	B ↑: moisture ↑
			A ↑: moisture ↓
Relative moisture retained (WTAT samples)	yes[1]	yes[1]	B ↑ : Presence of an optimum moisture
			A ↑: moisture ↑
Modified cohesion at 30 minutes	yes	no	B ↑: Presence of an optimum cohesion
			A ↑: Presence of an optimum cohesion
Modified cohesion at 60 minutes	yes[1]	no	B ↑: Presence of an optimum cohesion
			A ↑: Presence of an optimum cohesion

[1] Significant effect of aggregate surface area and its square amount

4.10 Resistance to rutting

Because the Type III aggregate gradation is used to fill rut distresses on the surface of roads with high traffic volume, it is necessary to select the aggregate gradation that provides maximum resistance to rut permanent deformation.

Rut distress under vehicle wheels can be due to insufficient structural support of layers under the binder surface layer, or also, can be a reason of inaccurate material selection in the mix design process of binder surface layer. Type III application of micro-surfacing can be used to fill the rut depth of up to 13 mm to recover the binder surface to its original situation, and improve the life of pavement up to 7 years.

However, the micro-surfacing materials such as binder emulsion, aggregate gradation, and other mix proportions should be accurately selected, so that the micro-surfacing mixture can resist against rutting during its predicted 7 year service life on the surface of the road. Multi-layer Loaded Wheel Test Vertical & Lateral Displacement (Method A-ISSA TB 109) test was used in this study to measure the resistance of micro-surfacing mixtures against rutting. This test also establishes the minimum binder emulsion content necessary to prevent excessive deformation of micro-surfacing mixture. As was already been shown, the micro-surfacing mixtures prepared using MG aggregate gradation and 8.1% emulsion residue, plus that of prepared with UG aggregate gradation and 8.6% binder emulsion residue, had higher amounts of 30 and 60-min cohesion compare to other micro-surfacing mixtures. Figure 4.17 shows that the mixture made by MG aggregate gradation and 8.1% binder emulsion residue had higher resistance to rutting deformation compare with the one consist of UG aggregate gradation and 8.6% binder emulsion residue. For the micro-surfacing design to be accepted, the vertical displacement at the center of the sample should be less than 10% of the thickness of the sample at the same place. Figure 4.17 also shows that, using vertical displacement test, the optimum amount of binder emulsion residue can be determined for the mixture.

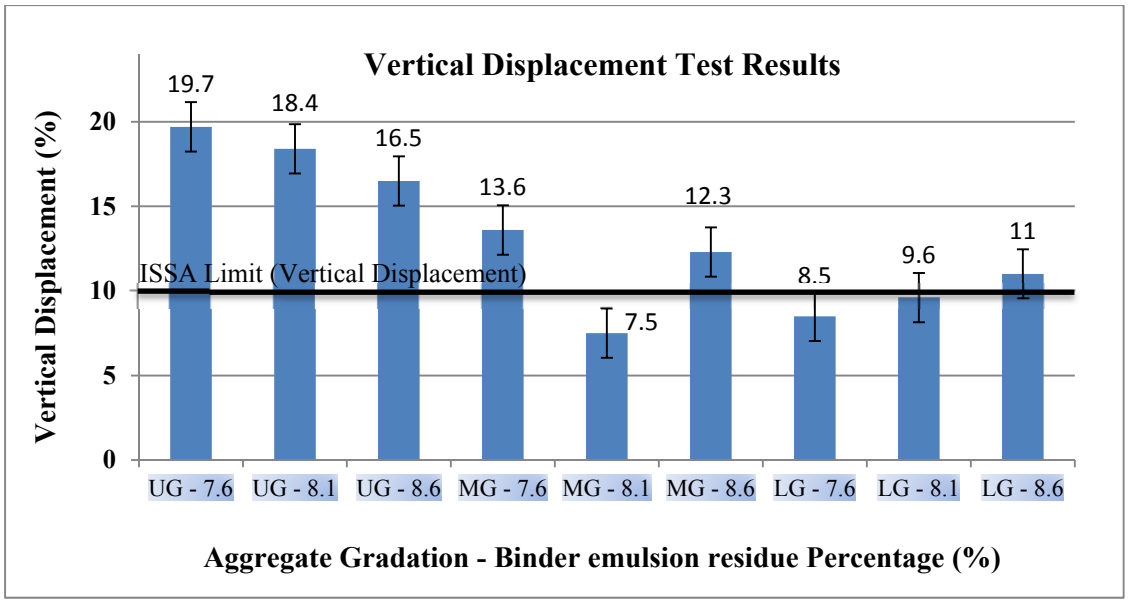

Figure 4.17 Plot of Raw data for vertical displacement test results

In the case of micro-surfacing mixtures prepared with MG aggregate gradation and different levels of binder emulsion residue, there observed an optimum amount of binder, in which the mixture shows its maximum resistance to rutting. It must be noted that the goal of performing vertical displacement test was to understand the role of aggregate gradation on the resistance of micro-surfacing mixtures. So, in all the prepared micro-surfacing mixtures for this test, 1% Portland cement was used in the sample. Normally, 1 to 2% Portland cement is added to micro-surfacing mixtures to improve the properties of mixture.

4.11 Selection of aggregate gradation for micro-surfacing mixtures

The design of micro-surfacing mixture is a process that requires the proper proportioning of materials to satisfy the mechanical properties, and filed performance. As discussed earlier, the total aggregate surface area plays an important role in the mixture properties such as cohesion, adhesion, abrasion, and resistance to rutting. Current micro-surfacing mix design standards, such as ISSA, provide the material specification for different application of micro-

surfacing mixture. Figure 4.18 shows the recommended aggregate gradations for Type II and III of micro-surfacing.

SIEVE SIZE	TYPE II PERCENT PASSING	TYPE III PERCENT PASSING	STOCKPILE TOLERANCE
3/8 (9.5 mm)	100	100	
# 4 (4.75 mm)	90 - 100	70 – 90	± 5%
# 8 (2.36 mm)	65 - 90	45 – 70	± 5%
# 16 (1.18 mm)	45 – 70	28 – 50	± 5%
# 30 (600 um)	30 – 50	19 – 34	± 5%
# 50 (330 um)	18 - 30	12 – 25	± 4%
#100 (150 um)	10 - 21	7 – 18	± 3%
#200 (75 um)	5 - 15	5 – 15	± 2%

Figure 4.18 ISSA micro-surfacing mix
design guide for selection of aggregates
Extracted from ISSA (2005, p. 10)

In this study three different aggregate gradations were selected within the grading range recommended by ISSA mix design standard for type III application of micro-surfacing. The selected aggregate gradations were close together, while, the variation in micro-surfacing mixture design results were significant due to changing the total aggregate surface area. Therefore, it is essential to recommend a narrow limit for aggregate gradation of Type III micro-surfacing mixtures. Based on the detailed laboratory observations in this study, the micro-surfacing mixtures prepared using mid-range (MG) aggregate gradation recommended by ISSA mix design standard for Type III application of micro-surfacing shown improved properties and performances. The micro-surfacing mixtures prepared using UG aggregate gradation shown good mixture properties and performances compare to those of prepared with MG and UG aggregate gradations. It was concluded that the modified maximum and minimum limit for aggregate grading of Type III application of micro-surfacing to fill rut on the surface of road located in area with high traffic should be within the UG and LG aggregate gradations studied in this study. The maximum limit of grading is recommended to

be on the UG aggregate gradation, while, the minimum limit of grading is suggested to be between MG and LG aggregate gradation to optimize the micro-surfacing mixture properties and performances. Table 4.11 and Figure 4.19 represent the modified mix aggregate grading recommended to select aggregate grading of Type III application of micro-surfacing.

Table 4.11 Modified and recommended aggregate grading for Type III micro-surfacing

Sieve No & Size		% Passing by Weight	Stockpile Tolerance,%
in	Mm	Type III PERCENT PASSING	
3/8	9.5	100	–
No. 4	4.5	75 – 85	+/- 2
No. 8	2.36	55 – 65	+/- 2
No. 16	1.18	35 – 45	+/- 2
No. 30	0.6	25 – 30	+/- 2
No. 50	0.3	15 – 20	+/- 1
No. 100	0.15	12 – 14	+/- 1
No.200	0.075	9 – 13	+/- 1

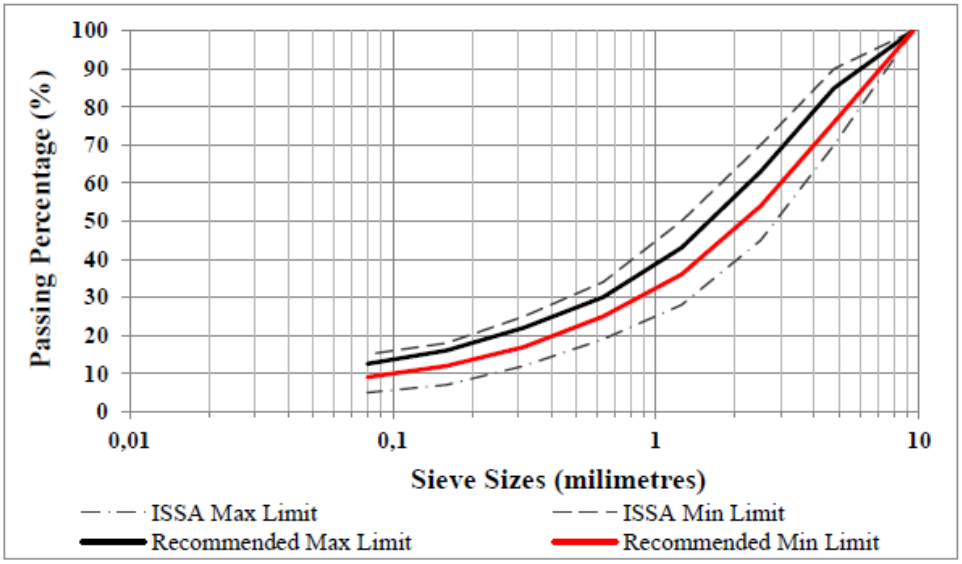

Figure 4.19 Modified and recommended aggregate grading for type III application of Micro-surfacing

4.12 Conclusion

The overall goal of this study was to improve the performance of Type III micro-surfacing mixtures to fill rut deformation of roads located in areas with high traffic volume through the development of a modified specification for selecting aggregate gradation. This was achieved through a two parts experimental program. In the first part, the influence of aggregate gradation and binder emulsion residue was studied and the sensitivity of different tests was evaluated. Then, in the second part, a modification to ISSA mix design standard for selecting aggregate grading for Type III application of micro-surfacing was suggested. Based on statistical analysis of the findings, the following conclusions are submitted:

1. Total amount of aggregate surface area of different aggregate gradations used to prepare micro-surfacing mixtures in this study appears to have a profound influence on the results of loaded wheel test, wet track abrasion tests, modified cohesion test, and retained moisture in LWT and WTAT samples. When the aggregate surface area increased in the mixture, the adhered sand in LWT decreased, while, the aggregate loss in WTAT increased with a lower rate;

2. The sensitivity of the test results of loaded wheel test to increase of the binder emulsion residue in the micro-surfacing mixtures was observed to be higher that of wet track abrasion test. This indicates that using LWT and WTAT to select optimum binder emulsion is not an accurate process in ISSA mix design procedure to design micro-surfacing mixtures;

3. The use of galvanized steel as specimen mounting plates in loaded wheel test do not allow water to evaporate through the curing process of mixture. Study of relative moisture retained in loaded wheel test samples after 24-hours curing show that as the binder emulsion residue increased, the retained moisture in samples was increased and subsequently the amount of sand adhered in loaded wheel test increased. Results of relative moisture retained in wet track abrasion test after 24-hours curing evident that as the binder emulsion increased, there observed an optimum amount of relative moisture

retained in WTAT samples, which was mixed, cast, and poured out onto the roofing felt pad;

4. The micro-surfacing mixtures prepared using MG aggregate gradation in this study had higher resistance to rutting deformation compare with those of prepared using UG and LG aggregate gradation. This shows the importance of accurately selecting aggregate gradation for Type III micro-surfacing mixtures. The modified aggregate grading suggested by this study shows to have maximum resistance to rutting, and is suited to be used in preparing micro-surfacing mixtures as rut filling materials on the surface of roads located at areas with high traffic volume.

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CHAPTER 5

EVALUATION OF REPEATABILITY AND REPRODUCIBILITY OF MICRO-SURFACING MIXTURE DESIGN TESTS AND THE EFFECT OF TOTAL AGGREGATES SURFACE AREAS ON THE TEST RESPONSES

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5.1 Abstract

The first part of this study evaluates the repeatability of the International Slurry Surfacing Association (ISSA) mixture design tests. Consistency of test results between two laboratories (MTQ and LCMB) and within material combinations was evaluated. Aggregate gradation and sample preparation method were varied, and the responses for various ISSA mix design test for micro-surfacing were examined. The repeatability of four ISSA mix design tests for micro-surfacing was computed. To do this, the micro-surfacing mixtures were prepared by four technicians at two laboratories in Quebec. Modified cohesion test, wet track abrasion test, loaded wheel test, and resistance to compaction test were those evaluated in this study. The effect of sample preparation method using aggregate splitting and sieve analysis on consistency of mixture design test results was also evaluated in this part of study. It was observed that employing sieve analysis method for micro-surfacing mixture preparation yields the more consistence test responses. For the second part of this study, the role of aggregate gradation, and their total surface area on cohesion, resistance to abrasion, and resistance to permanent deformation of micro-surfacing mixtures was studied. Two different type III applications of micro-surfacing mixtures which are used as rut-fill materials in highly traffic area were selected to determine the effects of aggregate total surface area on micro-

surfacing mix design test responses. It was found that the micro-surfacing mixtures prepared using aggregate gradation with more fine aggregates have higher resistance to rutting, bleeding, abrasion, moisture susceptibility, and early rolling traffic.

5.2 Introduction

Roads are an essential component of Quebec's economy as they ensure the movement of passengers and goods. Road Transport plays an important role in the economy of Quebec's province and provides the basic infrastructure for bringing the majority of the people who are living in far off villages into the mainstream of life by connecting them with the rest of the province. Quebec's road network includes approximately 185 000 kilometers of roads. Quebec Ministry of Transportation (MTQ) manages some 29 000 kilometers of freeways (commonly known in Quebec as autoroutes), national highways (Quebec's primary highways), regional highways (Quebec's secondary highways) and collector roads, as well as 4 700 bridges and overpasses, 1 200 kilometers of resource access roads and 3 600 kilometers of mining roads. The gross replacement cost of the road infrastructures under the MTQ's responsibility is estimated at over $30 billion for the entire province.

Pavement preservation is defined as a program employing a network-level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety, and meet motorist expectations (FHWA, 2005). Actions used for pavement preservation include routine maintenance, preventive maintenance (PM), and corrective maintenance (Uzarowski, 2007). Transportation agencies use chip seal, slurry seal, micro-surfacing, cape seal, fog seal, etc.

Slurry seal is a pavement coating that consists of fine and hundred percent crushed aggregates, emulsified asphalt and water which is applied to roadway. Slurry seals were developed and used for the first time in Germany, in the late 1920's (International Slurry Surfacing Association - (ISSA).

Micro-surfacing is a polymer modified quick setting, cold slurry paving system. This high performance cold asphalt mixture consists of a dense graded fine aggregates, polymer

modified asphalt emulsion, cement and water (ISSA, 1990). The role of asphalt emulsion and water is providing fluidity to the micro-surfacing mixture. Although micro-surfacing is applied in multi-stone thickness, the asphalt emulsion in it allows the mixture to remain stable too (M.P. Doyle, 1989). The heat is not used during the construction process. As the result, there is little initial hardening of binder (L.D. Coyne, 1964).

Micro-surfacing is differing from Slurry seal in many areas. The emulsified asphalt used for Micro-surfacing has higher polymer content and higher asphalt residual content. Using faster setting chemical in the asphalt emulsion applied in Micro-surfacing allows faster break of this product rather than Slurry Seal. This ability makes Micro-surfacing able to support traffic as quick as one hour after placement while Slurry Seal required more time in order to support traffic. Moreover, Micro-surfacing use high quality aggregates rather than Slurry Seal and this provide higher skid resistance which allow Micro-surfacing to be used in wheel ruts.

Among all mix design guidelines, an International Slurry Surfacing Association (ISSA) guideline is the most accepted and practiced around the world. Despite the differences between Slurry Seal and Micro-Surfacing (i.e., application thickness, traffic volume, and curing mechanisms), ISSA guideline suggests similar test methods and design procedure to evaluate Slurry Seal and Micro-surfacing. The ISSA mix design tests include modified cohesion (ISSA TB-139), wet track abrasion (ISSA TB-100), loaded wheel (ISSA TB-109), and resistance to compaction (ISSA TB-147). However, the consistency of test results using ISSA mix design test is questionable. The establishment of the repeatability of ISSA mix design tests is an initial investigation that provides a foundation for future micro-surfacing research.

Each micro-surfacing mixture formulation is a chemical system and is affected by many variables such as different combination of aggregates, class of emulsifier, and bitumen from various suppliers (C.R. Benedict, 19878). Setting (flocculation) of micro-surfacing mixture is a process in which emulsifier is absorbed by aggregate surface and binder molecules are joined to form the asphalt cement film around aggregates. The total aggregate surface area

plays an important role in flocculation process, and subsequently on coalescence (curing) of mixture.

5.3 Background

Edward M. Andrews et al studied the repeatability and reproducibility of micro-surfacing mix design tests (E. Andrew, 1995). In their report, the repeatability of micro-surfacing tests using materials falling within current micro-surfacing specifications was obtained. Material compositions were the only variation in their study, and the test responses were evaluated to determine repeatability and reproducibility of the tests. Different types and amounts of asphalt emulsion, and various types of aggregates with same gradation were used to prepare micro-surfacing mixtures in their study. The mix design tests were performed at one laboratory by a same technician for all micro-surfacing mixtures. The effects of different amounts of Portland cement additive in micro-surfacing mixtures were studied in their report as well. They reported improved properties of micro-surfacing mixtures with same aggregate gradation but different amounts of Portland cement.

However, other parts of measurement systems in a given material testing procedure such as equipment, technician, and sample preparation methods (aggregate splitting, and sieve analysis of aggregates) can be also a source of error in test responses. In the current study consistency of the micro-surfacing mix design test responses is evaluated for a given micro-surfacing formulation prepared using four technicians at two laboratories using different equipment of micro-surfacing, and employing different sample preparation methods.

The approach used in this study to compute the repeatability and reproducibility of ISSA mix design tests for micro-surfacing, and to compare the results obtained from a laboratory with those from other laboratories is same with that of used in CANADIAN ASPHALT MIX EXCHANGE PROGRAM (CAMEP). Thirty seven Canadian engineering organizations participated in the 2012 CAMEP. The exchange provides an opportunity for participants to compare their test results to those of other laboratories. The exchange evaluates the

volumetric and mechanical properties of an asphalt aggregate mixture using Marshall Mix design procedures, the gyratory compactor, and the ignition oven (Carter, 2012).

The effect of fine aggregates on properties of micro-surfacing mixtures at constant amount of Portland cement was further studied. The goal was to see if the properties of micro-surfacing mixtures can be improved by adding more fine aggregates in mixture. The amount of 2.5-5 mm aggregates were kept constant in micro-surfacing mixtures, while, the amount 0-2.5 mm aggregates were changed in to evaluate the change in properties of micro-surfacing mixtures.

5.4 Objective

The first objective of this study is to examine the repeatability of the test results obtained from the four mixture design tests proposed by the ISSA, including modified cohesion, wet track abrasion, loaded wheel, and resistance to compaction. The repeatability and reproducibility of the test results were estimated based on this study in which two laboratories and four operators were participated. Two laboratories from Ministère des transports du Québec (MTQ)- Laboratoire des chausses, and École de technologie supérieure (ÉTS) - Laboratoire sur les Chaussées et Matériaux Bitumineux (LCMB), were participated in this study. This process revealed more about the sample preparation method used in typical micro-surfacing mixtures. The study also provided an opportunity for MTQ and LCMB laboratories to compare their test results. It provided a mechanism for review and refinement of existing test methods and equipment.

The second objective of this study was to examine the effect of aggregate gradation on micro-surfacing mix design tests. To examine the role of aggregates surface area, two different aggregate gradations prepared using sieve analysis of aggregates were used in study. The amounts of asphalt emulsion, water, and cement were chosen based on a new mix design procedure developed by this writer (Robati, 2011). The resistance of formulated micro-surfacing mixture to rutting, bleeding, abrasion, moisture susceptibility, and early traffic rolling were then evaluated to determine the influence of fine aggregates in mixture.

5.5 Materials, Experiment Design, and Testing

All the materials used in sample preparation represent typical materials utilized for micro-surfacing projects in Quebec. The emulsion type used in all cases is CQS-lhP. The aggregates used in the study were Ray-Car (0-5 mm) with two different gradations satisfies type III requirements for aggregate gradation of ISSA mix design guideline. Figure 1 show two gradation curves for the aggregates used in this study. Four operators in MTQ and LCMB laboratories in Quebec prepared micro-surfacing mixtures. For the first part of study which was computing repeatability and reproducibility of micro-surfacing mix design tests, all four operators at MTQ and LCMB laboratories used gradation 1 of aggregates.

In order to calculate the repeatability and reproducibility of micro-surfacing mix design tests, the only difference between technicians was employing two different methods of aggregate splitting and sieve analysis in sample preparation. Operator one at MTQ (labeled 1), and operator two at LCMB (labeled 2) prepared mixtures using sample splitting method, while, operator three and four at LCMB (labeled 3 and 4) used aggregate analysis method for sample preparation. Both gradations 1 and 2 used in this study are between maximum and minimum aggregate gradation limits suggested by ISSA for Type III Micro-surfacing application which is used to correct the rut deformation on area with high traffic (Table 5.1). Gradation 1 is exactly at the middle of maximum and minimum limits suggested for type III micro-surfacing application, while, gradation 2 is slightly lower.

In second part of study, gradation 1 and 2 were employed to evaluate the effect of aggregate gradation on micro-surfacing mix design test responses. Table 5.1 shows the detail of type III aggregate gradations used in this study. As it can be seen from table and figure 1, the passing percentage of aggregates for sieve 3/8, No. 4 and 8 are same, while, for sieves No. 16 to 200, the amount of fine aggregates is more for gradation one than gradation two. Table 5.2 shows the experimental design used in parts one and two of this study.

Table 5.1 Gradations of the aggregates used in this study

Sieve Size		% Passing by Weight			Stockpile Tolerance,%
in	Mm	Gradation 1	Gradation 2	Type III (ISSA)	
3/8	9.500	100	100	100	
No. 4	4.750	88	90	70-90	+/- 5
No. 8	2.500	63	62	45-70	+/- 5
No. 16	1.250	44	38	28-50	+/- 5
No. 30	0.630	33	25	19-34	+/- 5
No. 50	0.315	23	17	12-25	+/- 4
No. 100	0.160	14	11	7-18	+/- 3
No.200	0.080	10	7.5	5-15	+/- 2
Total SA m²/kg		9.366	7.486		

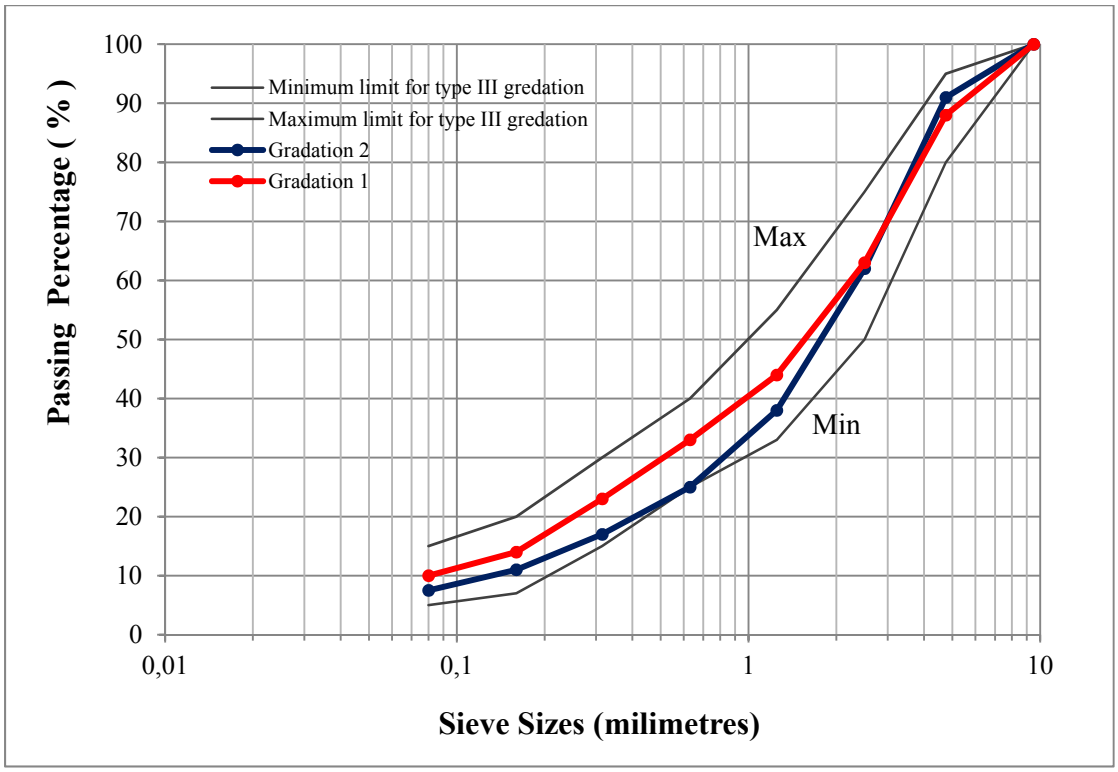


Figure 5.1 Gradation curve for Ray-Car 0-5 mm Aggregates

Table 5.2 Design of Experiment (DOE)

Technician	Laboratory	Aggregate Gradation	Sample preparation method
Part one of study			
1	MTQ	Gradation 1	Splitting
2	LCMB	Gradation 1	Splitting
3	LCMB	Gradation 1	Sieve analysis
4	LCMB	Gradation 1	Sieve analysis
Part two of study			
1	MTQ	Gradation 2	Sieve analysis
2	LCMB	Gradation 1	Sieve analysis

Emulsified asphalt used in this study is CQS-1HP asphalt emulsion. The term CQS-1HP is the standard name for micro-surfacing emulsions used in the industry and it conforms to all ISSA specifications. Asphalt emulsion consists of binder and water that evaporates as binder cures. Therefore, in designing micro-surfacing mixtures base on ISSA specifications, residual asphalt content of the binder must be more than 62.0%. CQS-1HP emulsion used in this study has 65.1% residual asphalt content, according to test results provided by McAsphalt Engineering Services. Other properties of CQS-1HP asphalt emulsions have been listed in Table 5.3.

Table 5.3 CQS-1HP Asphalt Emulsion properties from supplier

Tests	Results	ISSA Specifications		
		min		max
Viscosity @ 25°, SSF	28.0	20		100
Sieve,%	0.04	-		0.10
Coating Test,%	90.0	80.0		-
Residue by Distiliation to 204.4°,% mass	65.1	62.0		-
Particle Charge	Positive	Positive		
Settlement, 5 day,%	0.9	-		5
Tests on Residue				
Softening Point by R 7 B, °C	63	57		-
Kinematic Viscosity @ 135°C, mm²/sec	1825	650		-
Penetration @ 25°C, 100 g, 5 sec	75	40		90
Ductility @ 25 °C, cm	110+	40		-

Figure 5.2 shows ISSA micro-surfacing mix design equipment used in this study. The cohesion test is used to classify emulsified asphalt/aggregate mixture to slow or fast setting systems. It also can be used to establish baseline formulations of asphalt emulsion, water, aggregate, and cement additives suitable for further testing. In other words, suitable asphalt emulsion-water combination is selected based on results obtained after 30 and 60 minutes of curing at room temperature, 25°C (77°F). The minimum values required are 12 kilogram-centimeters for the 30 minutes test, 20 kg-cm for 60 minutes. Figure 5.2-a shows the modified cohesion tester used in this study. Wet track abrasion test is a field simulation test to measure the wearing qualities of micro-surfacing mixture under wet abrasion conditions. Wet track abrasion test establishes the minimum asphalt emulsion content necessary to prevent excessive raveling of cured micro-surfacing mixture. This test was conducted after curing the samples. Wet track abrasion test were performed on 1-hour and 6-day soaked sample to determine susceptibility to long-term moisture exposure.

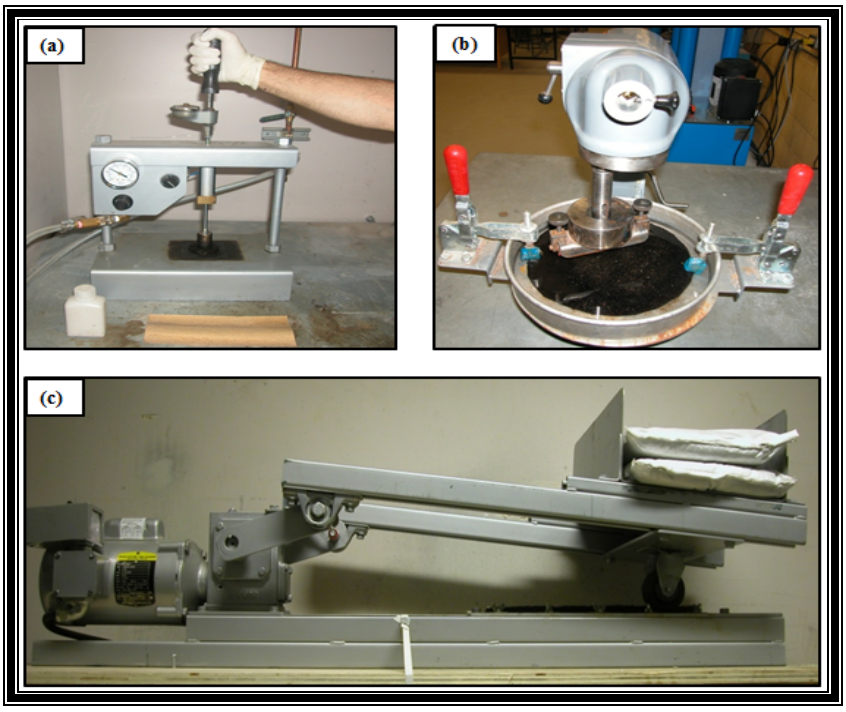


Figure 5.2 Micro-surfacing equipment used in this study
a) Modified cohesion tester b) Wet track abrasion tester
c) Loaded wheel tester

Figure 5.2-b shows the wet track abrasion machine used in this study. Loaded wheel test measures the resistance of mixture against flushing under heavy traffic. This test establishes the maximum asphalt emulsion content necessary to prevent flushing of cured micro-surfacing mixtures. The mixture is compacted by means of a loaded, rubber tired, reciprocating wheel. The measured parameter is the sand adhesion, which is an indirect measure of the amount of excess asphalt in the mix. Figure 5.2-c shows the loaded wheel test machine used in this study.

5.6 Statistical analysis

A summary of the results for ISSA mix design tests investigated in this study is presented in table 4. The complete results are presented in appendix II. The average value (X_{ave}), repeatability and reproducibility standard deviation (S_r, S_R), and 95% confidence limits for repeatability and reproducibility for each ISSA mix design tests are presented in this table.

As an example, for the loaded wheel test in Table 4, the average value reported by all of the laboratory-operators is 516.1 (g/m²). The repeatability standard deviation, S_r for this test is, 28.22 (g/m²) and reproducibility standard deviation, SR, is 54.24 (g/m²).

The 95% confidence limit for repeatability is computed with the following equation:

$$95\% \text{ Repeatability Confidence Limit} = 1.96 * 2 * \sqrt{S_r} \quad (5.1)$$

The 95% confidence limit for repeatability of loaded wheel test is 79.016 (g/m²). This means that approximately 95% of all pairs of loaded wheel test results on a given material from within a laboratory-operator can be expected to differ in absolute value by 79.016 (g/m²).

The 95% confidence limit for reproducibility is computed with the following equation:

$$95\% \text{ Repeatability Confidence Limit} = 1.96 * 2 * \sqrt{S_R} \quad (5.2)$$

The 95% confidence limit for reproducibility of loaded wheel test is 151.87 (g/m²). This means that approximately 95% of all pairs of loaded wheel test results on a given material from between a laboratory-operator can be expected to differ in absolute value by 151.87 (g/m²).

Formulations to compute precision are presented in equations 5.3 to 5.13 (ASTM E691).

(5.3)

x = Individual test result

(5.4)

n = Number of test results per lab

(5.5)

p = Number of laboratories

The cell average for each material is calculated using:

(5.6)

$$\bar{x} = Lab - operator\ average = \frac{\sum_1^n x}{n}$$

The cell standard deviation of, s, of the test results in each cell is calculated using the following equation:

(5.7)

$$S = Lab\ standard\ deviation = \sqrt{\frac{\sum_1^n (x - \bar{x})^2}{(n-1)}}$$

For each laboratory, the cell deviation, d, is calculated by subtracting the cell average from the average of the cell average:

(5.8)

$$d = Lab\ standard\ deviation = \bar{x} - x_a$$

Standard deviation of the cell averages (S_{Xave}) is the statistical measure of the dispersion of observed results expressed as the positive square root of variance and is calculated from following equation:

(5.9)

$$s_{Xave} = standard\ deviation\ of\ lab - operator\ average = \sqrt{\frac{\sum_1^p d^2}{(p-1)}}$$

The repeatability standard deviation (S_r) is the standard deviation of test results obtained under repeatability condition. It is calculated from below equation:

(5.10)

$$s_r = Repeatability\ standard\ deviation = \sqrt{\frac{\sum_1^p s^2}{p}}$$

The reproducibility standard deviation is, S_R, is the standard deviation of test results obtained under reproducibility condition.

It is calculated using following equation:

(5.11)

$$Reproducibility\ standard\ deviation =$$

$$s_R = the\ larger\ of\ sr\ and\ \sqrt{s^2{}_{Xave} + s_r{}^2 \times \frac{(n-1)}{n}}$$

h-consistency statistics value is calculated for each cell using below equation:

(5.12)

$$\text{The between} - \text{laboratory consistency statistic} = \frac{d}{s_{Xave}}$$

And, k-consistency statistics value is calculated for each cell using below equation:

(5.13)

$$\text{The within} - \text{laboratory consistency statistic} = \frac{s}{s_r}$$

Table 5.4 to 5.6 show an example of statistical calculation for loaded wheel test results using equations 5.3 to 5.13.

Table 5.4 presents the average of each lab-operator test results.

Table 5.4 Statistical analysis on loaded wheel test results (raw data)

Lab-operator	x_1	x_2	x_3	x_{ave}
1	531.43	516.67	509.29	519.13
2	546.9	642.1	560.9	583.30
3	479.76	450.24	479.76	469.92
4	501.91	494.52	479.76	492.06
$\bar{x}$	-	-	-	516.10

Table 5.5 presents the standard deviation, and average of each lab-operator test results along with their within h-consistency and between k-consistency.

Table 5.6 represents the h-crit, k-crit, and repeatability, reproducibility limit for loaded wheel test results.

Table 5.5 Statistical analysis on loaded wheel test results
(standard deviation, and average)

LWT	x	s	s^2	d	d^2	h	k
1	519.13	11.27	127.08	3.03	9.18	0.062	0.399
2	583.3	51.40	2642.08	67.2	4515.84	1.368	1.821
3	469.92	17.04	290.48	-46.18	2132.59	-0.940	0.604
4	492.06	11.28	127.18	-24.04	577.92	-0.490	0.400

And, table 6 shows the h and k-consistency, repeatability and reproducibility standard deviation and their limits for loaded wheel test performed in this study.

Table 5.6 Statistical analysis on loaded wheel test results
(repeatability and reproducibility standard deviation)

Statistical results sample	
Lab-operator average ($\bar{x}$)	516.1
Standard deviation of cell averages	49.11
Repeatability standard deviation (s_r)	28.22
Reproducibility standard deviation (s_R)	54.24
h-Critical	1.49
k-Critical	1.82
Repeatability Limit = $2.8 \times (s_r)$	79.1
Reproducibility Limit = $2.8 \times (s_R)$	151.8

5.7 Results and Discussions

5.8 Repeatability of ISSA Mix Design Tests

h and k consistency statistic plats were investigated in order to evaluate the difference within and between laboratories' test results. Figures 5.2 to 5.8 show bar graphs of the h and k consistency statistics, and their critical values for different combination of materials. h consistency graphs give an instant picture of the variability of the individual test methods. As it can be seen from Figures 5.2 to 5.8, the overall impression was that there is reasonable value of h consistency for MTQ and LCMB laboratories' test results. There were no any laboratories having h consistency value higher than the critical value of h consistency. This indicates that average test result of each laboratory-operator is not significantly different from the average obtained by the other laboratories. If h consistency exceeds its critical value for each laboratory-operator, it shows that they may have difficulty correlating to other

laboratory-operators and should investigate its testing equipment and procedures. However, h consistency for variation within LCMB laboratory for each of the ISSA mix design tests was comparatively lower; when sample were prepared using sieve analysis of aggregates. The h consistency value of MTQ laboratory' test results, using aggregates splitting during sample preparation, for both 30-min and 60-min modified cohesion test, and horizontal displacement tests, were close to critical h consistency value. The h consistency value of LCMB laboratory' test results, using aggregates splitting during sample preparation, for loaded wheel test and horizontal displacement, were close to critical h consistency value. This suggests that If a lab has a between laboratory-operators consistency statistic (h consistency statistic) that is close to the critical between-laboratory consistency statistic, h-crit , then its average test result is not significantly different from the average test results obtained by the other laboratory-operator. However, the lab may want to consider taking precautions to ensure that there are not any problems with its testing procedures and equipment. There may be a test method or procedure vagueness that permits a wide range of interpretation. Particular elements that can be checked are measurement system, operator technique, instrument, and materials. Because, the only difference between lab-operators in this study was the sample preparation method (aggregate splitting, and sieve analysis), it can be say that the sample preparation method should be done by sieve analysis of aggregates to yield consistent test results. Figures 5.2 to 5.8 also show the k consistency statistic value for the ISSA mix design tests. The main goal of evaluating the k consistency statistic plots is to find out if a particular material combination has large k or very small k values. High k values indicate imprecision within the material combination, while, very small k value may indicate insensitive measurement scale or other measurement problems (L.D. Coyne, 1964). The critical value of k was exceeded in 60-min modified wet cohesion, and 6-day soaked wet track abrasion test by MTQ laboratory. For 30-min modified cohesion test, the k consistency value was close to the critical value of k. It was also observed that the k consistency value of LCMB laboratory' test results, when sample were prepared using aggregate splitting, was also higher than that of critical k value for 1-hour soaked wet track abrasion test. For loaded wheel and vertical displacement tests, the k value was close to critical k value for LCMB laboratory test results when using aggregate splitting method.

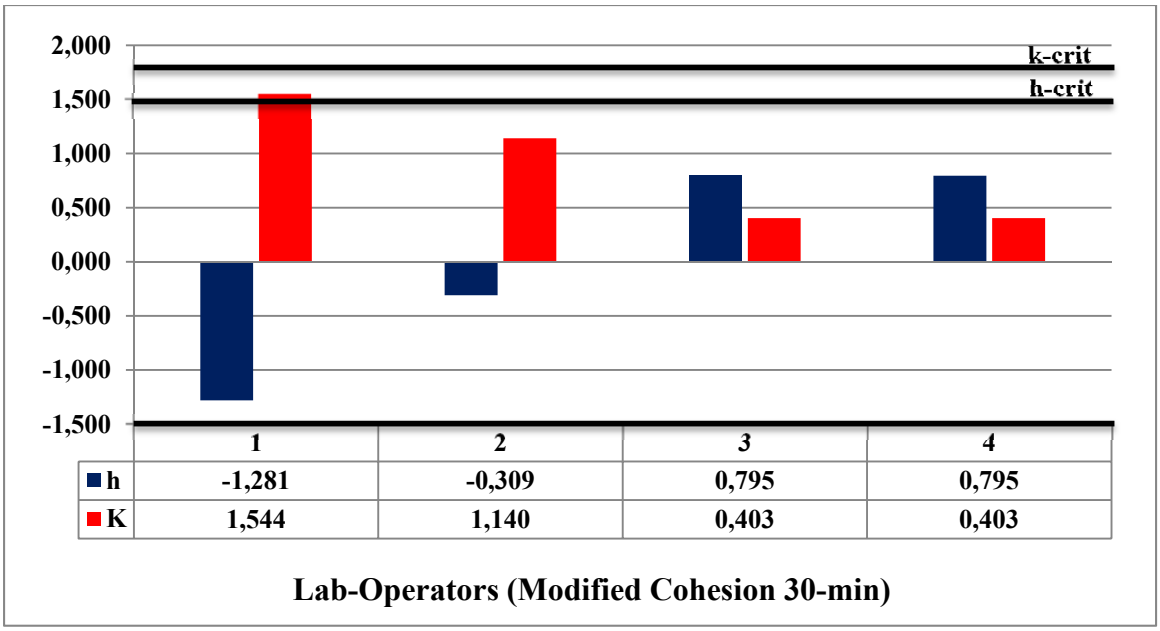


Figure 5.3 Modified cohesion test results (30-min), plot of h and k consistency statistics versus material type combinations

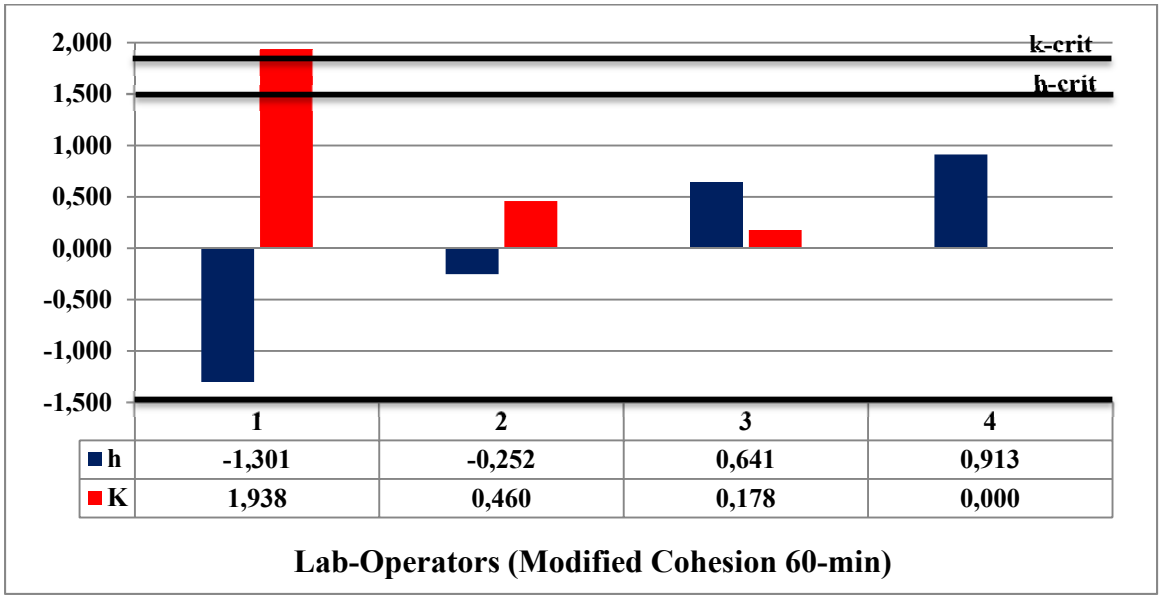


Figure 5.4 Modified cohesion test results (60-min), plot of h and k consistency statistics versus material type combinations

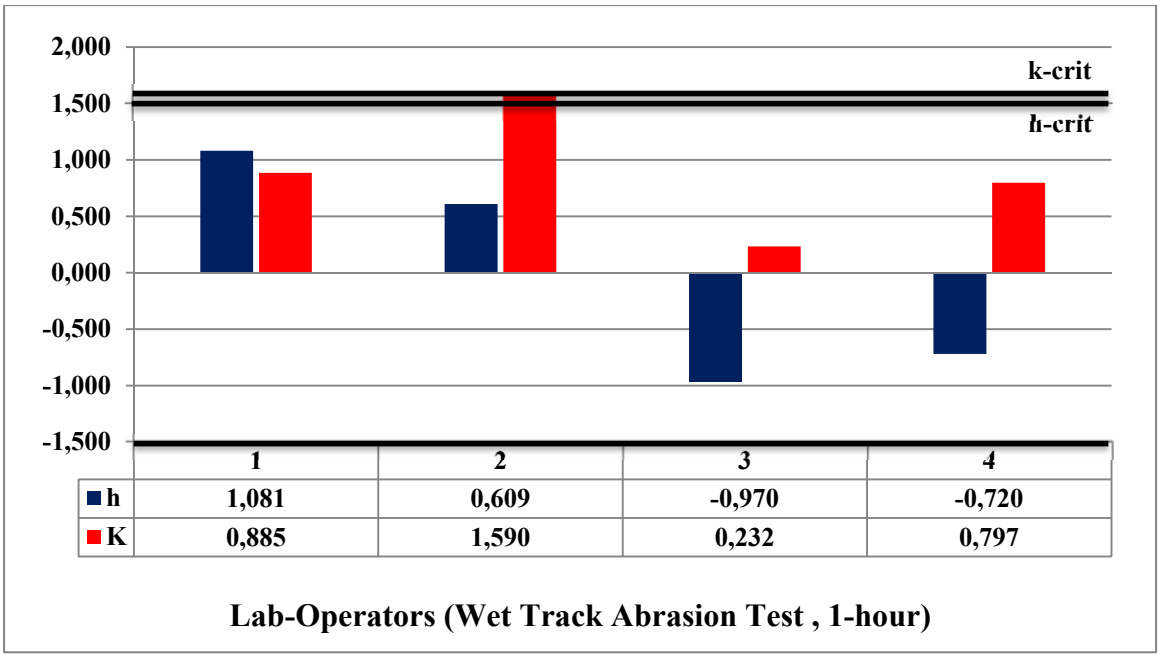


Figure 5.5 Wet track abrasion test results (1-hour soaked), plot of h and k consistency statistics versus material type combinations

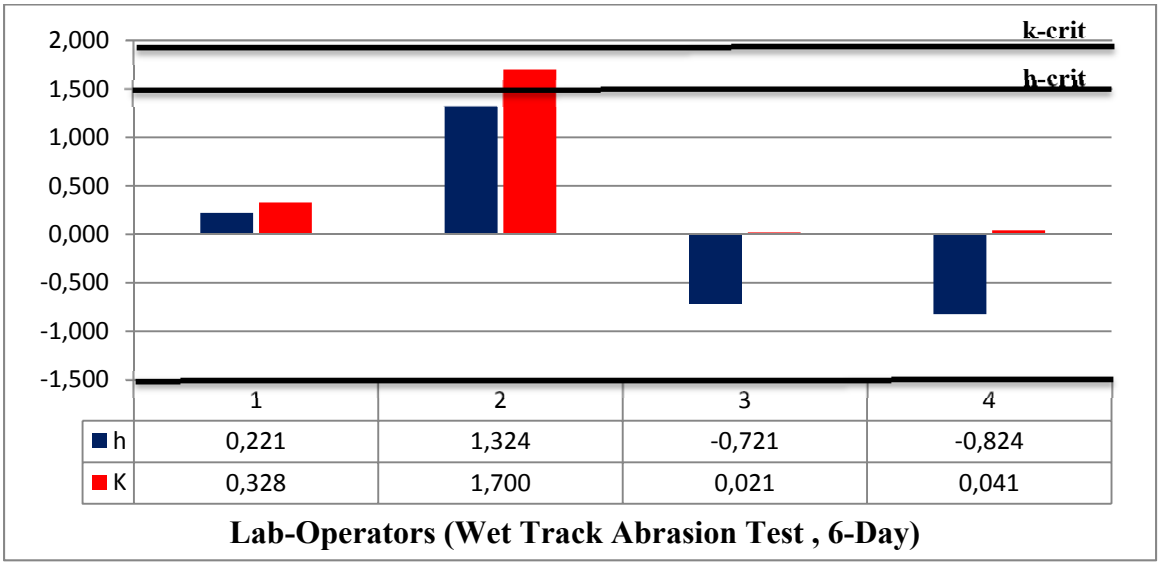


Figure 5.6 Wet track abrasion test results (6-day soaked), plot of h and k consistency statistics versus material type combinations

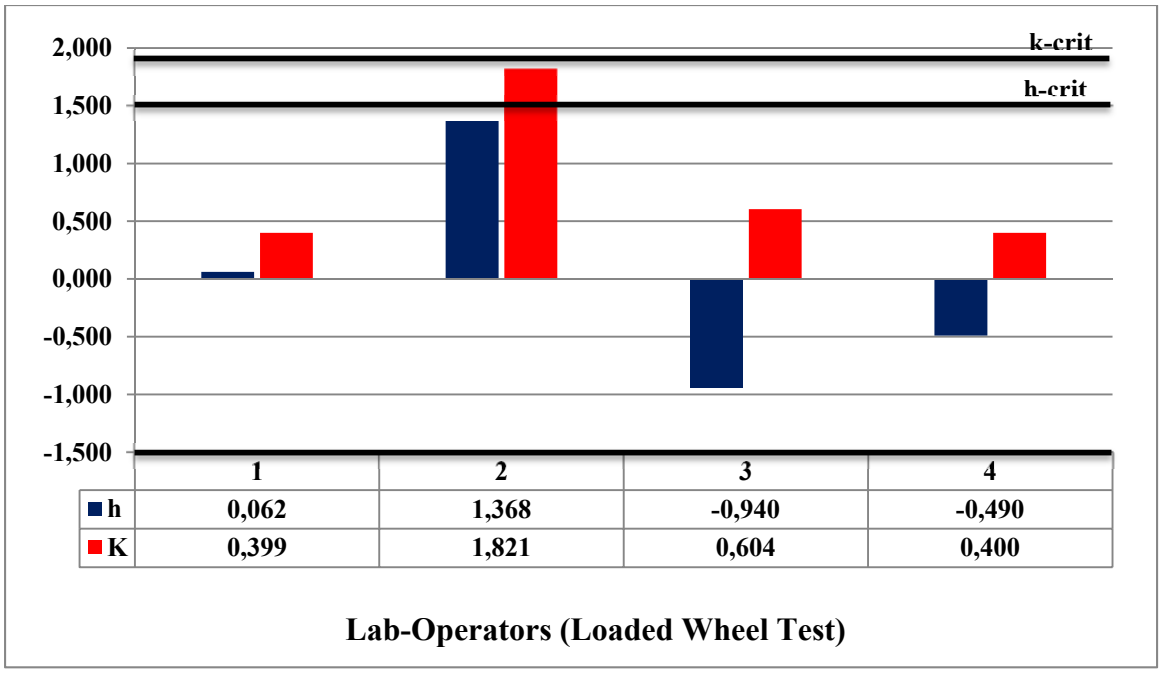


Figure 5.7 Loaded wheel test results, plot of h and k consistency statistics versus material type combinations

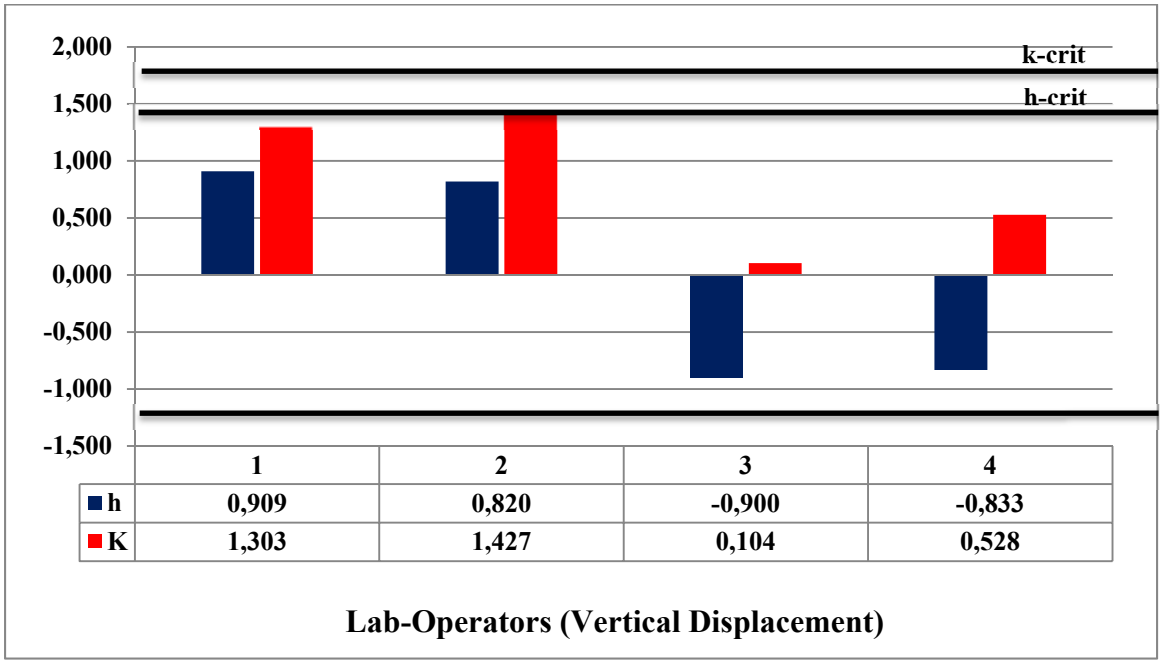


Figure 5.8 Vertical displacement test results, plot of h and k consistency statistics versus material type combinations

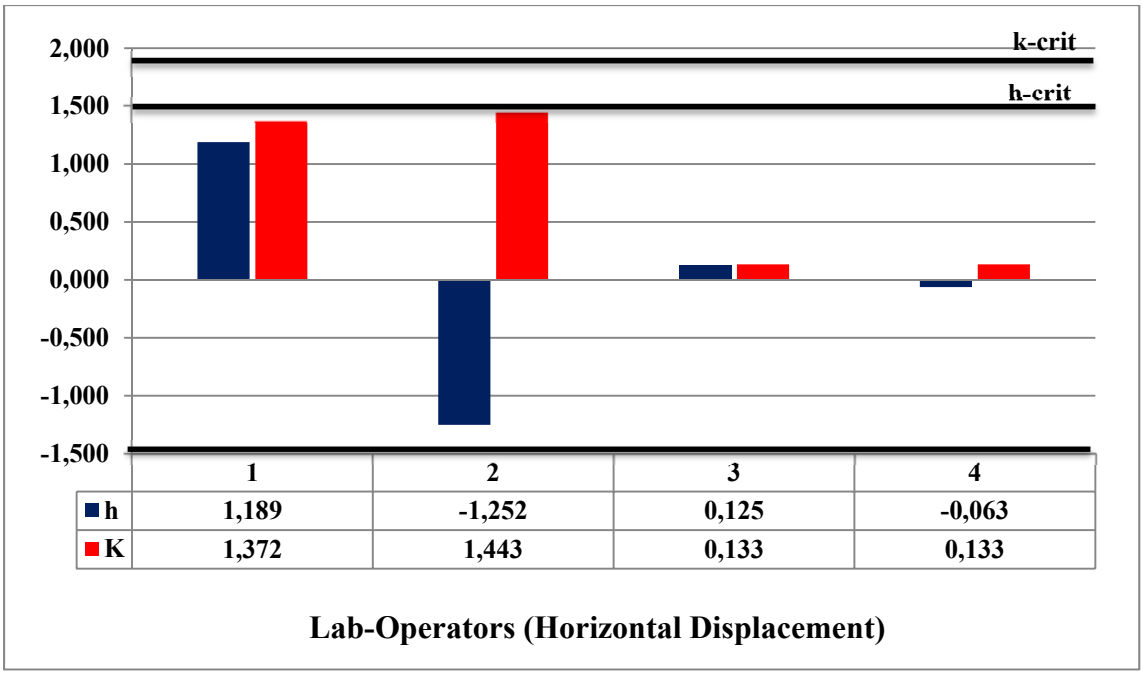


Figure 5.9 Lateral displacement test results, plot of h and k consistency statistics versus material type combinations

If a lab-operator has a within-laboratory consistency statistic (k consistency statistic) that exceeds the critical k value (k-crit), this indicates that its within-laboratory standard deviation is significantly different from that obtained by all of the laboratory-operators.

This may show that the laboratory is having problems repeating test results in its own laboratory and should investigate its testing procedures and equipment. For those laboratry-operators having k value close to critcal k value, taking precautions to ensure that there are not any problems with their testing procedures and equipment is recommended.

A summary of the results presented in this section is shown in Table 5.7. As it can be seen from this table, h and k consistency value of LCMB laboratory' test results were lower when sample prepared using sieve analysis of aggregate than that of aggregate splitting.

Table 5.7 Results summary for h and k consistency statistics
for all tests done in MTQ and LCMB

	2011						Lab-Operator out		Lab-Operator close	
Test	X_{ave}	S_x	S_r	S_R	$2.8S_r$	$2.8S_R$	h-stat	k-stat	h-stat	k-stat
ISSA Slurry Seal Mix										
Modified Wet Cohesion (30-min)	16.87	2.83	0.62	2.911	1.736	8.15			1	1
Modified Wet Cohesion (60-min)	19.06	3.218	1.40	3.439	3.92	9.62		1	1	
Wet Track Abrasion (1-hour soaked)	126.76	70.92	52.99	85.84	148.37	240.35		2		
Wet Track Abrasion (6-day soaked)	338.08	353.18	92.15	361.106	258.04	1011.1			2	2
Loaded Wheel (Sand Adhesion)	516.1	49.11	28.22	54.24	79.01	151.87			2	2
Vertical Displacement (Method A)	10.83	2.02	1.43	2.37	4.00	6.63				1,2
Lateral Displacement (Method-A)	8.7	1.59	1.14	3.43	3.21	9.60			1,2	

The 95 percent repeatability limit is defined as the maximum difference in test response between two individual test results obtained under repeatability condition. It may be expected to occur with a probability of approximately 0.95 (95 percent) (L.D. Coyne, 1964). Table 5.8 shows the ISSA tests precision index for the 95 percent repeatability limits along with test ranges and coefficient of variation. It illustrates the range of variability in data for each test performed.

Table 5.8 Test range, coefficient of variation and repeatability standard deviation

Test	Test Range (Average)	Cv	Rounded 95% Repeatability limit
Modified Wet Cohesion (30-min)	13.3-19.3 kg-cm	0.07-0.01	1.7 kg-cm
Modified Wet Cohesion (60-min)	14.88-22 kg-cm	0.18-0	4 kg-cm
Wet Track Abrasion (1-hour soaked)	57.9-203.4 g/m²	0.21-0.23	150 g/m²
Wet Track Abrasion (6-day soaked)	47.1-805.6 g/m²	0.08-0.19	260 g/m²
Loaded Wheel Test	469.9-583.3 g/m²	0.04-0.09	80 g/m²
Vertical Displacement	4.6-12.8 %	0.03-0.01	4 %
Lateral Displacement	6.7-10.6 %	0.25-0.15	3.2 %

5.8.1 Effect of aggregates gradation in the test responses

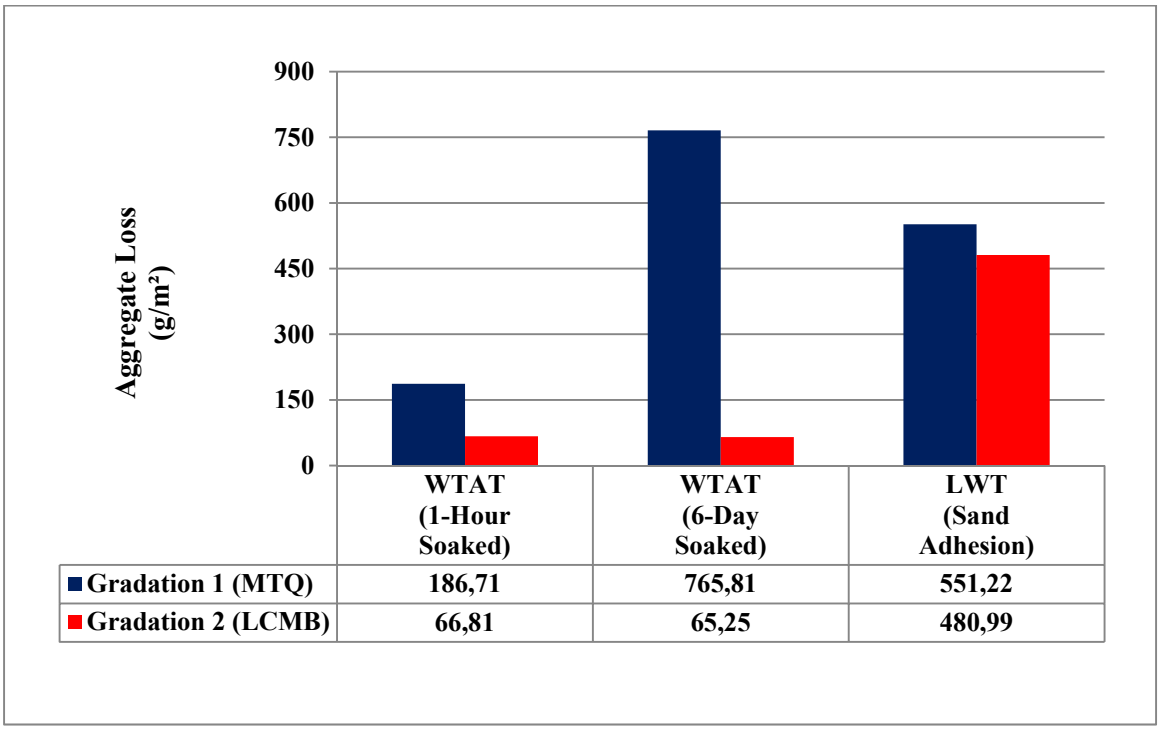
Analysis of data shows the significant effect of aggregates gradation on the ISSA mix design tests for micro-surfacing. This part of study reports the findings of a detailed laboratory investigation concerning the effect of aggregates gradation and their total specific area on the design parameters and properties of micro-surfacing mixtures. Two different aggregate gradations shown in Figure 5.1 were used to prepare micro-surfacing mixtures. The only variation was the total aggregates surface area, which was 7.486 m²/kg for gradation 1, and 9.366 m²/kg for gradation 2.

Figure 5.9 shows the results from the loaded wheel test (sand adhesion) to discuss the effects of variations in total aggregates surface area on the test results of specific micro-surfacing formulations. As it can be seen from this figure when mixtures contain higher aggregates surface area (Gradation 2), there is a sharp decrease in aggregate loss in wet track abrasion test.

But, the effect of aggregate gradation on sand adhered in loaded wheel tests is comparatively insignificant. The primary purpose of LWT is to determine maximum limit for adding asphalt emulsion in the mixture and is used in ISSA TB 111 and ISSA TB 143 mix design procedures for slurry seal and micro-surfacing to determine optimum binder content. In these guidelines, the WTAT will be performed at 1-hour and 6-day soak periods followed by tests using the LWT to determine the excess asphalt at the temperature that corresponds to the proposed traffic conditions (i.e., heavy at 35°C, moderate at 25°C, and low at 15°C).

Finally, the optimum binder content will be selected by evaluating the abrasion loss in the WTAT and the binder content versus pick up from the loaded wheel tester. While, the results of loaded wheel test is not as sensitive as the wet track abrasion test results to change in aggregate gradation. Thus the consistency for the loaded wheel test is poor which implies that the test method is vague and permits a wide range of interpretation. Figure 9 also indicates that there is substantial increase in short term aggregate loss due to action of vehicle wheels on micro-surfacing mixtures.

It also shows, from 6-day soaked wet track abrasion results, that the resistance of micro-surfacing mixture to moisture damage is reduced by increasing the total surface area of aggregates in gradation 2 than that of gradation 1. The overall conclusion from wet track abrasion tests and loaded wheel test is that the mixtures prepared using gradation 2 with higher total aggregates surface areas have more resistance to early aggregate loss and long-term moisture damage.



	WTAT (1-Hour Soaked)	WTAT (6-Day Soaked)	LWT (Sand Adhesion)
Gradation 1 (MTQ)	186,71	765,81	551,22
Gradation 2 (LCMB)	66,81	65,25	480,99

Figure 5.10 Comparison of Wet track abrasion 1-hour and 6-day soaked of samples prepared using aggregates gradations 1 and 2

Summary of test results and torque measured by modified cohesion tester at 30 and 60 minutes for prepared micro-surfacing mixtures are presented in Figure 5.11. As it can be seen from this figure, when mixture prepared with gradation 2, having more aggregate surface area than gradation one, the 30-min and 60-min cohesion of mixture were greater. This further indicates that the mixtures prepared using gradation 2 set quicker than that of mixtures prepared using gradation 1. The torque values were respectively 14.6 and 19.1 for

micro-surfacing mixtures prepared using type 1 and 2 aggregates gradation. Due to lower total surface area of aggregate with gradation 2, there observed excess asphalt emulsion in micro-surfacing mixtures prepared using this gradation. This excess asphalt emulsion caused the set time of mixture to be postponed. Analysis of 60-min modified cohesion test results shows that, the mixtures prepared using gradation 2 had higher average value of measured torque. The mean torque values were respectively 16.6 and 21.6 for micro-surfacing mixtures prepared using type 1 and 2 aggregates gradation. This indicates that the risk of early rolling traffic was reduces as the total aggregates surface area increased in mixtures with gradation 2 than that of with gradation 1, and the road can be open to traffic sooner. Same trend as 30-min modified cohesion results was observed in 60-min measured torque, and the set time was postponed due to excess asphalt emulsion in micro-surfacing mixtures prepared with grade 1 of aggregates having lower total aggregates specific surface area.

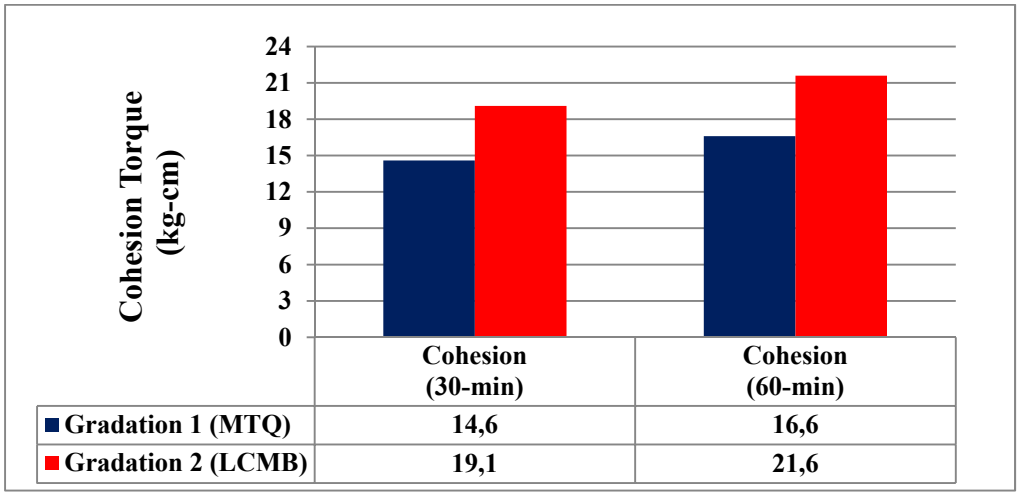


Figure 5.11 Comparison of 30-min and 60-min cohesion of samples prepared using aggregates gradations 1 and 2

Figures 5.12 shows lateral and vertical displacements at mid-length of specimens prepared with gradations 1 and 2. This figure indicates that the mixtures prepared using gradation 2 show relatively better rutting resistance as compared with the mixtures prepared with gradation 1. The reason for that may be the presence of excess asphalt in micro-surfacing

mixtures prepared with gradation 1. This also indicates that the gradation 2, which is at the middle of maximum and minimum limits suggested by ISSA guideline for type III micro-surfacing, when is mixed with asphalt emulsion to form micro-surfacing mixture, has more resistance to permanent deformation due to high traffic loading. However, analysis of data for lateral deformation did not show a significant change in lateral deformation between micro-surfacing prepared with gradation 1 and 2.

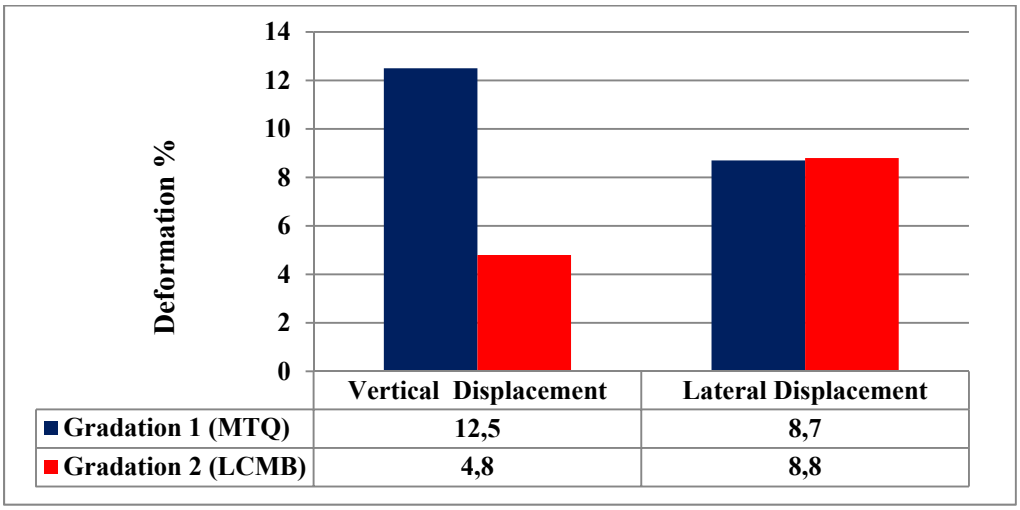


Figure 5.12 Comparison of Vertical and Lateral deformation of samples prepared using aggregates gradations 1 and 2

A summary of the results is presented in Table 5.9. Total aggregate surface area have a significant effect on the results of wet track abrasion test (1-hour and 6-day soaked sample), modified cohesion (30-min and 60-min), and vertical displacement tests. As for loaded wheel test and lateral displacement test, the test results were not significantly affected by total aggregate surface area. It is important to note that those results are valid only for the different materials used in this study. If one uses another type of emulsion which reacts differently with another type of aggregates, the results may vary. The results are also only valid in the range of added water and asphalt emulsion used in this study. On the other hand, the different values that were used are commonly used amount and are the quantities that give overall optimum results.

Table 5.9 Results summary for evaluation of aggregate gradation effects on test responses

Test	Significant Effect of Total Surface Area	Trand	Improved characteristic
Modified Cohesion (30-min)	yes	SA ↑ : Cohesion ↑	Quick-Set
Modified Cohesion (60-min)	yes	SA ↑ : Cohesion ↑	Early Rolling Traffic
Wet Track Abrasion (1-Hour soaked)	yes	SA ↑ : aggregate loss ↓	Abrasion
Wet Track Abrasion (6-Day soaked)	yes	SA ↑ : aggregate loss ↓	Moisture Susceptibility
Loaded Wheel (Sand Adhesion)	No	SA ↑ : adhered sand ↓	Bleeding
Vertical Displacement (Method-A)	yes	SA ↑ : deformation ↓	Rutting
Lateral Displacement (Method-A)	No	unchanged	Flow

5.9 Conclusion

The overall goal of this study was to compute repeatability and reproducibility of four ISSA mix design tests for micro-surfacing mixtures. This was achieved thru a vigorous statistical calculation of test results obtained from MTQ and LCMB laboratories in Quebec. The effect of total aggregate surface area was also investigated by using two different gradation of type III gradation for micro-surfacing. In the first part, the influence of different parameters was studied and the sensitivity of different tests was evaluated. Based on the statistical analysis of the findings, it was observed that the consistency of ISSA mix design test results was higher in the case of using sieve analysis method to reach desired aggregate gradation in micro-surfacing mixture. Within h consistency and between k consistency for the samples prepared using sieve analysis method was significantly lower than that of prepared using aggregates splitting methods. Repeatability and reproducibility of four ISSA mix design tests were also computed using a vigorous statistical analysis. It was also observed that, the total aggregates surface area has significant effect on the performance of micro-surfacing mixtures. A primary purpose of type III micro-surfacing mixtures is to fill rut deformation on road surface. It was observed that aggregates gradation 2 used in this study set quicker and has higher rut resistance than that of gradation 1. Resistance to moisture susceptibility, early rolling traffic, and short-term aggregates loss of micro-surfacing mixtures prepared using gradation 2 in this study was also higher, and is recommended to be used in typical micro-surfacing mixtures in area with high traffic loading in Quebec.

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CHAPTER 6

A NEW CONCEPTUAL MODEL FOR FILLER STIFFENING EFFECT ON ASPHALT MASTIC OF MICRO-SURFACING

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6.1 Abstract

The stiffening effect of the filler on the asphalt mastic of micro-surfacing was the focus of this research. One of the challenges that researchers are faced with in the field of bituminous materials is the interaction between filler and binder. In this study, a new conceptual model for filler stiffening of the mastic was developed which allows asphalt mix designer to establish the minimum and maximum filler concentration to incorporate in asphalt mixture. The proposed model has only one parameter that can be determined using specific properties of filler and asphalt emulsion. The model is based on the physicochemical interaction between filler and bitumen. Based on the model, the increase in mastic stiffness (|G*|) as a function of the increase in filler concentration, can be divided into three regions: diluted region, optimum concentration region, and concentrated region. A new property of filler, named Zeta potential, was introduced to determine the stiffening effect of filler on mastic. The effectiveness of the proposed model to capture the true behavior of mastic was also investigated through the correlation between the complex modulus of mastic and asphalt mix cohesion. Finally, the capability of the model to predict the complex modulus of a new set of filler-binder systems with different properties than those used to develop the model was evaluated. Using the proposed model, there is no need to test the mastic or asphalt mixture at different filler concentration in order to select the optimum filler amount.

6.2 Introduction

In 2011, a new mix design procedure and specification for type III micro-surfacing as rut-fill materials that accurately select the optimum mix proportions such as aggregate gradation, asphalt emulsion, water, and cement contents was developed (Robati et al., 2011; Robati et al., 2013). With the new mix design procedure and specification, we are able to select the optimum asphalt emulsion content and the aggregate gradation for micro-surfacing mixtures. However, the existing mix design procedures for micro-surfacing report the mix proportions with a large tolerance that results in low consistency of testing results.

Moreover, the micro-surfacing mix design tests are very operator dependent, which may lead to a significant variation in results between operators and laboratories. The new developed mix design procedure and specification for type III micro-surfacing were run with different operators and laboratories using same materials in order to establish the repeatability and reproducibility limits for each mix design tests (Robati et al., 2012; Robati et al., 2013).

Even using the accurate mix design procedure and specification, large variation in vertical deformation testing results on micro-surfacing mixtures prepared with the same materials but different filler types was observed. Therefore, it was decided to study the physical and chemical properties of filler on rutting resistance of micro-surfacing mixtures.

6.3 Literature review

One of the earliest studies to postulate the effect of filler on asphaltic materials is the work of Clifford Richardson in the beginning of 20th century (Richardson and Clifford, 1914). He reported that certain types of fillers such as silica, limestone dust, and Portland cement adsorb relatively thicker film of asphalt. In 1912, for the first time, Einstein reported the stiffness effect of fillers on a composite matrix. He developed coefficient of Einstein as the indicator of the rate of increase in stiffness of the matrix by incorporation of filler particles (Einstein, 1956).

Following the study conducted by Einstein, the stiffening effect of filler on asphaltic materials has been the focus of many specialists in the asphalt field. In 1930, Traxler reported which fillers' parameters are important in regard to their potential for stiffening the asphaltic materials. According to his study, size and size distribution of filler particles are the fundamental filler parameters as they affect the void content of filler. He also considered the surface area of filler particles and their shape as the influential parameters governing the stiffening effect of filler on asphaltic materials (Traxler, 1961).

In 1947, P. J. Rigden developed a new theory named the "fractional voids concept". He considered the asphalt required to fill the voids in a dry compacted bed as "fixed asphalt," while asphalt in excess of that amount was defined as "Free Asphalt" (Fig. 6.1). According to Rigden theory, the only factor affecting the viscosity of the filler-asphalt system is the fractional voids in filler. He reported that other characteristics of fillers, and also asphalt properties are less significant with regard to the viscosity of filler-asphalt system (Rigden, 1947).

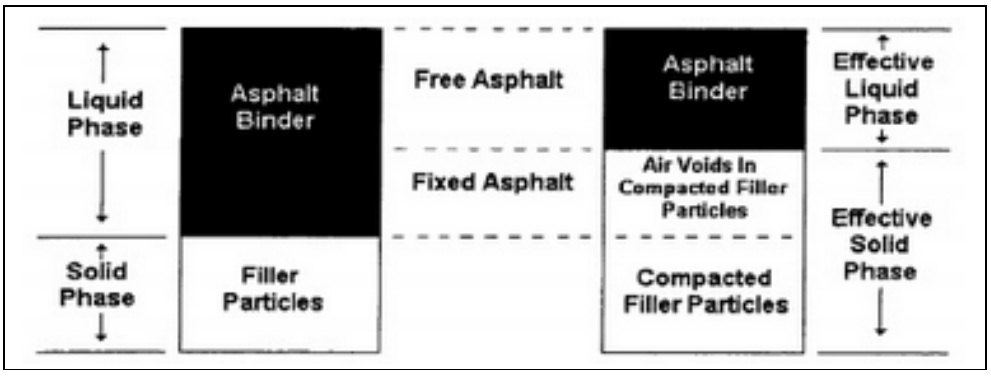

Figure 6.1 A Schematic Showing the Concept
of Fixed Asphalt and Free Asphalt
Extracted from B. J. Smith (2000, p. 35)

In 1962, Tunnicliff described the importance of filler particle size distribution as the main properties of filler affecting the filler-asphalt system. He reported that there is a gradient of stiffening effect, which has a bigger value at the surface of the particle size, and becomes weaker with distance from the surface, as shown in the Fig. 6.2 (Tunniclif, 1962).

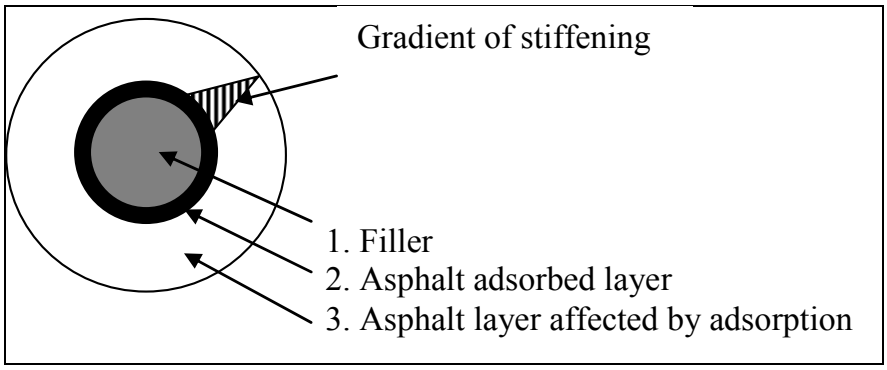

Figure 6.2 Schematic of Asphalt-Filler Interaction
Extracted from Tunniclif (1962, p. 17)

In 1973, Anderson and Goetz concluded that the type of filler affect the stiffening effect of filler on filler-asphalt system (Anderson and Goetz, 1973). They explained that the stiffening effect could be due to "the presence of some sort of physicochemical interaction" between filler and asphalt.

In 2010, Faheem and Bahia introduced a conceptual model for the filler stiffening effect of mastic. They postulated that the filler stiffening effect varies depending on the filler mineralogy and the concentration in the mastic (Faheem and Bahia, 2010). According to their study, the change in stiffness (G*) as a function of increase in filler concentration can be divided into two regions: diluted and concentrated (Fig. 6.3). In the diluted region, the filler particles are separated by enough free asphalt volume, while, in the concentration region the transition is due to the consumption of "Free Asphalt".

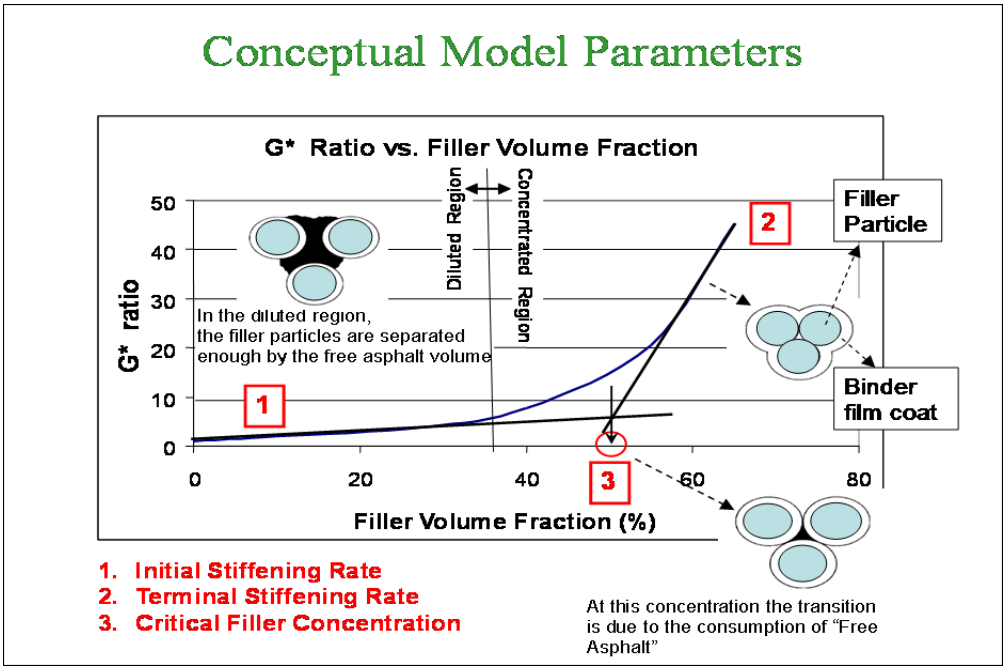

Figure 6.3 Schematic of the progress of stiffness in terms of filler influence
Extracted from Faheem, A., and H. Bahia (2010, p. 10)

In the early part of the 20th century, asphalt emulsion was used in the bituminous materials with the aim of lowering the application temperature. Asphalt emulsions are mainly used in road pavement preservation including both surface maintenance (e.g. chip seal and micro-surfacing) and structural maintenance (e.g. cold-in place recycling and full depth reclamation). In the case of asphalt emulsions, asphalt is mixed with water containing emulsifying agent in the presence of sufficient mechanical energy to break up the asphalt into droplets. Depending on the type of emulsifier agent (e.g. cationic, anionic, or nan-ionic), the asphalt droplets take up electric charge. The size and sign of the charge on the asphalt droplets can be measured and is expressed as the "zeta potential" of the droplet. In this paper zeta potential of the filler particles was studied as an effective filler property affecting the charge on asphalt droplets and so the stability of asphalt emulsion-filler systems. The presence of the charges on the particle surface results in a specific ions distribution which form an electric double layer (EDL) (Hunter 1981). The Stern model proposed that the counter-ions presented in between the surface and Stern plane form the Stern layer and the

other counter-ions located beyond the Stern plane form the diffuse part of the EDL (Shaw, 1980). The electrokinetic behavior of a charged particle surface depends on the zeta (ζ) potential of that charged surface, which is a measurable parameter and is directly proportionate with the stability of a colloidal system.

6.4 Objectives

The objectives of this study are:

1. To identify filler properties that can be used to model the increase in complex shear modulus (|G*|) of micro-surfacing mastic as a function of filler concentration, and establish minimum and maximum limits for the amount of filler with regard to the mastic and asphalt mixture properties;

2. To identify asphalt emulsion properties that can be used to model the increase in complex shear modulus (|G*|) of micro-surfacing mixture;

3. To Model micro-surfacing mastic stiffness in terms of filler-bitumen interaction;

6.5 Research approach

To fulfil the first objective, two types of asphalt emulsions and six types of mineral fillers are used to produce asphalt emulsion mastics of various properties. Mastics are then tested to calculate the |G*| ratio, which is the complex shear modulus |G*| of mastic divided by |G*| of the asphalt emulsion at zero filler concentration. The tests are performed using dynamic shear rheometer (DSR) at 64°C, and 10 Hz. Using curve fitting feature of stratigraphic software, various correlation models are fitted to the obtained data for selecting the most accurate model that can best describe the behaviour of mastic.

The main purpose of the first part of this study is to propose an empirical model for increase in complex shear modulus |G*| of binder as a function of filler concentration. The first hypothesis is that there is a minimum filler concentration in the mastic, at which the filler

particles begin to interact with surrounding binder. This interaction reaches its greatest amount at maximum filler concentration in the mastic. The second hypothesis is that there is a maximum filler concentration beyond which the binder in the mastic is affected by the filler causing the loss of adhesion between the filler particles and surrounded asphalt. The values of minimum and maximum filler concentration in the mastic are a function of the rate of the filler stiffening effect on mastic.

The second target of the study is to identify filler, and asphalt emulsion properties that could be used to model the increase in |G*| of asphalt emulsion mastic as a function of filler concentration. To accomplish this objective, filler of different sources, having a wide range of properties, are mixed with asphalt emulsion to prepare mastics of different properties. Using the model developed from the first part of the study, parameters of the model are then correlated with the selected properties of fillers and asphalt emulsion. Finally, a multiple regression analysis is used to relate the model parameters to the material properties. The goal is to establish the minimum and maximum limits of incorporated filler on asphalt emulsion using only the filler and/or asphalt emulsion properties.

In fact, the ultimate goal of this research is to capture a true mechanism of filler stiffening effect on asphalt emulsion. The interaction between filler and surrounding asphalt binder results in the cohesion development in the mastic itself, and also between mastic and aggregates in asphalt mixture.

The hypothesis is that there is a relationship between the amount of minimum and maximum filler concentrations in mastic, and the cohesion development of asphalt mixture. Within the minimum and maximum filler concentrations, the mastic is supposed to show excellent adhesion and cohesion to the aggregates by having a good mechanical interlock between binder and filler particles, and so the optimum cohesion for the asphalt mixture should be obtained.

For now, the ratio of binder to dust of aggregates is used in different standards to select optimum filler concentration in the asphalt mixtures. However, the consistency of this

method is not good, which leads to a wide range of interpretation of data due to various filler and binder properties.

This study proposes a model that establishes the value of minimum and maximum filler concentrations in the mastic based on material properties that can give an accurate estimation of optimum stiffening of mastic due to incorporation of filler in binder to form a mastic film around aggregates in the asphalt mixtures.

6.6 Materials and Methods

Two types of asphalt emulsions, plus six types of mineral fillers were used to prepare twelve mastics with various properties. The first type of emulsified asphalt used in this study is named “CQS-1HP”, which is a cationic quick setting polymer modified asphalt emulsion and was provided by Les Emulsion Bourget, in Montreal, Canada.

The base binder of this asphalt emulsion comes from a light crude source with low asphaltene content. The base binder of this emulsion was modified using latex polymer to get a PG 76-22 grade binder.

The second type of emulsified asphalt is named “low penetration” cationic bitumen emulsion. The based binder of this emulsion comes from a heavy crude source with high asphaltene content, and was modified using linear high molecular weight SBS polymer to get a PG 76-22 grade binder. This emulsion is stabilized using the Latexfalt® BioStab MY technology, and was provided by Latexfalt B.V Company in the Netherlands. Table 6.1 represents the properties of two bitumen emulsions used in the study. The information given in this table has been reported from the suppliers. Six types of fillers used in this study were selected to have a wide range of mineralogical and physical properties. Fillers were passed through 80 μm sieve, and analyzed by sedimentation test to have the filler gradation. Figure 6.4 and 6.5 show the gradation of fillers used in this study.

Table 6.1 CQS-1HP and low penetration asphalt emulsion properties from suppliers

Asphalt emulsion name	Type of base binder	Asphaltene (%)	Acid Type	Type of Polymer	Penetration	Residue by distillation	pH of emulsion
CQS-1HP	PG 64-22	14.7	Phosphoric	SBR latex	60 dmm	65.1 %	3.0
Low penetration	PG 70-22	20.6	Hydrochloric	Linear SBS	36 dmm	57%	2.2

The value of effective particle sizes, D10, D50, and D90 that correspond to the 10, 50, and 90% passing, were determined based on filler gradation and used in data analysis to consider the effect of filler gradation. Other filler properties such as Rigden voids (RV), Specific gravity (GS), Methylene blue value (MBV), pH and Zeta potential (ZP) of fillers were also measured and are presented in Table 6.2. The relative complex modulus (stiffness) of the mastics is measured at 0, 15, 25, 40, 50, and 65% filler volume fraction using DSR tester at 64 ˚C and 10 Hz. Volume fractions of filler at each filler concentration is determined by dividing the volume of the filler to the volume of the mastic.

Table 6.2 Measured properties of fillers

Measured property	Type of filler						Standard test
	Calcium quicklime	Hydrated lime	Lime kiln dust (LKD)	Granit	Limestone	Dolomite	
Rigden voids (%)	60.0	62.0	53.5	26.0	37.0	27.0	En 1097 - 4
D10 (µm)	2.5	5.0	3.5	2.0	2.0	3.0	ASTM D422 - 63
D50 (µm)	3.0	6.5	5.0	13	10	11	ASTM D422 - 63
D90 (µm)	5.0	12	13	16	14	15	ASTM D422 - 63
GS	3.31	2.35	3.2	2.68	2.72	2.81	ASTM D854 - 10
pH	12.5	12.5	12.5	6.0	7.0	11.0	ASTM D4972 - 01
MBV (gr/L)	15.0	10.0	7.0	2.0	1.5	2.0	EN 933-9
ZP (mV)	+26.4	+32.2	-17.4	-14.4	-16	-22.7	-

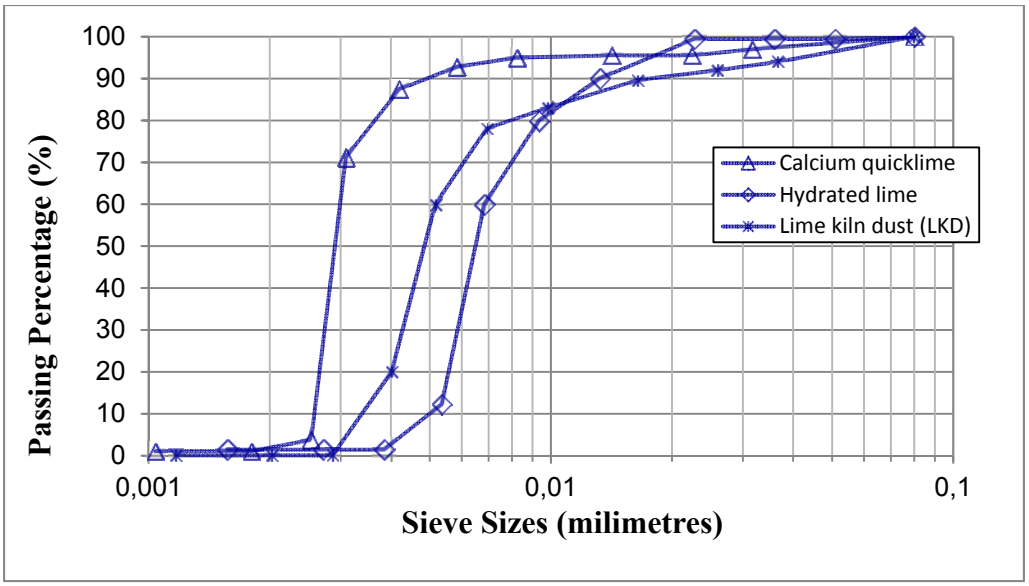

Figure 6.4 Filler gradation curve (Calcium quicklime, Hydrated lime, Lime kiln dust (LKD))

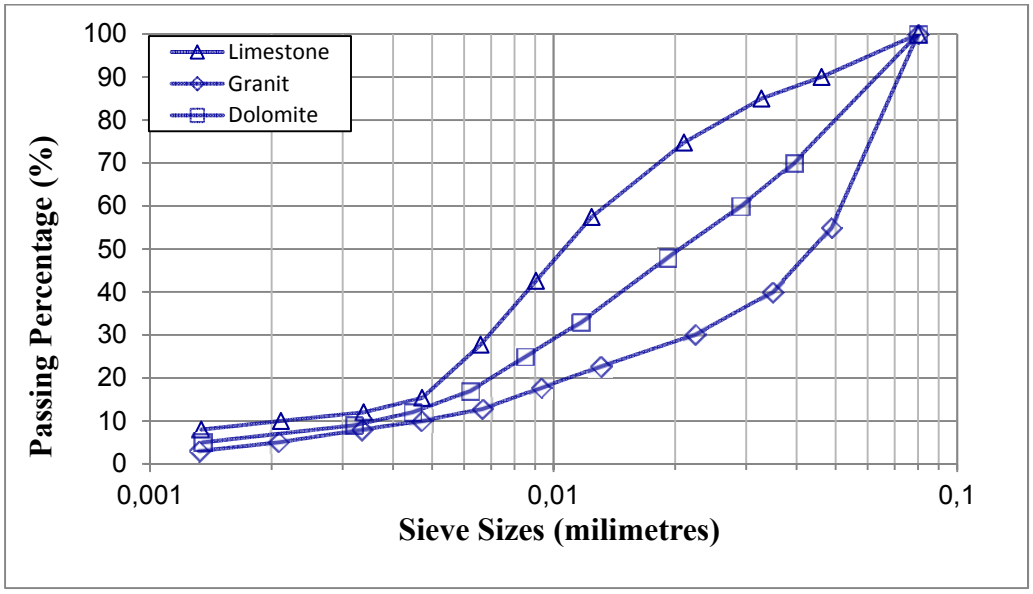

Figure 6.5 Filler gradation curve (Limestone, Granit, Dolomite)

As mentioned earlier, the stiffness ratio of the mastic is determined through dividing the stiffness of mastic at each filler concentration by the stiffness of the asphalt emulsion with no filler concentration. The plot of raw data of mastic stiffness ratio versus different filler volume fraction is then presented to develop an empirical model of mastic stiffness. The maximum concentration of filler is the amount that could be added into asphalt emulsion without having difficulty to mix filler with emulsion in laboratory.

Table 6.3 illustrates the experimental design used in this study including the controlled and dependent variables. In this experimental program, all 12 mastics were tested with 6 different filler contents, 3 replicates, for a total of 216 tests. All 72 generated mastics were tested to measure their complex shear modulus and the results were used for the modelling of increase in complex shear modulus due to incorporation of filler particles. Following the selection of a proper model, the effect of bitumen and filler properties on the parameters of the selected model was studied using the ANOVA multilevel factorial design. To do so, the most varied properties of filler and bitumen was selected, which are zeta potential and asphaltene content respectively.

Table 6.3 Design of Experiment (DOE)

Controlled Variables		
Filler properties	**Asphalt emulsion properties**	**Dependent Variables**
1. Rigden voids 2. D10 3. D50 4. D90 5. Specific Gravity 6. pH 7. Methylene blue 8. Zeta potential	1. Asphaltene content 2. Acid type and amount 3. Polymer type and amount 4. Penetration 5. pH of emulsion 6. Asphalt residue	• Relative complex shear modulus of mastic on asphalt binder at six different filler concentration (volume fraction) • Cohesion of micro-surfacing mixtures at six filler concentration

6.7 Results and discussion

In order to model the increase in stiffness of mastic due to the incorporation of filler, a conceptual model is proposed. The effectiveness of the model to compute minimum and maximum filler concentrations is evaluated. Filler and asphalt dominant properties are then substituted in the model. Finally, the capabilities of the model to predict the complex modulus of the new set of generated mastics are validated.

6.7.1 Mastic testing results

Figures 6.6 and 6.7 show the |G*| ratio of the mastics as a function of filler volume fraction. All points on the Figures 6.6 and 6.7 are measured experimental points. These figures demonstrate the plots for mastics respectively prepared with CQS-1HP and low penetration asphalt emulsions. As it can be seen from these figures the effect of hydrated lime filler on |G*| ratio of the mastics always is higher than other types of fillers, while the effect of limestone filler is the lowest. The data points of |G*| ratio of mastics presented in Figures 6.6 and 6.7 were used as starting points to generate the mastic stiffness model.

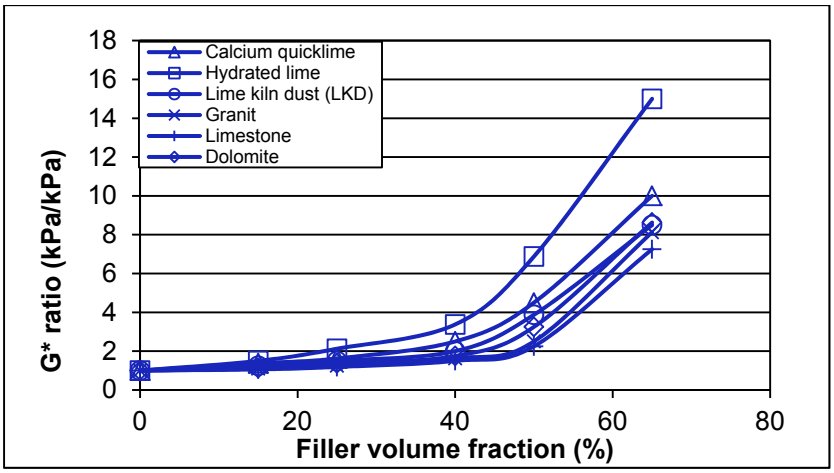

Figure 6.6 G* Ratio for mastics produced from fillers mixed with CQS-1HP asphalt emulsion

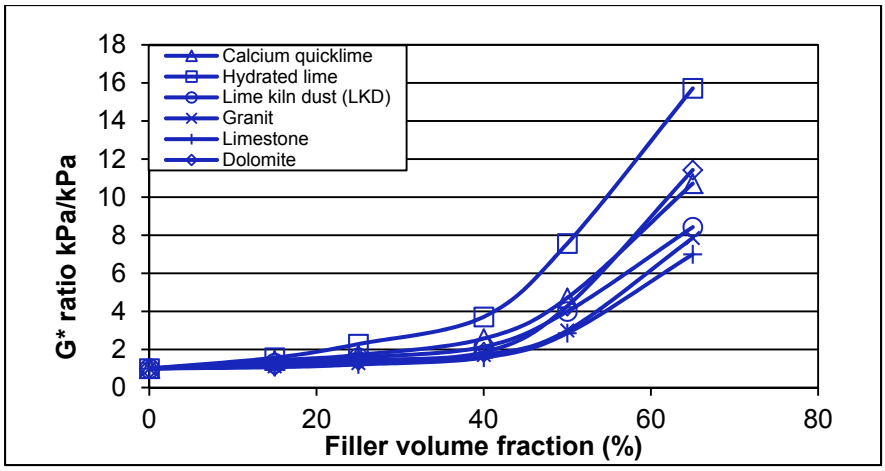

Figure 6.7 G* Ratio for mastics produced from fillers mixed with low penetration asphalt emulsion

6.7.2 Mastic stiffness modeling

The mastic stiffness modeling was done with the 3 replicates of all 72 different asphalt mastic mixes. Various correlation models were evaluated to fit the results for the |G*| ratio of mastics. It was observed that the correlation model which best fits (highest R^2) the data of relative | G*| of mastics is a parabola with the following equation (equation 6.1):

$$Y = (a + bX^2)^2 \quad (6.1)$$

Where:

Y: Relative Complex Modulus (kPa/kPa);
a: Relative |G*| of mastic at 0% filler to that of binder (Intercept of parabola);
b: Stiffening rate (Slope of parabola);
X: Filler volume fraction (%);

Equation 6.1 was fitted to the data using Statgraphic (version 10) curve fitting software. Examples of the fitted models are shown graphically in Figure 6.8. As it can be seen, the coefficient of correlation, shown by R^2, is at least 98.1%, which shows relatively a high

correlation between the fitted model and the raw data of |G*| ratio. This further means the high accuracy of the proposed model to predict |G*| ratio of mastic at any given filler concentration.

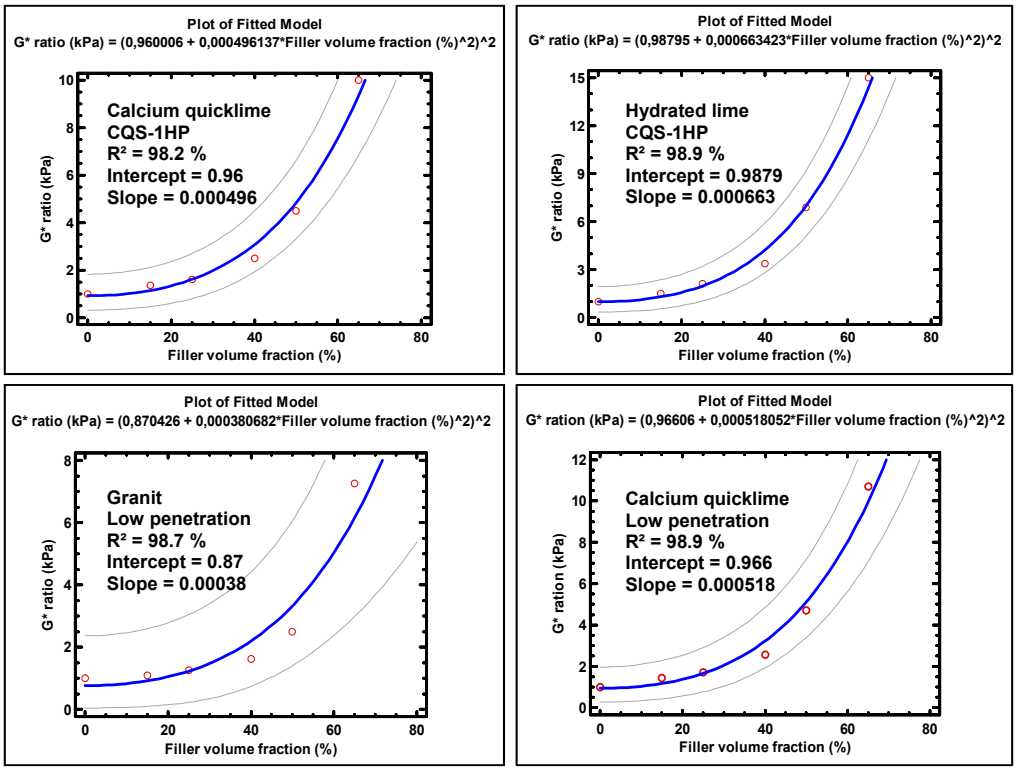

Figure 6.8. Examples of fitted model for mastic stiffness

Figure 6.9 shows the standardized effect of filler and binder properties on parameter “b” (or stiffening rate) of the proposed fitted model. Standardized effect of filler and binder types on parameter “b” was determined using ANOVA analysis of statgraphic software. Due to simplicity in design of the experiment, most varied properties of filler and binder in range of values were selected to determine the standardized effect of filler and binder type on “b” parameter. It was observed that for the filler, the zeta potential is the most variable property and asphaltene penetration is the most variable property for the bitumen.

In Figure 6.9, the filler type corresponds to zeta potential value of fillers, and asphalt type represents the asphaltene content of bitumen in the asphalt emulsion. ANOVA analysis to determine standardized effects of factors on responses is capable of computing the effect of

interaction between factors, in addition to the effect of each factor to the second power. This can help to better analyze the effect of different factors on the responses. Figure 6.9 shows that the filler and asphalt type have high effect on stiffening rate or parameter "b" of the model. Figure 6.9 also shows that the interactions between asphalt and filler properties have also an effect on the stiffening rate, or parameter "b", of the model.

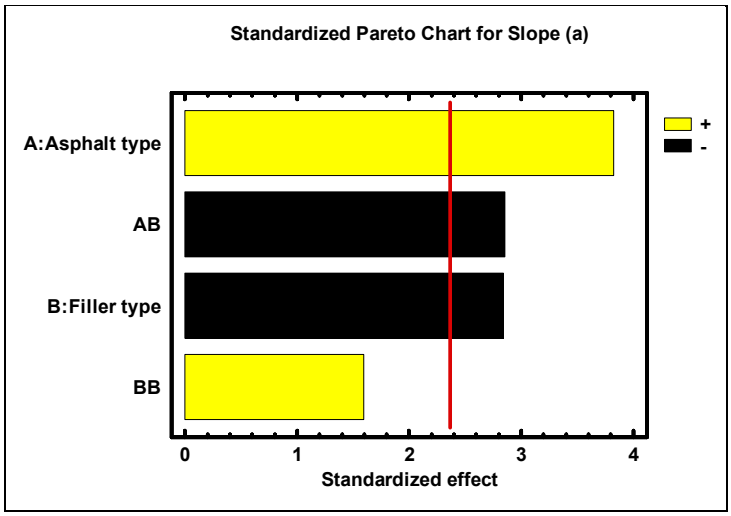

Figure 6.9 Pareto chart, effect of filler and asphalt emulsion type on parameter b of model (slope)

From the analysis presented in Figure 6.9, it can be concluded that the behavior of mastic in terms of stiffness is dependent of filler and asphalt properties.

Furthermore, it is important to note that the parameter "a" of the model corresponds to the value of |G*| ratio of mastic at 0% filler to that of binder (Intercept of parabola). This ratio is supposed to equal 1. The change in parameter "a" is due to the statistical variation of fitted curve to the different data points obtained from various combinations of filler-binder. In fact, it is reasonable to assume that the parameter "a" of model is equal to 1.

Therefore, the equation 6.1 can be simplified as below (equation 6.2):

$$Y = (1 + bX^2)^2 \quad (6.2)$$

Where:

Y: Relative Complex Modulus (kPa/kPa);
b: Stiffening rate (Slope of parabola);
X: Filler volume fraction (%);

6.7.3 Proposed conceptual model

Figure 6.10 shows the proposed mechanism by which the mineral filler interacts with the asphalt binder. As it can be seen from this figure, the increase in mastic stiffness (|G*|) as a function of the increase in filler concentration, can be divided into three regions: diluted region, optimum concentration region, and concentrated region. The first region is called diluted because of the rate of increase of the stiffness, which follows an almost a linear curve with a very low slope. Within the diluted region, there is minimal interaction between filler particles and the surrounded asphalt due to the presence of too much free asphalt in the system (asphalt in excess of filling the Rigden voids in fillers). In fact, the stiffening effect of filler particles in mastic at diluted region is very low. This region is shown by number 1 in the Figure 6.10.

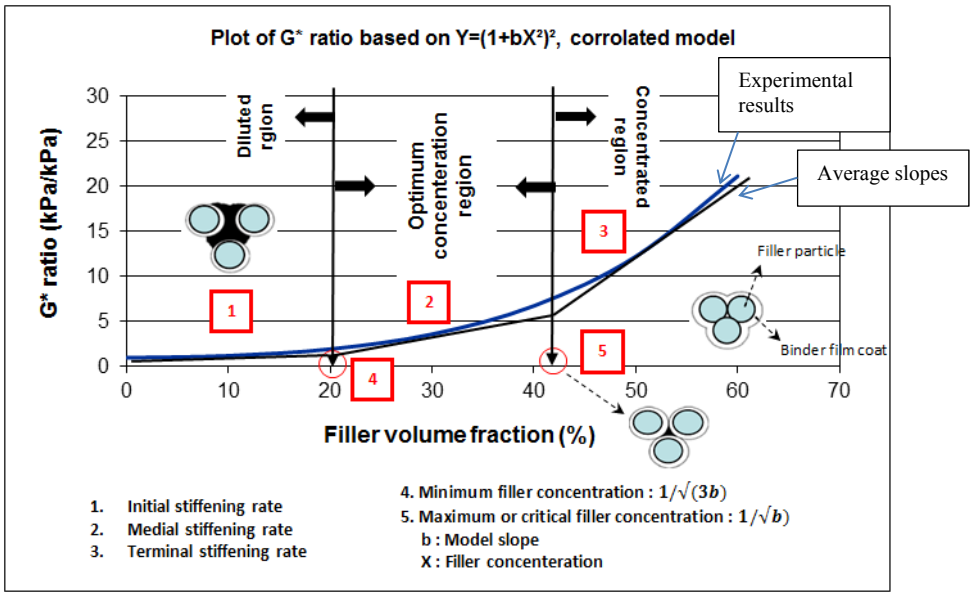

Figure 6.10 Proposed conceptual model for the increase in stiffness as a function of filler volume fraction

The second region is called the optimum concentration region, where the curve follows a parabola with a moderate slope (stiffening rate). Within the optimum concentration region, there is optimum interaction between filler particles. In this region, there is an optimum asphalt binder content in the mastic that can completely coat the filler particles. It should be noted that the starting and ending point of the curve at optimum concentration region corresponds to minimum and maximum filler concentration in the mastic, where the filler particles start to interact with surrounded asphalt binder. This interaction reaches its largest amount at the maximum filler concentration.

By addition of more filler particles in the mastic, the curve pushes toward the third region, which is called the concentrated region. In this region, there is not enough asphalt binder to completely coat the filler particles, so the mastic starts to lose its capability to adhere and bond aggregates together in the asphalt mix. This can also be explained by the presence of influenced asphalt binder in the mastic, which directly affects the rate of increase of stiffness of the mastic. This rate follows a curve with a steep slope. The concentrated region is shown with number 3 in Figure 6.10.

However, it is important to establish the limits in order to distinguish between the three regions explained in the model. Using equation (6.2), and setting the first and second order differential equations equal to zero, the points where the curve follows different slopes are determined. Equations (6.3) and (6.4) are the absolute value of complex number obtained for the variable X. Calculation is given as below:

$$Y = (1 + bX^2)^2 \longrightarrow Y = 1 + b^2 X^4 + 2\,b\,X^2$$

$$\frac{\mathrm{d}\,Y}{dX} = 0 \longrightarrow b^2\,4\,X^3 + 4\,b\,X = 0 \longrightarrow X = \frac{1}{\sqrt{b}}\,i$$

$$\longrightarrow |X| = \sqrt{(\frac{1}{\sqrt{b}})^2} \longrightarrow |X| = \frac{1}{\sqrt{b}} \qquad (6.3)$$

$$Y = (1 + bX^2)^2 \longrightarrow Y = 1 + b^2 X^4 + 2\,b\,X^2$$

$$\frac{\mathrm{d}\,Y}{dX} = 0 \longrightarrow b^2\,4\,X^3 + 4\,b\,X = 0 \longrightarrow \frac{\mathrm{d}^2\,Y}{dX^2} = 0$$

$$b^2\,12\,X^2 + 4\,b = 0 \longrightarrow X = \frac{1}{\sqrt{(3b)}}\,i \longrightarrow |X| = \frac{1}{\sqrt{3b}} \qquad (6.4)$$

Where:

Y: Relative Complex Modulus (kPa/kPa);
b: Stiffening rate (Slope of parabola);
X: Filler volume fraction (%);

It was obsereved that the value of "$\frac{1}{\sqrt{3b}}$" corresponds to the minimum filler concenteration in the mastic, where mastic starts to gain stiffness due to incorporation of filler. It was also seen that the value of "$\frac{1}{\sqrt{b}}$" corersponds to the point where the mastic experiences its maximum stiffness.

6.7.4 Effectiveness of model to calculate minimum & maximum filler concentrations

The proposed emperical model is able to establish limits for the value of minimum and maximum filler concenteration in the mastic. It was already hypothsised that, in the asphalt mixture, the mastic starts to develop cohesion with aggregates at minimum filler concentration, while this cohesion reaches to its greatest amount at maximum filler concenteration. However, the proposed model to calculate the increase in stiffness of mastic and the value of minimum and maximum filler concentrations are developped from the data points of mastic complex moduli obtained from DSR test. Therefore, it is necessary to validate the capability of the model to compute minimum and maximum filler concenteration in the mastic from another test. If the mastic shows its highest cohesion at maximum filler concentration, therfore, it is resonable to say that the asphalt mix itself shows its highest amount of cohesion at maximum filler concentration. Cohesion test on asphalt mixture were conducted at different filler concenteration to calculate the value of the minimum and maximum filler concenterations in the asphalt mixture. Due to the type of asphalt binder used in this study, which is a quick setting cationic asphalt emulsion, it was decided to prepare micro-surfaicing mixture to validate the effectiveness of proposed model. Micro-surfacing is a mixture of polymer modified asphalt emulsion with aggregates in presence of water and cement. This type of asphalt mixture is used to fill rut deformation on the road surface of high trafficed areas.

Figure 6.11 is a plot of raw data for wet cohesion values at 30 minutes for a micro-surfacing mixture prepared using CQS-1HP asphalt emulsion and 0-5 mm aggregates with hydrated lime as the filler. The tests were performed according to modified cohesion test presented in the technical bulletin number 139 of International Slurry Surfacing Association (ISSA TB 139). The cohesion of the micro-surfacing mixture was measured 30 minutes after mixing. From this figure, it can be seen that the curve of testing data follows a polynomial with two points, where the slope of the curve changes. These two points should correspond to the values of minimum and maximum filler concenterations obtained from DSR test on the mastics.

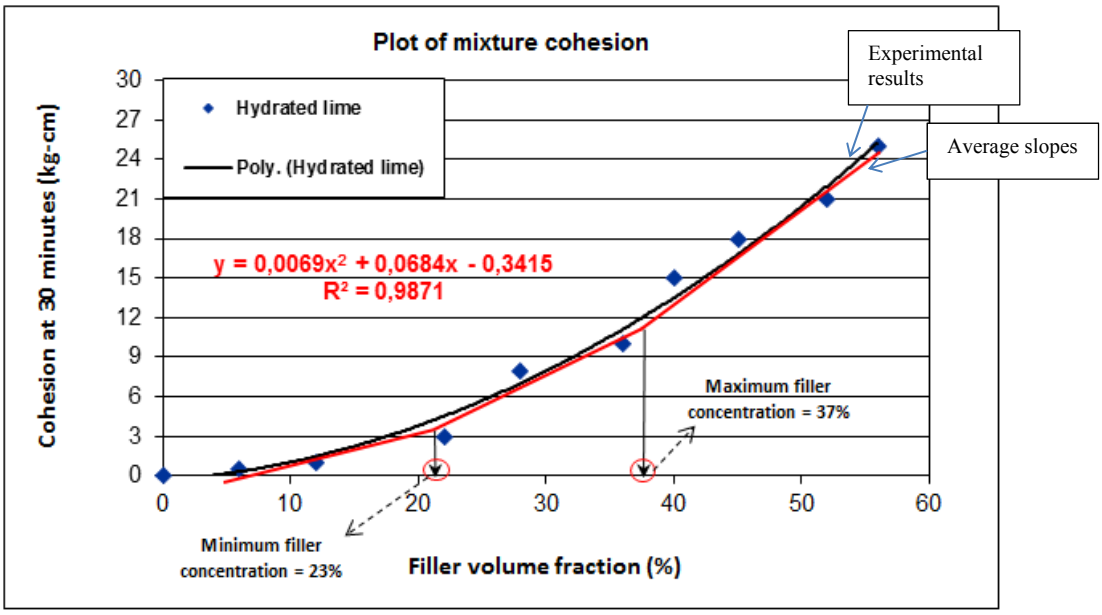

Figure 6.11 Cohesion of micro-surfacing mixture as a function of filler volume fraction (CQS-1HP asphalt emulsion, and Hydrated lime)

Table 6.4 presents the value of minimum and maximum filler concentration obtained from the proposed model of mastic stiffness, and the cohesion test on the asphalt mixture with different fillers. Figure 6.12 was prepared to correlate these two values with the values calculated by the proposed model.

High coefficient of correlations between the results confirms that the model is capable to compute the values of minimum and maximum filler concentrations both in the mastic and in the asphalt mix.

Table 6.4 Estimated minimum and maximum filler concentration based on the proposed model of stiffening in mastic and the cohesion test on the asphalt mix

Type of filler	Minimum filler concentration (%): $1/\sqrt{(3b)}$	Minimum filler concentration obtained from cohesion test (%)	Difference[1] (%)	Maximum filler concentration (%): $1/\sqrt{b}$	Maximum filler concentration obtained from cohesion test (%)	Difference[1] (%)
Calcium quicklime	25.8	24.0	6.9	44.7	43.0	3.8
Hydrated lime	22.5	23.0	2.1	38.9	37.0	4.8
Lime kiln dust	27.5	26.0	5.4	47.6	45.0	5.4
Granite	29.6	28.0	5.4	51.3	49.0	4.4
Limestone	31.3	31.0	0.9	54.2	52.0	4.0
Dolomite	27.5	26.0	5.4	47.6	46.0	3.3

1: $Difference = \frac{(Filler\ concentertaion\ obtained\ from\ model - Filler\ concenteration\ obtained\ from\ test)}{Filler\ concentertaion\ obtained\ from\ model}$

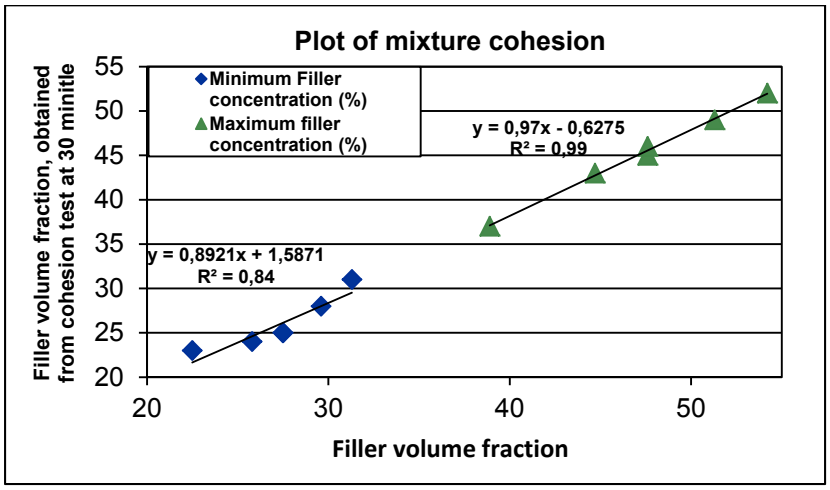

Figure 6.12 . Correlation between estimated minimum and maximum filler concentration

Figure 6.13 shows the mastics with different filler volume fractions. The goal here was to evaluate the effectiveness of proposed model to estimate the amount of minimum and maximum filler concentration in the mastic. Mastics were prepared using CQS-1HP asphalt emulsion and Granit filler. As it can be seen from this figure, at 30% filler volume fraction, the filler particles start to interact with the surrounded asphalt binder. This interaction reaches

its maximum at 50% filler volume fraction, where beyond this value there is not enough binder in mastic to coat filler particles. The uncoated filler particles are visible in the photo of mastic with 55% filler volume fraction.

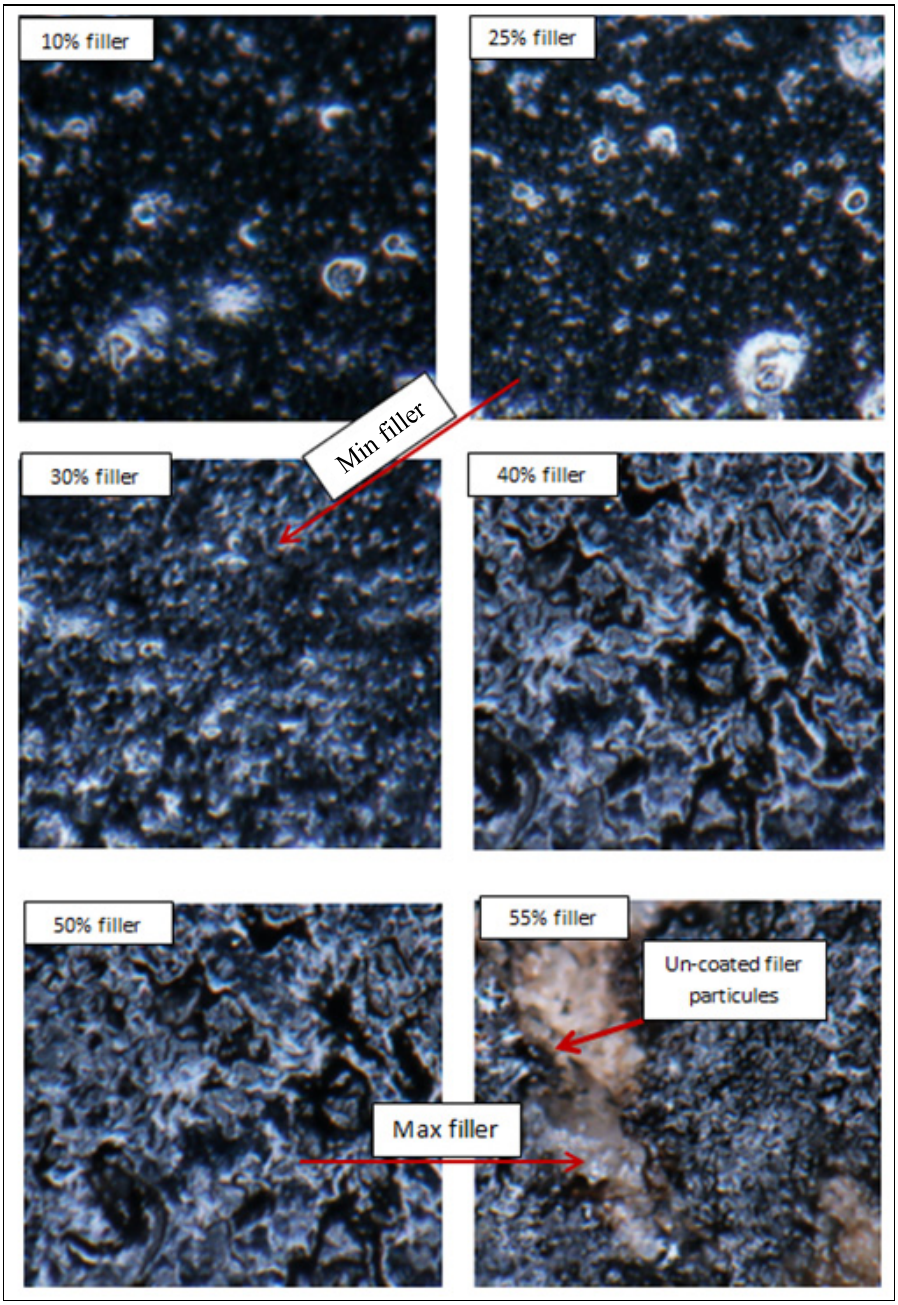

Figure 6.13 Photos of mastics prepared with CQS-1HP asphalt emulsion and Granit filler at different filler volume fractions

6.7.5 Effect of selective emulsion and filler properties on the stiffness of mastic

As it was explained earlier, the proposed model has only one parameter, which is named filler stiffening rate of mastic (parameter b). It was also shown that the filler stiffening effect is dependent of the filler and asphalt emulsion properties. Therefore, an analysis was performed to correlate the parameter "b" with the filler and asphalt properties studied in this work. Table 6.5 shows that the parameter "b" of model is correlated with asphaltene content, Rigden voids, and particle size (D10), pH, methylene blue, and zeta potential of filler. Between the physical properties of filler such as particle size (D10, D50, and D90), it was observed that particle size (D10) shows the highest correlation with the filler stiffening rate of the mastic. This indicates that, as the filler particle size decreases, the stiffening rate in the mastic increases.

Table 6.5 Correlation of model parameters with selected filler and emulsion properties

Type of emulsion	Model Parametre	Asphalthene (%)	Rigden Voids (%)	D10 (µm)	D50 (µm)	D90 (µm)	Specific Gravity	pH	Methylen Blue (g/L)	Zeta Potential (mV)
CQS-1HP	Slope (b)	0.82	0.8	0.88	-0.52	0.15	0.29	0.72	0.65	0.82
Low Penetration	Slope (b)	0.68	0.72	0.66	-0.4	-0.38	-0.44	0.69	0.68	0.78

The pH of filler in water also influenced the filler stiffening rate of the mastic. Four filler types used in this study (i.e. calcium quicklime, hydrated lime, lime kiln dust) had pH of greater than 7, which are said to be basic or alkaline. The other two types (i.e. limestone and granite) were respectively neutral and acidic. Both types of asphalt binders used in this study (CQS-1HP and low penetration) had respectively pH of 3.0 and 2.2. The four basic fillers developed higher rate of filler stiffening of the mastic compared to the acidic and neutral

fillers. This can be explained by the ability of filler to raise the pH of asphalt emulsion-filler system. As the basic fillers were added on asphalt emulsion, the pH of system rises quickly, which causes the emulsion to be destabilized and break faster (faster cohesion development). While in the case of acidic fillers, asphalt emulsion breaks at a lower rate.

The filler stiffening rate of the mastic is also affected by the zeta potential (ZP) of the filler. Zeta potential is a scientific term for electro-kinetic potential in colloidal systems. Zeta potential is the potential difference between the dispersion medium and the stationary layer of fluid attached to the dispersed particle. A value of 25 mV (positive or negative) can be taken as the arbitrary value that separates low-charged surfaces from highly-charged surfaces (Delgado 2007).

Hydrated lime and calcium quicklime in this study are said to have highly-charged surfaces. The other four types of fillers had low-charge surfaces. It was observed that there is a direct relationship between the zeta potential of fillers and the stiffening rate of the mastic. The higher the zeta potential value is, the higher the stiffening rate of the mastic is. This may be due to higher amount of adsorbed asphaltene onto the highly-charged surface of filler particles. Also, it can be explained by the higher stability and dispersion of fillers with highly-charged surfaces in the asphalt emulsion. Basically, for small filler particles, a high zeta potential will confer stability, which results in a high dispersion of filler particles in the system. This further indicates that fillers with highly-charged surfaces will resist aggregation. In the case of the fillers with low-charged surfaces, the fillers tend to rapidly coagulate or flocculate in the asphalt binder.

Normally, zeta potential itself is affected by the changes in the pH of the colloidal system, and also the type/concentration of the ionic surfactants (emulsifiers). In a colloidal system such as asphalt emulsion/filler before the set of the emulsion, the measurement of the zeta potential of the system as a function of pH and emulsifier type/amount can lead to information in formulating the asphalt emulsion product to give maximum stability of the filler particles in the mastic of micro-surfacing, or in determining the optimum condition for the flocculation and curing of the system. In this study, the analysis of the results showed that the mastic of micro-surfacing mixtures made with filler particles with high pH and zeta

potential values (measure in water) experienced higher cohesion and stiffness. This can be explained by the setting process of the quick setting asphalt emulsions, in which the free emulsifier is adsorbed onto the surface of filler particles with opposite charges that will neutralize the charge on the surface of the filler particles and so affecting the zeta potential. This further causes a significant instability of the colloidal system.

Methylene blue test had also shown correlation with stiffening rate in the mastic. Methylene blue value (MBV) is evaluated to quantify the amount of harmful clays of the smectite (montmorillonite) group, organic matter, and iron hydroxides present in the filler. Three types of lime fillers used in this study (i.e. calcium quicklime, hydrated lime, and lime kiln dust) had higher methylene blue value than the other fillers such as limestone, granite, and dolomite. The three lime fillers have shown higher stiffening rate of the mastic compared to the three others. This can be explained by the fact that the clay absorbs water in asphalt emulsion leading a faster flocculation of asphalt droplets and so faster cohesion development in the mastic.

6.7.6 Substituting filler and asphalt properties in the model

Using multiple regressions, the parameter "b" of the model was correlated with selected filler properties. The final model for parameter "b" explains 97% of consistency according to ANOVA analysis and is presented in below equation (equation 6.5):

(6.5)

$$b = 10^{-7}\,(2686 + 45.8\,As + 34.6 \times RV + 67.3 \times D10 + 94.7 \times pH - 213 \times MBV + 51.2 \times ZP)$$

Where:

As: Asphaltene content (%),
RV: Rigden voids (%);
D10: Effective filler size (µm);
pH: Power of Hydrogen;

MBV: Methylene blue values (g/L);
ZP: Zeta potential (mV);

It should be noted that the value of the minimum and maximum filler concentrations, both in the mastic and the asphalt mixture can be estimated using the properties of filler and asphalt emulsion. These two values can directly be measured using the filler properties and asphalt emulsion with high accuracy. This further indicates that there is no need for mastic or asphalt mix testing to establish the minimum and maximum limits for the amount of incorporated filler in the asphalt mixture. Figure 6.14 shows the plot of slope "b" predicted form the proposed model and observed from cohesion test on the asphalt mixture. As it can be seen from this figure, the coefficient of correlation is equal to 1. This means high capability of the proposed Equation 6.5 to predict the minimum and maximum filler concentrations in asphalt mixture using the properties of filler and asphalt.

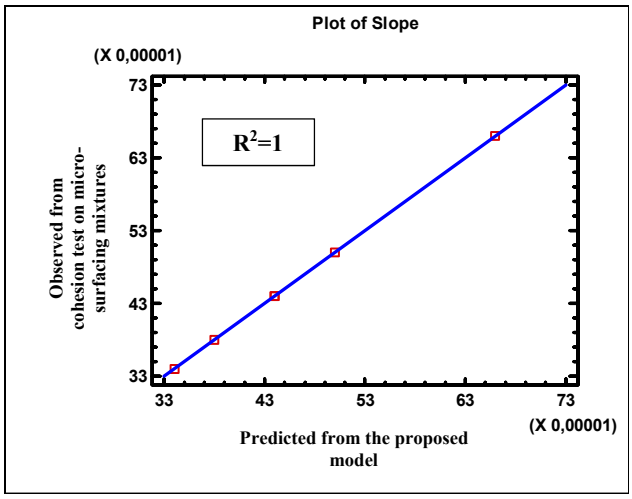

Figure 6.14 The plot of slope, "b", predicted form the proposed model and observed from cohesion test on the asphalt mixture

6.7.7 Validation of proposed model

In order to validate the proposed mastic stiffness model, it is necessary to use new experimental data generated from tests on mastic with different properties.

For this purpose, two different types of fillers and asphalt emulsions were used to generate four mastics of different properties than those tested to develop the model. Fly ash and Quartzite were selected as the new filler.

The emulsions were developed using different base binders modified with EVA polymer. New generated mastics were tested at three different filler concentration. Table 6.6 and 6.7 show the filler and asphalt emulsion properties used in the validation of the proposed stiffness model.

Table 6.6 Properties of Fillers Used in Validation of the Model

Filler properties				
Type of filler	**Rigden Voids (%)**	**D10 (μm)**	**pH**	**Zeta Potential (mV)**
Fly Ash	55	3	10	+19.5
Quartzite	30	2	6	+8.2

Asphalt emulsion properties					
Type of emulsion	**Base binder**	**Acid Type**	**Type of Polymer**	**Asphaltene (%)**	**pH of emulsion**
CRS-1H	PG 58-28	HCL	-	14.7	2.0
CMS-1HP	PG 64-28	HCL	EVA	14.7	2.2

Figure 6.15 illustrates the correlation between predicted and measured complex moduli. The correlation coefficient of 1 shows the high capability of the model to predict the true behavior of the new set of mastics. The model can be used in the micro-surfacing mix design

as an essential tool for establishing the limit for the amount of added filler. The authors believe that using the proposed model, Equation (6.2), there is no need to test the mastic or micro-surfacing mixtures at different filler concentration in order to select the optimum filler amount. The model is capable of determining the optimum filler amount using filler and asphalt emulsion properties. Some validations of the model were also conducted to evaluate the capability to predict the stiffness of the mastics generated from the hot mix asphalt (HMA). It was also observed that the model can successfully predict the stiffness of HMA mastics at different filler concentration. This indicates the possibility of using the proposed model to establish the filler limit in HMA mastics than using the ratio of binder to dust of aggregates.

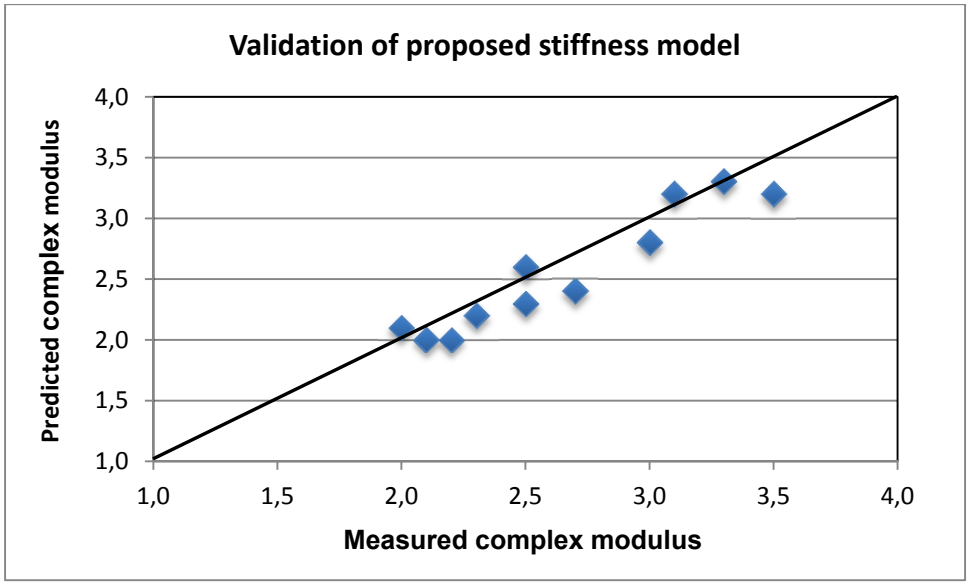

Figure 6.15 Correlation between measured and predicted complex modulus

6.8 Conclusions

Based on the detailed analysis of the results in this study, the following findings are presented:

1. A model was developed to predict the stiffness of the mastic at different filler concentration. The model stipulates that the mastic complex modulus as a function of filler volume fraction follows three regions: diluted region, optimum concentrated region, and concentrated region;

2. The final form of the model is shown as below, (equation 6.2):

(6.2)

$$Y = (1 + bX^2)^2$$

Where:
Y: Relative Complex Modulus (kPa/kPa)
X: Filler volume fraction (%)
b: Stiffening rate;

3. Using regression analysis of the ANOVA, the model parameter was correlated with the selected filler and binder properties. The model has only one parameter (b or stiffening rate), which was correlated with the filler and asphalt properties. Therefore, it is possible to capture true behavior of the mastic using selective filler and asphalt properties;

4. Filler properties with the highest impact on the model are: Rigden voids (RV), effective filler size (D10), power of hydrogen (pH) and methylene blue value (MBV). The stiffening rate, or parameter b, was successfully defined using the mentioned filler properties as well as the most varied properties of asphalt emulsion which the asphaltene. The final equation is shown as below, equation 6.5:

(6.5)

$$b = 10^{-7}\,(2686 + 45.8\,As + 34.6 \times RV + 67.3 \times D10 + 94.7 \times pH - 213 \times MBV + 51.2 \times ZP)$$

Where:

As: Asphaltene content (%),
RV: Rigden voids (%);
D10: Effective filler size (μm);
pH: Power of Hydrogen;
MBV: Methylene blue values (g/L);
ZP: Zeta potential (mV);

5. Minimum ("$\frac{1}{\sqrt{3b}}$") and maximum ("$\frac{1}{\sqrt{b}}$") filler concentrations were calculated and validated using modified cohesion test for micro-surfacing mixtures.

6. The proposed model was validated by new set of generated mastics with different properties than those used to develop the model. The model showed a high capability to predict the complex modulus of the mastics at different filler volume fractions. It is proposed that such model can be used as essential tools to predict the minimum and maximum filler concentrations both in cold asphalt mixture and HMA. It is suggested that the model be used in the European and North American mix design procedures for cold asphalt and HMA.

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CHAPTER 7

INCORPORATION OF RECLAIMED ASPHALT PAVEMENT AND POST-FABRICATION ASPHALT SHINGLES IN MICRO-SURFACING MIXTURES

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7.1 Abstract

The inclusion of Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) is relatively common in hot mix asphalt, but not in micro-surfacing. As of now, the micro-surfacing is composed only of virgin aggregates. In order to study the feasibility of incorporating RAP and RAS in micro-surfacing mixtures, a research project conducted at the Laboratoire sur les Chaussées et Matériaux Bitumineux (LCMB), at École de technologie supérieure (ÉTS) was done. The tests performed in the first part of the study to evaluate different properties of mixtures incorporating RAP and RAS into micro-surfacing mixtures prepared with virgin aggregates were the modified cohesion test, wet track abrasion test, and lateral/vertical displacement test. Then, the possibility of preparing micro-surfacing mixture using only RAP and RAS materials as the aggregate skeleton of the mix was studied. The results showed that it was possible to prepare micro-surfacing mixtures using 100 percent RAP materials. As for RAS, a limit of 17 percent is suggested. The results for the second part of study indicated that the maximum amount of added RAS in micro-surfacing mixture prepared using only RAP materials is 10 percent in order to respect the International Slurry Surfacing Association (ISSA) mix design standards.

7.2 Introduction

7.2.1 Importance of the Quebec Road Infrastructure Network

Road transport plays an important role in the Province of Quebec's economy and provides the basic infrastructure for bringing the majority of the people who are living in far off villages into the mainstream of life by connecting them with the rest of the province. Quebec's road network includes approximately 185,000 kilometres of roads. The Quebec Ministry of Transportation (MTQ) manages some 29,000 kilometres of freeways (commonly known in Quebec as autoroutes), national highways (Quebec's primary highways), regional highways (Quebec's secondary highways) and collector roads, as well as 4,700 bridges and overpasses, 1,200 kilometers of resource access roads and 3,600 kilometers of mining roads. The gross replacement cost of the road infrastructure under the MTQ's responsibility is estimated at over $30 billion for the entire province. Quebec's road network required a well-defined pavement preservation and maintenance plan in order to extend its service life (MTQ, 2012).

Pavement preservation is defined as a program employing a network-level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety, and meet motorist expectations (FHWA, 2005). Pavement preservation is a planned system of treating pavements at the optimum time to maximize their useful life. Pavement preservation enhances pavement longevity at the lowest cost. Actions used for pavement preservation include routine maintenance, Preventive Maintenance (PM), and corrective maintenance (Uzarowski, L., 2007). Transportation agencies use chip seal, slurry seal, micro-surfacing, cape seal, fog seal, etc. as pavement preservation treatments.

Moreover, global warming has become one of the most complicated issues for world leaders. The energy and greenhouse gas emissions for the production of one cubic metre of asphalt concrete can be reduced as recycled materials such as Reclaimed Asphalt Pavement (RAP) are added to the mix. Pavement preservation methods such as slurry and micro-surfacing, chip sealing and crack treatment are more environmental friendly methods because they use

fewer natural resources (e.g., aggregate, binder, etc.) than traditional methods of pavement maintenance. The incorporation of recycled materials such as RAP and Recycled Asphalt Shingles (RAS) in asphalt pavement materials helps further with reducing the embodied primary (fossil) energy and greenhouse gas emissions for initial pavement preservation methods.

7.2.2 Micro-surfacing

Micro-surfacing was developed in an attempt to form a thicker slurry seal that could be used in wheel paths and ruts in order to avoid long rehabilitation work on high traffic roads. Micro-surfacing was pioneered in Germany in the late 1960's and early 1970's (International slurry surfacing association, 2011). Micro-surfacing was the result of combining highly selected aggregates and bitumen incorporating special polymers and emulsifiers that allowed the product to remain stable even when applied in multi-stone thickness. Micro-surfacing was introduced in the United States in 1980 as a cost-effective way to treat the surface wheel-rutting problem and a variety of other road surface problems (International slurry surfacing association, 2011). Micro-surfacing is applied in double layer for addressing surface irregularities. Moreover, micro-surfacing has variety of applications where fast traffic times are of concern. It also can apply on concrete bridge decks, airports runways and night work.

Micro-surfacing is a polymer modified quick setting, cold slurry paving system. This high performance cold asphalt mixture consists mainly of dense-graded fine aggregates, polymer modified asphalt emulsion, cement and water (M.P. Doyle, 1989). The role of asphalt emulsion and water is to provide fluidity to the micro-surfacing mixture. Although micro-surfacing is applied in multi-stone thickness, the asphalt emulsion in it allows the mixture to remain stable as well (Tunniclif, 1962). No heat is used during the construction process. Because of this, there is little initial hardening of the binder (L.D. Coyne, 1964). However, while there are various applications of micro-surfacing mixtures, incorporation of recycled materials like RAP and RAS has not yet been carefully studied.

7.2.3 Reclaimed Asphalt Pavement

Recycling of Hot Mix Asphalt (HMA) pavement materials has become a viable alternative in road maintenance and rehabilitation, which results in a reusable mixture of aggregate and asphalt binder known as RAP. Material conservation, reduction of overall construction costs, preservation of the environment, and retention of existing highway geometrics are some of the benefits associated with using RAP in paving materials. Recycling asphalt pavements is considered to be a valuable approach for technical, economical, and environmental reasons (Kennedy, 1998).

Almost 80 percent of asphalt pavement materials milled from the surface of existing road are re-used in different paving layers such as surface layer, base, and sub-grades. This results in making the asphalt the most recycled construction materials within the U.S. (Pavement Recycling, 2010). Various states within U.S. have also reported significant savings when RAP is used in their paving activities (Page, G. C., 1987). It was estimated that about 33 percent of all asphalt pavement in the U.S. was recycled and incorporated into HMA (Sullivan, J., 1996).

The use of RAP helps reduce greenhouse gas emissions during the production of new asphalt pavement materials. It was shown that the inclusion of 20 percent RAP in the binder course mix for Canadian arterial and high volume highway designs reduced the total primary energy estimates by 3.5 to 5 percent for rigid pavements and from 5 to 7.5 percent for the flexible pavements (Kandhal, 1997).

Considering the cost of pavement materials, it was found that the incorporation of RAP into HMA pavement provides a saving ranging from 14 to 34 percent when the RAP content varyied between 20 to 50 percent (Kandhal, 1997). Other studies have focused on the evaluation of the effect of aged binder in RAP on the blended binder properties using in the final mixture. Bending Beam Rheometer (BBR) and Dynamic Shear Rheometer (DSR) testing can be used to estimate the performance grade of the blended binder given any amount of RAP binder replacement within the mixture, which permits the optimization of the RAP quantity in the mix (Daniel R., 2011).

In order to facilitate incorporating RAP in the design of HMA, many states have relied on blending charts developed by the Asphalt Institute in the late 1980's (Asphalt Institute, 1989).

7.2.4 Reclaimed Asphalt Shingles (RAS)

Every year, around 200,000 tonnes of asphalt shingles are sent to landfills in Quebec, which results in increased construction cost, as well as growing pressure on available landfill space. According to the website of Toits-de reve.com almost 80 percent of the roofs in Quebec are covered by asphalt shingles (Toit de Reve, 2009). Newcomb et al investigated the influence of RAS on properties of HMA mixtures and reported that up to 5 percent RAS could be used in HMA (D. Newcomb, 1993). Generally, it has been accepted that greater than 5 percent shingle content (by weight of aggregates) adversely decreased the performance.

This study will not examine the incorporation of RAS into HMA, but will evaluate the possibility of adding RAS into micro-surfacing. The study includes the feasibility of incorporating higher amounts of RAS than the maximum amount, 5 percent, used in HMA.

7.3 Objectives

The first objective of this study was to examine the feasibility of using recycled paving materials such as RAP and RAS in micro-surfacing mixtures. To do this, different proportions of RAP and RAS were added to micro-surfacing mixtures, and specific properties of those mixtures were determined and compared to conventional micro-surfacing mixtures prepared using 100 percent virgin aggregates. The goal was to evaluate a micro-surfacing mixture using 100 percent recycled aggregates materials with the incorporation of RAP and RAS to the mixture.

The second objective of this study was to establish limits for the amount of recycled materials (RAP and RAS) in micro-surfacing mixtures with respect to the International Slurry Surfacing Association (ISSA) guideline for micro-surfacing mix design.

7.4 Experimental program

7.4.1 Materials and Experimental Design

All of the materials used for sample preparation represent typical materials utilized for micro-surfacing projects in Quebec. The aggregates were 100 percent crushed 0-5 mm, RAP, and RAS with gradation satisfying the Type III requirements of the ISSA mix design guideline. Figure 7.1 and Table 7.1 show the gradation curves and ISSA standard for the aggregates used in this study.

This gradation is exactly in the middle of the maximum and minimum aggregate gradation limits suggested by ISSA for Type III micro-surfacing application and is considered as mid-range aggregate gradation. Type III application of micro-surfacing is used as a rut-fill material in areas with high traffic volume.

Table 7.1 Gradations of the Aggregates Used in this Study

Sieve No & Size		% Passing by Weight		Stockpile Tolerance,%
in	mm	Ray-Car	Type III	
3/8	9.500	100	100	–
No. 4	4.750	88	70-90	+/- 5
No. 8	2.500	63	45-70	+/- 5
No. 16	1.250	44	28-50	+/- 5
No. 30	0.630	33	19-34	+/- 5
No. 50	0.315	23	12-25	+/- 4
No. 100	0.160	14	7-18	+/- 3
No.200	0.080	10	5-15	+/- 2

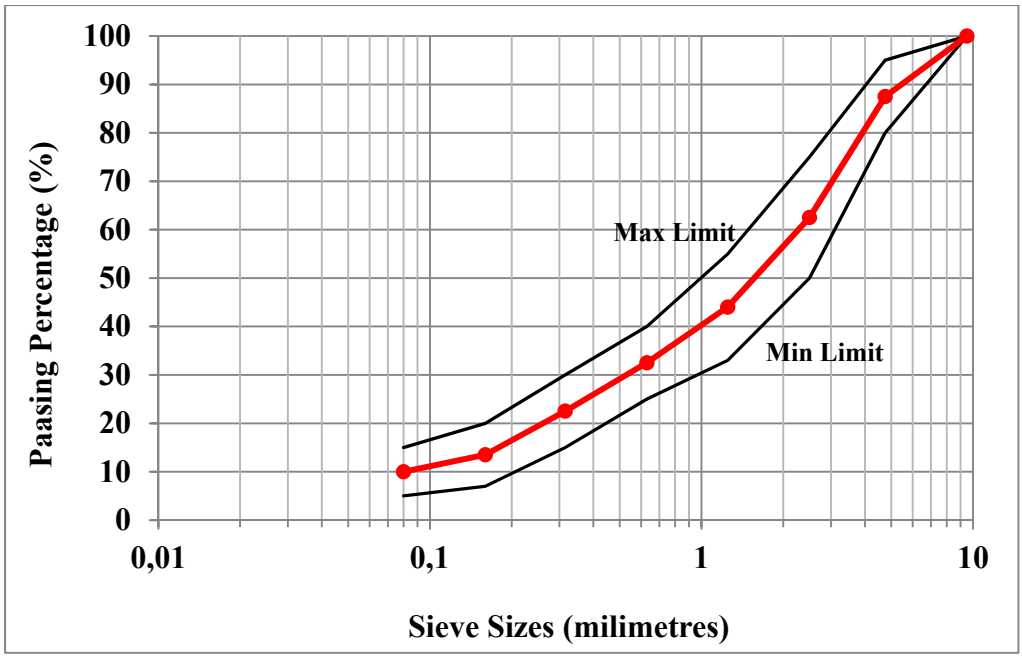

Figure 7.1 Gradation Curve for 0-5 mm Aggregates Used in this Study

The emulsified asphalt used in this part of study was CQS-1HP asphalt emulsion. The term CQS-1HP is the standard name for micro-surfacing emulsions used in the industry and it conforms to all ISSA specifications. Asphalt emulsion consists of asphalt binder and water that evaporates as the binder cures. Therefore, in designing micro-surfacing mixtures based on ISSA specifications, the residual asphalt content of the binder must be more than 62.0 percent. CQS-1HP emulsion used in this project has 65.1 percent residual asphalt content, according to test results provided by the manufacturer. Other properties of CQS-1HP asphalt emulsions have been listed in Table 7.2.

The first part of study reports the findings of a detailed laboratory investigation concerning the effect of RAP and RAS on the design parameters and properties of micro-surfacing mixtures. For this, one aggregate type (Ray-Car), one RAP and RAS source were used. The CQS-1HP asphalt emulsion, the amount of added water content, and Portland cement were kept constant to only investigate the effect of RAP and RAS on the properties of micro-surfacing mixtures.

The study consisted mainly of establishing a limit for the allowable amount of RAP and RAS that can be used in micro-surfacing mixtures without having a significant change in the mixture properties. With regard to the detailed laboratory findings obtained from the Phase 1 of this study, the allowable amount of added RAP and RAS to micro-surfacing mixtures is now presented.

Table 7.2 CQS-1HP Asphalt Emulsion
Properties from the Supplier

Tests	Results	ISSA Specifications	
		min	max
Viscosity @ 25°C (SSF)	28.0	20	100
Sieve (%)	0.04	-	0.10
Coating Test (%)	90.0	80.0	-
Residue by Distiliation to 204.4°C (% by mass)	65.1	62.0	-
Particle Charge	Positive	Positive	
Settlement, 5 day,%	0.9	-	5
Tests on Residue			
Softening Point by R 7 B (°C)	63	57	-
Kinematic Viscosity @ 135°C (mm²/sec)	1825	650	-
Penetration @ 25°C, 100 g, 5 sec (1/10 mm)	75	40	90
Ductility @ 25 °C (m)	1.10+	0.4	-

Eleven micro-surfacing mixtures were prepared using different blends of RAP/virgin aggregates, RAS/virgin aggregates, and RAS/RAP. Mixtures 1 through 3 were prepared using different blends of RAP/virgin aggregates. These mixtures were prepared based on the following RAP/virgin aggregate blends: 0/100, 50/50, and 100/0. Mixtures 4 through 7 were prepared using different blends of RAS/virgin aggregates. These mixtures were prepared based on the following RAS/virgin aggregate blends: 10/90, 17/83, 25/75, and 33/67. Table 3 shows the experimental design used in this study.

Table 7.4 shows the formulation used for preparing the micro-surfacing mixtures. It should be noted that the term “aggregate” mentioned in Table 7.4 can be considered as only virgin

aggregates or proportionate blends of RAP/virgin aggregates, RAS/virgin aggregates, and RAS/RAP. Five main properties of micro-surfacing mixtures including setting (flocculation), early rolling traffic, abrasion, rutting, and flow were evaluated through using three mixture design tests proposed by the ISSA. These tests examined included:

- the ISSA TB No. 139: Test method to classify emulsified asphalt/aggregate mixture systems using a modified cohesion tester and the measurement of set and cure characteristics at 30 and 60 minutes;

- the ISSA TB No. 100: Test method for wet track abrasion of slurry surfaces, one-hour soak and six-day soak;

- the ISSA TB No. 147 (Method A): Test method for measurement of stability and resistance to compaction, vertical and lateral displacement of multilayered fine aggregate cold mixes.

Table 7.3 Experimental Design Matrix

Mixture No.	Virgin Agg. (%)	RAP (%)	RAS (%)
Study Phase Number 1			
1	100	0	0
2	50	50	0
3	0	100	0
4	90	0	10
5	83	0	17
6	75	0	25
7	67	0	33
Study Phase Number 2			
1	0	100	0
2	0	90	10
3	0	83	17
4	0	75	25

Note: RAP is Reclaimed Asphalt Pavement and RAS is Recycled Asphalt Shingles.

Table 7.4 Mix Design Formulation used for Different Tests

Mix Components	Wet Track Abrasion Test	Loaded Wheel Test	Modified Cohesion Test
Percentage (%)			
Aggregate	100	100	100
Asphalt Emulsion	12.5	12.5	12.5
Portland Cement	1	1	1
Water	10	10	10
Weight (g)			
Aggregate	700	500	300
Asphalt Emulsion	87.5	62.5	37.5
Portland Cement	7	5	3
Water	70	50	30

7.5 ISSA Mixture Design Tests Evaluated

The ISSA Design Technical Bulletin A143 published in May 2005 contains guidelines for the laboratory evaluation of micro-surfacing mixture designs. The tests examined in this study include ISSA TB 139, 100, and 147 (Method A) as now described.

7.5.1 Modified Cohesion Test (ISSA TB 139)

The cohesion test is used to classify micro-surfacing mixtures as either slow or fast setting systems. It also can be used to establish baseline formulations of asphalt emulsion, water, aggregate, and cement additives suitable for further testing. In other words, suitable asphalt emulsion-water combination is selected based on results obtained after 30 and 60 minutes of curing at room temperature, 25°C (77°F). The minimum values required are 12 kilogram-centimetres for the 30-minute test and 20 kg-cm after 60-minutes. Figure 7.2a shows the modified cohesion tester used in this study. The 30-minute modified cohesion test result is

used to evaluate setting (flocculation) properties of micro-surfacing mixtures, while the 60-minute cohesion values can be considered as an evaluation of traffic time (i.e., early rolling traffic time occurs at a torque level of 20 kg-cm). In this study, five identical specimens of each micro-surfacing formulation were mixed and cast in 10 mm x 60 mm diameter ring moulds centered on the roofing felt squares and allowed to cure at room temperature. Torque measurement was made at suitable time intervals such as 30, 60, 90, 150, 210, and 270 minutes after casting (ISSA, 2005).

7.5.2 Wet Track Abrasion Test (ISSA TB 100)

The Wet Track Abrasion Test (WTAT) is a field simulation test to measure the wearing qualities of micro-surfacing mixture under wet abrasion conditions. The WTAT establishes the minimum asphalt emulsion content necessary to prevent excessive raveling of cured micro-surfacing mixtures. Samples were air-cured at l40°F (60°C) for one day followed by soaking for either 1 hour or 6 days in a water bath at room temperature. Figure 7.2b shows the WTAT machine used in this study. After completing the abrasion cycle, the specimen was removed from the pan and rinsed under slow running water to remove any debris. The specimen was then placed in an l40°F (60°C) oven to dry to a constant weight. The mass loss was reported as the abrasion loss of specimen. Tests were performed on 1-hour and 6-day soaked samples to determine resistance to abrasion and moisture susceptibility of the samples (ISSA, 2005).

7.5.3 Multilayer Loaded Wheel Test (Method A-ISSA TB 147)

The multilayer loaded wheel test measures the compaction or displacement characteristics of micro-surfacing under simulated rolling traffic compaction. Because micro-surfacing can be used for filling ruts, it should have proper resistance against vertical and lateral deformations under heavy traffic. This test also establishes the minimum asphalt emulsion content necessary to prevent excessive deformation of a micro-surfacing mixture. When a series of specimens containing a different range of asphalt emulsion content are tested, the optimum emulsion content for rutting resistance can be determined at the minimum vertical and lateral

displacements. The loaded wheel tester is shown in Figure 7.2c. The sample preparation and test procedure is the same as the WTAT with two exceptions. The aggregates are not further sieved through Sieve Number 4, and the specimen is air cured at room temperature for 18 hours prior to curing in a forced draft oven for a period of 24 hours. In this study, only the mold specimen with nominal thickness of 12.7 mm was used. The width and height of the specimen are measured (in the wheel path and at the mid-point of specimen length) before and after 1000 cycles of the 125 lb (56.7 kg) loaded wheel compaction (ISSA, 2005).

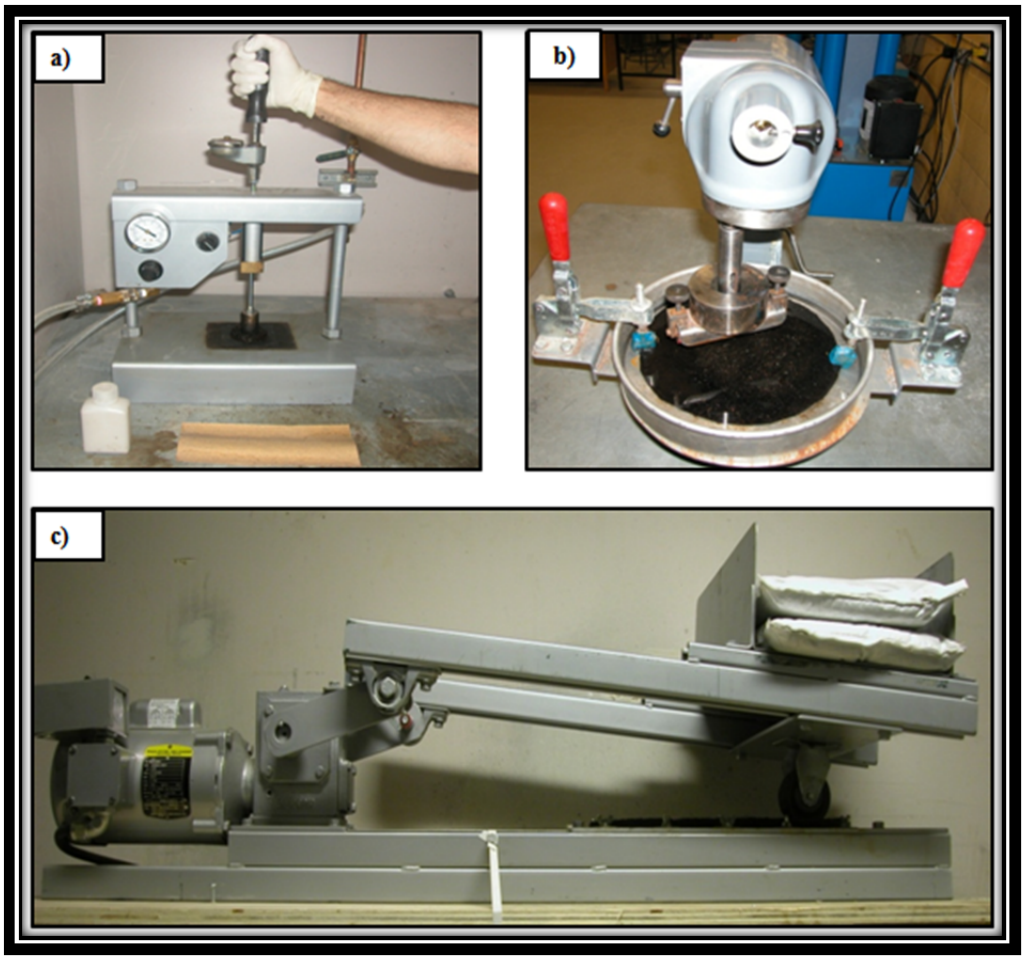

Figure 7.2 Micro-surfacing equipment used in this study a) Modified Cohesion Tester b) Wet Track Abrasion Tester c) Loaded Wheel Tester

In this study, the width and height of the specimen were measured after 1000, and 2000 cycles of the 125 lb (56.7 kg) loaded wheel compaction. Based on ISSA Design Technical Bulletin 147, May 2005, it has been found that unconfined vertical and lateral deformations that exceed 10 and 5 percent, respectively are not satisfactory for compacted, multi-layer applications. Multilayer loaded wheel test vertical & lateral displacement was conducted at 25°C, which corresponds to moderate traffic.

7.6 Results and discussions

7.6.1 Modified Cohesion Test Results

Micro-surfacing is a cold asphalt mixture whose internal strength is highly dependent on the setting (flocculation) and curing (coalescence) processes of the mixture. These processes are a function of time, and must be accurately controlled. Setting and curing that occurs too quickly (or too slowly) may result in a low quality micro-surfacing mixture. Normally, the micro-surfacing mixture applied to a road surface must be cured so that the road can be opened to traffic within 60 minutes after application. Using faster setting asphalt emulsion such as CQS-1HP in the micro-surfacing mixtures allows faster break of this product rather than slurry seal. This ability makes micro-surfacing able to support traffic as quickly as one hour after placement.

The modified cohesion test can measure the progress of setting and curing of micro-surfacing mixtures with time. The test usually is done within different time intervals and the torque is measured on top of the specimen as explained in Section 7.5.1. From field experience, a micro-surfacing mixture that respects the limits of this test will resist traffic loading as the set and curing process is completed within a reasonable amount of time. The torque measured at 30 and 60 minutes after placement characterizes well the development of strength of micro-surfacing mixtures. In the first part of this study, setting and curing characteristics of micro-surfacing mixtures were evaluated based on the blends of the different proportions of virgin aggregates, RAP, and RAS.

Figure 7.3 is a plot of raw wet cohesion values at 30 minutes for micro-surfacing specimens prepared using different blends of RAP/virgin aggregates, and RAS/virgin aggregates. As shown, with the exception of two mixtures prepared using 25 and 33 percent RAS (with respectively 75 and 67 percent virgin aggregates), all other mixtures have higher values of cohesion than the minimum limit of 12 kg-cm specified by ISSA for micro-surfacing mix design. The mixture prepared using 100 percent virgin aggregates had the highest value of 30-minute cohesion at 18.5 kg-cm followed by the mixture prepared using 50 percent RAP and 50 percent virgin aggregates (16 kg-cm), the mixture prepared with 10 percent RAS and 90 percent virgin aggregates (15.8 kg-cm), the mixture with 100 percent RAP (14 kg-cm) and the mixture with 17 percent RAS and 83 percent virgin aggregates (14 kg-cm). This shows possibility of preparing micro-surfacing mixture using 100 percent recycled materials such as RAP, although it should be noted that the micro-surfacing mixtures having higher values of 30-min cohesion are quicker set systems.

Figure 7.4 is a plot of raw wet cohesion values at 60-minutes for the same mixtures tested at 30-minutes in the modified cohesion tester. A similar trend was observed for the 60-minute modified cohesion test results. The 60-min cohesion value of micro-surfacing mixtures can be used to evaluate traffic characteristics of micro-surfacing mixtures. Early rolling traffic is a typical type of distress for micro-surfacing mixtures that can occur due to incomplete curing (coalescence) in the mixture.

Usually, those micro-surfacing mixtures having higher value of 60-min cohesion value than 20 kg-cm are cured enough and there were be less chance of early rolling traffic damage when they applied on the road surface. The results presented in Figure 7.4 show that, those mixtures which set faster (higher 30-minute cohesion values), cured more quickly as well and had higher resistance to early rolling traffic. Results of 60-minute cohesion value also indicate the possibility of preparing 100 percent recycled micro-surfacing materials using RAP. It also must be noted that the use of 17 percent RAS in virgin aggregates seems to be allowable based on the both 30 and 60-minute modified cohesion test results.

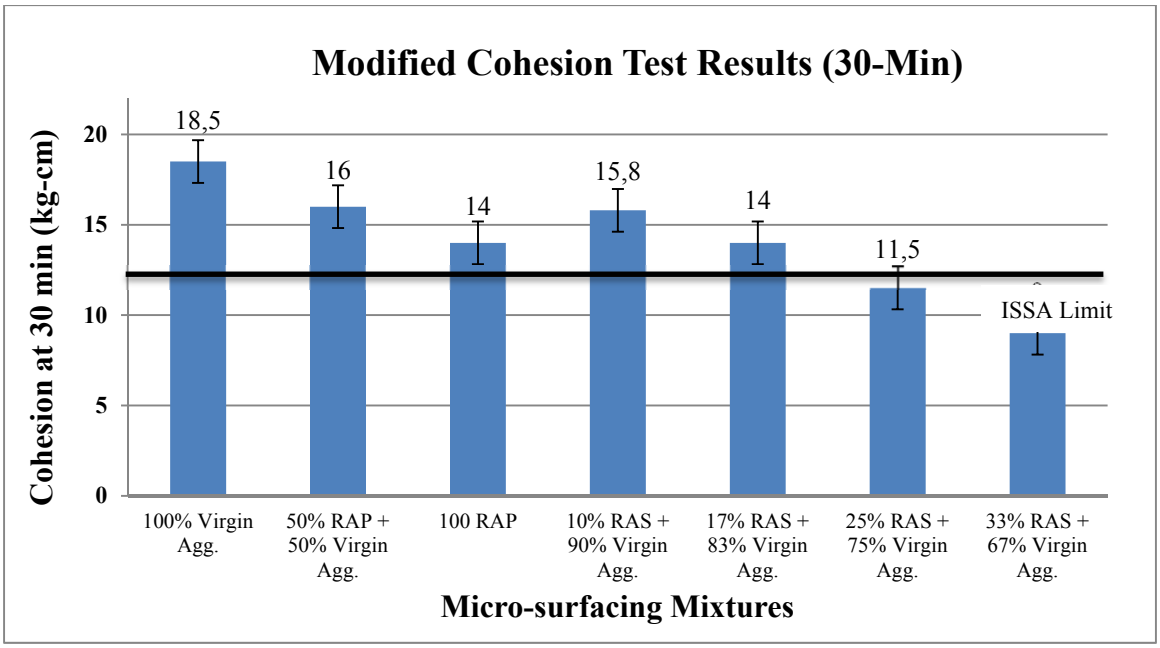

Figure 7.3 Plot of raw wet cohesion values at 30 minutes for different blends of Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS) and virgin aggregates

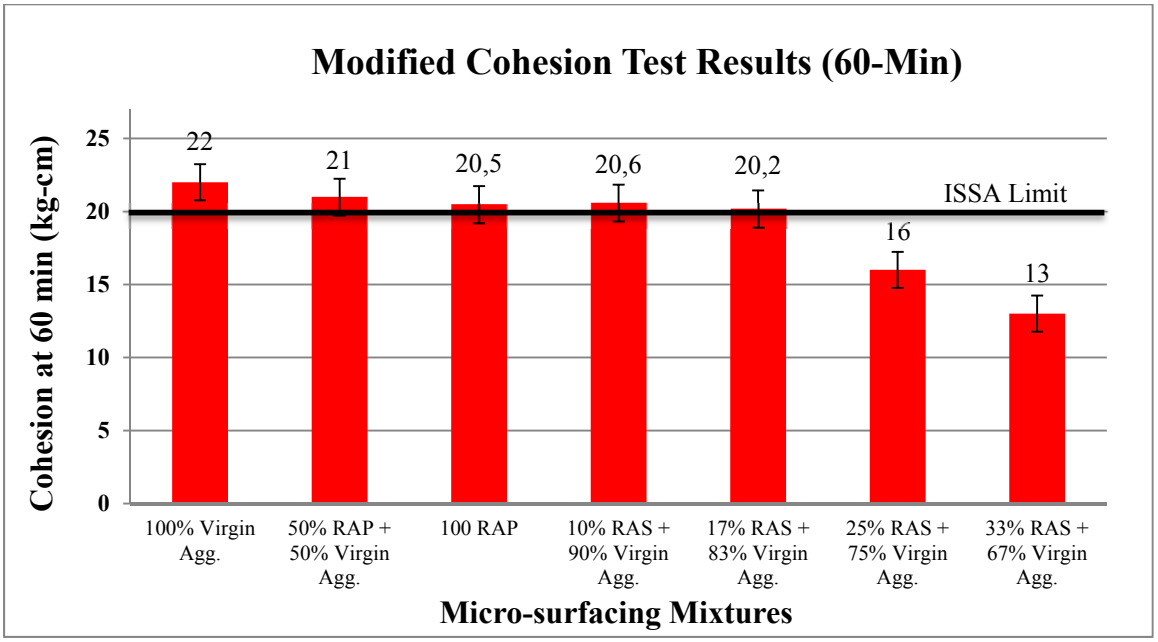

Figure 7.4 Plot of raw wet cohesion values at 60 minutes for different blends of Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS) and virgin aggregates

As shown in Figures 7.3 and 7.4, the test results suggested the potential to prepare micro-surfacing mixtures with 100 percent recycled materials using RAP. In the second part of this study, it was decided to prepare micro-surfacing materials using RAP and RAS alone, without any virgin aggregates. This could help with incorporating more recycled materials in micro-surfacing mixtures, which is favourable toward reducing the global warming potential and greenhous gas emissions associated with asphaltic materials. Figure 7.5 is a plot of raw wet cohesion values at 30 and 60 minutes for different blends of RAS and RAP. As shown, the mixtures consisting of 100 percent RAP or 10 percent RAS and 90 percent RAP have 30 and 60-minute cohesion values greater than the ISSA mix design specified limit. Therefore, it seems that the allowable amount of RAS in a mixture prepared using only RAP aggregates is 10 percent. However, more test results from the other ISSA mix design tests are required to measure different properties of these micro-surfacing mixtures. The other test results are presented in subsequent sections.

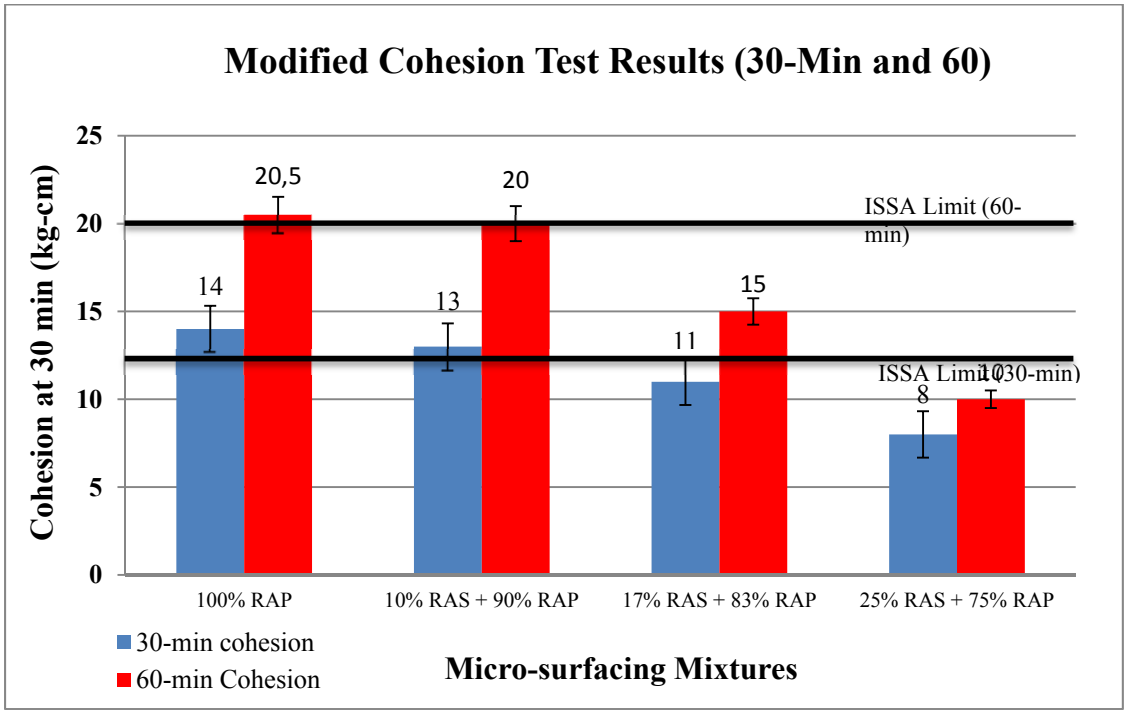

Figure 7.5 Plot of raw wet cohesion values at 30 and 60 minutes for different blends of Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS)

7.7 Wet Track Abrasion Test (WTAT) Results

Results from the WTAT (1-hour and 6-day soaked samples) are presented to evaluate the effects of variations in test results due to addition of different RAP and RAS proportions to the micro-surfacing mixtures. A maximum limit of 807 grams per square meter (g/m²) for WTAT is recommended by ISSA for the design of micro-surfacing mixtures. Figure 7.6 is a plot of raw wet track abrasion test results for 1-hour and 6-day soaked samples prepared using different blends of RAP/virgin aggregates, RAS/virgin aggregates, and RAS/RAP. As shown, all the test results are significantly less than the specified limit by ISSA for this test (807 g/m²).

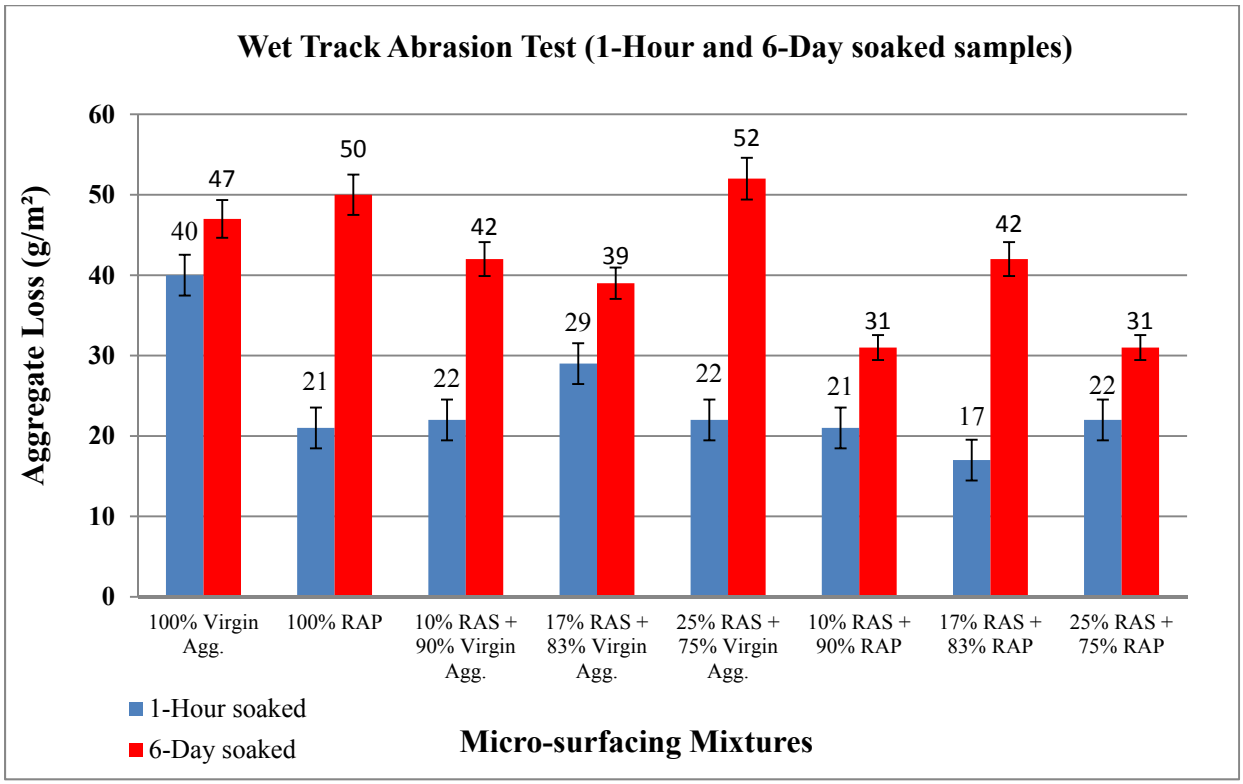

Figure 7.6 Plot of raw data for wet track abrasion test for 1-hour and 6-day soaked samples prepared using different blends of Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS) and virgin aggregates

From Figure 7.6, it can also be seen that there is not a significant variation within the test results; thus, indicating the consistency for the WTAT for the micro-surfacing mixtures prepares in both phases of this study is poor. This implies that the test method is vague and permits a wide range of interpretation. There was not observed a trend within the WTAT results for micro-surfacing mixtures prepared using different blends of RAP/virgin aggregates, RAS/virgin aggregates, and RAS/RAP. Obviously, the 6-day soaked test results were greater than that of 1-hour test results for different mixtures.

The WTAT is usually performed to evaluate the short-term abrasion and long-term moisture susceptibility of micro-surfacing mixtures. A sensitivity analysis to evaluate the effect of different levels of asphalt emulsion and water content on WTAT results, performed by the Author (Robati, 2011), showed that the variation of WTAT results is not significant. In the both parts of this study, the same poor consistency was observed for WTAT results.

Another mix design test was therefore required to evaluate micro-surfacing mixtures prepared using different amount of virgin aggregates, RAP, and RAS, in which a significant trend between results could be observed. It was decided to select a micro-surfacing mix design test which helps with measuring the resistance to deformation due to an applied load. Therefore, the multilayer loaded wheel test vertical & lateral displacement (Method A) test were selected. Section 7.8 presents the results obtained from this micro-surfacing mix design test.

7.8 Multilayer Loaded Wheel Test Vertical & Lateral Displacement (Method A) Test Results

Figures 7.7 to 7.9 show test results of lateral and vertical displacements at mid-length of micro-surfacing specimens prepared using different blends of RAP/virgin aggregates, RAS/virgin aggregates, and RAS/RAP during the first part of the study. The trend observed in the vertical/lateral displacement test (compaction test) was same as that observed during the modified cohesion test. With the exception of two mixes (25 percent RAS and 75 percent virgin aggregates, and 33 percent RAS and 67 percent virgin aggregate), all other mixes respected the limits specified within the ISSA TB 147 mix design test (Method A). For a

mix formulation to pass this test, the lateral and vertical displacements at the mid-length of the samples must be respectively less than 5 and 10 percent of the original width and thickness after 1000 cycle compactions of a 56.7 kg load. The micro-surfacing mixture prepared using 50 percent RAP and 50 percent virgin aggregates, as well as the mixture prepared with 10 percent RAS and 90 percent virgin aggregates (which had 30-minute cohesion values of 16 and 15.8 kg-cm, respectively), displayed higher resistance to compaction as well. The mixture prepared using 100 percent RAP and of the mixture prepared with 17 percent RAS and 83 percent virgin aggregates (which both had 30-minute cohesion values of 14 kg-cm) displayed lower resistance to compaction. Therefore, it seems that there is a good agreement between the results of modified cohesion and resistance to compaction tests. This may be because of the fact that quicker set and cure micro-surfacing mixtures will have more resistance to compaction. Figures 7.7 and 7.8 also show the possibility of preparing micro-surfacing mixture using 100% recycled materials such as RAP. The results also show the possibility of incorporating of 17 percent RAS into micro-surfacing mixtures prepared with virgin aggregates. But, it should be noted that the micro-surfacing mixtures having higher amount of RAS results in lower value of 30-min cohesion, and subsequently, lower resistance to compaction.

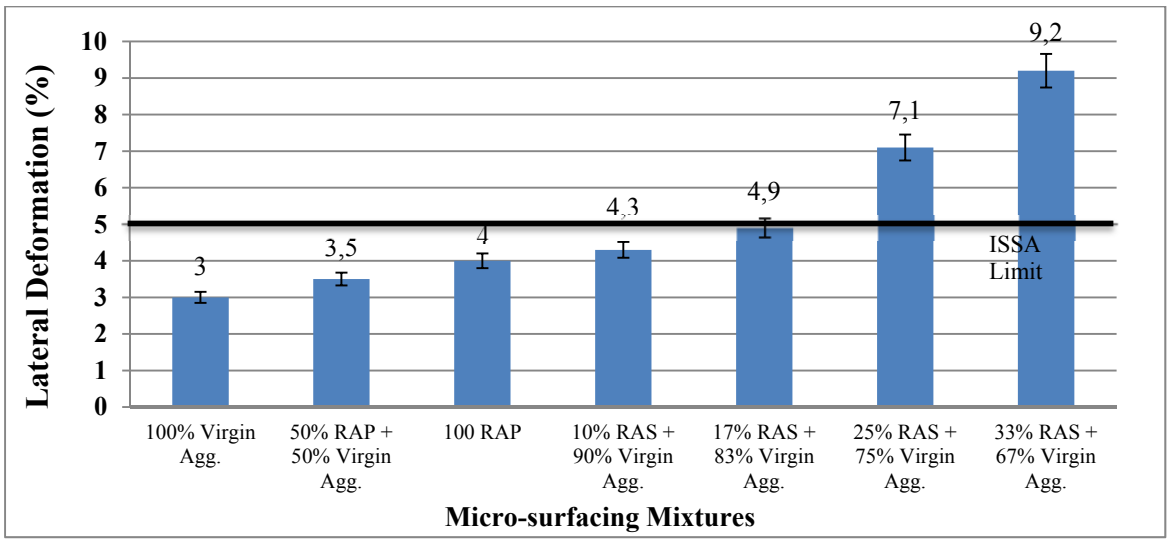

Figure 7.7 Plot of raw lateral displacement test data for samples prepared using different blends of Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS) and virgin aggregates

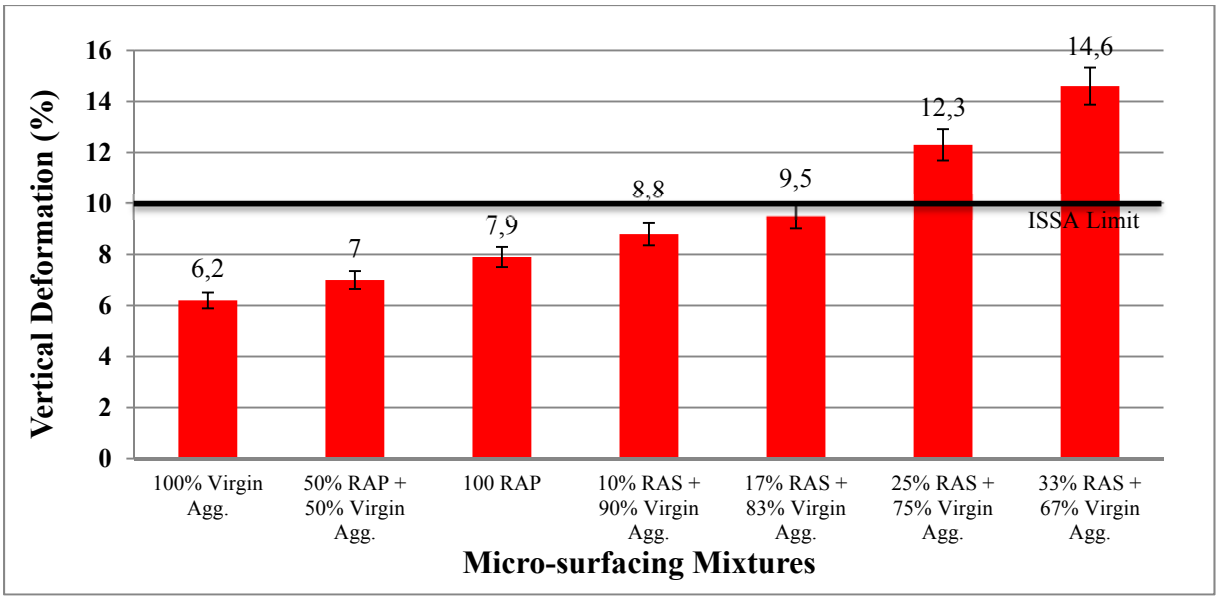

Figure 7.8 Plot of raw data for vertical displacement test for samples prepared using different blends of Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS) and virgin aggregates

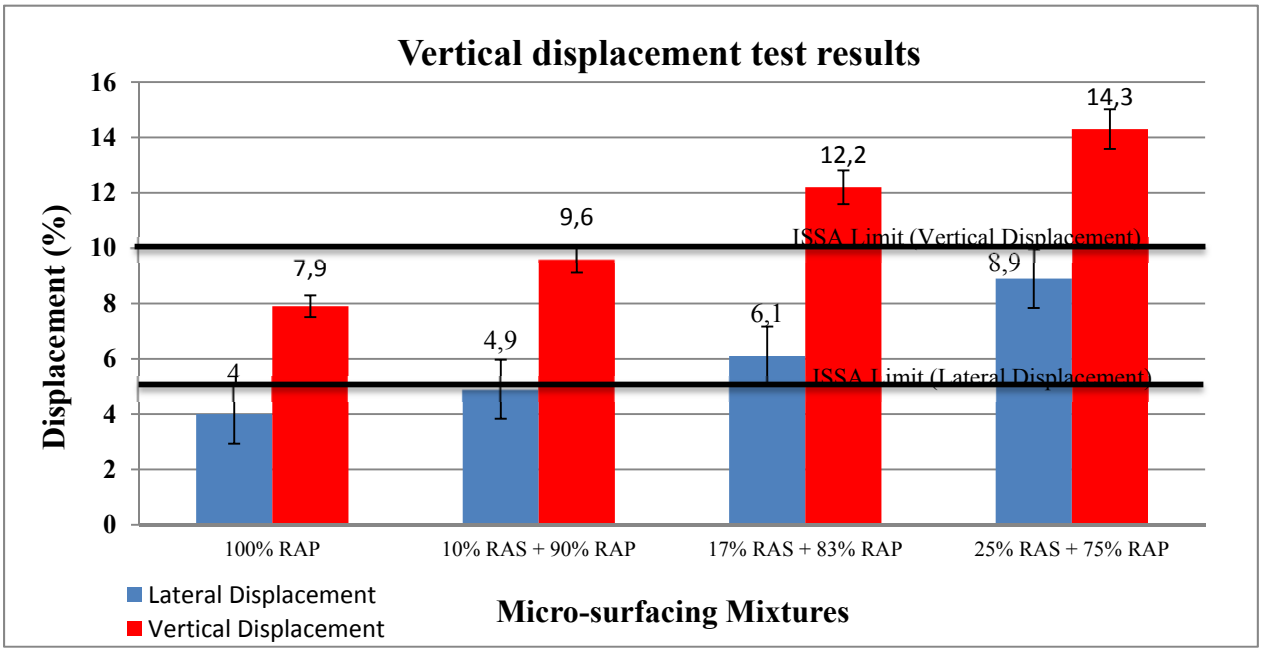

Figure 7.9 Plot of raw data for lateral and vertical displacement for samples prepared using different blends of Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS)

The aggregate gradation used in this study conforms to a Type III micro-surfacing, which is usually applied to fill rut deformation on the road surface at the areas with high traffic level. From Figure 7.8, which shows the resistance of micro-surfacing mixtures against rut deformation, it can be concluded that the incorporation of 100 percent RAP in mixture is allowable while respecting the limit of 10 percent vertical deformation after 1000 cycles of a 56.7 kg load. It also can be seen that the maximum limit of 17 percent RAS in micro-surfacing mixtures with virgin aggregates is acceptable, and the mixture respects the limit for rut resistance specified by the ISSA guideline.

As it was already mentioned, the second part of this study investigated the feasibility of incorporating RAS in micro-surfacing mixtures prepared with 100 percent RAP. Figure 7.9 is a plot of raw data for lateral and vertical displacement for samples prepared using different blends of RAS and RAP. As shown, the micro-surfacing mixture prepared with 10 percent RAS and 90 percent RAP respected both limits specified by ISSA for lateral and vertical displacement. It must also be noted that the same trend was observed in the modified cohesion test presented in Section 7.6.1 for the same micro-surfacing mixtures. From this result, it also can be understood that the maximum allowable amount of added RAS in a micro-surfacing mixture prepared with RAP materials is 10 percent. This was already seen in the modified cohesion test results at Section 7.6.1 as well. Figure 7.9 also shows that the mixture with 10 percent RAS still has a good resistance to rut deformation.

7.9 Results Summary

The impacts of the amount of added recycled materials such as RAP and RAS on the variation of micro-surfacing mix design test results were studied. A summary of the results presented in the previous sections is shown in Table 7.5. A comparison of test results for each micro-surfacing mixture with the limit specified by ISSA is presented. This table allows the establishment of a limit for recycled materials such as RAP and RAS in micro-surfacing mixtures. It seems that incorporating 17 percent RAS is the maximum limit for micro-surfacing mixtures prepared with virgin aggregates, while there is no limit for addition of RAP in micro-surfacing mixtures. Moreover, incorporating maximum 10 percent of RAS in

micro-surfacing mixtures prepared with RAP materials (and no virgin aggregates) seems to be allowable.

Table 7.6 summarizes the effect of RAP and RAS on different properties of micro-surfacing mixtures. The amount of added RAP and RAS in micro-surfacing mixtures has a significatnt effect on the results of the modified cohesion and lateral/vertical displacement tests. As for the WTAT, RAP and RAS do not have a significant effect on the test results.

However, it is important to note that those results are valid only for the different materials used in this study. If one uses another type of emulsion that reacts differently with another type of aggregate, the results may vary. The results are also only valid in the range of added RAP and RAS used in this study. On the other hand, the different values that were used are commonly used amount and are the quantities that give overall optimum results.

Table 7.5 Summary of test results with various blends of Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS) and virgin aggregates with comparison to ISSA Standard

Micro-surfacing mixtures with different blends	Cohesion Test		Wet Track Abrasion Test		Displacement Test	
	30-min	60-min	1-Hour	6-Day	Lateral	Vertical
First Phase of Study						
100% Agg	√	√	√	√	√	√
50% RAP/50% Agg	√	√	√	√	√	√
100% RAP	√	√	√	√	√	√
10% RAS/90% Agg	√	√	√	√	√	√
17% RAS/83% Agg	√	√	√	√	√	√
25% RAS/75% Agg	**X**	**X**	√	√	**X**	**X**
33% RAS/67% Agg	**X**	**X**	/	/	**X**	**X**
Second Phase of Study						
100% RAP	√	√	√	√	√	√
10% RAS/90% RAP	√	√	√	√	√	√
17% RAS/83% RAP	**X**	**X**	√	√	**X**	**X**
25% RAS/75% RAP	**X**	**X**	√	√	**X**	**X**

√ : Respects the ISSA limit, **X** : Does Not Respect ISSA limit, / : Not-tested.

Table 7.6 Summary of Test Results and the Significant Effect of Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS)

Test	Significant effect of RAP and RAS	Trend	Characteristics trend
Modified Cohesion (30-min)	Yes	RAP ↑ : Cohesion ↓ RAS ↑ : Cohesion ↓	Quick-Set: ↓
Modified Cohesion (60-min)	Yes	RAP ↑ : Cohesion ↓ RAS ↑ : Cohesion ↓	Early Rolling Traffic: ↑
Wet Track Abrasion (1-Hour)	No	No	Abrasion: No
Wet Track Abrasion (6-Day)	No	No	Moisture Susceptibility: No
Lateral Displacement (Method-A)	Yes	RAP ↑ : Deformation ↑ RAS ↑ : Deformation ↑	Flow: ↑
Vertical Displacement (Method-A)	Yes	RAP ↑ : Deformation ↑ RAS ↑ : Deformation ↑	Rutting: ↑

7.10 Conclusion

The overall goal of study was to evaluate the feasibility of incorporating recycled materials such as RAP and RAS in micro-surfacing mixtures while respecting the limits specified by the ISSA guideline for each mixture design test. This was achieved through a two phase experimental program. In the first part, the influence of different blends of RAP/virgin aggregates and RAS/virgin aggregates were studied and the sensitivity of different tests was evaluated. Then, in the second part, the feasibility of incorporating only RAP and RAS in micro-surfacing mixtures was studied. Based on statistical analysis of the findings and laboratory observations, it was concluded that any amount of RAP from 0 to 100 percent can be added to the conventional micro-surfacing mixtures prepared using virgin aggregates. This further means the possibility of preparing micro-surfacing mixture using 100 percent recycled materials. As for the allowable amount of added RAS in micro-surfacing mixtures

with virgin aggregates, the maximum amount of 17 percent was reported based on the sensitivity analysis of test results. Analysis of test results in the second part of the study showed that, when preparing micro-surfacing mixtures with RAP materials, it is allowable to add up to 10 percent RAS and 90 percent RAP in the mixture while still respecting the limits specified by the ISSA guideline for micro-surfacing mixture design.

This study provided an opportunity for preparing micro-surfacing mixtures using different recycled materials. The establishment of the limits for allowable amounts of added recycled materials in micro-surfacing mixtures is an initial investigation that provides a foundation for future micro-surfacing research in the direction of incorporating recycled materials.

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CHAPTER 8

NEW COLORED MICRO-SURFACING FORMULATION WITH IMPROVED DURABILITY AND PERFORMANCE

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8.1 Abstract

Colored asphalt materials are gaining more attention in the European market due to their architectural/aesthetic prospective and their effect as a signal on the road. Especially in Netherlands this technology has gained popularity and is currently used for red bicycle lanes for example.

Micro-surfacing mixture, as a pavement preservation and surface treatment method, is typically made with bitumen base mixes predominantly composed of virgin aggregates, and quick setting polymer modified bitumen emulsions. In order to study the feasibility of formulating colored micro-surfacing mixtures with increased durability, research was conducted at Latexfalt B.V. in The Netherlands in collaboration with Laboratoire sur les Chaussées et Matériaux Bitumineux (LCMB), at École de technologie supérieure (ÉTS) in Canada. The first part of the study examined the possibility of producing coloured micro-surfacing mixtures by using clear binder modified with different types of polymer. The goal was to compare the mechanical properties of such mixes versus that of the conventional bitumen-based micro-surfacing mixtures available in the European and North American

markets. Following the success of the first part of the study, the second part was focussed on further improving certain properties, especially rutting resistance. The detailed analysis of the test results of the first and the second part of the study showed that it is possible to produce colored micro-surfacing mixtures having superior durability and performance compared to the conventional micro-surfacing mixtures.

8.2 Introduction

Pavement preservation is defined as a program employing a network-level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety, and meet motorist expectations (FHWA, 2005). Actions used for pavement preservation include routine maintenance, preventive maintenance (PM), and corrective maintenance (Uzarowski, L., 2007). Transportation agencies use chip seal, slurry seal, micro-surfacing, cape seal, fog seal, etc.

Micro Surfacing is a polymer-modified cold-mix paving system that can remedy a broad range of problems on today's streets, highways, and airfields. It begins as a mixture of dense-graded aggregate, asphalt emulsion, water, and mineral fillers. It is designed to be applied in a semi-liquid condition with a specialized mixing and paving machine. By design it chemically changes from a semi-liquid material to dense cold mix asphalt that is able to carry normal traffic within one hour after application. Thus, micro-surfacing mixtures demands quick setting cationic bitumen emulsions that remain stable over a period of time from the emulsion manufacturing to the application on the road surface.

Storage stability of quick setting bitumen emulsion and final breaking rate has always been a challenge to address by researchers. An inadequacy in the storage stability of a bitumen emulsion is initially given by a settlement of emulsion, and thus degrading predominant properties of emulsion such as particle size distribution, breaking rate, adhesion, and viscosity. It is also well known in the art that emulsifying low penetration (hard) bitumen emulsion into a quick setting and storage table product is very difficult. However, once those bitumen emulsions are produced and incorporated to the aggregates, a very stiff micro-

surfacing mixture can be produced that resist well against rutting deformation under heavy traffic loading and so improving the life of pavement. Also, such a stiff micro-surfacing mixture can be produced using clear binder that is suitable to form a colored mixture. The colored micro-surfacing mixture can be used as a signal on the road.

8.3 Research Objective and back-ground

The rutting resistance of asphaltic materials is given by their stiffness at different temperatures. The stiffness itself is dependent of many parameters, such as the contact between aggregate particles, bitumen level, air voids, and also stiffness of the mastic. Normally, an accurate mix design procedure is required to appropriately select the material types and proportion, such as bitumen emulsion, aggregates, filler, cement, and water. A study was done, in which, the current micro-surfacing mix design procedures were reviewed and a modification to the actual ISSA mix design procedure for type III application of micro-surfacing as the most stiff, rut filling materials were suggested (Robati et al., 2013).

Typically, for an asphalt mix to have the most resistance to rutting, the aggregates particles should have the highest contact with one another, while the mix has low level of bitumen and high level of air voids. Another research has been conducted by the author to study the effect of aggregates gradation on rutting resistance of micro-surfacing mixtures. In the conclusion part of the article, the optimum aggregate gradation for the most resistance to rutting deformation were suggested with regard to the total aggregate surface area, and bitumen level in the micro-surfacing mixtures (Robati et al., 2013). In both researches, it was shown that an agreement exists between rutting resistance of micro-surfacing mixture, and the mix cohesion build up. If we assume that, under traffic loading, fracture in the mix would take place in the weaker phase, it could be in the mastic phase rather than the aggregates. Therefore, mastic stiffness is another influential parameter in the rutting resistance of mixture.

A research was also conducted by the author, where the effects of bitumen and filler properties on mastic stiffness were studied. It was evidenced that the mastic of micro-surfacing mixtures consist of low penetration grade (≤ 40 dmm at 25 C) bitumen would have

more resistance against deformation comparing the mastic of moderate to high penetration bitumen. It was also shown that, there is a correlation between mastic stiffness and the mix cohesion based on the filler volume fraction in the mastic and mixture (Robati et al., 2013). Therefore, in this study, it was decided to prepare micro-surfacing mixtures using low penetration bitumen, in order to improve the rutting resistance of mixture. It was also decided to investigate the feasibility of formulating the colored micro-surfacing products using hard bitumen.

The first objective of this study is to evaluate the feasibility of formulating the colored micro-surfacing mixtures using low penetration grade clear bitumen. The goal was to formulate and evaluate a micro-surfacing mixture with improved resistance against rut permanent deformation while respecting the ISSA specification for micro-surfacing products. To do so, bitumen emulsion from clear and straight run binders were produced and stabilized using BioStab MY.

The second objective of this study is to evaluate the effect of Styrene–butadiene–styrene (SBS), Styrene–butadiene–rubber (SBR) latex, and Ethylene vinyl acetate (EVA) on the rheology of bitumen residue, and also on the different properties of micro-surfacing mixtures. The overall goal was to select the appropriate type of polymer to modify the bitumen emulsion products in order to improve the rutting resistance of micro-surfacing mixtures. Processes of asphalt modification involving natural and synthetic polymers were patented as early as 1843 (Bates et al., 1987). SBS, SBR, and EVA polymers as the bitumen modifier are the most studied polymers (Becker et al., 2001; Bates et al., 1987; Wegan et al., 2001; Chen et al., 2002; Roque et al., 2004; Shukla et al., 2003; and Kim et al., 1999).

However, in a system like micro-surfacing, the binder is a cationic quick setting bitumen emulsion, which is obtained from emulsification of polymer modified bitumen, by dispersing the bitumen molecules trough water, and stabilizing them. Basically, low penetration grade polymer modified bitumen is very difficult to emulsify and becomes a storage stable and fast breaking bitumen emulsion.

Technically, storage stability is improved by adding more emulsifier to the aqueous phase (water phase) prior to emulsification. However, adding more emulsifier, negatively influence the breaking behavior of bitumen emulsions, and making them slower setting materials, which is obviously not desirable for micro-surfacing application.

In 2010, Alan James from AkzoNobel Surface Chemistry reported significant improvement in storage stability of bitumen emulsions under controlled breaking behavior using clay nano-particles (Gupta et al., 2005). In the current study, a bio-polymer was used for the first time to produce storage stable, fast setting bitumen emulsion from a low penetration, hard, and polymer modified base binder, which is suitable to significantly improve rutting resistance of micro-surfacing mixtures.

8.4 Materials Used in Study, and Experimental Design

Straight run bitumen, obtained from Venezuelan source, and clear binder (petroleum based) with improved drying quality, obtained from Netherlands, was used in this study. Totally six bitumen samples were generated, from which, four samples were modified using SBS and EVA polymers. Two other bitumen samples were remaining non-modified to better study the effect of polymer modification.

The six developed bitumen samples were then emulsified into the cationic quick setting bitumen emulsion using an Atomix (EmulBitume France) laboratory scale emulsification unit. An emulsifier mix of a Dimethyl Amino Propyl Amine, a Fatty Alcohol, and an Alkyl Polyamine was used in the soap phase at a pH of 2,2. Hydrochloric acid was used for all emulsions. The solid content of 57 to 57, 2 % by weight of the total emulsion was measured for all emulsions. Table 8.1 shows the measured properties of the bitumen emulsions, which were stabilized using bio-polymer. Latexfalt® BioStab MY is an emulsion stabilizer commercialized by Latexfalt, the Netherlands and is a formulation based on a water soluble 1,3-β-glucan biopolymer with 1,6- β bonded side chains. Due to its specific structure this material selectively interacts with and absorbs onto cationic surfaces. This biopolymer formulation will further on be designated as BioStab MY.

The emulsion were fabricated at the Latexfalt B.V Company in Netherlands, however, the properties of emulsion were measured at the LCMB research centre in Canada. The term LP in naming the emulsion refers to low penetration, and the letters B and Y refer to the straight run and clear binders. For example, LP.Y.EVA is the bitumen emulsion of EVA polymer modified clear binder.

Table 8.1 Properties of recovered binder of the generated bitumen emulsion

Emulsion name	Penetration of residual binder	Ring and ball (°C) on residue	Type of polymer	Ductility @ 25 °C, cm	Viscosity @ 25°, SSF	Sieve (2 mm), %
LP.B	50	40,0	—	80+	25	0,01
LP.B.SBS	36	72,0	Linear High Molecular Weight SBS	130+	28	0,02
LP.B.EVA	44	55,8	High Vinyl Content Ethylene Vinylacetate	100+	30	0,02
LP.B.Y	50	39,5	—	85+	28	0,01
LP.B.Y.SBS	37	72	Linear High Molecular Weight SBS	120+	30	0,02
LP.B.Y.EVA	37	51,4	High Vinyl Content Ethylene Vinylacetate	100+	33	0,02

The produced bitumen emulsions, and formulated micro-surfacing mixtures were compared against each other, and also against a reference bitumen emulsion, obtained from oil sand source in Canada.

Bitumen emulsion used as the reference sample, named CQS-1HP, was bought from McAsphalt in Canada.

The term CQS-1HP is the standard name for micro-surfacing emulsions used in the North America market, and it conforms to all the ISSA specifications. Table 8.2 shows the measured properties of this bitumen emulsion, which was modified using SBR latex polymer.

Table 8.2 Measured properties of reference bitumen emulsion from supplier (CQS-1HP)

Tests	**Results**	**ISSA Specifications**		
		min		**max**
Viscosity @ 25°, SSF	28.0	20		100
Sieve,%	0.04	-		0.10
Coating Test,%	90.0	80.0		-
Residue by Distiliation to 204.4°,% mass	65.1	62.0		-
Particle Charge	Positive	Positive		
Settlement, 5 day,%	0.9	-		5
Tests on Residue				
Softening Point by R 7 B, °C	63	57		-
Kinematic Viscosity @ 135°C, mm²/sec	1825	650		-
Penetration @ 25°C, 100 g, 5 sec	75	40		90
Ductility @ 25 °C, cm	110+	40		-

The aggregates used in the study were Ray-Car (0-5 mm), obtained from Quebec, Canada with same gradation satisfies type III requirements for aggregate gradation of ISSA mix design guideline (ISSA A-143). Fine aggregates (Filler) were purchased from DJL Construction Company in Montreal, Quebec.

Figure 8.1 and Table 8.3 show the gradation curves and ISSA standard for the aggregates used in this study. The aggregates gradation follows the middle of maximum and minimum gradation limits suggested by ISSA for Type III Micro-surfacing application, and is considered as mid-range (MG) aggregate gradation.

Table 8.3 and Figure 8.1; provide the sieve analysis, and gradation curves of used aggregate in this study.

Table 8.3 Sieve analysis and ISSA specification
for the aggregates used in this study

Sieve No & Size		% Passing by Weight				Stockpile Tolerance,%
in	mm	UG	MG	LG	Type III	
3/8	9,500	100	100	100	100	–
No. 4	4,750	91	88	84	70-90	+/- 5
No. 8	2,360	69	63	56	45-70	+/- 5
No. 16	1,180	49	44	38	28-50	+/- 5
No. 30	0,600	36	33	29	19-34	+/- 5
No. 50	0,300	26	23	19	12-25	+/- 4
No. 100	0,150	17	14	10	7-18	+/- 3
No.200	0,075	12,5	10	7,5	5-15	+/- 2
Total Aggregate Surface Area (m²/kg)		11	9,2	7,4	–	–

Figure 8.1 Middle aggregate gradation curves (Ray-Car 0-5 mm size)

In all the prepared micro-surfacing mixtures, 10% water was added to the aggregates prior to incorporation of bitumen emulsion. Plus, 1% cement was added to each of micro-surfacing mixtures. The bitumen emulsion content was kept constant for all the mixes with the value of 12.5%.

8.5 Results and Discussion

8.5.1 DSR test results on bitumen residues

In order to study the effect of polymer modification on the stiffness of the bitumen residue, a range of DSR tests were performed over a range of temperature from moderate to high (25 to 80 °C), and single frequency of 10 Hz. Figures 8.2 and 8.3 illustrate the testing results. Basically, $|G^*|/\sin \delta$ values are strongly correlated with rutting resistance of bituminous materials at high temperature. More precisely, at high temperatures, bituminous material having higher $|G^*|$ and lower δ are more likely to resist well against rutting deformation. Therefore, the testing results were presented at $|G^*|/\sin \delta$ versus temperature. As it can be seen from Figure 8.2, the bitumen residue modified with SBS polymer shown higher $|G^*|/\sin \delta$ values comparing unmodified, and EVA polymer modified bitumen. The $|G^*|/\sin \delta$ value for SBS modified samples were 1.62 times greater than that of unmodified bitumen at 64 °C. Also, the $|G^*|/\sin \delta$ values were greater at higher temperatures, showing more resistance to rutting. Figure 8.3 demonstrates a comparison between $|G^*|/\sin \delta$ values of bitumen residues recovered from LP.B (unmodified) bitumen, and that of original PG 58-28 bitumen over a range of temperature from 25 to 64 °C. Interestingly, the rutting reissuance of recovered bitumen residue from low penetration bitumen emulsion was 2.6 times greater than that of the original PG 58-28 binder. This indicates the potential of preparing cold mix asphalt, using low penetration bitumen emulsion, with superior rutting resistance than hot mix asphalt, using PG 58-28 bitumen.

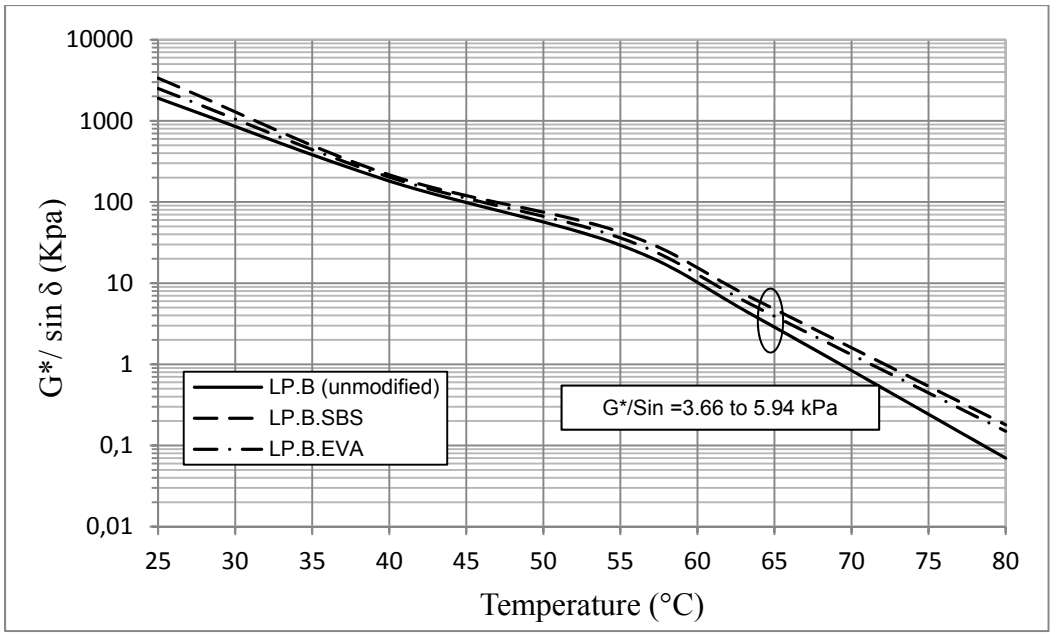

Figure 8.2 Complex modulus master curve measured at 10 Hz for LP.B, LP.B.SBS and EVA samples

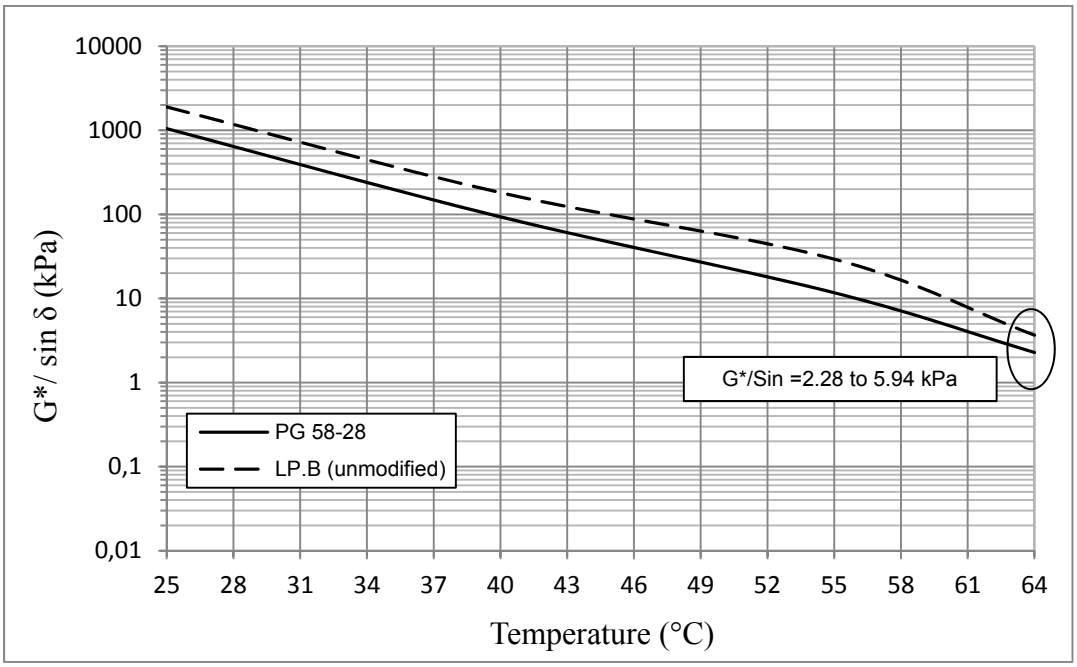

Figure 8.3 Complex modulus master curve measured at 10 Hz for LP.B sample and PG 58-28 binder

Huet-Sayegh analogical model (2S2P1D) was used for the modelling of linear viscoelastic properties of both EVA and SBS modified bitumen residues. The aim was to better study the effect of polymer modification on the resistance of bitumen against loading. 2S2P1D model includes combinations of two springs, two parabolic elements and one dashpot. Using this model, Black Diagram, master curve of complex modulus and phase angle were developed. From the black space diagram (see Figure 8.4), and master curve of complex modulus (see Figure 8.5), it can be seen that the SBS polymer improves more the stiffness of binder comparing EVA polymer. This can be illustrated by the greater elasticity of SBS modified bitumen at higher temperatures comparing the EVA one. It was also observed that the behaviour of EVA modified bitumen residue does not follow linear viscoelastic behaviour under small strain loading at high temperature (80 °C). This is due to the melting point of EVA polymer which is 68 °C, and that the polymer became melted at 80 °C. The data points of EVA modified sample which are not fitted to 2S2P1D mode are shown by drawing circle around them on the black space diagram. Master curve of phase angle (see Figure 8.6), also shown a significant reduction in phase angle for SBS modified bitumen comparing the EVA modified bitumen at high frequency and low temperature. This further indicates more elastic behaviour of SBS modified bitumen at high frequency, which is desirable for rutting resistance.

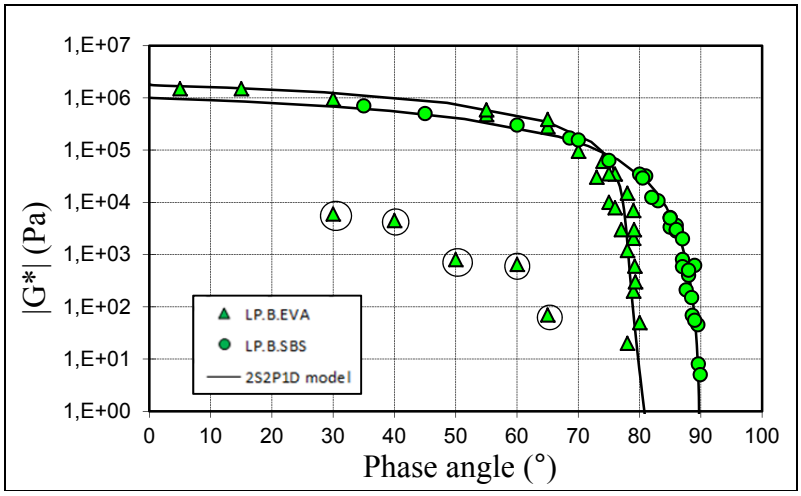

Figure 8.4 Complex modulus in Black space
developed for LP.B.SBS and LP.B.EVA bitumen samples

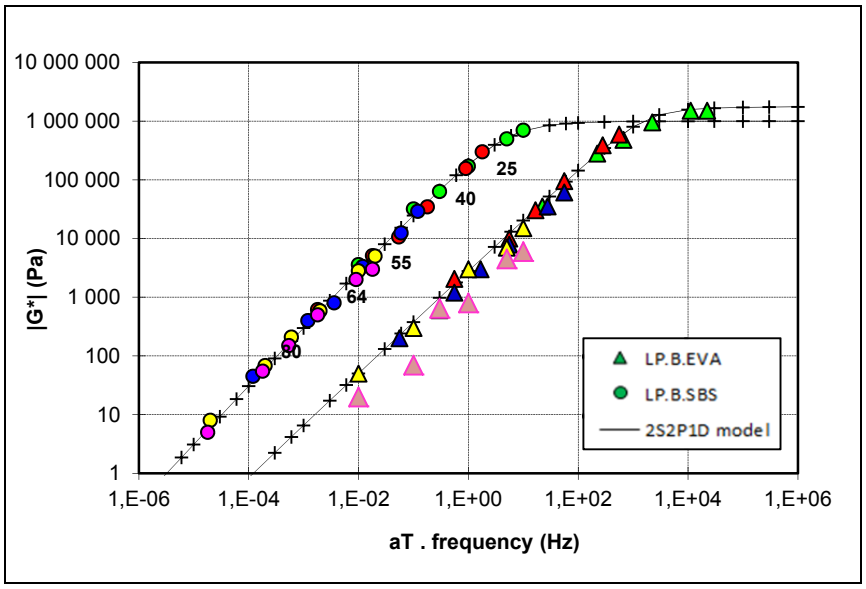

Figure 8.5 Master curve of the norm of Complex modulus developed for LP.B.SBS and LP.B.EVA bitumen samples

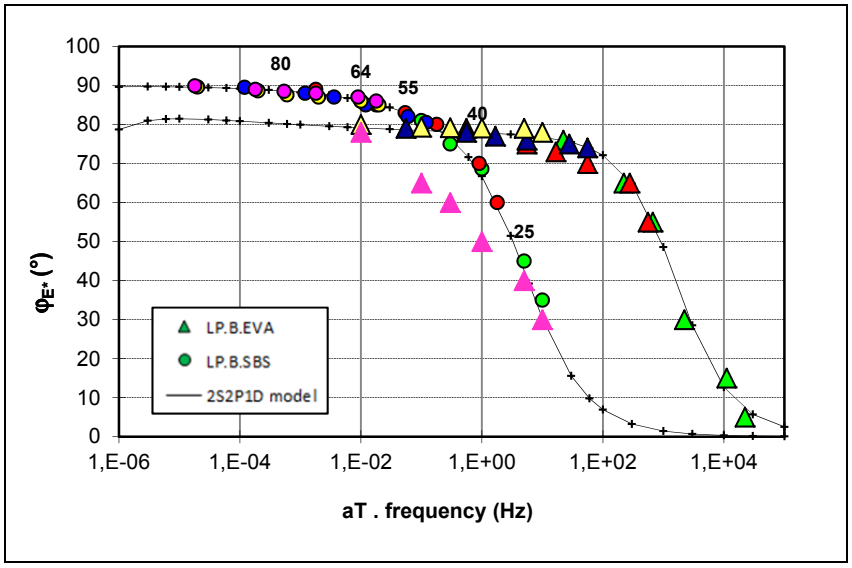

Figure 8.6 Master curve of the phase angle of Complex modulus developed for LP.B.SBS and LP.B.EVA bitumen samples

8.5.2 Test on Micro-surfacing mixtures

Figure 8.7 shows the colored and conventional micro-surfacing mixtures prepared for wet track abrasion and loaded wheel tests. The mixtures were made using same materials and formulation, except the bitumen emulsion, which was different for mixes.

Figure 8.7 Colored and conventional micro-surfacing mixtures prepared for wet track abrasion and loaded wheel tests

The six Mixtures were formulated using, LP.B, LP.B.SBS, LP.B.EVA, LP.Y, LP.Y.SBS, and LP.Y.EVA emulsions, while the reference mix was made with CQS-1HP that was SBR latex polymer modified emulsion.

Figure 8.8 shows the plot of raw data for 30-min cohesion test results. The cohesion of micro-surfacing mixtures is an important property of mixture that can be used to classify the system as slow or fast setting. According the ISSA mix design procedure, for the micro-surfacing design to be accepted, the amount of 30 and 60-min cohesion must be, respectively, higher than 12 and 20 kg-cm. All the six micro-surfacing formulation using low penetration bitumen in this study have passed the requirements for a quick setting system. They also met the specification for 60-min cohesion values, which characterized the resistance to the early rolling traffic. The results of 60-min cohesion test are not presented here. In both 30-min and 60-min cohesion test results, it was observed that the mix prepared with SBS modified

bitumen emulsion develops more cohesion with aggregates, comparing the unmodified, EVA polymer modified samples, and Latex modified mixes (reference mix).

Figure 8.9 illustrates the wet track abrasion test results at one-hour soaking condition. The WTAT is usually performed to evaluate the short-term abrasion, long-term moisture susceptibility, as well as wearing properties of micro-surfacing mixtures. All six mixes, plus the reference mix, showed a good resistance against aggregate loss under traffic simulated abrasion condition.

However, mix number 2 and 5 that were modified using SBS polymer had higher resistance to aggregate loss or raveling comparing other mixes. Same trend was also observed for the 6-day soaked test results. 6-day soaked test results is not presented here. Under the action of vehicle's tire and wet condition, it is possible that the aggregates being abraded and the bitumen become washed off. This is also called stripping, which is the primary reason for most of the pavement distresses, specially raveling. For a mixture to resist against raveling, the bitumen emulsion should be compatible with aggregates in terms of the chemical reaction during the break and cure of emulsion. Some of the aggregates may neutralize acid in CQS-1HP asphalt emulsion, causing the PH to rise quickly. This later causes the emulsion to be destabilized, to set faster, and cure with lower rate, which is not desirable. In this study, all the emulsions shown a good compatibility with aggregates, and so less aggregate loss in wet track abrasion test were reported.

Figure 8.10 demonstrates the vertical displacements testing results at mid-length of micro-surfacing mixtures after 1000, 2000, and 3000 cycle compactions of 56.7 kg load. As it can be seen from this figure, mix number 2 has shown higher resistance against rutting comparing other mixes. This indicates the effectiveness of SBS polymer to modify the mix and improve stiffness. This is also in agreement with the DSR results on bitumen residue, showing stiffer residue for SBS modified bitumen.

Around 35% improvement in rutting resistance was obtained in the case of micro-surfacing mixtures prepared with SBS modified low penetration bitumen binder in comparison to that of mixes made by typical SBR latex modified bitumen emulsions available in North America

market. Moreover, there can be observed an agreement between cohesion test results and vertical deformation test results. Basically, the SBS modified mix that developed higher cohesion values, shown also higher resistance to rutting deformation. Plus, reference mix that were modified using SBR latex polymer, shown higher resistance against rutting than that of modified with EVA polymer. This can be explained by the correlation between mastic stiffness and mixture cohesion at specific filler concentration. Typically, when the mixture cohesion value is greater, stiffer mastic around aggregates will be formed, and thus more resistance to rutting is likely to happen. Increment in rutting resistance can also be explained by increasing the bitumen elasticity by polymer modification. It was observed that the SBS polymer modified bitumen had higher elasticity comparing the EVA and SBR latex modified bitumen. Normally, more elastic materials are more brittle, and thus resist better against loading deformations.

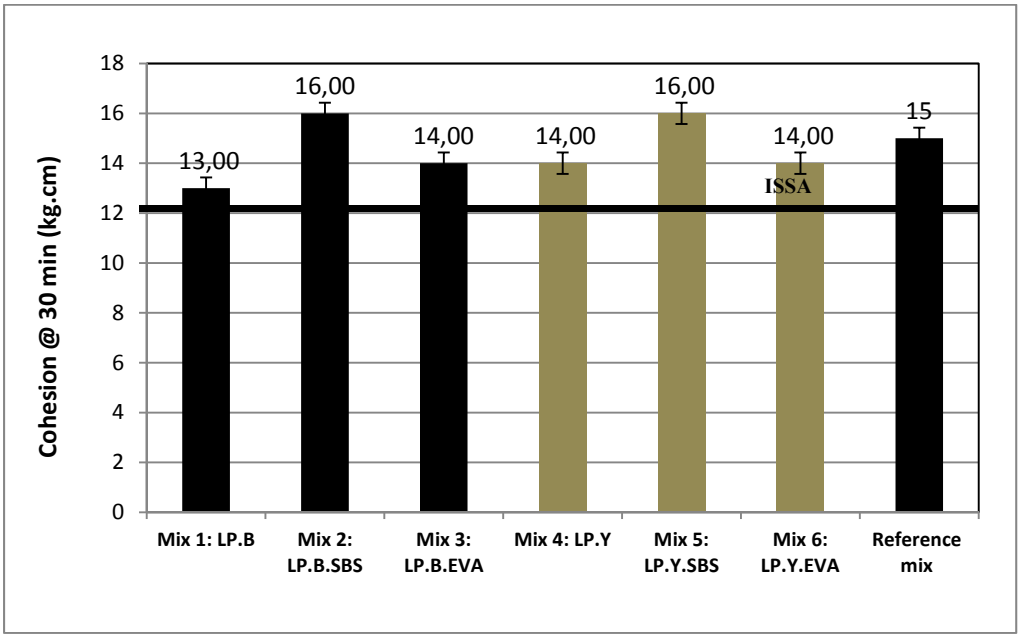

Figure 8.8 30-min modified cohesion test results for mix 1 to 6, and the reference mix

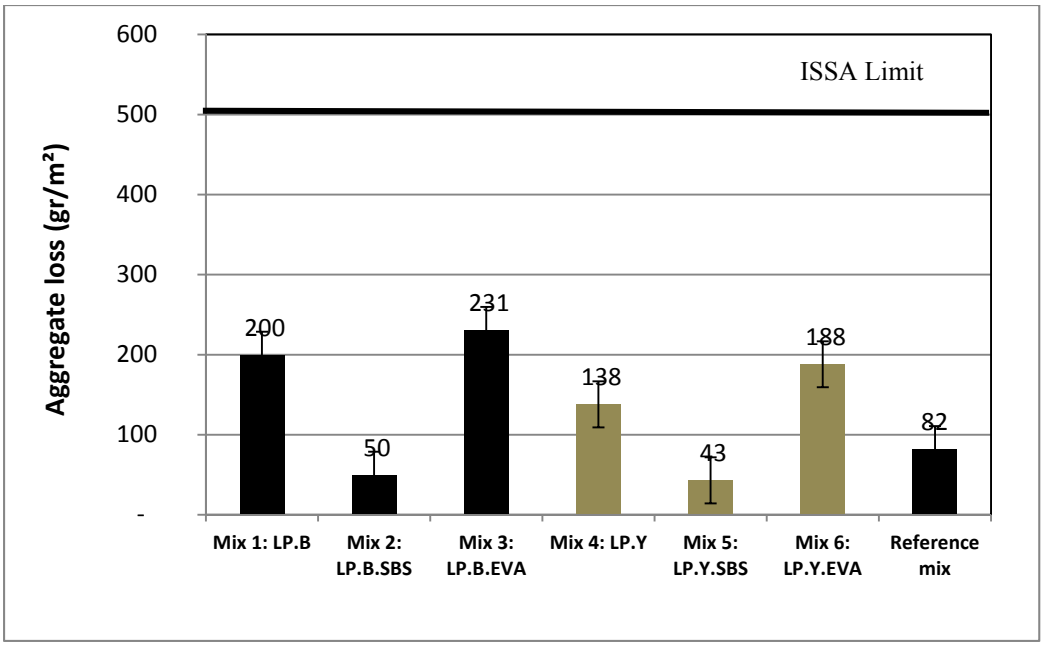

Figure 8.9 Wet track abrasion test results at one-hour soaking condition for mix 1 to 6, and the reference mix

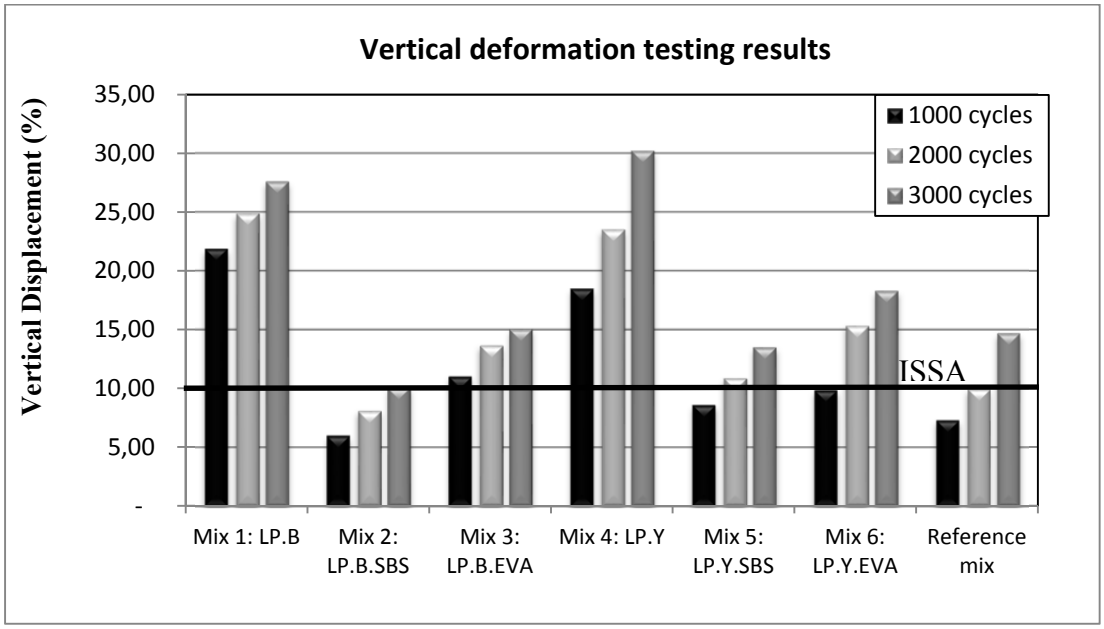

Figure 8.10 Vertical displacements testing results at mid-length of micro-surfacing mixtures after 1000, 2000, and 3000 cycle compactions of 56.7 kg load for mixes 1 to 6 and the reference mix

8.5.3 Further improving rutting resistance of micro-surfacing mixtures

Following the success in the first part of study to develop colored micro-surfacing mixtures with superior rutting resistance comparing the conventional mixes, it was decided to further improve resistance of those products against rutting. To do so, the mix number 2 and 5 modified with SBS polymer that shown greater rutting resistance, were selected for further strengthening against loading. Four new produced binders were modified using two different types of SBS polymer.

All four binders were emulsified to a bitumen emulsion using same formulation and materials used to emulsify the bitumen in the first part of study. Table 8.4 represents the measured properties of the produced bitumen emulsions.

Table 8.4 Measured properties of the bitumen emulsions, produced in the second phase of study

Emulsion characterization	Straight run bitumen emulsion		Clear binder emulsion	
	Developmental 2	Developmental 3	Developmental 2a	Developmental 3a
Water content (%)	41.8	44.0	44.5	44.7
Viscosity (s) ISO 4 mm.	–	–	48	40
Viscoity (s) STV 2/40	46	40	–	–
pH	2.4	2.6	2.1	2.1
Average particle size (µm)	12.3	17.5	8.5	8.8
Particle size > 8 µm (%)	33	51	35	34
Stability with cement (s)	90-100	300-360 min	100-120	90-110

8.5.4 DSR test results on further modified bitumen emulsions

Figure 8.11 and 8.12 show the master curve of complex modulus (G*), and G*/ sin δ values for the bitumen residue obtained from reference sample, developmental 2 and 3. The DSR test was performed at 10 different temperatures ranging from 35 to 80 °C, and 18 frequencies from 0.01 to 100 Hz on the bitumen residue. As it can be seen from this figures, at low frequencies and temperatures, the bitumen residue of developmental 3 had greater G* and G*/ sin δ comparing those of reference sample and developmental 2. This indicates higher potential of the developmental 3 bitumen to resist against rutting deformation in the form of micro-surfacing mixture. At moderate frequencies, bitumen residue of developmental 2 had greater stiffness following by bitumen residues of developmental 3 and reference sample.

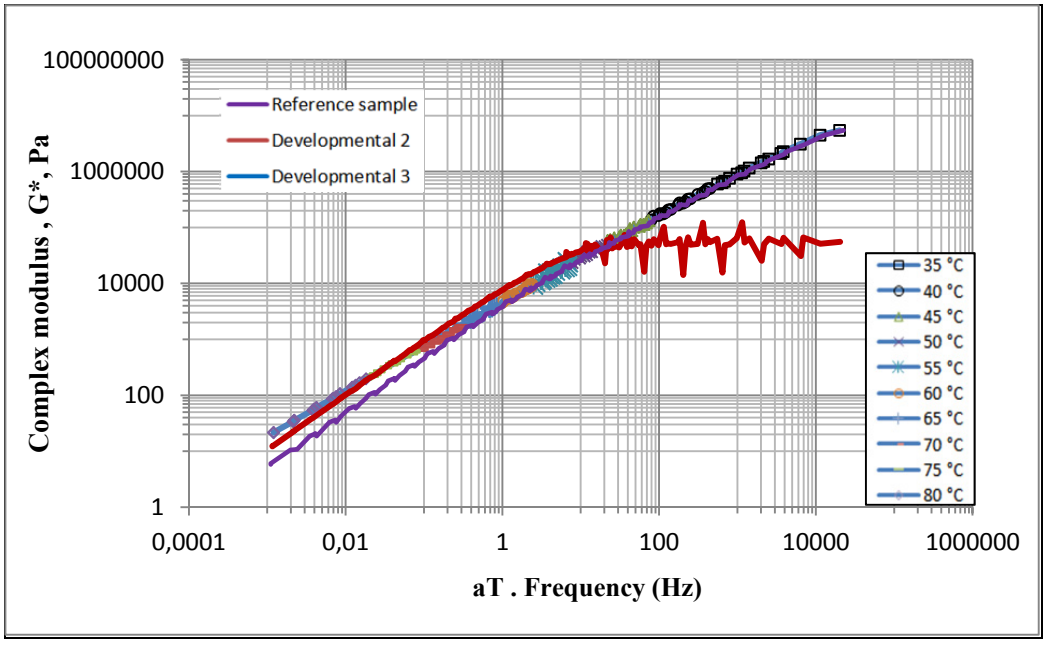

Figure 8.11 Curve of complex modulus (G*) values for the bitumen residue obtained from reference sample, developmental 2 and 3

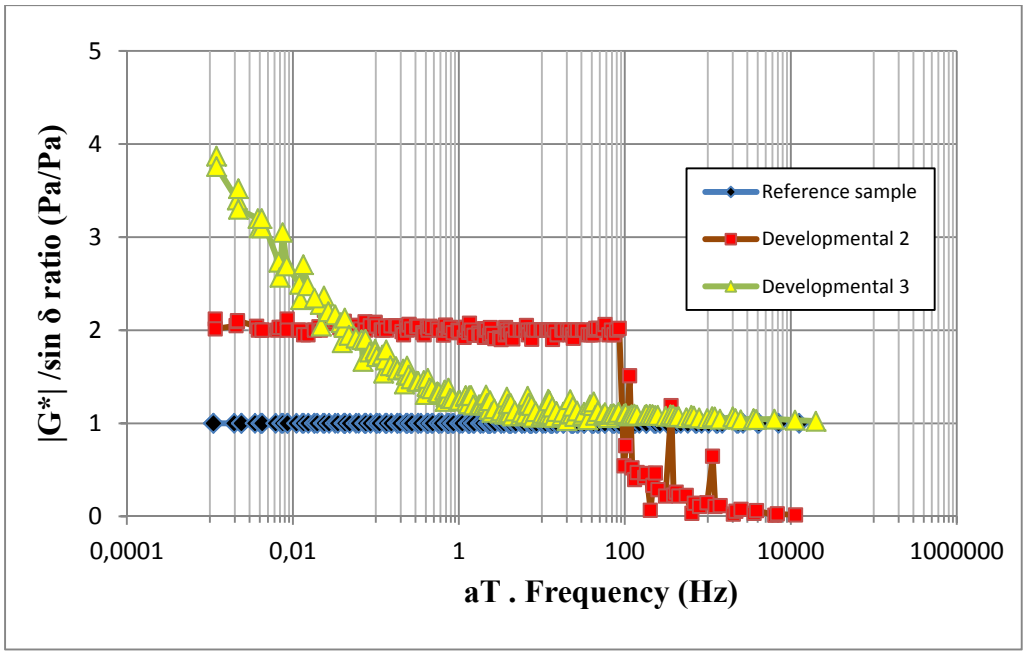

Figure 8.12 Curve of complex modulus (G*), and G*/ sin δ values for the bitumen residue obtained from reference sample, developmental 2 and 3

At high temperatures and frequencies, however, there were no difference between stiffness of developmental 3 and reference sample, but, a significant reduction in stiffness for bitumen residue of developmental 2 was observed. This special behaviour for the bitumen residue of developmental 2 is given by the polymer in it. Same trend were observed in developmental 2a and 2b with regard to the bitumen residue of their reference sample. The DSR results obtained from testing the residue of the clear binders are not presented here.

8.5.5 Vertical deformation test results

Figure 8.13 demonstrates the vertical displacements testing results at mid-length of micro-surfacing mixtures number 1 to 6 after 1000, 2000, and 3000 cycle compactions of 56.7 kg load. As it can be seen from this figure, we succeed to further strengthen the both colored and conventional micro-surfacing mixtures against rutting. Micro-surfacing mixes number 3 and 6 prepared with developmental 3 and 3a bitumen were subjected to repeated cycles of vertical loading without reaching to the failure mode up to 3000 cycles.

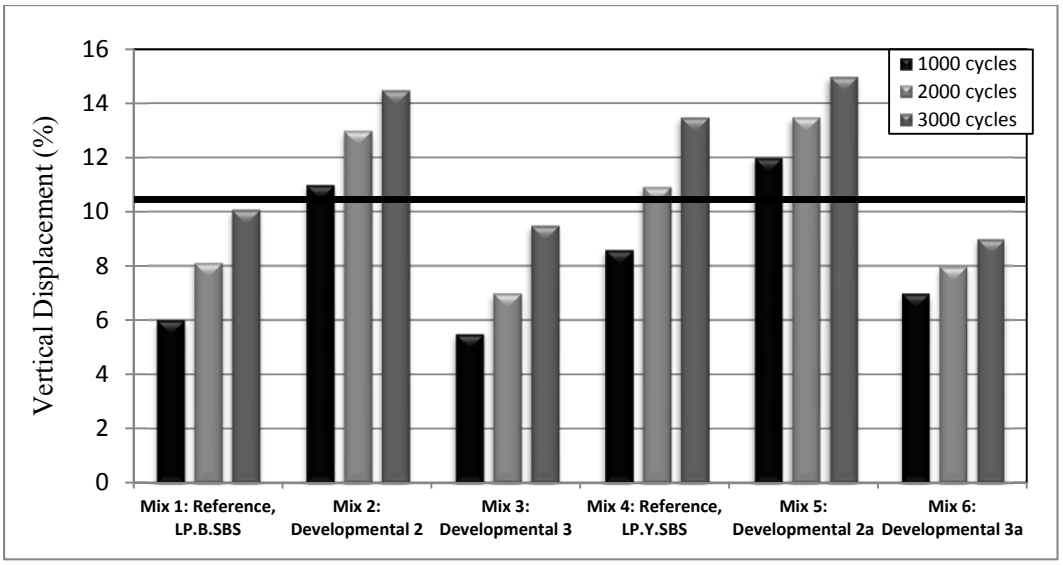

Figure 8.13 Vertical displacements testing results at mid-length of micro-surfacing mixtures after 1000, 2000, and 3000 cycle compactions of 56.7 kg load for mixtures number 1 to 6

A reduction of around 10 percent in vertical deformation was observed for mixes prepared with developmental 3 and 3a bitumen comparing to their reference mixtures. Also a correlation was observed between DSR results of the bitumen residues and rutting resistance of mixes. The vertical displacement test was performed at frequency of 1 Hz and temperature of 25 °C. At low frequencies and temperatures, mixes made by developmental 3 and 3a bitumen were reported to be stiffer than other mixes.

In overall, a significant improvement of around 45% in rutting resistance of micro-surfacing mixtures was achieved using low penetration bitumen emulsion modified with SBS polymer and stabilized using nano-particles, in comparison to the mixes prepare with the conventional SBR latex modified bitumen emulsions. Another interesting fact was that, such a significant improvement in rutting resistance of micro-surfacing mixes was achieved using lower level of bitumen residue in the mixes prepared with low penetration bitumen emulsion stabilized with nano-particles. For the mixes made with conventional SBR latex modified bitumen emulsion, the amount of bitumen residue was 8.1%, however, for the mixes with low penetration bitumen emulsion the amount of residue binder in mix was 7%. This further

indicates the potential of the hard bitumen emulsions to form a cold mix with the same bitumen proportions than the conventional HMA with 5% bitumen content.

8.6 Conclusion

The overall goal of this study was to evaluate the feasibility of formulating colored and micro-surfacing mixtures with superiors rutting resistance comparing the conventional mixtures available in the North American market. The low penetration grade, hard bitumen obtained from straight run and clear binders were emulsified and stabilized using specific nano-particles. The base binders were already modified by SBS, EVA, and SBR latex. DSR test on the bitumen residue were performed to study the effect of polymer modification on rheology of bitumen residue. A series of micro-surfacing mixtures with same formulation, and aggregate gradation/type were tested to evaluate for their superior rutting performance comparing non-polymer modified and conventional micro-surfacing mixtures. From analysis of results, following conclusions are reported:

1. The BioStab MY used in this study significantly improves storage stability of quick setting bitumen emulsion under extremely acidic condition (pH ~ 2), where most of the bitumen emulsion stabilizers undergo acid hydrolysis, and thus losing the ability to stabilize the bitumen emulsions;

2. SBS modified low penetration bitumen residue shown higher stiffness comparing the EVA modified bitumen residue, indicating more resistance against loading. This can be explained by the more elasticity of the SBS modified bitumen than EVA modified;

3. Bitumen residue obtained from unmodified low penetration bitumen emulsion was stiffer than the original PG 58-28 bitumen. This indicates the potential of forming cold mix asphalt with the same stiffness as conventional HMA mixes;

4. Huet-Sayegh analogical model (2S2P1D) was used for the modelling of linear viscoelastic properties of both EVA and SBS modified bitumen residues. SBS modified bitumen residue have shown higher stiffness and lower phase angle than the EVA modified bitumen residue. This proves more elastic behaviour for the SBS modified bitumen residue, and thus more potential to resist against loading. It was also observed that the behaviour of EVA modified bitumen residue does not follow linear viscoelastic behaviour under small strain loading at high temperature (80 °C);

5. In both 30-min and 60-min cohesion test results, it was observed that the micro-surfacing mixture prepared with SBS modified bitumen emulsion develops more cohesion with aggregates, comparing the unmodified, EVA polymer modified samples, and Latex modified mixes (reference mix). It was also observed that the SBS modified mixture has superior properties than other mixes in terms of resistance against aggregate loss (abrasion) and rutting. This can be explained by the stiffer and more cohesive mastic formed around the aggregates, and thus stronger cohesion builds up for the mix, which improves resistance against rutting;

6. Micro-surfacing mixtures were further strengthened against rutting using different type of SBS polymer. In overall, a significant improvement of around 45% in rutting resistance of micro-surfacing mixtures was achieved using low penetration bitumen emulsion modified with SBS polymer and stabilized using BioStab MY, in comparison to the mixes prepare with the conventional SBR latex modified bitumen emulsions;

7. Such a significant improvement in rutting resistance of micro-surfacing mixes was achieved using lower level of bitumen residue, in the mixes prepared with low penetration bitumen emulsion stabilized with BioStab MY. This further indicates the potential of the hard bitumen emulsions to form a cold mix with the same bitumen proportions than the conventional HMA with 5% bitumen content.

8.7 References

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CONCLUSION

This PhD program is based on the experimental and analytical investigations of rutting resistance of micro-surfacing mixtures. Due to its intricacy, there exist numerous research problems that require research and investigation to be solved. During this Ph.D. program, a research including a large experimental campaign on the characterisation of rutting resistance of micro-surfacing mixtures was performed to solve the relevant research problems. Various aspects involved in rutting resistance of micro-surfacing mixtures were investigated analytically and experimentally. The materials used, the scope and all the detailed experimental program and analysis are presented in six different papers which are presented in this manuscript-based Ph.D. thesis.

The results of this research program have significantly contributed to the increase of knowledge in the field of micro surfacing materials. For instance, we now have a better understanding of the role of each component of the mixes on its mechanical behaviour. We also have a better grasp on the effect of the mastic on the rutting resistance and also a better understanding on how to use hard bitumen in asphalt emulsion. More specifically, the principal aspects studied in this research program are presented here.

1. Evaluation of a modification of current micro-surfacing mix design procedure: Inaccurate selection of the mix proportions' contents using the mix design procedure can be a reason for the permanent deformation on asphaltic materials. The main objective of this study is to develop a new mix design procedure for type III micro-surfacing mixtures with regard to maximum resistance against rutting deformation. The effect of mix proportions such as asphalt emulsion, water and cement contents on micro-surfacing mix design test responses was studied. A new mix design procedure is proposed for type III application of micro-surfacing, taking into account the rutting resistance of this product. Mix proportions such as asphalt emulsion residue and water contents can be chosen based on rutting resistance and cohesion of micro-surfacing mixtures. The effectiveness of proposed mix design method was validates using different material types. The results of this study have been submitted to the Canadian Journal of Civil Engineering;

2. Evaluation of test methods and selection of aggregate gradation for type III application of micro-surfacing: Rutting resistance of asphaltic materials is highly dependent of the gradation, angularity of aggregates, and also the bitumen level in the mix. The effect of aggregates gradation, type and bitumen level on the micro-surfacing mix design test responses were studied with the aim of suggesting new specification for type III application of micro-surfacing with regard to maximizing the rutting resistance. A new specification to select aggregate grading is proposed. The modified aggregate grading suggested by this study, when used in micro-surfacing, shows to have maximum resistance to rutting. The new aggregate gradation is suited to be used in preparing micro-surfacing mixtures as rut filling materials on the surface of roads located at areas with high traffic volume. Results of this study have been published in the International Journal of Pavement Engineering and Asphalt Technology (PEAT);

3. Evaluation of repeatability and reproducibility of micro-surfacing mix design tests: The micro-surfacing mix design tests are very operator dependent, which may lead to a significant variation and inconsistency in the testing results. The main objective of this study is to establish the repeatability and reproducibility limits for each micro-surfacing mix design test using the new proposed mix design procedure. Repeatability and reproducibility limits are proposed for every micro-surfacing mix design test. It was also observed that the consistency of the mix design test results can significantly improve when using the sieve analysis method to reach desired aggregate gradation in micro-surfacing mixture. The results of this study are published in Australian Journal of Civil Engineering;

4. A new conceptual model for filler stiffening effect on the asphalt mastic of micro-surfacing: The filler type and amount in micro-surfacing mixtures are critical factors that highly influence the rutting resistance of mixture. Normally, at critical filler volume fraction, mastic shows more stiffness resulting in a micro-surfacing mixture with higher rutting resistance. A new model to predict the true behavior of the mastic stiffness in

micro-surfacing mixtures was developed. The model is also capable of predicting the minimum and maximum filler concentrations in micro-surfacing mixtures using filler and asphalt properties. Besides, the effectiveness of new model to predict the minimum and maximum filler concentrations is validated using cohesion test on micro-surfacing mixtures. Unlike the existing model for mastic stiffness behaviour that follows two regions, the new model stipulates that the mastic complex modulus as a function of filler volume fraction follows three regions. Diluted region, optimum concentrated region, and concentrated region. This was also validated using the microscopic photos from the mastics at different filler concentration. Thus, a better understanding of the mechanism in which the filler gives stiffness to the mastic is provided using the proposed new theory. Furthermore, the model showed a high capability to predict the complex modulus of the mastics at different filler volume fractions. It is proposed that such model can be used as essential tools to predict the minimum and maximum filler concentrations both in cold and hot asphalt mixtures. The results of this study are accepted to be published in the Journal of Materials in Civil Engineering.

5. Incorporation of Reclaimed Asphalt Pavement and Post-Fabrication Asphalt Shingles in Micro-Surfacing Mixture: The overall goal of this study was to evaluate the feasibility of incorporating recycled materials such as RAP and RAS in micro-surfacing mixtures using the new proposed mix design procedure for type III application of micro-surfacing. It was concluded that any amount of RAP from 0 to 100 percent can be added to the conventional micro-surfacing mixtures prepared using virgin aggregates. As for the allowable amount of added RAS in micro-surfacing mixtures with virgin aggregates, the maximum amount of 17 percent was reported. This study also proved the possibility of using the new proposed micro-surfacing mix design procedure to be employed for different recycled materials. The results had been published in the 58th proceeding of annual Canadian Technical Asphalt Association (CTAA);

6. New colored micro-surfacing formulations with improved durability and performance: The overall goal of this study is to evaluate the feasibility of formulating colored micro-

surfacing mixtures with superior rutting resistance using polymer and nanoparticle modification. Using BioStab MY and polymer modified bitumen, it is possible to produce asphalt emulsions from low penetration (hard) bitumen with excellent storage stability. This new generation of asphalt emulsions can improve rutting resistance of micro-surfacing mixtures up to 45% compared with conventional mixes. It was also observed that the SBS polymer can improve rutting resistance of micro-surfacing mixtures compared with SBR and EVA polymers. In overall, such a significant improvement in rutting resistance of micro-surfacing mixes was achieved using lower level of bitumen residue in the mixes prepared with new generated asphalt emulsions. This further indicates the potential of the hard bitumen emulsions to form a cold mix with the same properties as the conventional HMA with 5% bitumen content. The results of this study are published in 13th International Conference on Pavement Engineering and Infrastructure in UK.

RECOMMENDATIONS AND FUTURE STUDIES

Based on this research, the following recommendations and suggestions for future works are presented.

1. The new proposed mix design procedure and specification is highly recommended for selecting the mix proportions and aggregate grading for type III application of micro-surfacing as rut filling materials on road surface. Therefore, it should be validated for other types of slurry seal and micro-surfacing products such as type II micro-surfacing;

2. The new proposed mix design procedure needs to be verified with the field performance of micro-surfacing mixtures under various environmental conditions and traffic levels;

3. The new proposed stiffness model for asphalt mastic is recommended to be used in ISSA, Europeans and other mix design procedure for selecting the appropriate amount of added filler content to the micro-surfacing mixtures. It is also recommended to use the new model to predict the stiffness of mastics instead of having to test them;

4. The new proposed stiffness model for asphalt requires to be correlated with the results obtained from rutting resistance of micro-surfacing mixtures both in laboratory and field performance;

5. Effect of the emulsifier type and amount on the stiffness rate of mastic as a function of filler concentration needs to be studied;

6. Effect of filler chemical properties such as zeta potential is needed to be studied to better understand the mechanism of filler stiffening to the mastic;

7. RAP and RAS materials are recommended to be used in micro-surfacing mixtures at the specified quantities in order to produce more environmental micro-surfacing mixtures. RAP and RAS from various sources should be tested to confirm the obtained results;

8. SBS polymer is recommended to be used for modification of micro-surfacing mixtures against rutting deformation. SBS polymer significantly improve the rutting resistance of micro-surfacing mixes over various range of temperature and frequencies rather than the SBR latex and EVA polymers. It would be beneficial to test other types of polymer to evaluate their effect on rutting resistance;

9. Asphalt emulsions prepared using low penetration bitumen is recommended to be used in micro-surfacing mixtures as they significantly improve the resistance against rutting. Tests with different low penetration based binder and different emulsion stabilizer should be performed to complete this part of the study.

APPENDIX I

RAW TEST RESULTS DATA FOR MICRO-SURFACING MIX DESIGN TESTS

The Annexes contains results for each test replicate for the paper presented in chapter 3. There were twelve asphalt residue-water combinations for loaded wheel test and wet track abrasion test, and nine asphalt residue-water combinations for modified cohesion test, mixing time test, and study of relative moisture retained in sample. The material variant within each material combination is the quantity of asphalt cement and added water content. At the bottom of each table, the mean, standard deviations, and variance are given.

Table A-1 Loaded Wheel Test results for samples prepared using Ray Car aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 7% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Excess Asphalt (g/m²)
1	632,1	636,1	295,24
2	633,3	637,5	310
3	631,1	635,1	295,24
Mean	632,17	636,23	300,16
Std	1,10	1,21	8,52
var	1,21	1,45	72,62

Table A-2 Loaded Wheel Test results for samples prepared using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue with 7% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Excess Asphalt (g/m²)
1	633,5	638,5	369,05
2	632,2	637,1	361,67
3	625,8	631	383,81
Mean	630,50	635,53	371,51
Std	4,12	3,99	11,27
var	16,99	15,90	127,08

Table A-3 Loaded Wheel Test results for samples prepared using raycar aggregate and 8,6% CQS-1HP Asphalt emulsion residue with 7% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Excess Asphalt (g/m²)
1	640,9	647,7	501,91
2	635,1	641,7	487,14
3	632,2	639	501,91
Mean	636,07	642,80	496,99
Std	4,43	4,45	8,53
var	19,62	19,83	72,72

Table A-4 Loaded Wheel Test results for samples prepared using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 8% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Excess Asphalt (g/m²)
1	625,6	630,6	369,05
2	629,1	634,2	376,43
3	632,1	636,9	354,29
Mean	628,93	633,90	366,59
Std	3,25	3,16	11,27
var	10,58	9,99	127,08

Table A-5 Loaded Wheel Test results for samples prepared using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue with 8% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Excess Asphalt (g/m²)
1	635	641,9	509,29
2	631,9	638,4	479,76
3	640,7	647,5	501,91
Mean	635,87	642,60	496,99
Std	4,46	4,59	15,37
var	19,92	21,07	236,18

Table A-6 Loaded Wheel Test results for samples prepared using raycar aggregate and 8,6% CQS-1HP Asphalt emulsion residue with 8% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Excess Asphalt (g/m²)
1	625,7	632,8	524,05
2	635,2	642,2	516,67
3	617,9	624,7	501,91
Mean	626,27	633,23	514,21
Std	8,66	8,76	11,27
var	75,06	76,70	127,08

Table A-7 Loaded Wheel Test results for samples prepared using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 9% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Excess Asphalt (g/m²)
1	627,5	631,7	310
2	637,5	641,5	295,24
3	616,5	620,6	302,62
Mean	627,17	631,27	302,62
Std	10,50	10,46	7,38
var	110,33	109,34	54,46

Table A-8 Loaded Wheel Test results for samples prepared using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue with 9% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Excess Asphalt (g/m²)
1	624,7	631,5	501,91
2	630	636,7	494,52
3	616,5	623	479,76
Mean	623,73	630,40	492,06
Std	6,80	6,92	11,28
var	46,26	47,83	127,18

Table A-9 Loaded Wheel Test results for samples prepared using Ray Car aggregate and 8,6% CQS-1HP Asphalt emulsion residue with 9% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Excess Asphalt (g/m²)
1	640,7	646,8	450,24
2	645,9	651,9	442,86
3	633,9	639,7	428,1
Mean	640,17	646,13	440,40
Std	6,02	6,13	11,27
var	36,21	37,54	127,08

Table A-10 Loaded Wheel Test results for samples prepared using Ray Car aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 10% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Excess Asphalt (g/m²)
1	635,3	642,2	509,29
2	642,2	648,9	494,52
3	620	626,6	487,14
Mean	632,50	639,23	496,98
Std	11,36	11,44	11,28
var	129,09	130,92	127,21

Table A-11 Loaded Wheel Test results for samples prepared using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue with 10% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Excess Asphalt (g/m²)
1	653,1	659,6	479,76
2	634,8	640,9	450,24
3	650,7	657,2	479,76
Mean	646,20	652,57	469,92
Std	9,95	10,17	17,04
var	98,91	103,52	290,48

Table A-12 Loaded Wheel Test results for samples prepared using Ray Car aggregate and 8,6% CQS-1HP Asphalt emulsion residue with 10% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Excess Asphalt (g/m²)
1	653,9	661,9	590,48
2	630,8	638,4	560,95
3	640,1	648,1	590,48
Mean	641,60	649,47	580,64
Std	11,62	11,81	17,05
var	135,09	139,46	290,67

Table B-1 Wet Track Abrasion 1-Hour soak test results for mixtures prepare using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 7% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (1-Hour Soaked) (g/m²)
1	637,3	634,6	88,83
2	610,5	607,9	85,54
3	670,5	667,8	88,83
Mean	639,43	636,77	87,73
Std	30,06	30,01	1,90
var	903,41	900,52	3,61

Table B-2 Wet Track Abrasion 6-Day soak test results for mixtures prepare using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 7% water and without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (6-Day Soaked) (g/m²)
1	677,4	673,5	128,31
2	630,5	626,8	121,73
3	660	655,9	134,89
Mean	655,97	652,07	128,31
Std	23,71	23,58	6,58
var	562,10	556,24	43,30

Table B-3 Wet Track Abrasion 1-Hour soak test results for mixtures prepare using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue**,** 7% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (1-Hour Soaked) (g/m²)
1	650	648,6	46,06
2	622	620,2	59,22
3	630,9	629,1	59,22
Mean	634,30	632,63	54,83
Std	14,31	14,53	7,60
var	204,67	211,00	57,73

Table B-4 Wet Track Abrasion 6-Day soak test results for mixtures prepare using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue, 7% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (6-Day Soaked) (g/m²)
1	610,5	607	115,15
2	625,1	621,8	108,57
3	650,2	646,6	118,44
Mean	628,60	625,13	114,05
Std	20,08	20,01	5,03
var	403,21	400,37	25,26

Table B-5 Wet Track Abrasion 1-Hour soak test results for mixtures prepare using raycar aggregate and 8,6% CQS-1HP Asphalt emulsion residue**,** 7% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (1-Hour Soaked) (g/m²)
1	621,8	620	59,22
2	640,9	639,4	49,35
3	610,5	608,8	55,93
Mean	624,40	622,73	54,83
Std	15,37	15,48	5,03
var	236,11	239,69	25,26

Table B-6 Wet Track Abrasion 6-Day soak test results for mixtures prepare using raycar aggregate and 8,6% CQS-1HP Asphalt emulsion residue**,** 7% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (6-Day Soaked) (g/m²)
1	614,6	611,2	111,86
2	622,2	618,8	111,86
3	650,3	647,2	101,99
Mean	629,03	625,73	108,57
Std	18,81	18,98	5,70
var	353,64	360,05	32,47

Table B-7 Wet Track Abrasion 1-Hour soak test results for mixtures prepare using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue**,** 8% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (1-Hour Soaked) (g/m²)
1	629,4	627,1	75,67
2	655,2	653,2	65,8
3	618,8	616,3	82,25
Mean	634,47	632,20	74,57
Std	18,72	18,97	8,28
var	350,49	359,91	68,55

Table B-8 Wet Track Abrasion 6-Day soak test results for mixtures prepare using Ray Car aggregate and 7,6% CQS-1HP Asphalt emulsion residue**,** 8% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (6-Day Soaked) (g/m²)
1	606	603,2	92,12
2	623,9	621,3	85,54
3	667,9	665	95,41
Mean	632,60	629,83	91,02
Std	31,85	31,77	5,03
var	1014,67	1009,42	25,26

Table B-9 Wet Track Abrasion 1-Hour soak test results for mixtures prepare using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue**,** 8% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (1-Hour Soaked) (g/m²)
1	635,5	634,3	39,48
2	690,5	689,5	32,9
3	659,1	657,9	39,48
Mean	661,70	660,57	37,29
Std	27,59	27,70	3,80
var	761,32	767,09	14,43

Table B-10 Wet Track Abrasion 6-Day soak test results for mixtures prepare using raycar aggregate and 8,1% CQS-1HP emulsion residue **,** 8% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (6-Day Soaked) (g/m²)
1	608,6	606,4	72,38
2	610,3	608,2	69,09
3	620,1	617,8	75,67
Mean	613,00	610,80	72,38
Std	6,21	6,13	3,29
var	38,53	37,56	10,82

Table B-11 Wet Track Abrasion 1-Hour soak test results for mixtures prepare using raycar aggregate and 8,6% CQS-1HP emulsion residue**,** 8% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (1-Hour Soaked) (g/m²)
1	631,5	629,9	52,64
2	620,9	619,2	55,93
3	680,2	678,7	49,35
Mean	644,20	642,60	52,64
Std	31,62	31,72	3,29
var	1000,09	1006,03	10,82

Table B-12 Wet Track Abrasion 6-Day soak test results for mixtures prepare using raycar aggregate and 8,6% CQS-1HP Asphalt emulsion residue**,** 8% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (6-Day Soaked) (g/m²)
1	634,4	632,4	65,8
2	640,2	638,2	65,8
3	677,9	675,8	69,09
Mean	650,83	648,80	66,90
Std	23,62	23,56	1,90
var	557,86	555,16	3,61

Table B-13 Wet Track Abrasion 1-Hour soak test results for mixtures prepare using raycar aggregate and 7,6% CQS-1HP emulsion residue**,** 9% water without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (1-Hour Soaked) (g/m²)
1	629,1	626,7	78,96
2	635,2	633	72,38
3	665,2	662,8	78,96
Mean	643,17	640,83	76,77
Std	19,32	19,28	3,80
var	373,40	371,82	14,43

Table B-14 Wet Track Abrasion 6-Day soak test results for mixtures prepare using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue**,** 9% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (6-Day Soaked) (g/m²)
1	609	607,4	52,64
2	612,5	610	82,25
3	630,3	628	75,67
Mean	617,27	615,13	70,19
Std	11,42	11,22	15,55
var	130,46	125,85	241,74

Table B-15 Wet Track Abrasion 1-Hour soak test results for mixtures prepare using raycar aggregate and 8,1% CQS-1HP emulsion residue**,** 9% water without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (1-Hour Soaked) (g/m²)
1	633,4	631,4	64,81
2	677,1	675	69,09
3	657,8	655,6	72,38
Mean	656,10	654,00	68,76
Std	21,90	21,84	3,80
var	479,59	477,16	14,41

Table B-16 Wet Track Abrasion 6-Day soak test results for mixtures prepare using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue**,** 9% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (6-Day Soaked) (g/m²)
1	625,8	623,3	82,25
2	633,3	630,7	85,54
3	660,9	658,4	82,25
Mean	640,00	637,47	83,35
Std	18,48	18,50	1,90
var	341,67	342,34	3,61

Table B-17 Wet Track Abrasion 1-Hour soak test results for mixtures prepare using raycar aggregate and 8,6% CQS-1HP emulsion residue**,** 9% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (1-Hour Soaked) (g/m²)
1	634,2	633,3	29,61
2	641,9	641,3	19,74
3	620,5	619,4	36,19
Mean	632,20	631,33	28,51
Std	10,84	11,08	8,28
var	117,49	122,80	68,55

Table B-18 Wet Track Abrasion 6-Day soak test results for mixtures prepare using raycar aggregate and 8,6% CQS-1HP Asphalt emulsion residue**,** 9% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (6-Day Soaked) (g/m²)
1	630,8	629,5	42,77
2	612,3	611,1	39,48
3	650,6	649,5	36,19
Mean	631,23	630,03	39,48
Std	19,15	19,21	3,29
var	366,86	368,85	10,82

Table B-19 Wet Track Abrasion 1-Hour soak test results for mixtures prepare using raycar aggregate and 7,6% CQS-1HP emulsion residue**,** 10% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (1-Hour Soaked) (g/m²)
1	622,4	620,8	52,64
2	633,8	632,1	55,93
3	642,2	640,6	52,64
Mean	632,80	631,17	53,74
Std	9,94	9,93	1,90
var	98,76	98,66	3,61

Table B-20 Wet Track Abrasion 6-Day soak test results for mixtures prepare using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue**,** 10% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (6-Day Soaked) (g/m²)
1	622,5	620,5	65,8
2	635,7	633,7	65,8
3	642,4	640,7	55,93
Mean	633,53	631,63	62,51
Std	10,13	10,26	5,70
var	102,52	105,21	32,47

Table B-21 Wet Track Abrasion 1-Hour soak test results for mixtures prepare using raycar aggregate and 8,1% CQS-1HP emulsion residue**,** 10% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (1-Hour Soaked) (g/m²)
1	642,9	641,4	49,35
2	666,3	665	42,77
3	684,4	682,9	49,35
Mean	664,53	663,10	47,16
Std	20,81	20,82	3,80
var	432,90	433,27	14,43

Table B-22 Wet Track Abrasion 6-Day soak test results for mixtures prepare using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue**,** 10% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (6-Day Soaked) (g/m²)
1	630,8	629,2	52,64
2	625,5	624	49,35
3	678,8	677,6	39,48
Mean	645,03	643,60	47,16
Std	29,36	29,56	6,85
var	862,16	873,76	46,90

Table B-23 Wet Track Abrasion 1-Hour soak test results for mixtures prepare using raycar aggregate and 8,6% CQS-1HP emulsion residue**,** 10% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (1-Hour Soaked) (g/m²)
1	643,5	642,3	39,48
2	663,7	662,7	32,9
3	677,9	676,7	39,48
Mean	661,70	660,57	37,29
Std	17,29	17,30	3,80
var	298,84	299,25	14,43

Table B-24 Wet Track Abrasion 6-Day soak test results for mixtures prepare using raycar aggregate and 8,6% CQS-1HP Asphalt emulsion residue**,** 10% water, without mineral filler.

Sample No	Original Weight (g)	Final Weight (g)	Wear Value (6-Day Soaked) (g/m^2)
1	618	617	32,9
2	615,3	614,6	23,03
3	659,7	658,6	36,19
Mean	631,00	630,07	30,71
Std	24,89	24,74	6,85
var	619,59	612,05	46,90

Table C-1 Relative Moisture Retained in Loaded Wheel Test samples prepared using raycar aggregate and 7,6% CQS-1HP emulsion residue, 7% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	674,6	628,3	48,9	1,11
2	613,5	565	48,5	1,17
3	678,9	630,2	48,7	1,13
Mean	655,667	607,833	48,700	1,137
Std	36,581	37,107	0,200	0,031
var	1338,143	1376,923	0,040	0,001

Table C-2 Relative Moisture Retained in Wet Track Abrasion Test samples prepared using raycar agg and 7,6% CQS-1HP emulsion residue, 7% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	567,8	520,7	47,1	1,41
2	655,3	607,2	48,1	1,24
3	611,2	563,8	47,4	1,36
Mean	611,433	563,900	47,533	1,337
Std	43,750	43,250	0,513	0,087
var	1914,103	1870,570	0,263	0,008

Table C-3 Relative Moisture Retained in Loaded Wheel Test samples prepared using raycar agg and 8,1% CQS-1HP emulsion residue, 7% water and without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	683,4	634,2	49,2	1,27
2	645,1	596,1	49	1,3
3	610,5	561,5	49	1,3
Mean	646,333	597,267	49,067	1,290
Std	36,466	36,364	0,115	0,017
var	1329,743	1322,343	0,013	0,000

Table C-4 Relative Moisture Retained in Wet Track Abrasion Test samples prepared using raycar agg and 8,1% CQS-1HP emulsion residue, 7% water without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	598,8	547,6	51,2	0,93
2	614,4	563	51,4	0,9
3	605,5	554,2	51,3	0,92
Mean	606,233	554,933	51,300	0,917
Std	7,826	7,726	0,100	0,015
var	61,243	59,693	0,010	0,000

Table C-5 Relative Moisture Retained in Loaded Wheel Test samples prepared using raycar agg and 8,6% CQS-1HP emulsion residue, 7% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	691	640,9	50,1	1,33
2	635,4	585,7	49,7	1,4
3	642,9	592,9	50	1,34
Mean	656,433	606,500	49,933	1,357
Std	30,170	30,008	0,208	0,038
var	910,203	900,480	0,043	0,001

Table C-6 Relative Moisture Retained in Wet Track Abrasion Test samples prepared using raycar agg and 8,6% CQS-1HP emulsion residue, 7% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	600,3	549,6	50,7	1,23
2	634,2	583,7	50,5	1,26
3	663,8	613,1	50,7	1,22
Mean	632,767	582,133	50,633	1,237
Std	31,774	31,779	0,115	0,021
var	1009,603	1009,903	0,013	0,000

Table C-7 Relative Moisture Retained in Loaded Wheel Test samples prepared using raycar agg and 7,6% CQS-1HP emulsion residue, 8% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	675,2	624	51,2	1,55
2	647,1	595,4	51,4	1,52
3	610,5	559,3	51,2	1,55
Mean	644,267	592,900	51,267	1,540
Std	32,443	32,422	0,115	0,017
var	1052,543	1051,210	0,013	0,000

Table C-8 Relative Moisture Retained in Wet Track Abrasion Test samples prepared using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 8% water and without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	613,3	558,8	54,5	1
2	684	629,6	54,4	1,02
3	652,9	598,2	54,7	0,96
Mean	650,067	595,533	54,533	0,993
Std	35,435	35,475	0,153	0,031
var	1255,643	1258,493	0,023	0,001

Table C-9 Relative Moisture Retained in Loaded Wheel Test samples prepared using raycar agg and 8,1% CQS-1HP emulsion residue, 8% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	683,8	632,2	51,6	1,69
2	664,3	612,8	51,5	1,71
3	663,2	611,6	51,6	1,69
Mean	670,433	618,867	51,567	1,697
Std	11,589	11,563	0,058	0,012
var	134,303	133,693	0,003	0,000

Table C-10 Relative Moisture Retained in Wet Track Abrasion Test samples prepared using raycar agg and 8,1% CQS-1HP emulsion residue, 8% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	617,5	561	56,5	0,88
2	611,9	555,5	56,4	0,89
3	644,4	587,9	56,5	0,88
Mean	624,600	568,133	56,467	0,883
Std	17,374	17,338	0,058	0,006
var	301,870	300,603	0,003	0,000

Table C-11 Relative Moisture Retained in Loaded Wheel Test samples prepared using raycar agg and 8,6% CQS-1HP emulsion residue, 8% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	667,4	625,7	51,8	1,87
2	615,2	563,4	51,8	1,87
3	645,2	593,1	52,1	1,81
Mean	642,600	594,067	51,900	1,850
Std	26,197	31,161	0,173	0,035
var	686,280	971,023	0,030	0,001

Table C-12 Relative Moisture Retained in Wet Track Abrasion Test samples prepared using raycar agg and 8,6% CQS-1HP emulsion residue, 8% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	613,2	556,6	56,6	1,07
2	619,9	563,3	56,6	1,07
3	668,9	612,4	56,5	1,09
Mean	634,000	577,433	56,567	1,077
Std	30,409	30,467	0,058	0,012
var	924,730	928,223	0,003	0,000

Table C-13 Relative Moisture Retained in Loaded Wheel Test samples prepared using raycar agg and 7,6% CQS-1HP emulsion residue, 9% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	623,9	571,35	52,55	2,14
2	633,7	581,3	52,4	2,17
3	688,1	635,4	52,7	2,12
Mean	648,567	596,017	52,550	2,143
Std	34,586	34,468	0,150	0,025
var	1196,173	1188,036	0,023	0,001

Table C-14 Relative Moisture Retained in Wet Track Abrasion Test samples prepared using raycar agg and 7,6% CQS-1HP emulsion residue, 9% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	610,5	553,6	56,9	1,42
2	664	607,2	56,8	1,44
3	625,9	568,8	57,1	1,39
Mean	633,467	576,533	56,933	1,417
Std	27,541	27,624	0,153	0,025
var	758,503	763,093	0,023	0,001

Table C-15 Relative Moisture Retained in Loaded Wheel Test samples prepared using raycar agg and 8,1% CQS-1HP emulsion residue, 9% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	670,3	617,2	53,1	2,26
2	612,8	559,8	53	2,28
3	651,7	598,8	52,9	2,29
Mean	644,933	591,933	53,000	2,277
Std	29,341	29,310	0,100	0,015
var	860,903	859,053	0,010	0,000

Table C-16 Relative Moisture Retained in Wet Track Abrasion Test samples prepared using raycar agg and 8,1% CQS-1HP emulsion residue, 9% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	634,5	575,3	59,2	1,25
2	652,9	593,4	59,5	1,21
3	611,4	552,3	59,1	1,27
Mean	632,933	573,667	59,267	1,243
Std	20,794	20,599	0,208	0,031
var	432,403	424,303	0,043	0,001

Table C-17 Relative Moisture Retained in Loaded Wheel Test samples prepared using raycar agg and 8,6% CQS-1HP emulsion residue, 9% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	633,8	581	52,8	2,5
2	663,9	611,4	52,5	2,55
3	610,4	557,7	52,7	2,52
Mean	636,033	583,367	52,667	2,523
Std	26,820	26,928	0,153	0,025
var	719,303	725,123	0,023	0,001

Table C-18 Relative Moisture Retained in Wet Track Abrasion Test samples prepared using raycar agg and 8,6% CQS-1HP emulsion residue, 9% water, without mineral filler.

Sample No	Original Weight before Cure (g)	Weight after 24-Hours Cure (g)	Moisture Loss (%)	Relative Moisture Retained (%)
1	621,9	562,5	59,4	1,42
2	642,9	583,3	59,6	1,39
3	648,2	588,8	59,4	1,42
Mean	637,667	578,200	59,467	1,410
Std	13,909	13,872	0,115	0,017
var	193,463	192,430	0,013	0,000

Table D-1 Modified Cohesion test results for mixture prepared using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 8% water and without mineral filler.

Sample No	Cohesion @ 30 min (kg-cm)	Cohesion @ 60 min (kg-cm)
1	13,0	16,0
2	13,0	16,0
3	13,0	15,5
4	13,0	15,0
5	12,5	16,0
Mean	12,9	15,7
Std	0,2	0,4
var	0,1	0,2

Table D-2 Modified Cohesion test results for mixture prepared using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue with 8% water and without mineral filler.

Sample No	Cohesion @ 30 min (kg-cm)	Cohesion @ 60 min (kg-cm)
1	16,0	18,5
2	16,0	18,0
3	15,0	18,5
4	16,0	17,0
5	15,0	18,5
Mean	15,6	18,1
Std	0,5	0,7
var	0,3	0,4

Table D-3 Modified Cohesion test results for mixture prepared using raycar aggregate and 8,6% CQS-1HP Asphalt emulsion residue with 8% water and without mineral filler.

Sample No	Cohesion @ 30 min (kg-cm)	Cohesion @ 60 min (kg-cm)
1	17,0	18,0
2	17,0	19,0
3	17,0	19,0
4	16,0	19,0
5	16,0	18,5
Mean	16,6	18,7
Std	0,5	0,4
var	0,3	0,2

Table D-4 Modified Cohesion test results for mixture prepared using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 9% water and without mineral filler.

Sample No	Cohesion @ 30 min (kg-cm)	Cohesion @ 60 min (kg-cm)
1	13,0	16,0
2	12,0	16,0
3	13,0	16,0
4	13,0	16,0
5	12,5	15,0
Mean	12,7	15,8
Std	0,4	0,4
var	0,2	0,2

Table D-5 Modified Cohesion test results for mixture prepared using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue with 9% water and without mineral filler.

Sample No	Cohesion @ 30 min (kg-cm)	Cohesion @ 60 min (kg-cm)
1	19,0	21,0
2	18,0	20,0
3	19,0	22,0
4	19,0	22,0
5	19,0	21,5
Mean	18,8	21,3
Std	0,4	0,8
Var	0,2	0,7

Table D-6 Modified Cohesion test results for mixture prepared using raycar aggregate and 8,6% CQS-1HP Asphalt emulsion residue with 9% water and without mineral filler.

Sample No	Cohesion @ 30 min (kg-cm)	Cohesion @ 60 min (kg-cm)
1	16,0	18,0
2	16,0	18,0
3	16,0	19,0
4	16,0	19,0
5	15,0	19,0
Mean	15,8	18,6
Std	0,4	0,5
var	0,2	0,3

Table D-7 Modified Cohesion test results for mixture prepared using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 10% water and without mineral filler.

Sample No	Cohesion @ 30 min (kg-cm)	Cohesion @ 60 min (kg-cm)
1	12,0	14,0
2	12,0	15,0
3	11,0	14,5
4	10,0	15,5
5	12,0	15,0
Mean	11,4	14,8
Std	0,9	0,6
Var	0,8	0,3

Table D-8 Modified Cohesion test results for mixture prepared using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue with 10% water and without mineral filler.

Sample No	Cohesion @ 30 min (kg-cm)	Cohesion @ 60 min (kg-cm)
1	16,0	19,5
2	16,5	19,0
3	16,0	19,0
4	16,0	18,0
5	15,5	19,5
Mean	16,0	19,0
Std	0,4	0,6
var	0,1	0,4

Table D-9 Modified Cohesion test results for mixture prepared using raycar aggregate, 8,6% CQS-1HP Asphalt emulsion residue with 10% water and without mineral filler.

Sample No	Cohesion @ 30 min (kg-cm)	Cohesion @ 60 min (kg-cm)
1	14,0	17,0
2	14,5	17,0
3	15,0	17,5
4	14,0	17,5
5	14,5	17,5
Mean	14,4	17,3
Std	0,4	0,3
var	0,2	0,1

Table E-1 Mixing Time test results for mixture prepare using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 8% water and without mineral filler.

Sample No	Mixing Time (Min)
1	120,00
2	129,00
Mean	124,50
Std	6,36
var	40,50

Table E-2 Mixing Time test results for mixture prepared using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue with 8% water and without mineral filler.

Sample No	Mixing Time (Min)
1	130,00
2	138,00
Mean	134,00
Std	5,66
var	32,00

Table E-3 Mixing Time test results for mixture prepared using raycar aggregate and 8,6% CQS-1HP Asphalt emulsion residue with 8% water and without mineral filler.

Sample No	Mixing Time (Min)
1	141,00
2	144,00
Mean	142,50
Std	2,12
var	4,50

Table E-4 Mixing Time test results for mixture prepared using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 9% water and without mineral filler.

Sample No	Mixing Time (Min)
1	135,00
2	140,00
Mean	137,50
Std	3,54
var	12,50

Table E-5 Mixing Time test results for mixture prepared using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue with 9% water and without mineral filler.

Sample No	Mixing Time (Min)
1	180,00
2	187,00
Mean	183,50
Std	4,95
var	24,50

Table E-6 Mixing Time test results for mixture prepared using raycar aggregate and 8,6% CQS-1HP Asphalt emulsion residue with 9% water and without mineral filler.

Sample No	Mixing Time (Min)
1	202,00
2	210,00
Mean	206,00
Std	5,66
var	32,00

Table E-7 Mixing Time test results for mixture prepared using raycar aggregate and 7,6% CQS-1HP Asphalt emulsion residue with 10% water and without mineral filler.

Sample No	Mixing Time (Min)
1	185,00
2	199,00
Mean	192,00
Std	9,90
var	98,00

Table E-8 Mixing Time test results for mixture prepared using raycar aggregate and 8,1% CQS-1HP Asphalt emulsion residue with 10% water and without mineral filler.

Sample No	Mixing Time (Min)
1	202,00
2	221,00
Mean	211,50
Std	13,44
var	180,50

Table E-9 Mixing Time test results for mixture prepared using raycar aggregate and 8,6% CQS-1HP Asphalt emulsion residue with 10% water and without mineral filler.

Sample No	Mixing Time (Min)
1	285,00
2	300,00
Mean	292,50
Std	10,61
var	112,50

APPENDIX II

RAW TEST RESULTS DATA FOR CALCULATING REPEATABILITY AND REPRODUCIBILITY OF MICRO-SURFACING MIX DESIGN TESTS

This appendix includes the raw test results data that have been used to calculate the repeatability and reproducibility of micro-surfacing mix design tests as presented in chapter 5. To do so, four operators in laboratories of Minster de Transport Quebec (MTQ) and Ecole de technologie superieure (ETS) have performed the tests.

Table A Vertical displacement test results obtained from four operators performing the tests at MTQ and ETS laboratories.

Operator name	Number	Duplicate 1	Duplicate 2	Duplicate 3	X avg
Simon	1	11.83	14.97	11.5	12.77
Alex	2	13.1	14	10	12.37
masoud	3	4.5	4.6	4.8	4.63
Masoud	4	4.3	4.7	5.8	4.93
X avg-avg	–	–	–	–	8.68

Table B Loaded wheel test results obtained from four operators performing the tests at MTQ and ETS laboratories.

Operator name	Number	Duplicate 1	Duplicate 2	Duplicate 3	X avg
Simon	1	531.43	516.67	509.29	519.13
Alex	2	546.9	642.1	560.9	583.30
masoud	3	479.76	450.24	479.76	469.92
Masoud	4	501.91	494.52	479.76	492.06
X avg-avg	–	–	–	–	516.10

Table C Wet track abrasion test (1-hour) test results obtained from four operators performing the tests at MTQ and ETS laboratories.

Operator name	Number	Duplicate 1	Duplicate 2	Duplicate 3	Duplicate 4	Duplicate 5	Duplicate 6	Xavg
Simon	1	240.17	167.79	213.85	171.08	273.07	154.63	203.43167
Alex	2	144.76	98.7	59.22	194.11	269.78	253.33	169.98333
masoud	3	64.81	69.09	72.38	49.35	42.77	49.35	57.958333
Masoud	4	115.15	108.57	118.44	39.48	32.9	39.48	75.67
X avg-avg	–	–	–	–	–	–	–	126.76083

Table D Wet track abrasion test (6-Day) test results obtained from four operators performing the tests at MTQ and ETS laboratories.

Operator name	Number	Duplicate 1	Duplicate 2	Duplicate 3	Xavg
Simon	1	1345.61	437.57	394.8	725.993
Alex	2	730.38	700.77	985.73	805.627
masoud	3	82.25	85.54	82.25	83.3467
Masoud	4	49.35	42.77	49.35	47.1567
X avg-avg	–	–	–	–	415.531

Table E Modified cohesion (30-min) test results obtained from four operators performing the tests at MTQ and ETS laboratories.

Operator name	Number	Duplicate 1	Duplicate 2	Duplicate 3	Duplicate 4	X avg
Simon	1	14	13	12	14	13.25
Alex	2	16	17	15.5	15.5	16
masoud	3	19	19	19	19.5	19.125
Masoud	4	19	19	19.5	19	19.125
X avg-avg	–	–	–	–	–	16.875

Table F Modified cohesion (60-min) test results obtained from four operators performing the tests at MTQ and ETS laboratories.

Operator name	Number	Duplicate 1	Duplicate 2	Duplicate 3	Duplicate 4	X avg
Simon	1	12	15	14	18.5	14.875
Alex	2	17.5	19	18	18.5	18.25
masoud	3	21	21	21	21.5	21.125
Masoud	4	22	22	22	22	22
X avg-avg	–	–	–	–	–	19.0625

Table G Horizontal displacement test results obtained from four operators performing the tests at MTQ and ETS laboratories.

Operator name	Number	Duplicate 1	Duplicate 2	Duplicate 3	X avg
Simon	1	9.1	12.3	10.5	10.6
Alex	2	7.9	4.8	7.4	6.7
masoud	3	8.9	8.7	9	8.9
Masoud	4	8.6	8.8	8.5	8.6
X avg-avg	–	–	–	–	8.7

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