EVALUATION OF ALTERNATIVE TEST PROCEDURES FOR COLD IN-PLACE RECYCLING MIX DESIGNS

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EVALUATION OF ALTERNATIVE TEST PROCEDURES FOR COLD IN-PLACE RECYCLING MIX DESIGNS

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Abstract: For Cold Recycling mix designs, the use of the raveling test (ASTM D7196) in combination with other tests maybe patented by Road Science and their predecessors. Due to uncertainties with the patent on the mix design procedure, many agencies have been reluctant to use the mix design procedure. There is also a concern that the specification value for minimum indirect tensile strength is not as well documented as the more conventional Marshall stability.

The two objectives of this study were to determine an alternative test for the raveling test that fit in to the current mix design procedure and verify the specification value for minimum indirect tensile strength to perform the Asphalt Recycling and Reclaiming Association's (ARRA's) mix design with confidence. Recycled asphalt pavement (RAP) from three different sources was obtained, along with CSS-1 and CSS-1h emulsions from a previous study and seven new RAP sources, along with CSS-1h emulsions were obtained for the current study.

The study incorporated the most promising results from the previous study. However, it could not verify percent retained Marshall stability as an alternative for the raveling test possibly due to lack of temperature control in the asphalt lab. Marshall stability of 1250 lbs was also found to equate with 41.3 psi indirect tensile strength.

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CHAPTER I

INTRODUCTION

Background

For Cold Recycling mix designs, the use of the raveling test (ASTM D7196) in combination with other tests maybe patented by Road Science and their predecessors. Due to uncertainties with the patent on the mix design procedure, many agencies have been reluctant to use the mix design procedure.

The Asphalt Recycling and Reclaiming Association (ARRA) has developed construction guidelines, mix design procedures and quality control guidelines for Cold Recycling (Cold In-place Recycling (CIR) and Cold Central Plant Recycling (CCPR)), Hot In-place Recycling (HIR) and Full Depth Reclamation (FDR). The ARRA mix design procedure for cold recycling uses the raveling test. Many agencies would like to see a replacement for the raveling test to remove concerns about the patents.

ARRA's mix design guidelines for cold recycling using bituminous recycling agents (1) originally used Marshall equipment but indirect tensile strength testing was added because some agencies no longer have Marshall equipment and or cannot make four inch diameter samples using their Superpave Gyratory Compactor (SGC). However, there is concern that the specification value for minimum indirect tensile strength is not as well documented as the more conventional Marshall stability.

Objective

The objective of this study was to determine an alternative test for the raveling test that fit in to the current mix design procedure. In order to obtain an alternative test for raveling loss, the most promising results from a previous study (2) were incorporated and new tests related to fully cured indirect tensile strength, fully cured Marshall stability and immediately tested Marshall stability were conducted.

The other objective of this study was to determine if there is a correlation between Marshall stability and indirect tensile strength and verify the specification value for minimum indirect tensile strength so that agencies that no longer have Marshall equipment or no longer wish to use Marshall equipment can perform the CR 201 (1) mix design with confidence.

Scope

Seven different RAP sources were obtained for this study along with CSS-1h emulsified asphalt. Three different RAP sources used from the previous study (2) were also incorporated into this study. All mixtures from the previous study were made with CSS-1 and CSS-1h emulsified asphalt. Samples were mixed with water and emulsified asphalt and were compacted using a SGC. To evaluate the relationship between fully cured indirect tensile strength and fully cured Marshall stability, samples were prepared and tested using recommended mix design guidelines for ARRA’s CR201 (1). Indirect tensile strength and Marshall stability were tested in accordance with AASHTO T 283 (ASTM D4867) and AASHTO T 245 (ASTM D6927), respectively.

To evaluate indirect tensile strength and Marshall stability tests as a possible replacement for the raveling test, the RAP samples from this study were tested for indirect tensile strength test, Marshall stability at various curing conditions and percent raveling loss was determined in accordance with ASTM D7196. The data was combined with the data from the previous study (2) that gave the most promising test result and the relationship between indirect tensile strength and Marshall stability tests at various curing conditions and percent raveling loss was determined.

CHAPTER II

LITERATURE REVIEW

Introduction

Recycled pavements, which are properly designed and constructed, perform as well as pavements built with all new materials (3). In order to preserve, rehabilitate and reconstruct existing pavement networks and save construction materials, pavement recycling is a practical, economical and sustainable method.

With the increase in traffic volume and gross vehicle weight, with tightly budgeted funds and with mature road way networks, more emphasis has been placed on preventive maintenance and preservation of existing roadways. In many states the condition and level of service of the roadways is significantly reduced because funds cannot keep pace with the increased maintenance demands (4).

Many researchers describe that a road should be maintained at an acceptable level of service to reduce cost. A World Bank study stated that, compared to the money needed to maintain a road after an 80 percent drop in roadway quality, a dollar spent at the first 40 percent drop in roadway quality will result in a savings from $3 to $ 4 (5). Hence, a properly and timely applied pavement maintenance program, including asphalt recycling, maximizes the effectiveness of the budget to maintain, preserve, reconstruct and rehabilitate roadways.

There are five broad categories of asphalt recycling which are Cold Planing (CP), Hot Recycling (HR), Hot In-Place Recycling (HIR), Full Depth Reclamation (FDR) and Cold Recycling (CR) which consists of Cold In-Place Recycling (CIR) and Cold Central Plant Recycling (CCPR) (5). This study focus on the performance tests of Cold In-Place Recycling.

Overview of CIR and CCPR

Cold Recycling (CR) is one of the five broad categories of asphalt recycling that have been defined by ARRA to describe the various asphalt recycling methods. Cold In-Place Recycling (CIR) and Cold Central Plant Recycling (CCPR) are the two subcategories of cold recycling. Cold in-place recycling recycles 100 percent of the reclaimed asphalt pavement (RAP) in place without the application of heat saving considerable money and energy. Cold central plant recycling is an alternative recycling process when stockpiles of high quality RAP are available or when it is not possible to in-place recycle the pavement (4).

Cold Recycling uses bituminous recycling agents, either emulsified asphalt or foamed asphalt. Treatment depth for CIR is between 3 to 5 inches (75 to 150 mm). To improve early strength gain and resistance to moisture damage additives like cement or lime dust are added in small quantities. Since all work is done on site, the transportation of materials is not required except for additives being used (6).

CIR is performed with different types of trains based on equipment configuration (5, 7). They are single unit trains, two unit trains and multi-unit trains.

Single unit trains pulverize and add recycling agent based on the treatment depth, width and the anticipated forward speed of the unit. Figure 1 shows a single unit recycling train. Addition and mixing of the recycling agent is conducted in the milling machine cutting chamber. On the plus side, it has higher mobility compared to multi-unit trains with 150 feet. Single unit trains are shorter in length with only 70 feet. However, it provides limited control of RAP gradation and material proportioning.

FIGURE 1 Single Unit Recycling Train (7)

Two unit trains consists of a large full lane width cold planer and mix paver. This type of train pulverizes, screens, crushes, and adds recycling agent based on weight of RAP. Mixing is performed in a pugmill. On the plus side, it offers high control of process and mobility but it provides limited control of RAP size. Figure 2 shows a two unit recycling train.

FIGURE 2 Two Unit Recycling Train

Multi-unit trains consists of a cold planer and different trailer mounted units such as a screening unit, which is used to remove oversize RAP and resize the RAP. This type of train pulverizes, screens, crushes, and adds recycling agent based on the weight of the RAP. Mixing is performed in a pugmill. However, it has longer length which limits its mobility. Figure 3 shows multi-unit recycling train.

FIGURE 3 Multi-unit Recycling Train (5)

Cold Central Plant Recycling (CCPR) is a viable alternative when it is not possible to in-place recycle the pavement or stockpiles of high quality RAP are available (7). The mix can be stockpiled for later use for applications such as maintenance blade patching or pothole repair or they can also be used immediately (5). CCPR can be performed using a multi-unit train in a stationary mode or a pugmill mixer. The CCPR process is essentially the same as CIR except it uses existing stockpiles of RAP. Figure 4 shows a cold central plant recycling unit.

FIGURE 4 Cold Central Plant Recycling (7)

Benefits of Cold Recycling

In addition to the rehabilitation of deteriorated asphalt pavements, some of the advantages of cold recycling are (8, 9, 10, 11, 12).

- Conservation of energy compared to other reconstruction methods
- Conservation of resources (asphalt cement, aggregate, fuel) by reusing the existing pavement structure
- Improved mix characteristics
- Surface irregularities and cracks are eliminated or reduced
- Compared with conventional flexible pavement reconstruction methods, it is cost effective

- The recycling process needs less time than conventional pavement reconstruction methods.
- May be performed under traffic and the road user inconvenience is small because a single lane is required for the process

Emulsified Asphalt Recycling Agents

According to their reactivity, emulsified asphalt can be classified as Rapid Setting (RS) which sets quickly in contact with clean aggregates of low-surface area, Medium Setting (MS) which sets less quickly so that they can be mixed with aggregates of low surface area and Slow Setting (SS) emulsions which mix with reactive aggregates of high surface area. Based on the charge on the droplets, emulsions can be cationic or anionic. Cationic emulsions are emulsions which carry positive charges whereas anionic emulsions carry negative charges (13, 14).

In the past, full depth reclamation used cold slow setting emulsions and medium setting asphalt emulsions were used for CR operations (8). Due to the slower set, CIR was not widely used on high traffic volume roads because of longer delays while the emulsion is curing. Since early strength is an important component of CIR, the new process uses CSS and has an emulsifier chemistry that breaks and cures more quickly, giving the earlier strength needed for early compaction and traffic return (15).

Mix Design Methods

There is no nationally accepted mix design procedure for cold recycling mixtures. However, agencies have adopted mix design procedures developed by equipment and materials suppliers. Some of the CR mix design procedures are discussed below.

AASHTO-AGC Task Force 38

A joint task force from AASHTO, AGC and ARTBA conducted a review on several mix design procedures of CIR practice in 1998 and recommended mix design procedures using both Marshall and Hveem equipment as part of the review. The procedures are basically the same with minor modifications for differences in the respective equipment (16). These procedures are rarely used today having been replaced with more recent methods that use Superpave technology to make the best use of asphalt paving technology.

Engineered Emulsion Method

Due to the lack of performance-related mix design methods, some agencies lacked sufficient confidence to use CIR. Koch materials developed an improved emulsion chemistry to give higher early strength and improved coating and film thickness and developed performance related test methods to improve the reliability of the mix design and construction process.

The mix design procedure used SGC compaction and the asphalt emulsion mix can be tested and evaluated for performance using the raveling test (ASTM D 7196), a thermal cracking test (AASHTO T 322), dry and conditioned Marshall stability test (AASHTO T 245) (15).

The procedure was patented and can be found on many agencies web pages. However, many agencies are reluctant to use the mix design procedure due to uncertainties with the patents on the mix design procedure concerning the use of the raveling test.

ARRA CR 201 Cold Recycle Mix Design

The Koch materials mix design employs the thermal cracking test. The test is expensive to perform, few agencies or labs can perform the test and it is seldom performed on hot mix asphalt. Therefore, ARRA published a simplified version of the Koch materials mix design that removed the thermal cracking test and added an option for using indirect tensile strength rather than Marshall stability. The ARRA procedure (1) was used in this study and is described below. The steps for a Cold Recycle mix design by ARRA is shown in figure 5.

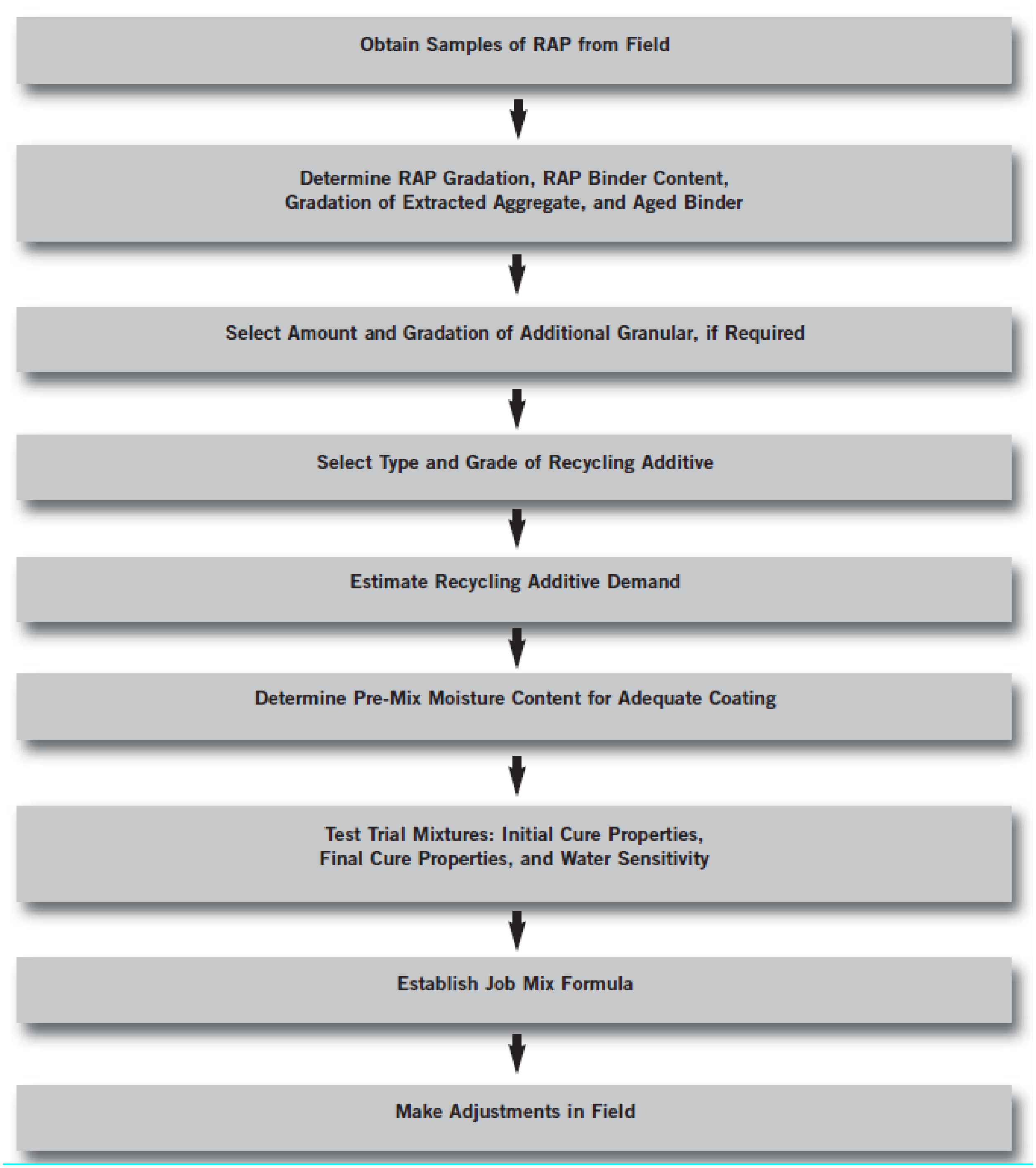

FIGURE 5 Cold Recycling Mix Design Flow Chart (3)

RAP is dried to a constant mass at 104 ± 4 ^{0}F (40 ± 2 ^{0}C) prior to mixing. Typically 1.5 to 3 % moisture is added in order to compensate for the moisture added at the milling head during construction. A minimum of three emulsified asphalt contents, typically between 1 to 4 % are added at the appropriate rate. Recycling additives (if any) are added the same way as they are added during field production. The entire mixture is mixed for not more than 1 minute at 77 ± 5 ^{0}F (25 ± 5 ^{0}C) and then it is compacted at the mixing temperature using SGC. Figure 6 shows Superpave Gyratory Compactor. A total of six specimens are prepared at each recycling agent content for indirect tensile strength testing or Marshall stability testing, 3 for dry cured specimens and 3 for moisture cured specimens. Samples are compacted using 30 gyration of the SGC at 1.25^{0} angles and 600 kPa stress. The specimens are compacted to 2.5± 0.1 inch (63.5 ± 2.5mm) tall and 4 inch (100mm) in diameter for Marshall testing and 3.7±0.1 inch (95±5mm) tall and 6 inch (150 mm) for indirect tensile strength testing.

FIGURE 6 Superpave Gyratory Compactor (SGC)

After compaction, the samples are cured in a forced draft oven at 140 ± 2 ^{0}F (60 ± 1 ^{0}C) to a constant weight for at least 16 hours but not more than 48 hours. Constant weight is defined as a 0.05% change in weight in 2 hours. After curing, specimens are cured at room temperature from 12 hours to 24 hours. Two additional specimens are prepared for Theoretical Maximum Specific Gravity in accordance with AASHTO T 209 (ASTM D2041).

Indirect tensile strength (ITS) test is conducted according to AASHTO T 283 (ASTM D4867) without the optional freeze cycle. Compacted and cured specimens for indirect tensile strength test are placed in a leak-proof bag in a water bath at 77 ± 2 ^{0}F (25 ± 1 ^{0}C) for 30-45 minutes immediately prior to testing. Figure 7 shows indirect tensile strength test set up. For ITS, compressive load is applied along the diametral axis of 150 mm diameter specimen at a controlled vertical and constant deformation rate of 50.8 mm/min or 2 inch/min until failure occurs (17). Marshall stability is determined using AASHTO T 245 (ASTM D6927) at 104 ± 2 ^{0}F (40 ± 1^{0}C) for 30-45 minutes immediately prior to testing. Figure 8 shows Marshall stability test set up.

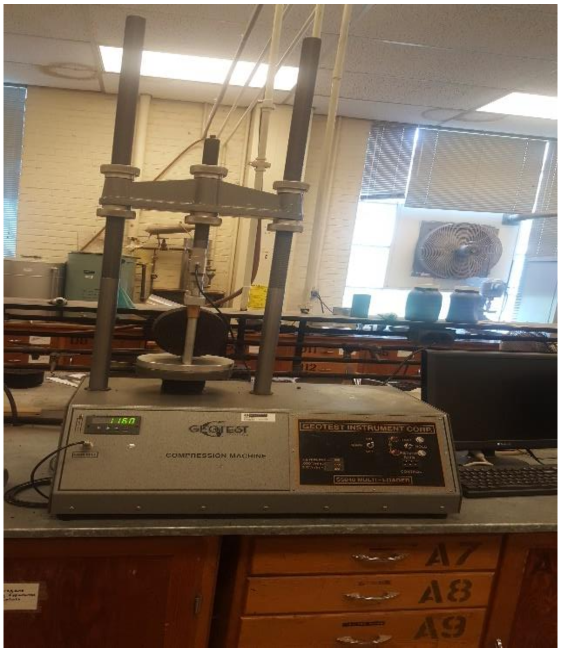

FIGURE 7 Indirect Tensile Strength Test Setup

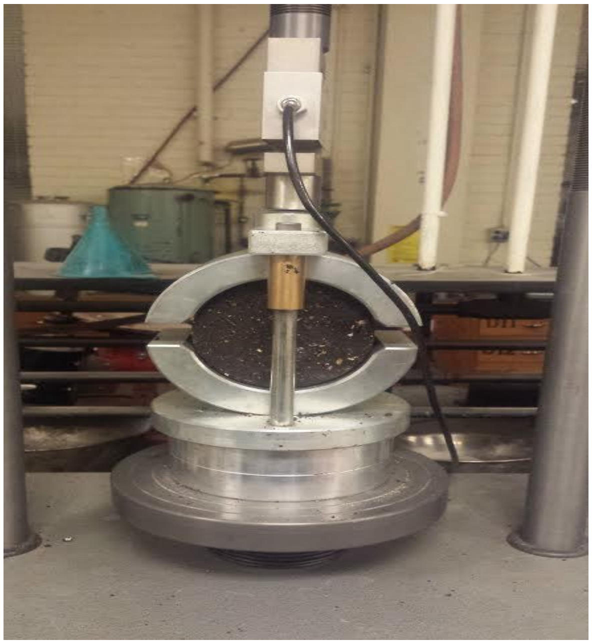

FIGURE 8 Marshall Stability Test Setup

Moisture conditioning is conducted on 3 compacted, cured specimens at each recycling agent content by applying a vacuum of 2 psi to 10 psi (13 to 67 kPa) absolute pressure

10 to 26 inch (254 to 660 mm) of Hg partial pressure for a time duration required to vacuum saturate specimens to 55 to 75 percent saturation.

Specimens are tested for resistance to moisture induced damage or moisture sensitivity. For tensile strength ratio testing (AASHTO T 283 or ASTM D4867), specimens are submerged in a 77 ± 2 °F (25 ± 1 °C) water bath for 24 hours and indirect tensile strength is determined in accordance with AASHTO T 283 (ASTM D4867) immediately after removal from the water bath. For retained Marshall stability testing, specimens are submerged in a 77 ± 2 °F (25 ± 1 °C) water bath for 23 hours followed by a one hour soak at 104 ± 2^{0}F (40 ± 1 ^{0}C) and Marshall stability is determined in accordance with AASHTO T 245 (ASTM D6927) immediately after removal from the water bath.

Marshall compacted specimens use retained Marshall stability ratio where the average Marshall stability of moisture conditioned specimens are divided by the average Marshall stability of dry specimens. Indirect tensile strength testing uses tensile strength ratio (TSR), the average tensile strength of conditioned specimens divided by the average dry tensile strength.

There are no firm guidelines or threshold values for strength tests. ARRA currently recommends minimum Marshall stability values of 1250 lbs. (5.56 kN) at 104 ± 2 °F (40 ± 1 °C) or indirect tensile strengths of 45 psi (310 kPa) at 77 ± 2 °F (25 ± 1 °C) at the optimum recycling agent content. ARRA mix design requirements for Tensile Strength Ratio/ Retained Stability Ratio is a minimum of 0.7 and it may be reduced to 0.6, provided that moisture condition indirect tensile strength or conditioned Marshall stability exceeds the minimum dry strength/stability requirement.

The raveling test (ASTM D7196), conducted in the laboratory on SGC compacted samples, was developed to simulate the raveling that can occur on the newly recycled pavement. The test measures how quickly an emulsified asphalt breaks and cures under specified temperature and relative humidity. When emulsified asphalt is used as a bituminous binder, two specimens are prepared in accordance with ASTM D7196 at the optimum recycling agent content for a specific gradation. For a raveling test, mass of test specimens is selected so that when 6 inch (150 mm) diameter specimens are compacted in the SGC to 20 gyrations, the specimens will be 2.75 ± 0.2 inch (70 ± 5 mm) tall. The specimens are compacted at room temperature and conditioned at 50 ± 2 °F (10 ± 1 °C) at 50% relative humidity for 4 hours ± 5 minutes immediately after compaction.

After controlled curing, the specimen is mounted in a Hobart mixer and subjected to abrasion by a free floating rubber hose for 15 minutes or until the samples disintegrate to the point it is unreasonable to continue the test. The average percent raveling loss of the two specimens is determined in accordance with ASTM D7196. Figure 9 shows raveling test setup and figure 10 shows specimens after raveling test.

FIGURE 9 Raveling Test Setup

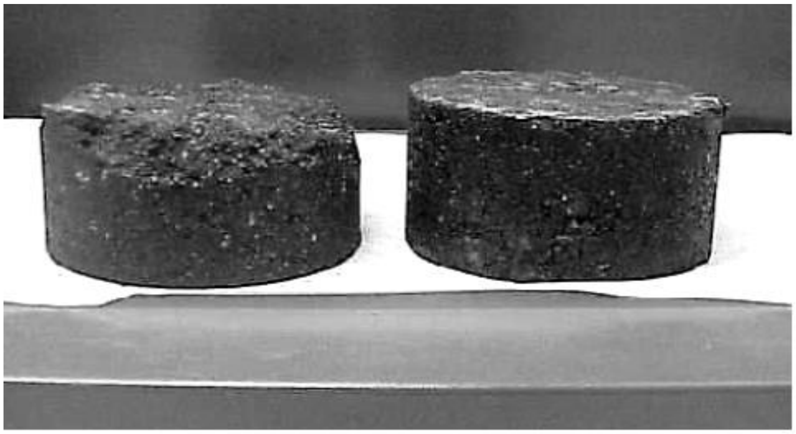

FIGURE 10 Specimens After Testing (15)

The ARRA recommended mix design parameters are provided in table 1 and should be parts of all cold recycle mix designs.

TABLE 1 Minimum Cold Recycling Mix Design Requirements for Emulsified Asphalt

Test Method	Criteria	Property
Indirect Tensile strength AASHTO T 283 (ASTM D4867)	Minimum 45 psi (310 kpa)	Cured Strength
Marshall Stability AASHTO T 245 (ASTM D6927)	Minimum 1,250 lbs (5560 N)	Cured stability
Tensile strength ratio / Retained Marshall Stability Based on Moisture Conditioning AASHTO T 283 (ASTM D4867) AASHTO T245(ASTM D6927)	Minimum 0.7	Resistance to Moisture-Induced Damage
Raveling Test of Cold Mixed Bituminous Mixtures ASTM D7196	Maximum 7 % loss	Resistance to Raveling

CHAPTER III

MATERIALS AND TEST PLAN

Objective

The objective of this study was to determine an alternative test for the raveling test that fit into the current mix design procedure. In order to obtain an alternative test for raveling loss, the most promising results from a previous study (2) were incorporated and new tests related to fully cured indirect tensile strength, fully cured Marshall stability and immediately tested Marshall stability were conducted.

The other objective of this study was to determine if there is a correlation between Marshall stability and indirect tensile strength and verify the specification value for minimum indirect tensile strength so that agencies that no longer have Marshall equipment or no longer wish to use Marshall equipment can perform the CR 201 (1) mix design with confidence.

Materials

Reclaimed Asphalt Pavement (RAP)

This study used three different RAP sources from a previous study (2) and are shown in table 2 with their identification key. Seven new RAP sources were used in this study and are shown in table 3 along with their routes, which were used as an identification key.

For indirect tensile strength testing, two of the previously obtained RAP sources, Enid and Oklahoma City, are used for the current study.

TABLE 2 RAP Sources and Identification Key for Previous Study (2)

Site	Source	Identification Key
1	Perkins, Ok	PER
2	Oklahoma City, Ok	OKC
3	Enid, Ok	ENI

TABLE 3 RAP Sources for Current Study

Site	State	Route	County
1	Kansas	US-283	Ford
2	Kansas	US-24	Graham
3	New York	US-11	Chatagua
4	Vermont	RT-2	Montpelier
5	Iowa	K-42	Plymouth
6	Arizona	RT-94	Maricopa
7	Oklahoma	OKC-2 *	-

* OKC-2 is used as an identification key for Oklahoma State RAP.

The OKC-2 RAP was not from a route, but is a RAP combined from the contractor stockpiles of Perkins, Oklahoma City and Enid sources.

RAP Properties

For each RAP, the material was dried to a constant mass at 104 ± 4^0F (40 ±2^0C). Table 4 shows RAP gradations used to batch the samples. For RAP from Vermont, which is RT-2, field gradations from a previous study were used (17) and for others representative samples were obtained and gradation was determined in accordance with AASHTO T27. After drying, all RAPs were separated by sieve size through the No.16 sieve.

TABLE 4 Batched Gradations of RAP

Batched RAP Gradations								
State	**KS**	**KS**	**NY**	**VT**	**IA**	**AZ**	**OK**	**OK**
RAP ID	**US-283**	**US-24**	**US-11**	**RT-2**	**K-42**	**US-94**	**OKC-2**	**PER, OKC, ENI**
Sieve size	**Percent Passing**							
3/2"	100	100	100	100	100	100	100	100
1"	96	100	100	100	94	100	100	100
3/4"	69	100	96	94	85	96	95	95
1/2"	60	96	79	78	70	78	80	80
3/8"	54	84	67	62	61	65	70	70
No. 4	40	54	32	34	41	34	50	50
No. 8	19	50	16	19	27	20	32	32
No. 16	7	25	7	11	13	10	20	20

Asphalt Emulsion

The asphalt emulsions used for the previous study were CSS-1 and CSS-1h. The asphalt emulsions used for this study were a CSS-1h. The emulsions for both studies were supplied by Ergon.

Test Plan

Introduction

In order to determine if there is a correlation between Marshall stability and indirect tensile strength so that agencies that no longer have Marshall equipment or no longer wish to use Marshall equipment can perform the Cold Recycling mix design, fully cured indirect tensile strength and fully cured Marshall stability test results were compared.

To determine an alternative test that fit in to the current mix design procedures for raveling test, our previous study (2) showed percent retained Marshall stability from testing immediately compared to fully cured to be the most promising. To verify the results of this study, additional testing of fully cured Marshall stability and immediately tested Marshall stability from different RAP sources were conducted. Fully cured indirect tensile strength was checked to be an alternative test for percent raveling loss only for the current study.

Test Preparation

Batching

Samples were batched using gradations shown in table 4 to the mass required by the respective test.

Based on ASTM D7196 and ARRA's CR 201 (1), sample specimens were batched to the mass that produces a 2.75 ± 0.2 inch (70 ± 5 mm) tall, 6 inch (150 mm) diameter specimens for raveling test. Hence, a mass of 2450 grams was used to batch raveling test specimens.

Based on AASHTO T 283(ASTM D4867) and ARRA's CR 201 (1), sample specimens were batched to the mass that produces 3.7 ± 0.1 inch (95±5mm) tall, 6 inch (150 mm) diameter specimens for indirect tensile strength. Hence, a mass of 3300 grams was used to batch indirect tensile strength test specimens.

Based on AASHTO T 245 (ASTM D6927) and ARRA's CR 201 (1), sample specimens were batched to the mass that produces 2.5±0.1 inch (63.5 ± 2.5 mm) tall, 4 inch (100 mm) diameter specimens for Marshall stability test. Hence, a mass of 950 grams was used to batch Marshall stability test specimens.

Mixing

Mixing of the test specimens were performed manually. First, the RAP was mixed thoroughly with two percent water. Next, the desired amount of emulsified asphalt content (EAC) was added in appropriate rate and mixed at room temperature for approximately 60 seconds.

Compaction

All specimens were compacted immediately after mixing by Superpave Gyratory Compactor (SGC) in accordance with CR 201 (1) at room temperature. To fulfill the mix design criteria, raveling test specimens were compacted at 20 gyrations. For the same reason, Marshall stability and indirect tensile strength test specimens were compacted at 30 gyrations.

Testing

Raveling Test

The raveling test was performed in accordance with ASTM D7196. After compaction, the specimens were immediately taken out from the mold and cured for 4 hours ± 5 minutes in the environmental chamber at 50 % relative humidity and 10 ^{0} C temperature. Just prior to testing, the specimens were weighed and then the samples were abraded for 15 minutes and weighed immediately. After abrasion, ASTM D7196 was followed to determine percent raveling loss.

Indirect Tensile Strength

Indirect tensile strength test specimens were tested at fully cured conditions according to ARRA's CR201 (1). That means after compaction the specimens were cured at 140±2^{0}F (60 ±1^{0}C) for a minimum of 16 hours and maximum of 48 hours to a constant mass. Constant mass is defined as less than 0.05% change in mass in 2 hours. After curing, the samples were cooled at room temperature for 24 hours. According to AASHTO T 283 (ASTM D4867), indirect tensile strength was determined at 77±2^{0}F (25 ±1^{0}C). To attain this temperature, specimens were put in a leak- proof bag in a water bath for 30-45 minutes right before testing.

Marshall Stability

After compaction the sample specimens were immediately taken out from the mold and tested at two temperature and curing conditions.

Marshall stability test specimens were tested at fully cured conditions according to ARRA's CR201. That means after compaction the specimens were cured at 140 ± 2^0F (60 ± 1^0C) for a minimum of 16 hours and maximum of 48 hours to a constant mass. Constant mass is defined as less than 0.05% change in mass in 2 hours. After curing, the samples were cooled at room temperature for 24 hours. According to AASHTO T 245 (ASTM D6927), Marshall stability was determined at 104 ± 2^0F (40 ± 1^0C) and not 60^0C as recommended in CR201. To attain this temperature, specimens were put in a leak- proof bag in a water bath for 30-45 minutes right before testing.

One set of samples were tested for Marshall stability immediately after compaction at room temperature. Due to work in Engineering Annex Asphalt Laboratory, large swings in room temperature of 10^0F – 15^0F were occasionally experienced.

From the previous study, sample conditioning and number of test replicates are shown in table 5 for CSS-1 emulsion and in table 6 for CSS-1h emulsion. For the current study, sample conditioning and number of test replicates are shown in table 7.

TABLE 5 Number of Replicates Tested and Curing Condition for CSS-1, Previous Study (2)

RAP ID	EAC (%)	Raveling	Marshall Stability	Conditioning
PER	2.75	2	2	50% humid, 10 °C
PER	2.75	-	2	Immediate
PER	2.75	-	2	Oven Cured 60 °C
PER	3.00	2	2	50% humid, 10 °C
PER	3.00	-	2	Immediate
PER	3.00	-	2	Oven Cured 60 °C

TABLE 6 Number of Replicates Tested and Curing Condition for CSS – 1h, Previous Study (2)

RAP ID	EAC (%)	Raveling	Marshall Stability	Conditioning
PER	2.75	2	2	50% humid, 10 °C
PER	2.75	-	2	Immediate
PER	2.75	-	2	Oven Cured 60 °C
PER	2.50	2	2	50% humid, 10 °C
PER	2.50	-	2	Immediate
PER	2.50	-	2	Oven Cured 60 °C
OKC	2.50	2	2	50% humid, 10 °C
OKC	2.50	-	2	Immediate
OKC	2.50	-	2	Oven Cured 60 °C
ENI	2.50	2	2	50% humid, 10 °C
ENI	2.50	-	2	Immediate
ENI	2.50	-	2	Oven Cured 60°c
ENI	2.00	2	-	50% humid, 10 °C
ENI	2.00	-	2	Immediate
ENI	2.00	-	2	Oven cured 60 °C
ENI	1.50	2	-	50% humid, 10 °C
ENI	1.50	-	2	Immediate
ENI	1.50	-	2	Oven cured 60 °C

TABLE 7 Number of Test Replicates Test and Curing Condition for CSS – 1h, Current Study

State	RAP ID	EAC (%)	Raveling	Indirect Tensile Strength	Marshall Stability	Conditioning
Kansas	US-283	2.00	2	-	-	50% humid, 10 °C
Kansas	US-283	2.00	-	2	2	Fully Cured at 60^0C
Kansas	US-283	2.00	-	-	2	Immediately
Kansas	US-24	2.00	2	-	-	50% humid, 10 °C
Kansas	US-24	2.00	-	2	2	Fully Cured at 60^0C
Kansas	US-24	2.00	-	-	2	Immediately
Kansas	US-24	2.50	2	-	-	50% humid, 10 °C
Kansas	US-24	2.50	-	2	2	Fully Cured at 60^0C
Kansas	US-24	2.50	-	-	2	Immediately
Iowa	K-42	2.50	2	-	-	50% humid, 10 °C
Iowa	K-42	2.50	-	2	2	Fully Cured at 60^0C
Iowa	K-42	2.50	-	-	2	Immediately
Iowa	K-42	3.00	2	-	-	50% humid, 10 °C
Iowa	K-42	3.00	-	2	2	Fully Cured at 60^0C
Iowa	K-42	3.00	-	-	2	Immediately
Oklahoma	OKC-2	2.50	2	-	-	50% humid, 10 °C
Oklahoma	OKC-2	2.50	-	2	2	Fully Cured at 60^0C
Oklahoma	OKC-2	2.50	-	-	2	Immediately
Oklahoma	OKC-2	3.00	2	-	-	50% humid, 10 °C
Oklahoma	OKC-2	3.00	-	2	2	Fully Cured at 60^0C

TABLE 7 Continued

State	RAP ID	EAC (%)	Raveling	Indirect Tensile Strength	Marshall Stability	Conditioning
Oklahoma	OKC-2	3.00	-	-	2	Immediately
Vermont	RT-2	1.50	2	-	-	50% humid, 10 °C
Vermont	RT-2	1.50	-	2	2	Fully Cured at 60^0C
Vermont	RT-2	1.50	-	-	2	Immediately
Arizona	RT-94	2.00	2	-	-	50% humid, 10 °C
Arizona	RT-94	2.00	-	2	2	Fully Cured at 60^0C
Arizona	RT-94	2.00	-	-	2	Immediately
Arizona	RT-94	2.50	2	-	-	50% humid, 10 °C
Arizona	RT-94	2.50	-	2	2	Fully Cured at 60^0C
Arizona	RT-94	2.50	-	-	2	Immediately
Arizona	RT-94	3.00	2	-	-	50% humid, 10 °C
Arizona	RT-94	3.00	-	2	2	Fully Cured at 60^0C
Arizona	RT-94	3.00	-	-	2	Immediately
New York	US-11	2.50	2	-	-	50% humid, 10 °C
New York	US-11	2.50	-	2	2	Fully Cured at 60^0C
New York	US-11	2.50	-	-	2	Immediately
Oklahoma	ENI	1.50	-	2	-	Fully Cured at 60^0C
Oklahoma	ENI	2.00	-	2	-	Fully Cured at 60^0C
Oklahoma	ENI	2.50	-	2	-	Fully Cured at 60^0C
Oklahoma	OKC	2.50	-	2	-	Fully Cured at 60^0C

CHAPTER IV

TEST RESULTS

Raveling Test

This study used the emulsified asphalt contents (EAC) used on each project (17) and at lower EAC contents to get a spread in raveling test results. Samples compacted in the SGC and cured in environmental chamber at 50% relative humidity and 10^0C temperature were tested for raveling according to ASTM D7196. The results of the raveling test for our previous study are shown in table 8 and from the current test in table 9.

TABLE 8 Results of Raveling Test, Previous Study (2)

RAP ID	Emulsion Type	EAC (%)	Percent Raveling loss		
			Sample 1	Sample 2	Average
PER	CSS-1	2.75	12.2	*	12.2
PER	CSS-1	3.00	1.1	1.2	1.2
PER	CSS-1h	2.50	3.6	3.5	3.6
PER	CSS-1h	2.75	2.5	2.7	2.6
OKC	CSS-1h	2.50	15.4	*	15.4
ENI	CSS-1h	2.50	2.5	2.2	2.4
ENI	CSS-1h	2.00	3.0	4.0	3.5
ENI	CSS-1h	1.50	6.8	6.9	6.9

* Sample completely disintegrated

TABLE 9 Results of Raveling Test, Current Study

RAP ID	Emulsion Type	EAC (%)	Percent Raveling Loss		
			Sample 1	Sample 2	Average
US- 283	CSS-1h	2.00	2.5	3.3	2.9
US-24	CSS-1h	2.00	1.9	2.7	2.3
US-24	CSS-1h	2.50	0.9	1.8	1.4
OKC-2	CSS-1h	2.50	17.3	18.4	17.9
OKC-2	CSS-1h	3.00	1.7	0.9	1.3
K-42	CSS-1h	2.50	19.8	21.4	20.6
K-42	CSS-1h	3.00	9.4	8.1	8.8
RT-94	CSS-1h	2.00	20.8	21.9	21.4
RT-94	CSS-1h	2.50	19.1	20.1	19.6
RT-94	CSS-1h	3.00	17.9	19.6	18.8
RT-2	CSS-1h	1.50	1.4	2.7	2.1
US-11	CSS-1h	2.50	1.9	2.9	2.4
US-11	CSS-1h	2.00	*	*	

* Sample completely disintegrated

Indirect Tensile Strength

Indirect tensile strength, determined in accordance with AASHTO T 283 (ASTM D4867), is shown in table 10. This average indirect tensile strength was used to check if there is a relationship with fully cured Marshall stability and percent raveling loss.

TABLE 10 Indirect Tensile Strength for Fully Cured Samples

RAP ID	EAC (%)	Emulsion Type	Gyrations	Indirect tensile strength (psi)		
				Sample 1	Sample 2	Average
US -283	CSS-1h	2.00	30	48.6	47.8	48.2
US-24	CSS-1h	2.00	30	41.4	39.7	40.6
US-24	CSS-1h	2.50	30	38.6	39.4	39.0
ENI	CSS-1h	2.00	30	47.4	50.7	49.0
ENI	CSS-1h	2.50	30	46.9	47.5	47.2
ENI	CSS-1h	1.50	30	48.6	51.1	49.8
OKC	CSS-1h	2.50	30	54.0	55.3	54.6
K-42	CSS-1h	2.50	30	46.6	45.8	46.2
K-42	CSS-1h	3.00	30	41.3	43.8	42.5
OKC-2	CSS-1h	2.50	30	49.2	50.3	49.8
OKC-2	CSS-1h	3.00	30	60.1	60.3	60.2
RT-2	CSS-1h	1.50	30	41.1	41.6	41.3
RT-94	CSS-1h	2.00	30	38.2	33.4	35.8
RT-94	CSS-1h	2.50	30	32.2	32.8	32.5
RT-94	CSS-1h	3.00	30	30.3	31.9	31.1
US-11	CSS-1h	2.50	30	34.4	36.1	35.3

Marshall Stability

Samples that were compacted in the SGC and fully cured were tested for Marshall Stability according to AASHTO T 245 (ASTM D6927) and CR 201(1) for two temperature conditions. First condition was specimens that were tested immediately after compaction. Table 11 and table 12 shows immediately tested Marshall stability test results for our previous study (2) and current study, respectively. The second temperature condition is shown in table 13 which is fully cured Marshall stability test at 104±2^{0}F (40 ±1^{0}C) from the previous study. Table 14 shows fully cured Marshall stability test results for the current study.

TABLE 11 Results of Marshall Stability for Samples Tested Immediately, Previous Study (2)

RAP ID	Emulsion Type	EAC (%)	Gyrations	Marshall Stability (lbs) Tested Immediately		
				Sample 1	Sample 2	Average
PER	CSS-1	2.75	20	499.2	644.8	572.0
PER	CSS-1	2.75	30	748.8	790.4	769.6
PER	CSS-1	3.00	20	780.4	758.8	769.6
PER	CSS-1	3.00	30	980.6	849.8	915.2
PER	CSS-1h	2.50	20	780.0	738.4	759.2
PER	CSS-1h	2.50	30	956.8	904.8	930.8
PER	CSS-1h	2.75	20	800.8	759.2	780.0
PER	CSS-1h	2.75	30	1008.8	1029.6	1019.2
OKC	CSS-1h	2.50	20	741.2	675.8	708.5
OKC	CSS-1h	2.50	30	806.6	948.3	877.45
ENI	CSS-1h	1.50	30	1080.0	1154.4	1117.2
ENI	CSS-1h	2.00	30	1268.8	1310.4	1289.6
ENI	CSS-1h	2.50	20	1154.4	1190.0	1172.2
ENI	CSS-1h	2.50	30	1530.0	1530.0	1530.0

TABLE 12 Results of Marshall Stability for Samples Tested Immediately, Current Study

RAP ID	Emulsion Type	EAC (%)	Gyrations	Marshall Stability (lbs) Tested Immediately		
				Sample 1	Sample 2	Average
US 283	CSS-1h	2.00	30	1398.7	1566.5	1482.6
US 24	CSS-1h	2.00	30	1663.4	1588.2	1625.8
US 24	CSS-1h	2.50	30	1702.3	1705.2	1703.8
OKC-2	CSS-1h	2.50	30	1534.4	1406.1	1470.3
OKC-2	CSS-1h	3.00	30	1505.6	1703.2	1604.4
K-42	CSS-1h	2.50	30	1091.2	1206.0	1148.6
K-42	CSS-1h	3.00	30	1184.1	1165.3	1174.7
RT-2	CSS-1h	1.50	30	1207.0	1239.3	1223.2
RT-94	CSS-1h	2.00	30	1033.3	969.6	1001.4
RT-94	CSS-1h	2.50	30	1047.9	973.8	1010.8
RT-94	CSS-1h	3.00	30	1160.3	887.4	1023.8
US-11	CSS-1h	2.50	30	1251.8	1199.5	1225.7

TABLE 13 Results of Marshall Stability for Samples Tested Fully Cured, Previous Study (2)

RAP ID	Emulsion Type	EAC (%)	Gyrations	Marshall Stability (lbs) Tested at 40 °C		
				Sample 1	Sample 2	Average
PER	CSS-1	2.75	20	1487.2	1497.6	1492.4
PER	CSS-1	2.75	30	1705.6	1674.4	1690.0
PER	CSS-1	3.00	20	1632.8	1508.0	1570.4
PER	CSS-1	3.00	30	1705.6	1736.8	1721.2
PER	CSS-1h	2.50	20	1341.6	1289.6	1315.6
PER	CSS-1h	2.50	30	1612.0	1519.2	1601.6
PER	CSS-1h	2.75	20	1320.8	1404.0	1362.4
PER	CSS-1h	2.75	30	1705.6	1580.8	1643.2
OKC	CSS-1h	2.50	20	2049.2	2114.6	2081.9
OKC	CSS-1h	2.50	30	2245.4	2212.7	2229.1
ENI	CSS-1h	1.50	30	1404.0	1383.2	1393.6
ENI	CSS-1h	2.00	30	1480.0	1497.6	1488.8
ENI	CSS-1h	2.50	20	1380.0	1390.0	1385.0
ENI	CSS-1h	2.50	30	1736.8	1747.2	1742.0

TABLE 14 Results of Marshall Stability for Samples Tested Fully Cured, Current Study

RAP ID	Emulsion Type	EAC (%)	Gyrations	Marshall Stability (lbs) Tested at 40 °C		
				Sample 1	Sample 2	Average
US 283	CSS-1h	2.00	30	1115.0	1148.4	1131.7
US 24	CSS-1h	2.00	30	999.6	984.9	992.3
US 24	CSS-1h	2.50	30	1067.4	1105.7	1086.6
OKC-2	CSS-1h	2.50	30	2318.4	2241.0	2279.7
OKC-2	CSS-1h	3.00	30	1837.1	1691.5	1764.3
K-42	CSS-1h	2.50	30	1543.5	1701.7	1622.6
K-42	CSS-1h	3.00	30	1730.2	1529.3	1629.8
RT-2	CSS-1h	1.50	30	1230.7	1190.7	1210.7
RT-94	CSS-1h	2.00	30	1349.6	1309.4	1329.5
RT-94	CSS-1h	2.50	30	1185.4	1400.1	1292.8
RT-94	CSS-1h	3.00	30	1290.0	1274.0	1282.0
US-11	CSS-1h	2.50	30	1183.5	1189.5	1186.5

CHAPTER V

ANALYSIS OF RESULTS

By integrating test results in chapter four and our previous related study, the following analysis was performed. The analysis was performed to find an alternative test that fit into the current mix design procedure by finding a relationship between percent raveling loss and Marshall stability at various curing conditions or indirect tensile strength test. The second objective was to determine if there is a correlation between Marshall stability and indirect tensile strength test results.

The test results from the previous study (2) are indicated using triangular shape data labels on the graph and for the current study rectangle shape data labels are used.

Percent Raveling Loss and Fully Cured Indirect Tensile Strength

The plot of indirect tensile strength for fully cured specimens versus percent raveling loss is shown in Figure 11. The coefficient of determination (R^2) for the linear trend line is 0.08 which indicates there is little relationship between indirect tensile strength and percent raveling loss.

The equation together with the graph on Figure 11 also indicates percent raveling loss and fully cured indirect tensile strength are negatively correlated, indicating that as the indirect tensile strength increases, the raveling loss goes down.

The poor correlation was as expected as indirect tensile strength was performed on fully cured samples and percent raveling loss evaluates breaking and initial cure of the emulsion.

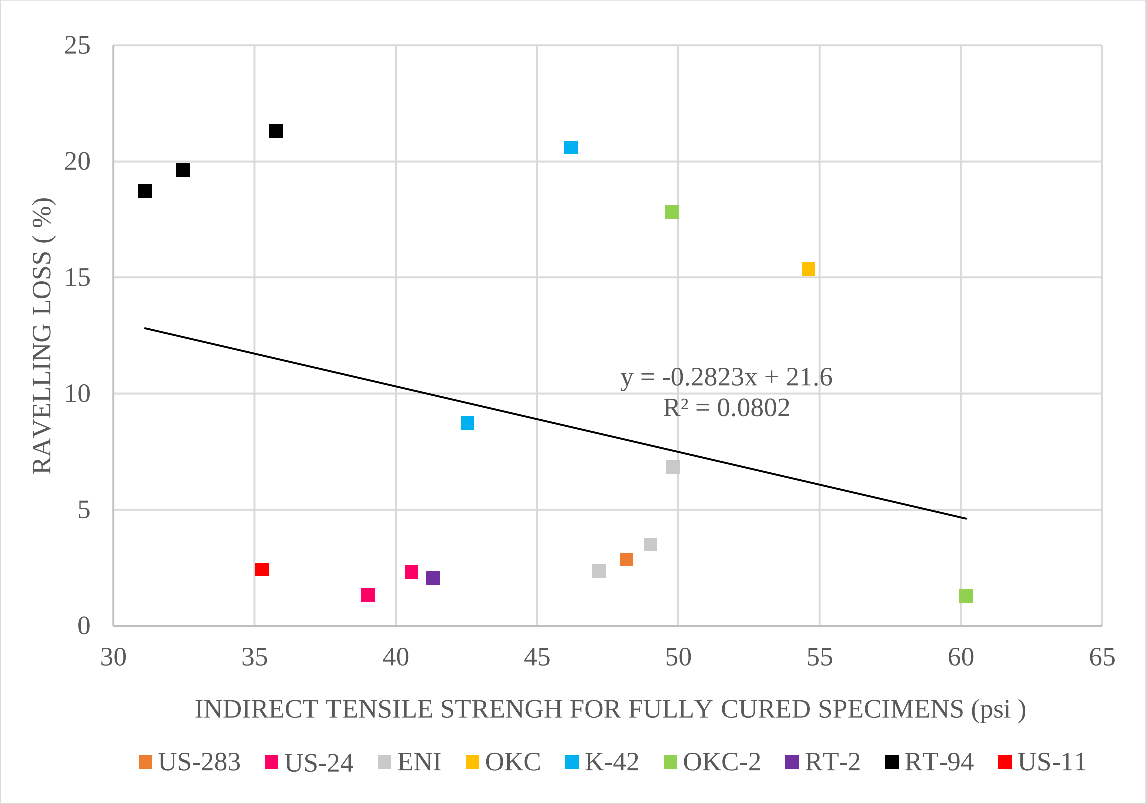

FIGURE 11 Plot of Fully Cured Indirect Tensile Strength vs. Percent Raveling Loss

Percent Raveling Loss and Fully Cured Marshall Stability

The plot of Marshall stability for fully cured specimens versus percent raveling loss from the previous study is shown in figure 12. The coefficient of determination (R^2) value of 0.40 indicated that there was no strong correlation between the data points. The relationship between fully cured Marshall stability and percent raveling loss for the current study is shown in figure 13. Again, the coefficient of determination (R^2) value of 0.22 indicates that there is no good correlation between the test results. For the graph using the combined test results in figure 14, the coefficient of determination (R^2) is 0.14. As with indirect tensile strength, the correlation is poor. The figure shows that as Marshall stability increases, percent raveling loss increases as well. This is opposite of what we would expect and the trend line is highly influenced by the two data points with Marshall stability over 2000 lbs. Fully cured Marshall stability is not an indication of breaking and initial strength of the specimen.

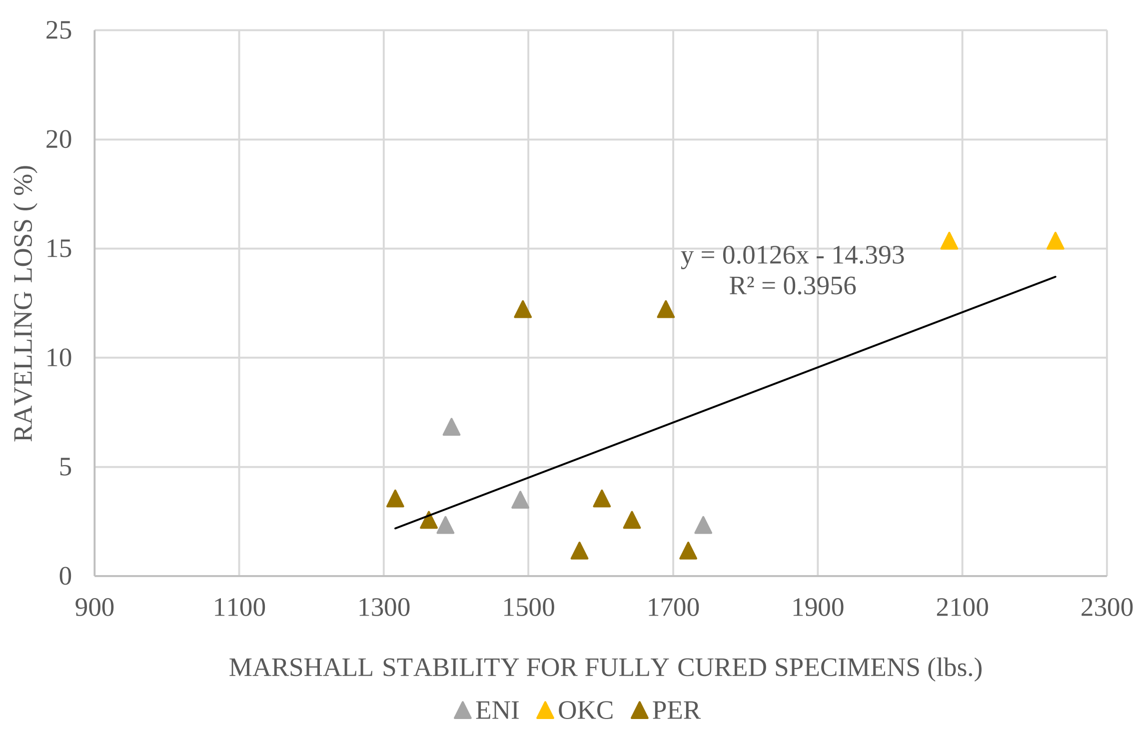

FIGURE 12 Plot of Percent Raveling Loss and Fully Cured Marshall Stability, Previous Study (2)

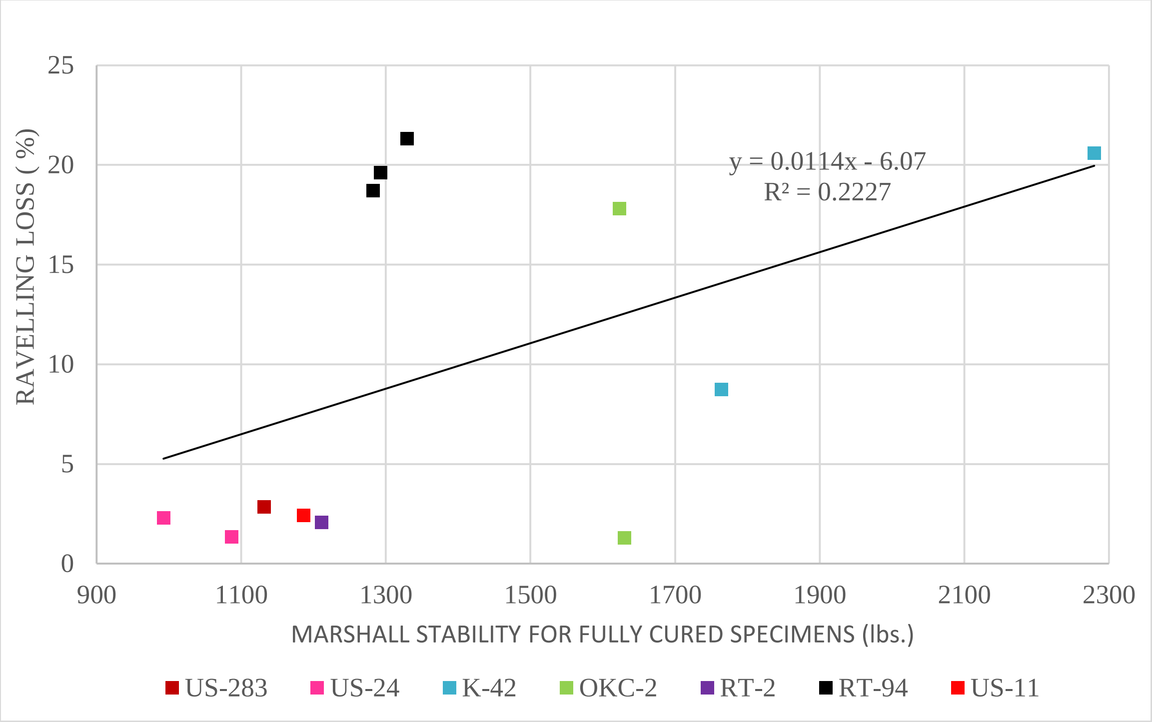

FIGURE 13 Plot of Percent Raveling Loss and Fully Cured Marshall Stability, Current Study

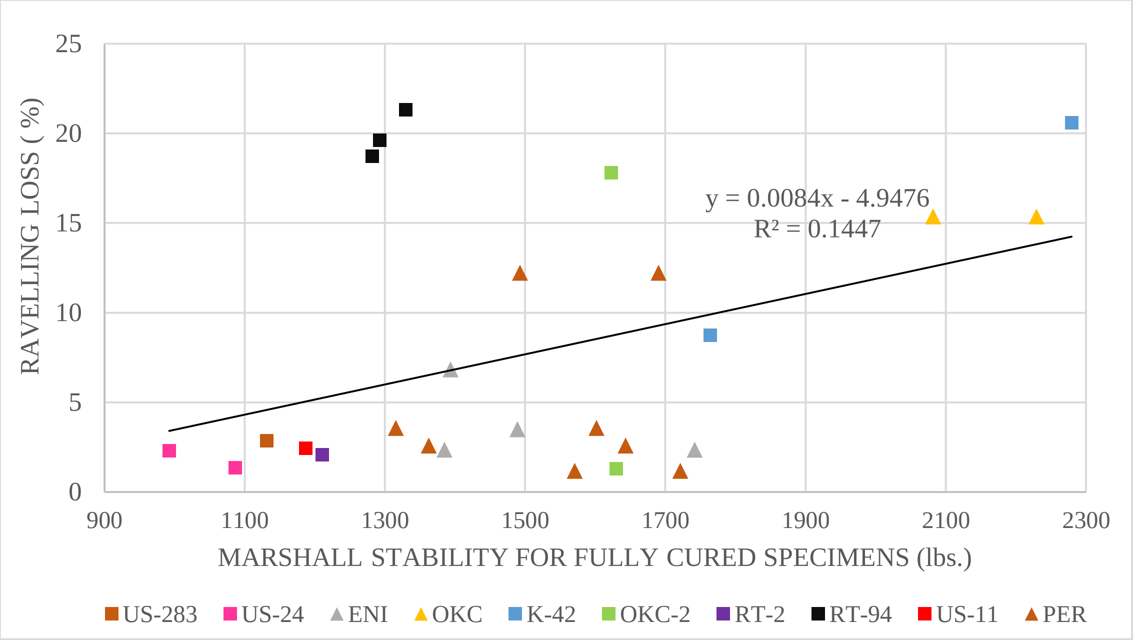

FIGURE 14 Plot of Percent Raveling Loss and Fully Cured Marshall Stability, Combined Data

Percent Raveling Loss and Immediately Tested Marshall Stability

The plot of Marshall stability for immediately tested specimens versus percent raveling loss from the previous study is shown in figure 15. The coefficient of determination (R^2) value of 0.21 indicates that there is no strong correlation between the data points. The relationship between immediately tested Marshall stability and percent raveling loss of the current study is shown in figure 16. Again, the coefficient of determination (R^2) value of 0.29 indicates that there is no good correlation between the test results. For the graph using the combined test results in figure 17, coefficient of determination (R^2) is 0.05. It shows that the correlation is poor.

Due to work in the Engineering Annex, the Asphalt Lab occasionally experienced large swings in room temperature and the inability to control room temperature may have adversely affected results of the immediately tested Marshall stability samples. Marshall stability test results for specimens tested immediately from the current study are greater than previous study test results. This may have been due to temperature variation since Marshall stability tests were conducted at different times of the year.

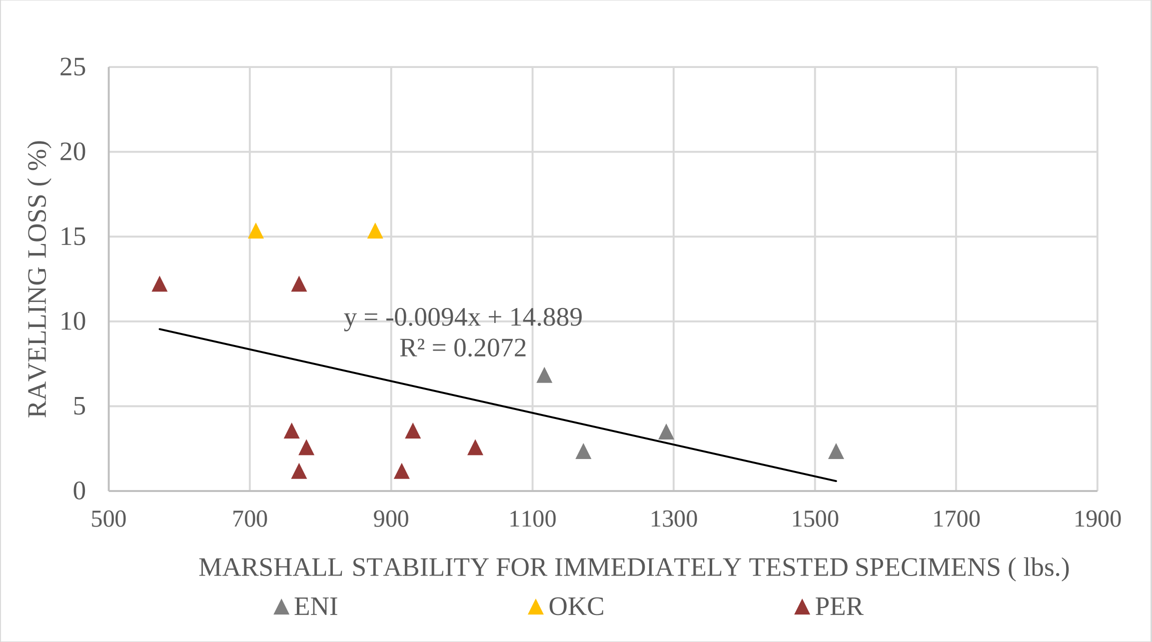

FIGURE 15 Plot of Immediately Tested Marshall Stability and Percent Raveling Loss, Previous Study (2)

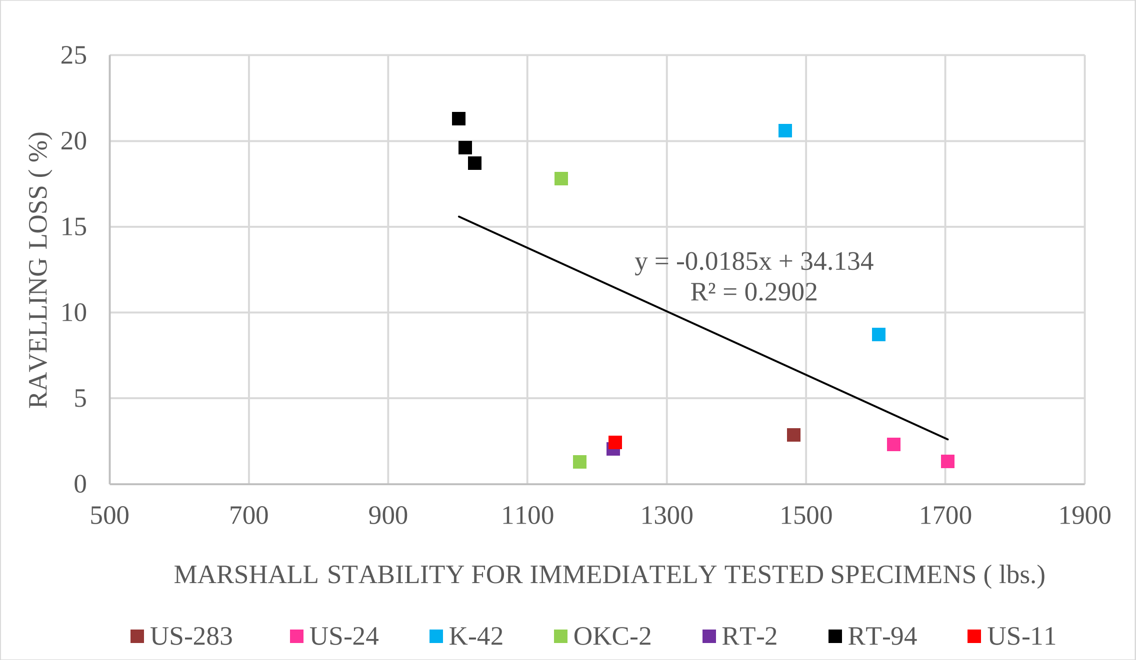

FIGURE 16 Plot of Immediately Tested Marshall Stability and Percent Raveling Loss, Current Study

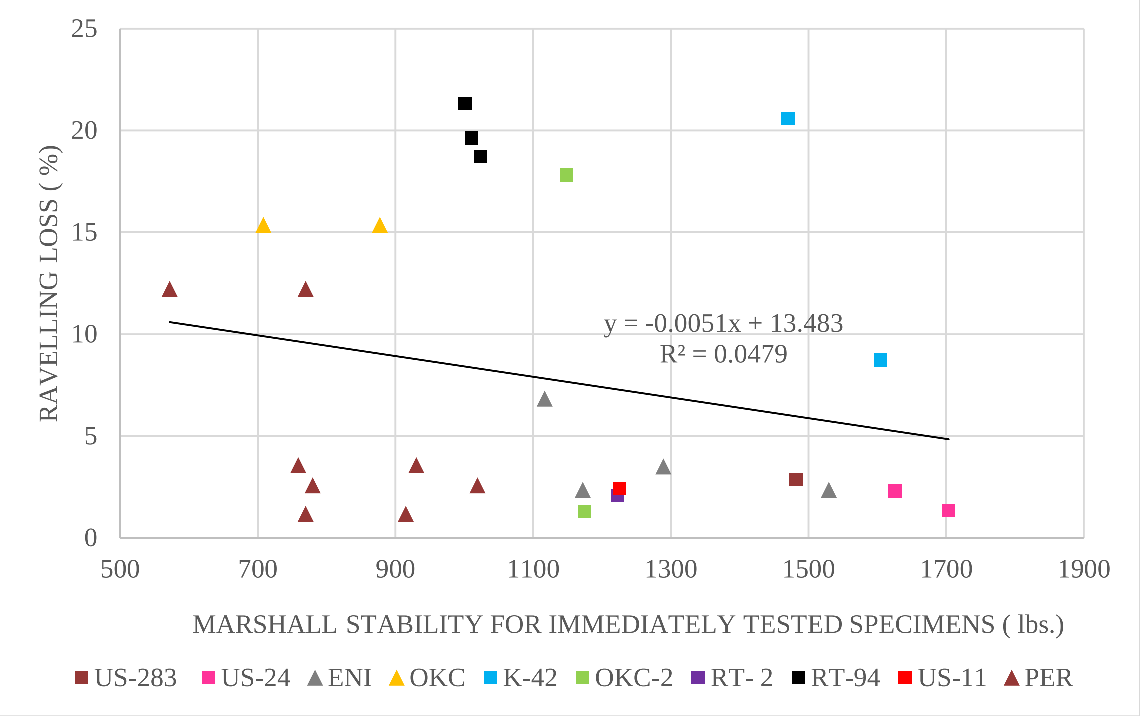

FIGURE 17 Plot of Immediately Tested Marshall Stability and Percent Raveling Loss, Combined Data

Percent Retained Marshall Stability

The plot of percent retained Marshall stability for fully cured specimens with respect to immediately tested specimens versus percent raveling loss from the previous study is shown in figure 18. The coefficient of determination (R^2) value of 0.39 indicated that there was no strong correlation between the data points. The relationship between percent retained Marshall stability for fully cured specimens with respect to immediately tested specimens versus percent raveling loss of the current study is shown in figure 19. Again, the coefficient of determination (R^2) value of 0.49 indicates that there is no good correlation between the test results. For the graph using the combined test results in figure 20, coefficient of determination (R^2) is 0.12. It shows that the correlation is poor.

Due to work in the Engineering Annex, the Asphalt Lab occasionally experience large swings in room temperature and the inability to control temperature may have adversely affected results of the immediately tested Marshall stability samples. Percent retained Marshall stability test results of the current study is greater than previous study test results. This may have been due to temperature variation since Marshall stability for immediately tested specimens is highly affected by temperature.

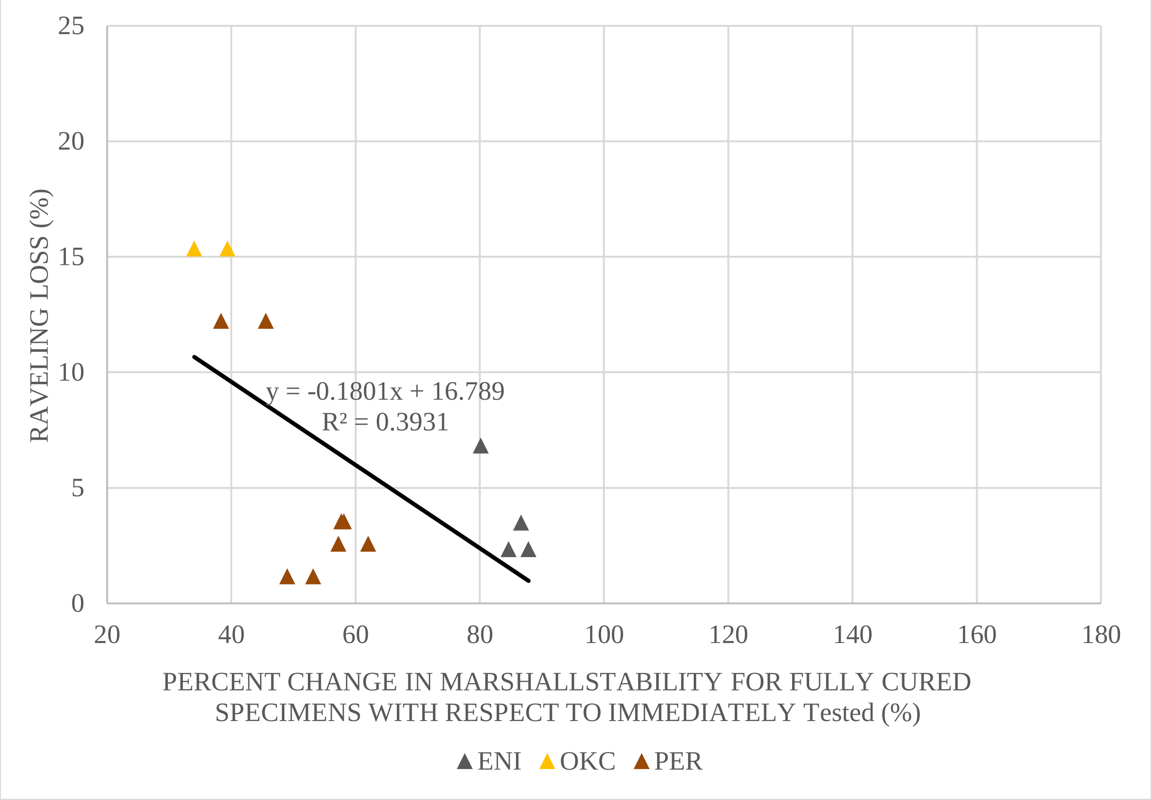

FIGURE 18 Plot of Percent Retained Marshall Stability and Percent Raveling Loss, Previous Study (2)

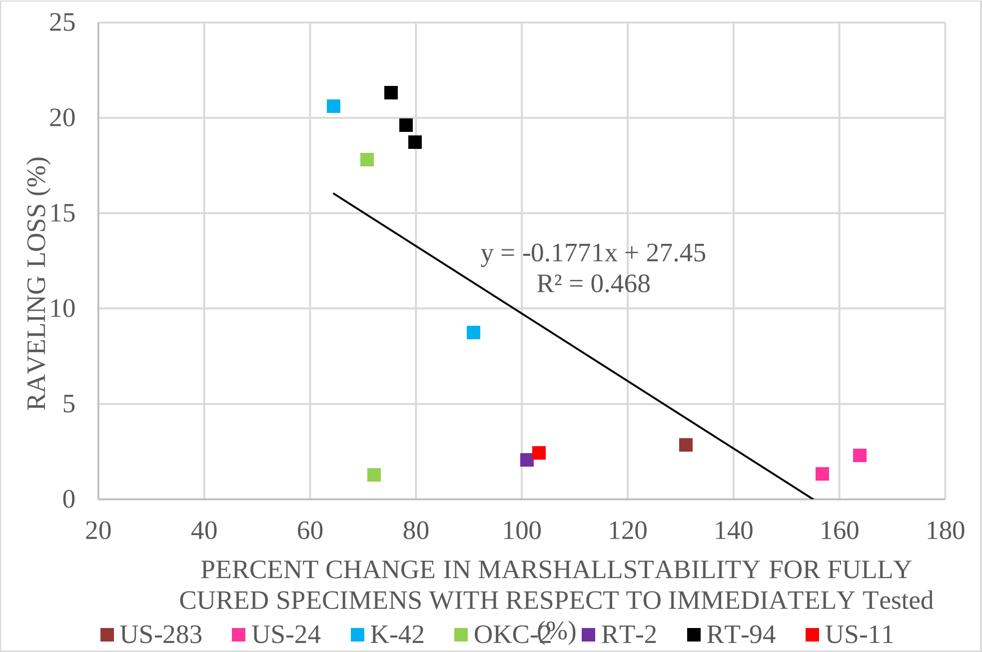

FIGURE 19 Plot of Percent Retained Marshall Stability and Percent Raveling Loss, Current Study

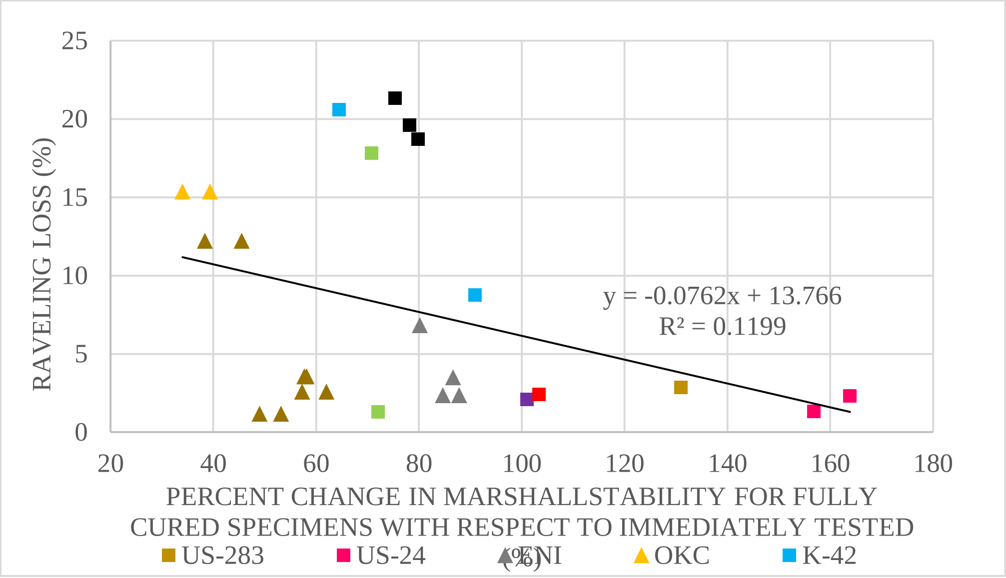

FIGURE 20 Plot of Percent Retained Marshall Stability and Percent Raveling Loss, Combined Data

Threshold Analysis

ARRA's CR201 (1) recommends a maximum of 7 % loss for the raveling test. Due to the poor coefficient of determination a threshold analysis was performed. The threshold point between percent retained Marshall stability for fully cured specimens with respect to immediately tested specimens and percent raveling loss for the previous study is shown in figure 21. Approximately 50 % retained Marshall stability is a pass/fail threshold for the raveling test. Four of five samples with less than 50 % retained Marshall stability failed the raveling test of greater than 7 % mass loss and nine of nine samples with greater than 50 % retained Marshall stability passed the raveling test.

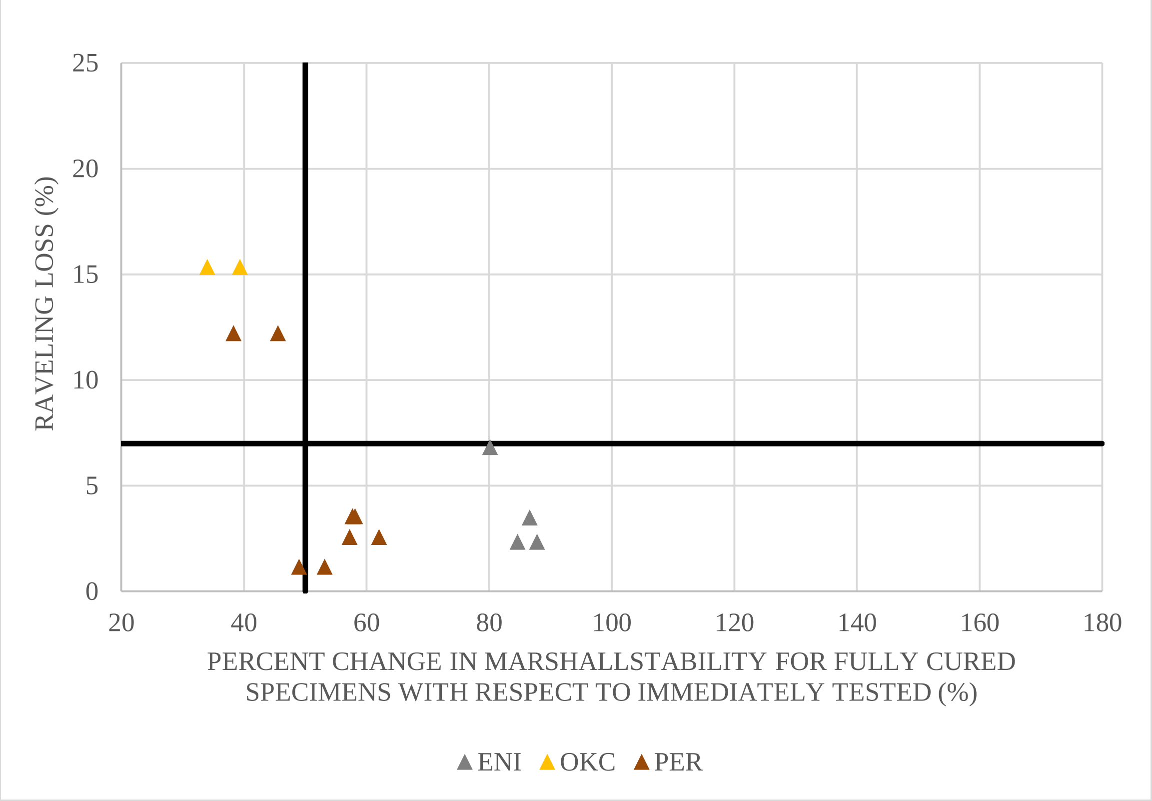

FIGURE 21 Threshold Analysis between Percent Raveling Loss and Percent Retained Marshall Stability, Previous Study (2)

Figure 22 shows the threshold point between percent retained Marshall stability for fully cured specimens with respect to immediately tested specimens and percent raveling loss for the current study using 50% threshold point to verify the results of the previous study. However, this threshold point was not verified since all of the samples lie above 50% retained Marshall stability. Hence, for the current study a different threshold point was observed at 85 % retained Marshall stability. Figure 23 shows that five of six samples below 85% retained Marshall stability failed the raveling test whereas five of six samples above 85% retained Marshall stability passed the raveling test.

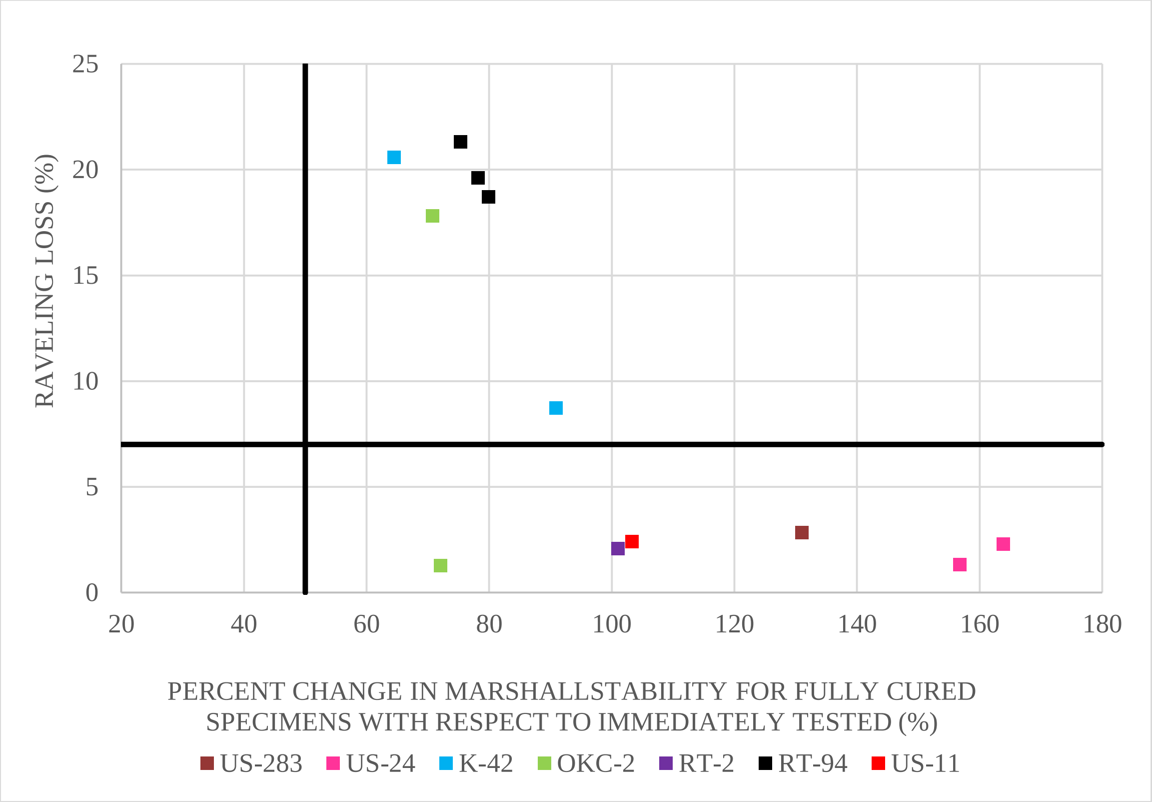

FIGURE 22 Threshold Analysis between Percent Raveling Loss and Percent Retained Marshall Stability Using Previous Study Test Results, Current Study

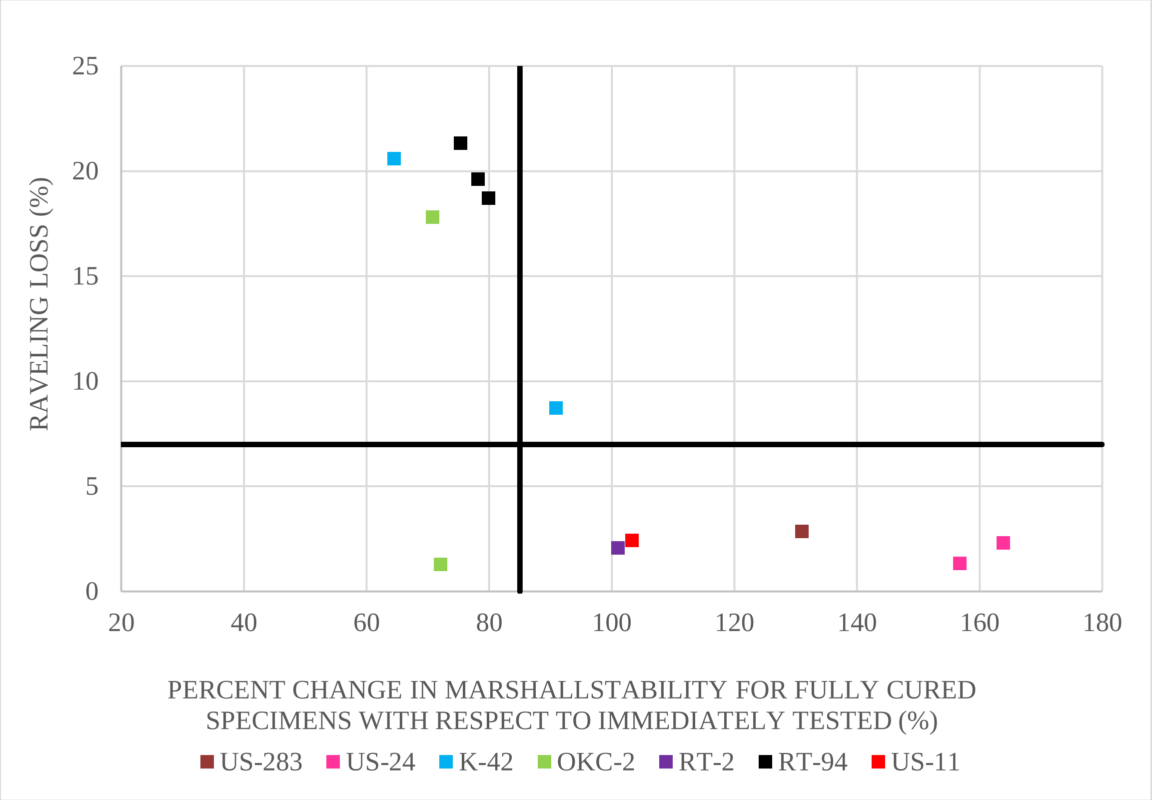

FIGURE 23 Threshold Analysis between Percent Raveling Loss and Percent Retained Marshall Stability, Current Study

The threshold point between percent retained Marshall stability for fully cured specimens with respect to immediately tested specimens and percent raveling loss for the combined test results of the two studies is shown in figure 24. A threshold point observed at 50 % retained Marshall stability for the previous study is shown by a solid line in figure 24. Figure 24 also shows a threshold point observed at 85% percent retained Marshall stability for the current study using a broken line. A threshold value could not be determined for the combined data and it is believed that this could be due to the difference in room temperature in Asphalt lab during the year.

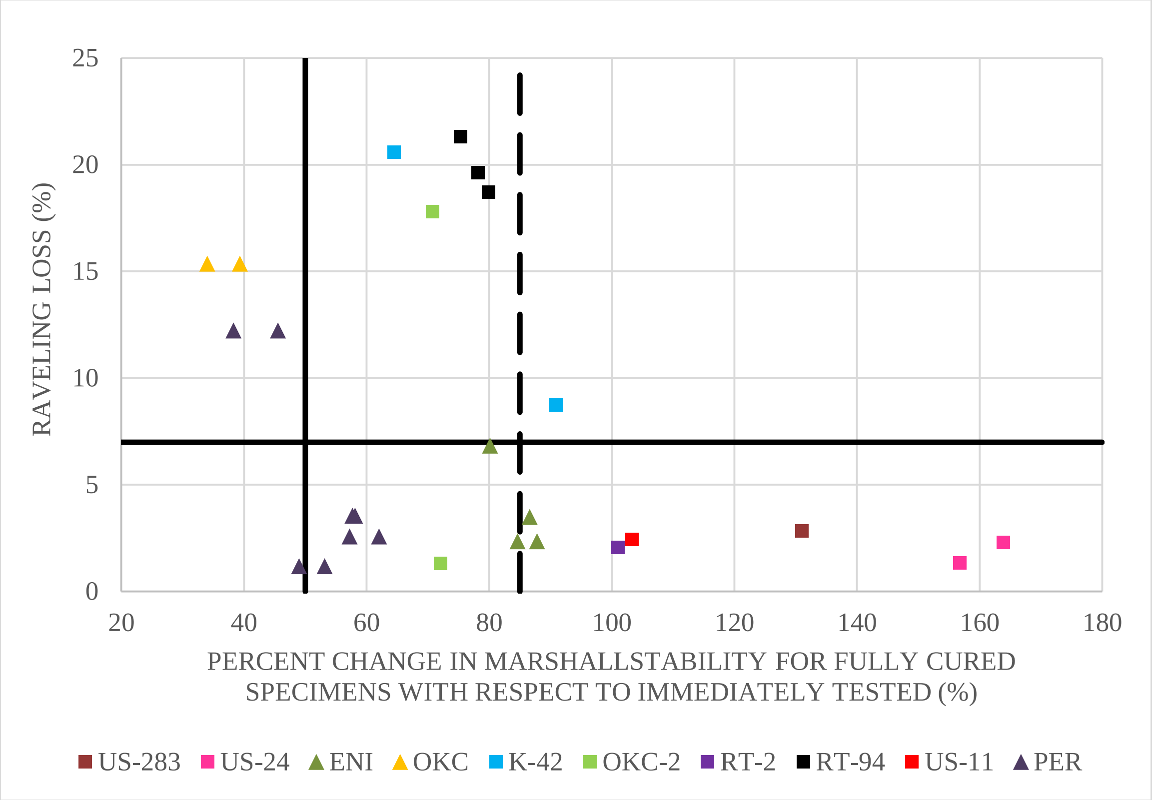

FIGURE 24 Threshold Analysis between Percent Raveling Loss and Percent Retained Marshall Stability, Combined Data

Indirect Tensile Strength and Marshall Stability

The plots of Marshall Stability for fully cured specimens and indirect tensile strength is shown in figure 25. The coefficient of determination (R^2) for the linear trend line is 0.28, indicating fully cured indirect tensile strength test did not correlate well with percent raveling loss. However, using the trend line shown in figure 25 the CR 201 (1) mix design requirement for Marshall stability of 1250 lbs equates with 41.3 psi of indirect tensile strength. This CR 201 (1) mix design requirement of 45 psi for indirect tensile strength is approximate to 1250 lbs of Marshall stability mix design requirement.

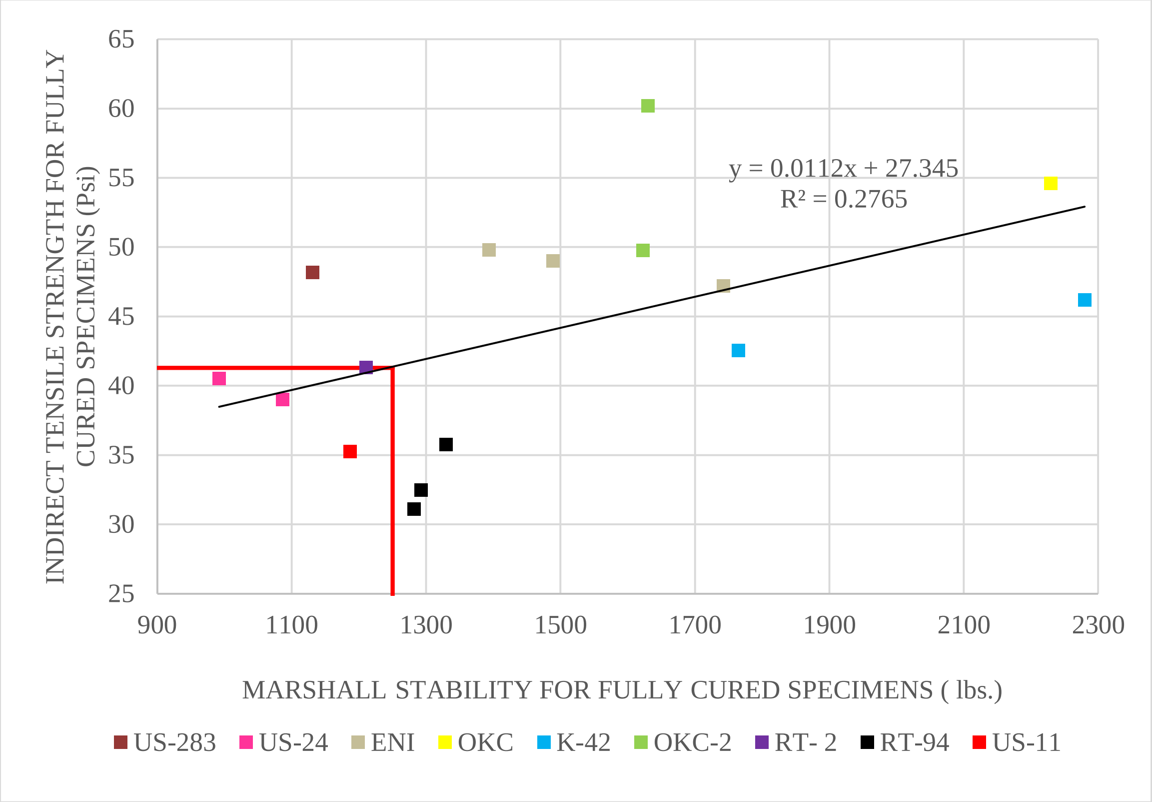

FIGURE 25 Plot of Marshall Stability and Indirect Tensile Strength

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following conclusions were obtained based on the limited test results of this study:

- With the exception of K-42 tested at 3% EAC which resulted in 8.7% percent raveling loss, the raveling test results ranged between 1 - 4% and 12 - 22%. The CR 201 specification limit of a maximum of 7 % mass loss seems reasonable.
- Fully cured indirect tensile strength did not correlate with percent raveling loss.
- Fully cured and immediately tested Marshall stability did not correlate with percent raveling loss.
- Percent retained Marshall stability did not correlate with percent raveling loss.
- The threshold value of 50% retained Marshall stability from the previous study did not separate passing and failing raveling test results for this study.
- For the current study a threshold value of 85% retained Marshall stability separated passing and failing raveling test results. The difference from the previous study could be attributed to difference in room temperature in the Asphalt Lab for the two studies.
- Marshall stability of 1250 lbs correlated with 41.3 psi indirect tensile strength.

- The relationship between indirect tensile strength and Marshall stability is not strong but the CR 201 mix design requirement of 45 psi for indirect tensile strength is a reasonable approximation of 1250 lbs.

Recommendations

Based on the test results and test analysis of this study, the following recommendations are derived:

- At this time, it’s not recommended to replace the raveling test in CR 201 mix design with retained Marshall stability for cured and immediately tested samples.
- If retained Marshall stability is used, the procedure will need additional verification with a temperature tolerance for the samples tested immediately at room temperature.
- CR 201 mix design requirement of 45 psi for indirect tensile strength can be used as equivalent to 1250 lbs Marshall stability.

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