EVALUATION OF TEST PROCEDURES FOR THE RAVELING TEST IN COLD RECYCLING MIX DESIGNS

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INTRODUCTION

PROBLEM STATEMENT

Cold In-Place Recycling (CIR) method is one of the forms of asphalt pavement recycling which is environmental friendly and cost effective. With CIR a milling machine removes the asphalt pavement to a depth of 3 to 5 inches. The reclaimed asphalt pavement (RAP) is then sized and mixed with a bituminous recycling agent. Bituminous recycling agents consist of either emulsified asphalts or foamed (expanded) asphalt. The treated RAP is then placed and compacted using conventional asphalt paving equipment. The CIR process recycles 100 percent of the RAP in place without the application of heat.

Currently there are no nationally accepted mix design methods for CIR mixtures. The CIR mix design procedures adopted by most state highway agencies originated from mix design procedures developed by equipment and materials suppliers. Most agencies follow the mix design procedures developed by Wirtgen (1) for CIR with foamed asphalt. Most CIR mix designs using emulsified asphalt are based on procedures developed by Road Science and their predecessors. . As per ARRA (2), CIR mix designs with emulsified asphalt consist of evaluating the strength of the recycled mixture using Marshall stability or indirect tensile strength, retained Marshall stability or tensile strength ratio to evaluate resistance to moisture induced damage, and the Raveling test (ASTM D7196) is performed to evaluate

the emulsified asphalt's breaking and curing properties and the mixtures resistance to raveling under initial traffic. Road Science and their predecessors hold a patent on the mix design process and the use of raveling test in combination with other tests. The patents have not been uniformly enforced over the years causing uncertainty about the use of the Raveling test as a part of CIR mix designs, resulting in reluctance on the part of some agencies to use CIR with emulsified asphalts.

OBJECTIVE

The objective of the study is to determine if there is an alternative test for the raveling test that would easily fit into the current mix design procedures. The objective of the study would be met by evaluating the performance of CIR mixtures made with emulsified asphalt by comparing Marshall stability and unconfined compressive strength tests performed at various curing conditions and comparing the results to the Raveling test.

SCOPE

RAP samples are collected from three different sources. All mixtures were made with CSS-1 and CSS-1h emulsified asphalt. To find an alternative for raveling test, samples were made and tested for percent raveling loss in accordance with ASTM D7196, Marshall stability in accordance with AASHTO T 245 (ASTM D6927) and unconfined compressive strength in accordance with AASHTO T167. For Marshall stability and unconfined compressive strength tests samples were tested after being fully cured, moist cured and tested immediately without curing.

CHAPTER II

LITERATURE REVIEW

ASPHALT RECYCLING

Population growth and development over the years has led to increase in road networks, particularly asphalt paved roads to meet the demands of growing traffic. However, the availability of funds did not keep up with the expansion of road networks and almost no attention was paid to pavement maintenance. Over the years as traffic volume expanded and the cost of pavement construction increased, the demand for preservation and maintenance of existing roads increased (1).

Moreover, in the past few decades, there has been an exponential increase in the usage of roadways. Considering this demand, along with the available funds and the obligation to provide safe journey, there has been an increase in maintenance, thus leading to substantial increase in the need for rehabilitation of the existing pavements. Considering the funds available for maintenance, preservation, rehabilitation and reconstruction, innovative techniques were needed to achieve more from less. This desire has led to considerable growth in asphalt recycling (1).

Asphalt recycling has gained popularity in the past few decades. It is a way of improving the life span of existing roadways. The petroleum crisis in 1970's and the development of cold planing equipment gave birth to asphalt recycling of the existing roads. The concept

of asphalt recycling dates back to 1900's, however, only moderate improvements in asphalt recycling occurred until mid-1970. Society has been aware of the effects of the materials used on the roads on the environment. Asphalt recycling meets the goals of society drastically reducing the environmental impact and energy consumption, thus providing a safe and effective road ways to the expanding traffic (1).

Asphalt recycling has been broadly classified into five categories by Asphalt Recycling and Reclaiming Association (ARRA). They are (1, 3)

1. Cold Planing (CP)
2. Hot Recycling
3. Hot In Place Recycling (HIR)
4. Full Depth Reclamation (FDR)
5. Cold Recycling (CR)

Cold Planing (CP)

According to ARRA (1) Cold planing is defined as the controlled removal of an existing pavement to a desired depth, longitudinal profile and cross slope, using specially designed equipment. The textured surface can also be used as driving surface with the other asphalt recycling methods. Moreover, CP is used to eliminate slipperiness. Some advantages of CP are restoring drainage, correction of longitudinal profile and cross slope, energy conservation compared to other methods and highly productive with less disruption (1).

Hot Recycling

In order to produce a recycled mix, Reclaimed Asphalt Pavement (RAP) is combined with new asphalt binder, virgin aggregates and recycling agents (as required) in a central plant. This process is called as Hot Recycling and uses the heat transfer method to soften the RAP so that it can be mixed with other materials. Hot Recycling is the most common method for asphalt recycling and uses specially designed batch or drum mix plants. There are many advantages of this process with some of them being the elimination of disposal problems, non-renewable resources conservation and maintenance of curb reveal height with overhead clearance.

Hot In-place Recycling (HIR)

The process of heating and softening of existing pavement by allowing it to be hot milled or scarified to a specific depth is called Hot In-place Recycling. Then, the loosened asphalt is mixed and compacted with conventional HMA paving equipment. The complete recycling (100%) of the existing pavement is completed by the HIR on site. ARRA recognizes three basic HIR process, they are repaving, surface recycling and remixing (4). Major advantages of HIR include treatment of complete roadway width and rutting, elimination of potholes along with minor surface cracking, non-renewable resource conservation and ride quality improvement (1). Figure 1 shows a Hot In-Place Recycling unit.

FIGURE 1 Hot in-place recycling unit

Full Depth Reclamation (FDR)

FDR is the rehabilitation technique in which the full thickness of the asphalt pavement and a predetermined portion of the underlying materials is uniformly pulverized and blended to provide an upgraded, homogenous base material. FDR consists of a series of steps that include pulverization/reclamation of the existing materials, adding more materials, mixing, and initial shaping of the resultant mix, final shaping, compaction, and application of a bituminous surface or wearing course (1)**.** The depth of FDR depends on the existing pavement thickness, subgrade soil conditions and expected future traffic but typically it is from 150 to 300 mm (6 to 12 in) (5). The equipment used for this process are motor grader, stabilizing additive unit, rollers and reclaimer unit. Major advantages of FDR include eliminations of bumps, potholes, patches, cracks and dips, deteriorated base reshape, energy and non-renewable resources conservation and subgrade deficiency correction. Figure 2 shows a Hot In-Place Recycling unit.

FIGURE 2 Full depth reclamation unit

Cold Recycling (CR)

According to ARRA (1) Cold Recycling (CR) is defined as a rehabilitation technique that corrects pavement defects by utilizing existing pavement materials without application of heat during the recycling process. Based on the process used Cold Recycling is classified into two sub–categories, they are Cold Central Plant Recycling (CCPR) and Cold In–place Recycling (CIR).

Cold Central Plant Recycling (CCPR)

Cold Central Plant Recycling is a process in which recycling of asphalt takes place in a central location using a stationary cold mix plant or portable cold mix plant. In CCPR, RAP is screened, crushed, sized and mixed with an asphalt recycling agent. The recycled material can be used immediately or stockpiled for later use (1). Figure 3 shows a CCPR unit.

FIGURE 3 Cold central plant recycling

Cold In-place Recycling (CIR)

Cold In-place recycling is an asphalt pavement rehabilitation method in which water, recycling agent and existing pavement materials are mixed in place without application of heat. As per ARRA (1), Cold In-place Recycling is defined as a partial depth recycling process involving 2 to 5 inches of the existing pavement. CIR can be used to remove

thermal and reflective cracks, maintain clearance, improve poor aggregate gradations, minimize the need for new material, smooth, improved surface. It can also be used to eliminate transverse and longitudinal cracks (6, 7, 8).

In the CIR process, the existing pavement is milled or pulverized, crushed, screened and mixed with recycling agent. Virgin aggregate or recycling agent or both can be added to the RAP material which is then laid and compacted (3, 9). Water is added during various points in the process. For dust control 1 to 2 percent of water is added at the milling head. Additional 1 to 2 percent of water may be added at the pug mill to help the mixing and coating process (9). Figure 4 shows a CIR equipment train.

FIGURE 4 Cold In-Place Recycling equipment

CIR TRAIN CONFIGURATIONS

Single Unit Train

Single unit trains are of different varieties. Generally it contains cutting head which mills the pavement to the required depth and cross slope, sizes the RAP and blends the material with recycling agent. Desired gradation of the RAP can be achieved by the operating direction of the cutting head, forward speed of train and by use of pressure and breaker bars in the mixing chamber (3). Blending of recycling agent is done by a spray bar in the mixing chamber. Recycling agent is added based on the treatment width, length and moving speed of the train. Unit weight and volume may vary along the length of roadway resulting in small variations in the application rate of recycling agent.

The recycled mixture is placed by screed attached to the back unit or conveyed to a windrow for pickup by an asphalt paver. Figure 5 depicts the working of a single unit train.

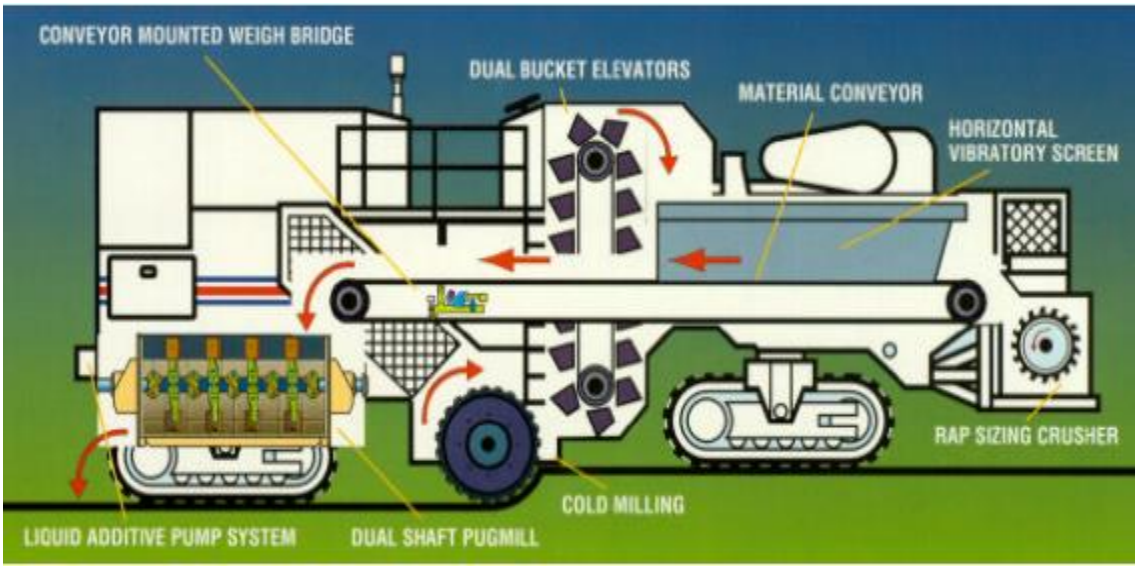

FIGURE 5 A schematic of a single unit recycling train (10)

Advantages of single unit train are shorter length (70 feet compared to 150 feet of multiple unit CIR) and higher mobility. Hence it could be used in areas where roads are having a low turning radius. Disadvantages are limited control of RAP, limitation on precise material proportioning and limitation on grade control.

Two Unit Train

Two unit train consists of a large full lane of cold planer and mix paver. A Cold planer is used for crushing and screening of RAP, after which the RAP is directed to mix paver. Mix pavers may equipped with scalping screens to remove oversize materials. Mix pavers contain pug mill that mixes the material and a screed for placement of material. The application rate of recycling agent can be accurately controlled by a mix paver having feed belt with belt scale along with a processing computer.

Recycling agent is added based on the RAP size, independent of treatment width, length and forward speed of the train. The two unit train provides an intermediate to high degree of process control since treatment volume and recycling agent application rates are directly linked, but additional crushing or sizing of RAP are not required (1). Advantages of two unit train higher process of control and higher mobility. Disadvantages are limited control of RAP size and grade control.

Multi-Unit Train

Multi-unit CIR trains consists of various trailer mounted units. It comes with a cold planer to remove RAP, a screening unit to resize the size of RAP and a pug mill to add and mix the recycling agent. The mixture from the pug mill is directly deposited into a paver hopper or a windrow and placed with an asphalt paver with a windrow elevator. Sizing of RAP is

controlled by the screens in the screening unit. Over size material is sent back to the crusher and then again passed over the screens. The desired gradation of RAP proceeds to the pug mill through belt scale on a conveyor. The Amount of recycling agent adding in the plug mill is determined by the metering system using the unit weight of material on the belt scale. When the material is not mixing in the chamber, recycling agent liquid pumping by the motor is shut off by positive interlock system. The total delivery and rate of flow of the liquid recycling that is introduced into the mixture is registered by the meter which is connected to the pump. Material from the plug mill is deposited into paver hopper or windrow elevator and placed in the paver.

The main advantages of multi-unit trains are desired gradation of material achieved by the computerized metering system, guaranteed maximum RAP size and a greater ability to adjust the fluctuations in grade. The major disadvantages are the length of the train resulting in less mobility than shorter trains. Figure 6 depicts the working of a single unit train.

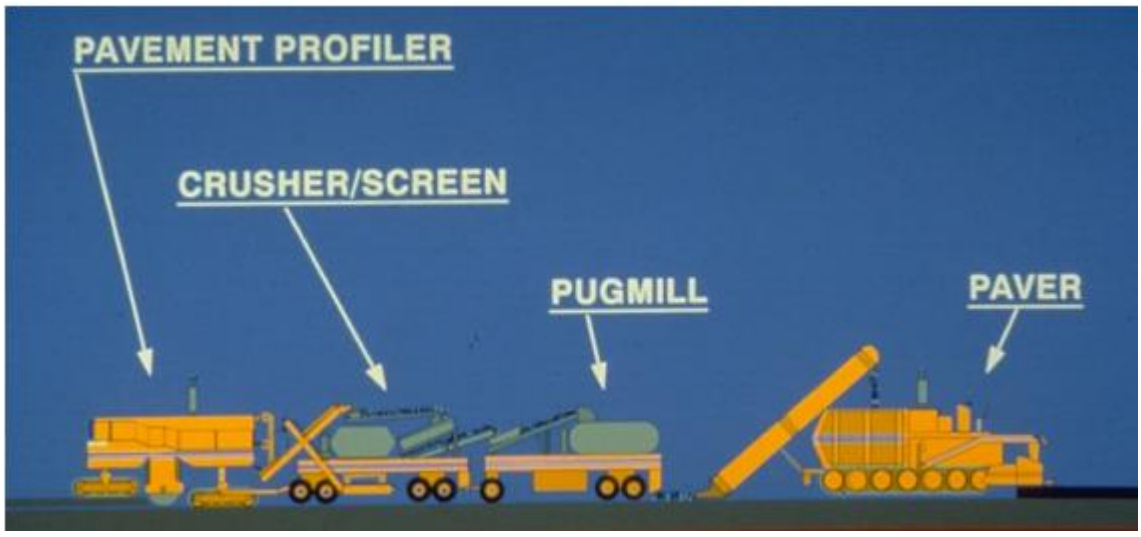

FIGURE 6 A schematic of a multi-unit recycling train (10)

RECYCLING AGENTS FOR CR

The dispersion of small droplets of liquid into another liquid is called an Emulsion. Depending on their charge and reactivity, emulsions are classified into different categories. The droplets which carry a positive charge are Cationic emulsions and those which carry a negative charge are anionic emulsions. Rapid-setting (RS) emulsions are more reactive and set quickly in contact with clean aggregates of low surface area. Medium-setting (MS) emulsions set less quickly and they can be mixed with aggregates of low surface area. Slow-setting (SS) emulsions are non-reactive and used with reactive aggregates of high surface area (11).

For the proper performance of CR projects, it is always necessary to make the right selection of the grade and type of the recycling agent. The designer selects the appropriate amount of recycling agent with the help of mix design. However, multiple recycling agents are available for CR use and also design requirements are met by more than one type of recycling agent. Most commonly used recycling agents are Emulsified Asphalt and foamed asphalt.

Emulsified Asphalt

Emulsified asphalt is one of the type of bituminous recycling agent used for CR. The type of recycling agent and application rate is determined by a mix design. For CIR, the emulsified recycling agent should be formulated to match the in place mixing and placement times, environmental conditions and should allow sufficient early strength to allow the roadway traffic by the end of the day. For CCPR it requires different conditions depends on haul time or whether they are stockpiled for later use.

Asphalt Binder for Foamed Asphalt

Foamed asphalt is a mixture of air, water and hot asphalt. Foamed asphalt occurs when cold water comes in contact with hot asphalt resulting in expansion of asphalt binder into millions of bubbles. The asphalt binder provide at the job site should not have any additives or properties that inhibit the ability to produce foamed asphalt that meets the minimum expansion and half-life criteria and also they should be capable enough to be selected to ensure optimum foaming characteristics that are met in the field. The expansion ratio is defined as the volume of foamed asphalt to residual unfoamed asphalt and the half-time is defined as the time for the foamed asphalt to lose half of its expanded volume. Typically to achieve optimum foaming characteristics asphalt binder must exceed temperature of 320 °F and this temperature may vary depending on the type of asphalt binder used, but the asphalt binder should not be heated above 375 °F. The typical minimum expansion ratio is 8 and half time is about 6 seconds.

To maintain the required expansion rate and halftime of the foamed asphalt it should be equipped with a heating system capable of maintaining the temperature of asphalt flow. The binder injection system should contain two independent pumping systems and spray bars to regulate the water used to increase the moisture content for compaction and also the foamed asphalt system should be computer controlled, the rate of addition of water into the hot asphalt binder should be automatically kept at a constant percent by mass of asphalt binder. An inspection or test nozzle should be fitted at one end of the spray bar to produce a representative sample of foamed asphalt binder.

ADDITION OF RECYCLING ADDITIVES

Recycling additives (new aggregates, cement or lime) may be added to improve CR mixture properties as determined by the mix design.

Additive Addition in CIR

In CIR, recycling additive cement can be added in a dry or slurry form. Dry recycling additives are applied by spreading the material on the pavement ahead of the milling operations. One pass of the train is sufficient to mix all the materials. Slurry may be added directly to the mixing chamber or most commonly it is sprayed over the cutting teeth of the cold planer.

A mechanical spreader is used for dry spreading of cement which is capable of spreading the additives at the specified weight per unit area and it should also have working scales and distance measuring devices to control the spread rate. If cement is spread ahead of the milling operation the distance between the spreader and the recycling train should be reduced approximately during windy days. To minimize the fugitive dust there should be dust control measures employed. When wind forces are such that the cement has potential to become airborne, pre wetting of the road way prior to spreading and, if necessary, lightly wetting of the top of the spread cement should be considered. There should be enough care to be taken so that the force of water spraying the top of the cement is not great enough to cause dust. No traffic other than the recycling equipment should pass over the spread cement.

CIR CONSTRUCTION PROCESS

The construction process involved in CIR consists of the following steps

Preparation of Construction Area

Areas of non-uniform materials or pavement thickness should be identified. Excess dirt, mud, vegetation, standing water, combustible materials, oils and other objectionable materials should be removed from the road way by sweeping, blading or other approved method.

Milling the Existing Pavement

The second step would be to cold mill or pulverize the existing. The optimum depths of CR lie between the ranges of 2 to 5 inches. The depths greater than 4 inch are reported to decrease the operating speed produce an oversize RAP

Crushing and Screening of RAP Material

The RAP material is typically crushed to a level of 100 percent passing the 1.5 to 2.0 inch sieve. Several agencies suggested that the RAP top size has to be less than half of the depth of the final recycle layer (1, 9).

Addition of Recycling Agent and Additives

New recycling agent and additives, if desired, are added to the RAP material which is then mixed in the cutting chamber of a train unit or in the pug mill of multiple unit trains.

Lay down and Compaction

Once pulverizing and mixing is complete the RAP is either deposited in a windrow on the road surface and placed with a paver or deposited directly into the paver

Compaction is a one or two stage operation. Initial or break down rolling can be accomplished by a pneumatic or vibratory steel wheel rollers, or combination of both. This is followed by intermediate rolling with a double drum vibratory steel wheeled rollers. Second stage compaction requires 3 to 7 days following laydown. The secondary compaction can be accomplished by using a steel wheel or pneumatic roller (1).

Curing and Surfacing

Compacted CR mixtures must cure before a wearing course is placed. The total moisture content of the RAP may consists of water added to mix, water added to the cutting/milling head and the in place moisture of existing pavement. There is a possibility of premature failure of CIR mix or wearing surface mix if the surface is sealed prior to adequate loss of moisture premature. Rate of curing depends on several factors, including temperature and humidity levels (1).

MIX DESIGN

A cold recycling mix design is a laboratory procedure which helps in assuring the performance characteristics required for long term service life of recycled pavement. Though a mix design is recommended adjustments may be required in the field to the recycling agent content to obtain optimum performance. The design of cold recycling

asphalt pavement has resulted in the proposal of two theories which are briefly described as below

1. The milling is treated as a black aggregate along with some of the hardened asphalt coating. Also, in order to coat the milled particles, the asphalt content is designed. The main assumption in this case is that the milling will act as an aggregate.

2. The physical and chemical characteristics of asphalt are evaluated in the old pavement. The asphalt is restored to its original condition by adding a softening agent or recycling rejuvenating agent. The main assumption in this case is that a new asphalt is created and also 100% softening is attained.

A conclusion that the combination of two theories have resulted into a third theory referred as effective asphalt theory which is shown as,

Effective asphalt = % emulsion + % of softened asphalt

On the basis of effective asphalt theory, the asphalt content in the mixture which is known as effective asphalt is produced when the added emulsion is added to a percentage of the softened old asphalt. The softness to old asphalt, the percentage of asphalt in the old mix and the recycled asphalt pavement gradation is directly related to the percentage of asphalt which is directly softened (12).

Currently there is no nationally accepted method for design of CR mixtures. The CIR laboratory procedures are developed by most of the state highway agencies and organizations on their own. One of the first attempt to standardize CR mix design in the

USA was the *1998 AASHTO-AGC-ARTBA joint committee Task Force 38 Report on cold recycling of asphalt pavements*. According to ARRA (1) the common methodologies used in mix-design procedures includes the following steps

1. Coring or Milling is used to collect the representative RAP samples.
2. The RAP characteristics such as RAP gradation, viscosity, asphalt content, aggregate gradation after extraction of asphalt and aged binder penetration from shall be determined
3. The need for new aggregate is established, if required.
4. The quantity of type of recycling agent are selected.
5. The need of pre-mix moisture is determined.
6. The recycled mixture is mixed, compacted, cured and tested.
7. Establish a job mix formula.
8. Necessary field adjustments are made during construction.

Cold In-Place Recycling Laboratory Mix design by ARRA

ARRA suggested laboratory mix design procedure for cold in-place recycling mixtures and it was incorporated in *CR201 Recommended Mix Design Guidelines for Cold Recycling Bituminous Recycling Agents* (2). This method suggests the percent and grade of recycling agent to use in CIR of bituminous pavements. In this method, cold milling is used to obtain the RAP samples. Determining the asphalt content and aggregate gradation of RAP constitute the material evaluation. RAP shall be dried to a constant mass at 104 ± 4 °F (40

± 2 °C) prior to mixing. The oven dried RAP is mixed with 2 to 3% water and a minimum of three recycling agent contents. A total of 6 specimens at each recycling agent content are prepared for indirect tensile strength testing or Marshall stability testing, 3 for cured and 3 for moisture conditioned specimens. After compaction, specimens shall be place in a forced draft oven at a temperature 140 ± 2 °C (60 ± 1 °C) to constant weight for at least 16 hours but not more than 48 hours. Additional two specimens are prepared for determining Theoretical Maximum Specific Gravity according to AASHTO T 209 (ASTM D2011).

For Indirect tensile strength testing , compacted and cured specimens are brought to test temperature by placing each specimen in a leak proof bag and submerging in a water bath at 77 ± 2 °F (25 ± 1 °C) for 30-45 minutes immediately prior to testing in accordance with AASHTO T 283 (ASTM D4867). Marshall stability is determined in accordance with AASHTO T 283 (ASTM D4867) at 104 ± 2 °F (40 ± 1°C) after 2 hour temperature conditioning in a forced draft oven or by placing specimens in a leak prof bag in a water bath at 104 ± 2 °F (40 ± 1 °C) for 30-45 minutes prior to testing.

Moisture conditioning shall be conducted on 3 compacted, cured specimens at each recycling agent by applying a vacuum of 2 psi to 10 psi for a time duration required to saturate specimens to 55 to 75 percent. For Tensile strength ratio testing specimens shall be submerged in a water bath at temperature 77 ± 2 °F (25 ± 1 °C) for 24 hours and indirect tensile strength is determined in accordance with AASHTO T 283 (ASTM D4867). For retained Marshall stability testing specimens shall be submerged in a water bath at temperature 77 ± 2 °F (25 ± 1 °C) for 23 hours followed by a one hour soak at 104 ± 2 °F (40 ± 1 °C) and Marshall stability is determined in accordance with AASHTO T 283

(ASTM D4867). Retained stability is defined as the average moisture conditioned specimen strength or stability divided by the average dry specimen strength or stability.

If emulsified asphalt is used as the bituminous binder, two additional specimens shall be prepared in accordance with ASTM D7196 at optimum asphalt content for determination of percent raveling loss. Specimens shall be compacted at 77 ± 9 °F (25 ± 5 °C) and immediately cured at 50 ± 2 °F (10 ± 1 °c) , 50% relative humidity for 4 hours ± 5 minutes. After curing specimens are tested immediately to determine percent raveling loss in accordance with ASTM D7196. The below table 1 shows the recommended cold recycling mix design requirements.

TABLE 1 Recommended Cold Recycling Mix Design Requirements

Test Method	**Criteria**
Indirect Tensile strength AASHTO T 283 (ASTM D4867)	Minimum 45 psi
Marshall Stability AASSHTO T 245 (ASTM D6927)	Minimum 1,250 lb
Tensile Strength Ratio/Retained Marshall Stability	Minimum 0.70
Raveling Test of Cold Mixed Bituminous Mixtures ASTM D7196	Maximum 7.0% loss

ADVANTAGES OF COLD IN-PLACE RECYCLING

The advantages of cold in-place recycling are summarized below (9, 13, 14, 15)

- There is no wastage of asphalt, as it is 100% effectively used.
- The underlying aggregate can be integrated into the mix in small amounts.
- Preservation of natural resources.
- Diesel fuel saving- as there is no import or export of material by trucks from project site
- Reconstruction is done in a much faster way.
- Roads rebuild work can be done in a few days or less.
- There will be less delay of commuting.
- The recycled road is open to traffic during reconstruction most of the time with minimal effect to the residents.
- The delay time is reduced for bus transportation and emergency services.
- The cost of cold in-place recycling projects accounts to only one half to one-third of the traditional reconstruction cost method.
- The roads are provided with stronger foundation as thicker asphalt bases are built by recycling. Also, the life span of the roads is renewed to their original construction.
- Geometrics can be easily altered.
- Reflection cracking can be eliminated.
- Improves ride quality and skid resistance.

CHAPTER III

MATERIALS AND TESTING PLAN

OBJECTIVE

The objective of the study is to determine if there is an alternative test for the raveling test that would easily fit into the current mix design procedures. The objective of the study would be met by evaluating the performance of CIR mixtures made with emulsified asphalt by comparing Marshall stability and unconfined compressive strength tests performed at various curing conditions and comparing the results to the Raveling test.

MATERIALS

Asphalt Emulsion

The asphalt emulsions used in this study are CSS – 1h and emulsion CSS – 1 both from Ergon.

RAP

RAP was obtained from three different sources for use in this research project. The RAP sources and identification key are shown in table 2

TABLE 2 RAP Source and Identification key

Contractor	Source	Identification Key
The Cummins Construction Co. Inc.	Perkins	PER
Haskell Lemon Construction Co.	Oklahoma City, West Plant	OKC
The Cummins Construction Co. Inc.	Enid	ENI

RAP Properties

The RAP obtained from the three different sources was oven dried to a constant mass at 104 ± 4 °F (40 ± 2 °C). Two, 1500 g samples of RAP from each source were batched to the medium gradation as cited in ARRA CR201 (2). To determine the percent asphalt content and aggregate gradation, the ignition furnace is run in accordance with AASHTO T 308. AASHTO T 30 was performed on the recovered aggregate for gradation. The gradations of recovered aggregate, batched RAP gradation and percent asphalt content are shown in table 3.

TABLE 3 Gradation of Recovered Aggregate and RAP

Gradation of Recovered Aggregate (average)				Batched Gradation of RAP
RAP Source ID	**PER**	**OKC**	**ENI**	
Sieve size	**Percent Passing**			
1"	100	100	100	100
3/4"	97	97	100	95
1/2"	90	91	98	80
3/8"	84	84	93	70
No. 4	66	69	81	50
No. 8	50	56	65	32
No. 16	41	45	54	20
No. 30	35	36	43	
No. 50	27	26	35	
No. 100	16	15	23	
No. 200	9.6	9.2	12.1	
Asphalt Content (%)	5.47	4.47	5.97	

TEST PLAN

Specimen Preparation

Batching

According to the requirements of the tests, the specimens are batched to the gradation shown in table 2. The specimens are batched to a mass that produces 2.4 to 2.6 (63.5 ± 2.5 mm) inch tall specimen of 4 inch (100 mm) diameter for determining Marshall stability (AASHTO T 245). For Unconfined Compressive strength testing (AASHTO T 167) 4 inch (100 mm) diameter specimens are normally used and the mass increased to produce a 4.52 $\pm$ 0.20 inches (115 $\pm$ 5 mm) tall specimen. For raveling test (ASTM D7196) 6 inch (150 mm) diameter specimens are used and the mass increased to produce a 2.75 $\pm$ 0.20 inches (70 ± 5 mm) tall specimen.

Mixing

The RAP is brought to the desired mixing temperature before mixing the RAP with water and recycling agent. Most of the mixing is carried at the temperature of 77 ± 9 °F (23 ± 5 $^{\circ}$C). Before mixing, emulsified recycling agents should be brought to the manufacturer's recommended temperature. Mixing is done manually for less than 60 seconds.

Compaction

Specimens are compacted immediately after mixing at ambient temperature of 77±9 °F (23 ± 5 $^{\circ}$C). For raveling test samples are compacted for 20 gyrations using a Superpave gyratory compactor (SGC). For Marshall stability and Unconfined compressive strength

testing samples are compacted using a SGC compactor for 20 gyrations to match the specimens compacted for raveling test and 30 gyrations to meet the mix design criteria.

Testing

Raveling Test

A 2450 g sample of RAP from each RAP source was batched to the gradation shown in table 2 for making a samples of height 70 ± 5 mm. and mixed with desired emulsified asphalt and moisture content.

The samples were compacted in 150 mm gyratory compaction mold compacted for 20 gyrations to yield a 70 ± 5 mm high cylinder after compaction. After compaction, samples were extruded immediately from the compaction mold and cured in environmental chamber at 50% relative humidity and 10 °C for 4 hours ± 5 minutes. Specimens are tested for average percent raveling loss according to ASTM D7196 immediately after curing. Figure 7 shows raveling test equipment.

FIGURE 7 Raveling test

Marshall Stability

A 950 g sample of RAP from each RAP source is batched to the gradation shown in table 2 for making a samples of 2.50 ± 0.10 in (63.5 ± 2.5 mm) thickness and mixed with desired emulsified asphalt and moisture content.

The samples were compacted in 100 mm gyratory compaction mold compacted for 20 gyrations to a thickness of 2.50 ± 0.10 in (63.5 ± 2.5mm). A 970 grams of RAP is batched to the gradation shown in table 2 for the samples compacted for 30 gyrations to make a thickness of 2.50 ± 0.10 in (63.5 ± 2.5mm). Samples are extruded immediately from the compaction mold. One set of samples were tested immediately without curing, other set of samples were tested immediately after curing in environmental chamber at 50% relative humidity and 10 °C for 4 hours ± 5 minutes and final set of samples were tested at 40 ± 1 °C after being fully cured by placing in oven at a temperature of 60 °C for a minimum of 16 – 48 hours. After 16 hours the samples were checked every 2 hours until mass loss was less than 0.05%, for a maximum of 48 hours oven drying. Specimens are placed in a leak proof bag and placed in a water bath at temperature 40 °C for 30-45 minutes and then tested immediately in accordance with AASHTO T 245 (ASTM D6927). Figure 8 shows Marshall stability on compacted samples

Unconfined Compressive Strength

A 1770 g sample of RAP from each RAP source is batched as per the gradation shown in table 2 for making a cylindrical samples of height 115 ± 5 mm and mixed with desired emulsified asphalt content and moisture content.

The samples were compacted in 100 mm gyratory compaction mold compacted for 20 gyrations to a height of 115 ± 5 mm. A 1790 grams of RAP is batched to the gradation shown in table 2 for the samples compacted for 30 gyrations to make a height of 115 ± 5 mm. Samples are extruded immediately from the compaction mold and tested after curing them in three different conditions in the same manner as Marshall stability. Fully cured specimens were cooled to 23 °C and tested in accordance with AASHTO T 167. Figure 9 shows unconfined compressive strength testing on compacted samples. The number of replicates and sample conditioning are shown in the table 4 and 5, respectively.

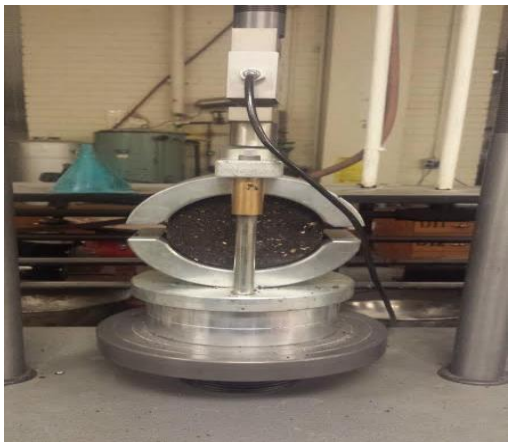

FIGURE 8 Marshall stability testing

FIGURE 9 Unconfined compressive strength testing

TABLE 4 Number of Replicates Tested and Curing Condition for CSS-1

RAP Source ID	EAC Content	Raveling	Marshall Stability	Unconfined Compressive Strength	Conditioning
PER	2.75	2	2	2	50% humid, 10 °C
		-	2	2	Immediate
		-	2	2	Oven Cured 60 °C
	3.00	2	2	2	50% humid, 10 °C
		-	2	2	Immediate
		-	2	2	Oven Cured 60 °C

TABLE 5 Number of Replicates Tested and Curing Condition for CSS – 1h

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

CHAPTER IV

TEST RESULTS

MIX DESIGN

Mix design was performed on the RAP which was obtained from Perkins and Oklahoma City using CSS – 1h emulsion in accordance with CR201 (2). Retained stability is calculated by dividing the average Marshall stability of moisture conditioned specimens by the average Marshall stability of dry specimens. The results of the mix design are summarized in table 6.

TABLE 6 Results of Marshall Stability Test

RAP Source ID	EAC Content (%)	Wet Stability (lbs)			Dry Stability (lbs)			Retained Stability
		Sample 1	Sample 2	Average	Sample 1	Sample 2	Average	
PER	2.25	998.4	1164.8	1081.6	1393.6	1383.2	1388.4	0.78
	3.00	1331.2	1206.4	1268.8	1414.4	1445.6	1430.0	0.89
	3.75	1526.0	1395.2	1460.6	1476.8	1497.6	1487.2	0.98
OKC	2.25	1558.7	1645.9	1602.3	2430.7	2463.4	2447.1	0.65
	3.00	1635.0	1765.8	1700.4	2474.3	2583.3	2528.8	0.67
	3.75	1842.1	1874.8	1858.4	2757.7	2616.0	2686.8	0.69

RAVELING TEST

The Raveling test was performed to evaluate the percent raveling loss of compacted RAP specimens and to determine if there is a relationship between percent raveling loss and Marshall stability or unconfined compressive strength. Samples were prepared from different RAP sources with 2% water content and with emulsified asphalt content as shown in tables 3 and 4. The samples were compacted in 150 mm gyratory compaction mold compacted for 20 gyrations to yield a 70 ± 5 mm high cylinder after compaction. The samples were tested immediately after curing them in environmental chamber at 50% relative humidity and 10 °C for 4 hours ± 5 minutes. The test was conducted in accordance to ASTM D7196 and the test results are summarized in the table 7.

TABLE 7 Results of Raveling Test

RAP Source ID	Emulsion Type	EAC (%)	Percent Raveling loss		
			Sample 1	Sample 2	Average
PER	CSS-1	2.75	12.23	*	12.2
PER	CSS-1	3.00	1.13	1.23	1.2
PER	CSS-1h	2.50	3.61	3.49	3.5
PER	CSS-1h	2.75	2.45	2.69	2.6
OKC	CSS-1h	2.50	15.36	*	15.4
ENI	CSS-1h	2.50	2.53	2.17	2.4
ENI	CSS-1h	2.00	2.98	4.01	3.5
ENI	CSS-1h	1.50	6.78	6.91	6.8

* Samples completely disintegrated

MARSHALL STABILITY TEST

The test was performed to determine the Marshall stability of compacted RAP specimens and to determine if there is a relationship between percent raveling loss. Samples were prepared from different RAP sources with 2% water content and with emulsified asphalt content as shown in tables 3 and 4. The samples were compacted in 100 mm gyratory compaction mold compacted for 20 and 30 gyrations to a thickness of 2.50 ± 0.10 in (63.5 ± 2.5mm). One set of samples were tested immediately without curing, other set of samples were tested immediately after curing them in environmental chamber at 50% relative humidity and 10 °C and final set of samples were tested after fully cured. The test was conducted in accordance to AASHTO T 245 (ASTM D6927) and the test results are summarized in the table 8, 9, 10, respectively.

TABLE 8 Results of Marshall Stability for Samples Tested Immediately

RAP Source ID	Emulsion Type	EAC (%)	Gyrations	Marshall Stability (lbs) Tested at 23 ± 5 °C		
				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
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 9 Result of Marshall Stability for Samples Fully Cured

RAP Source 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
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	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	1390	1385.0
ENI	CSS-1h	2.50	30	1736.8	1747.2	1742.0

TABLE 10 Result of Marshall Stability for Samples Tested after Curing at 50% Relative Humidity, 10 °C

RAP Source ID	Emulsion Type	EAC (%)	Gyrations	Marshall Stability (lbs) Tested at 10 °C		
				Sample 1	Sample 2	Average
PER	CSS-1	2.75	20	1799.2	1747.2	1773.2
PER	CSS-1	2.75	30	2059.2	2038.4	2048.8
PER	CSS-1	3.00	20	1788.8	1851.2	1820.0
PER	CSS-1	3.00	30	2225.6	2350.4	2288.0
PER	CSS-1h	2.50	20	1830.4	1851.2	1840.8
PER	CSS-1h	2.50	30	2215.2	2080.0	2147.6
PER	CSS-1h	2.75	20	2100.8	2246.4	2173.6
PER	CSS-1h	2.75	30	2433.6	2548.0	2490.8
OKC	CSS-1h	2.50	20	2158.2	2234.5	2196.3
OKC	CSS-1h	2.50	30	2332.6	2387.1	2359.8
ENI	CSS-1h	2.50	20	2110.0	2132.0	2121.0
ENI	CSS-1h	2.50	30	2200.0	2210.0	2205.0

UNCONFINED COMPRESSIVE STRENGTH TEST

The test was performed to determine the unconfined compressive strength of compacted RAP specimens and to determine if there is a relationship between percent raveling loss. Samples were prepared from different RAP sources with 2% water content and with emulsified asphalt content as shown in tables 3 and 4. The samples were compacted in 100 mm gyratory compaction mold compacted for 20 and 30 gyrations to a height of 115 ± 5 mm. One set of samples were tested immediately without curing, other set of samples were tested immediately after curing them in environmental chamber at 50% relative humidity and 10 °C and final set of samples were tested after fully cured. The test was conducted in general to AASHTO T 167 and the test results are summarized in the table 11, 12, 13, respectively.

TABLE 11 Result of Unconfined Compressive Strength for Samples Tested Immediately

RAP Source ID	Emulsion Type	EAC (%)	Gyrations	Unconfined Compressive Strength (psi) Tested at 23 ± 5 °C		
				Sample 1	Sample 2	Average
PER	CSS-1	2.75	20	36.16	35.33	35.7
PER	CSS-1	2.75	30	41.91	40.27	41.1
PER	CSS-1	3.00	20	34.51	38.62	36.6
PER	CSS-1	3.00	30	45.20	43.55	44.4
PER	CSS-1h	2.50	20	32.05	32.87	32.5
PER	CSS-1h	2.50	30	41.91	43.55	42.7
PER	CSS-1h	2.75	20	35.33	39.44	37.4
PER	CSS-1h	2.75	30	48.48	45.20	46.8
OKC	CSS-1h	2.50	20	40.27	36.16	38.2
OKC	CSS-1h	2.50	30	48.48	46.02	47.3
ENI	CSS-1h	2.50	20	38.62	45.20	41.9
ENI	CSS-1h	2.50	30	49.31	50.95	50.1

TABLE 12 Result of Unconfined Compressive Strength for Samples fully cured

RAP Source ID	Emulsion Type	EAC (%)	Gyrations	Unconfined Compressive Strength (psi) Tested at room temperature		
				Sample 1	Sample 2	Average
PER	CSS-1	2.75	20	110.95	115.06	113.0
PER	CSS-1	2.75	30	125.74	128.21	126.9
PER	CSS-1	3.00	20	132.31	125.74	129.0
PER	CSS-1	3.00	30	150.40	140.53	145.5
PER	CSS-1h	2.50	20	130.67	125.74	128.2
PER	CSS-1h	2.50	30	146.29	138.89	142.6
PER	CSS-1h	2.75	20	132.31	138.89	135.6
PER	CSS-1h	2.75	30	148.75	152.86	150.8
OKC	CSS-1h	2.50	20	149.57	154.50	152.0
OKC	CSS-1h	2.50	30	161.90	157.79	159.8
ENI	CSS-1h	2.50	20	122.45	124.92	123.7
ENI	CSS-1h	2.50	30	140.53	136.42	138.5

TABLE 13 Result of Unconfined Compressive Strength for Samples Tested after Curing at 50% Relative Humidity, 10 °C

RAP Source ID	Emulsion Type	EAC (%)	Gyrations	Unconfined Compressive Strength (psi) Tested at 10 °C		
				Sample 1	Sample 2	Average
PER	CSS-1	2.75	20	73.96	75.61	74.8
PER	CSS-1	2.75	30	83.82	78.07	80.9
PER	CSS-1	3.00	20	80.54	70.67	75.6
PER	CSS-1	3.00	30	94.51	92.87	93.7
PER	CSS-1h	2.50	20	78.89	83.82	81.7
PER	CSS-1h	2.50	30	91.22	95.33	93.3
PER	CSS-1h	2.75	20	84.65	89.58	87.1
PER	CSS-1h	2.75	30	99.44	100.26	99.8
OKC	CSS-1h	2.50	20	92.87	87.93	90.4
OKC	CSS-1h	2.50	30	101.91	96.15	99.0
ENI	CSS-1h	2.50	20	92.04	96.97	94.5
ENI	CSS-1h	2.50	30	104.37	109.30	106.84

CHAPTER V

ANALYSIS OF RESULTS

This chapter provides the analysis of the experimental data. The analysis was performed to determine if there was a relationship between percent raveling loss and Marshall stability or unconfined compressive strength tested at various curing conditions.

MARSHALL STABILITY

Fully Cured

Figure 10 shows the relation between percent raveling loss and Marshall stability of fully cured specimens tested at 40 °C. The variability between these points is determined by the R square value of 0.3956 or 39.56%. It indicates that there was no strong correlation between them.

50% Relative Humidity Curing

Figure 11 shows the relation between percent raveling loss and Marshall Stability of specimens cured at 50% relative humidity, 10 °C for 4 hours ± 5 minutes and tested immediately after curing. The variability between these points is determined by the R square value of 0.0001 or 0.01%. It indicates that there was no strong correlation between them.

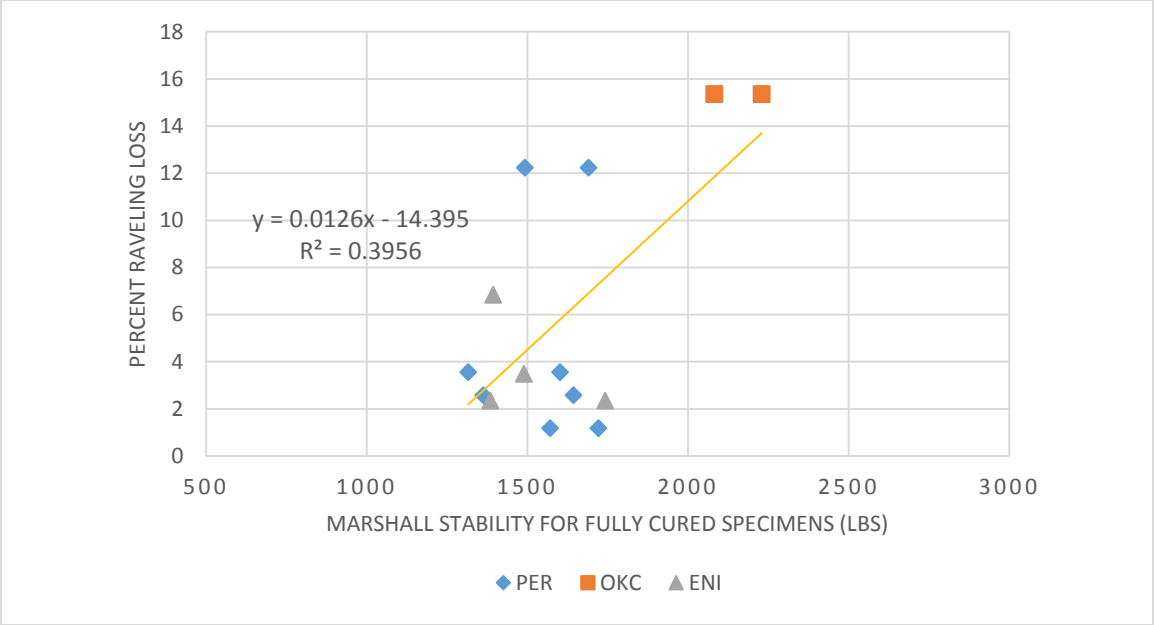

FIGURE 10 Plot of percent raveling loss vs Marshall stability for fully cured specimens

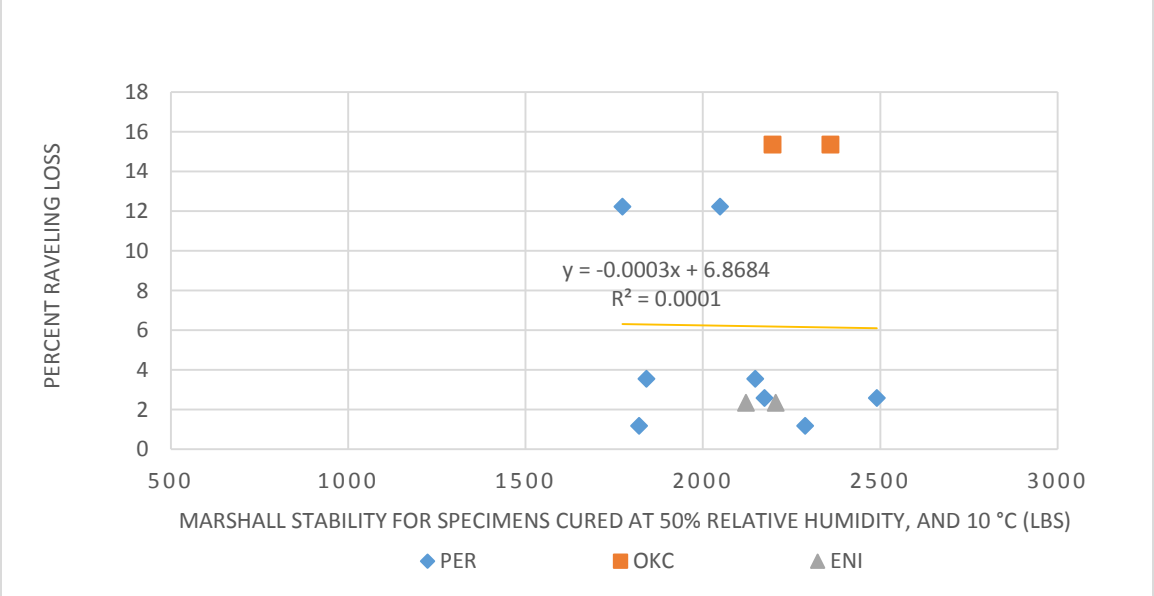

FIGURE 11 Plot of percent raveling loss vs Marshall stability for specimens cured at 50% relative humidity, 10 °C tested at 10 °C

Tested Immediately

Figure 12 shows the relation between percent raveling loss and Marshall Stability of specimens tested immediately after compaction at room temperature. The variability between these points is determined by the R square value, which is 0.2073 or 20.73%. It indicates that there was no strong correlation between them.

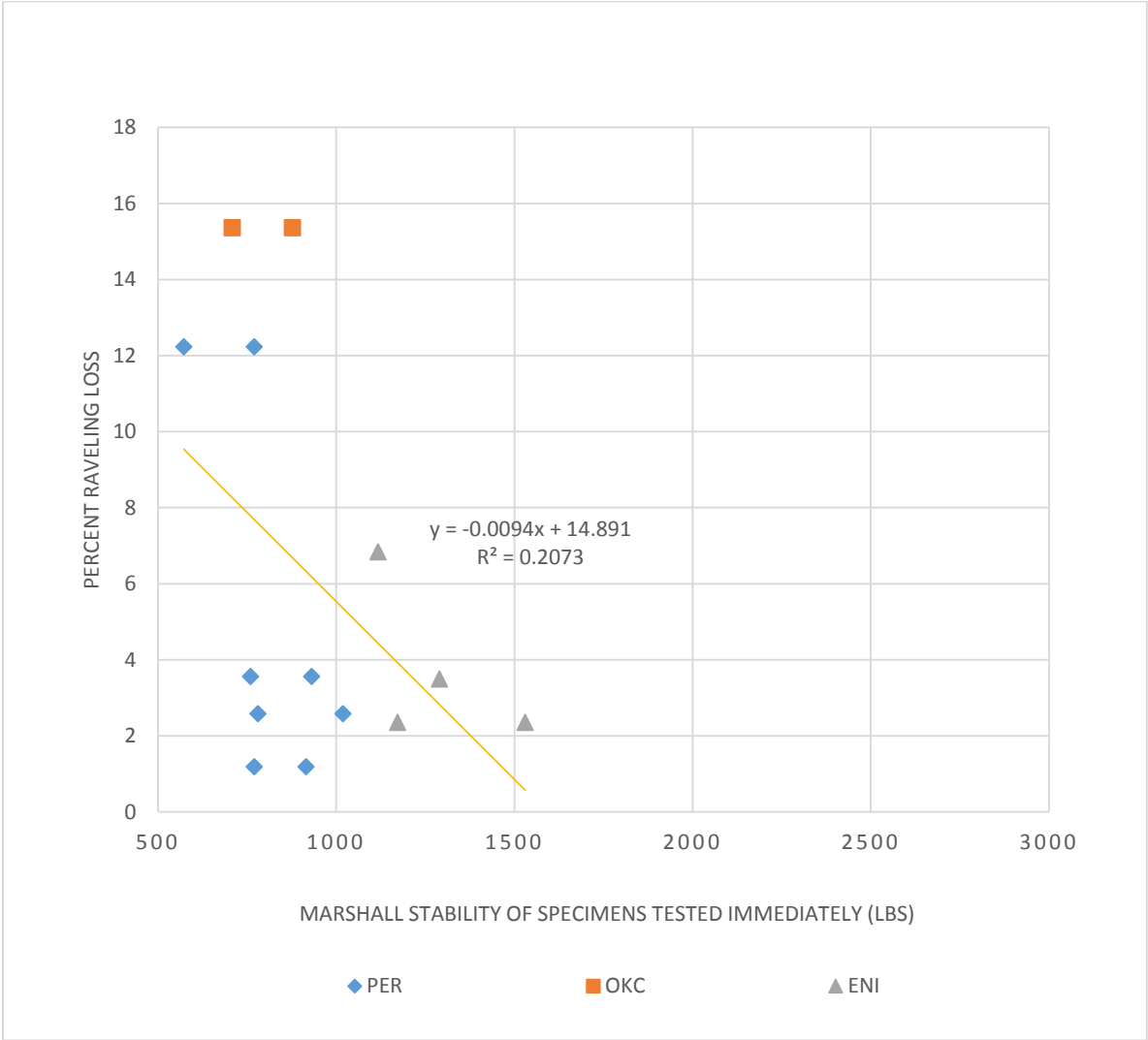

FIGURE 12 Plot of percent raveling loss vs Marshall stability for specimens tested immediately without curing

PERCENT MARSHALL STABILITY

Percent Marshall stability is the value obtained by dividing the average value of Marshall stability for specimens cured at 50% relative humidity, 10 °C or average value of Marshall Stability for specimens tested immediately by average value of Marshall stability for specimens tested after fully cured.

Fully Cured

Figure 13 shows the relation between percent raveling loss and percent change in Marshall Stability of specimens tested immediately with respect to specimens tested after fully cured. The variability between these points is determined by the R square value of 0.3932 or 39.32%. It indicates that there was no strong correlation between them.

50% Relative Humidity Curing

Figure 14 shows the relation between percent raveling loss and percent change in Marshall Stability of specimens cured at 50% relative humidity, 10 °C with respect to specimens tested after fully cured. The variability between these points is determined by the R square value of 0.5037 or 50.37%. It indicates that there was no strong correlation between them.

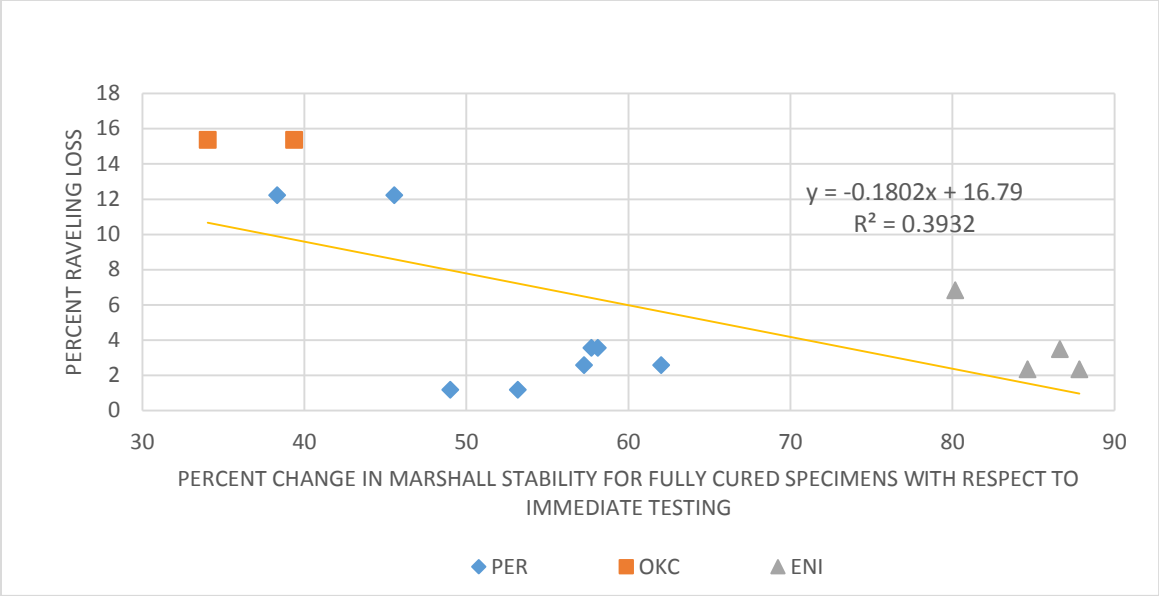

FIGURE 13 Plot of percent raveling loss vs percent change in Marshall stability for fully cured specimens

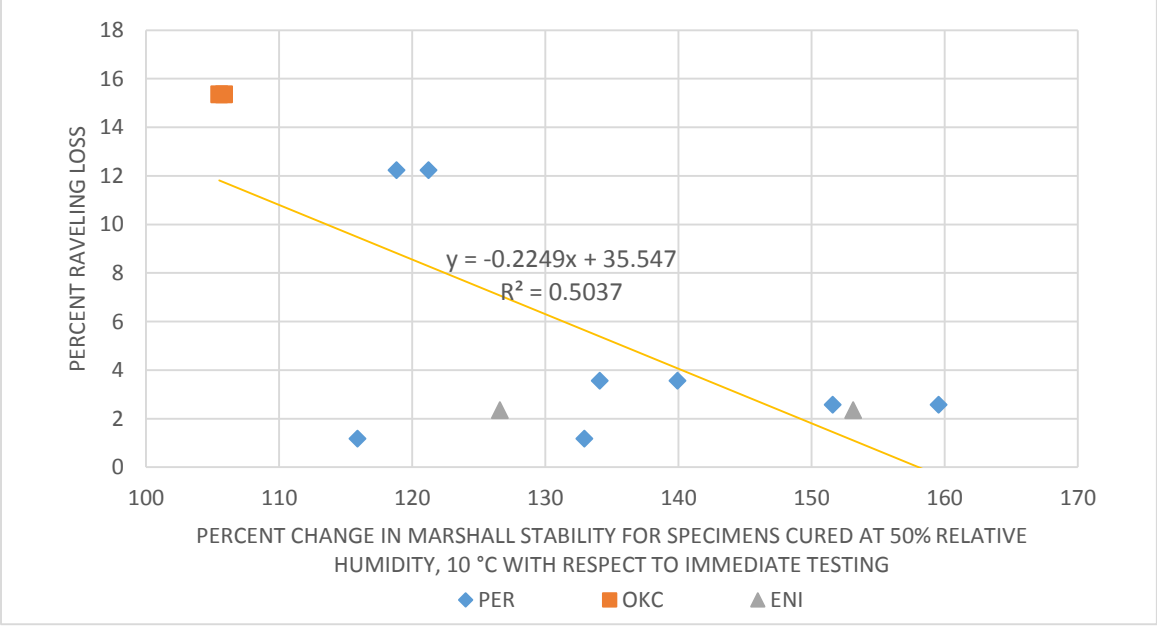

FIGURE 14 Plot of percent raveling loss vs percent change in Marshall stability for specimens cured at 50% relative humidity, 10 °C

UNCONFINED COMPRESSIVE STRENGTH

Fully Cured

Figure 15 shows the relation between percent raveling loss and unconfined compressive strength for fully cured specimens tested at room temperature. The variability between these points is determined by the R square value of 0.03 or 3%. It indicates that there was no strong correlation between them.

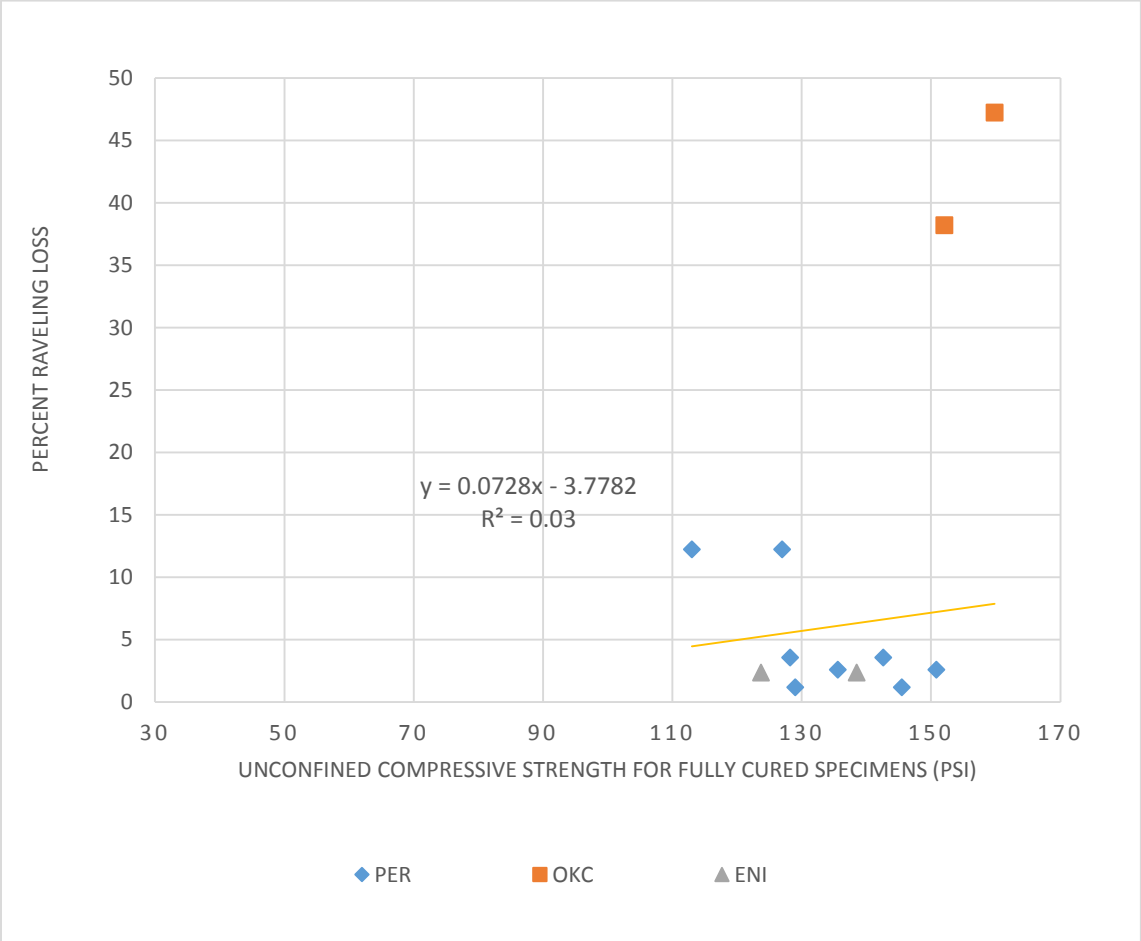

FIGURE 15 Plot of percent raveling loss vs unconfined compressive strength for fully cured specimens

50% Relative Humidity Curing

Figure 16 shows the relation between percent raveling loss and Unconfined Compressive Strength of specimens tested after cured at 50% relative humidity, 10 °C for 4 hours ± 5 minutes and tested immediately after curing. The variability between these points is determined by the R square value of 0.0247 or 2.47%. It indicates that there was no strong correlation between them.

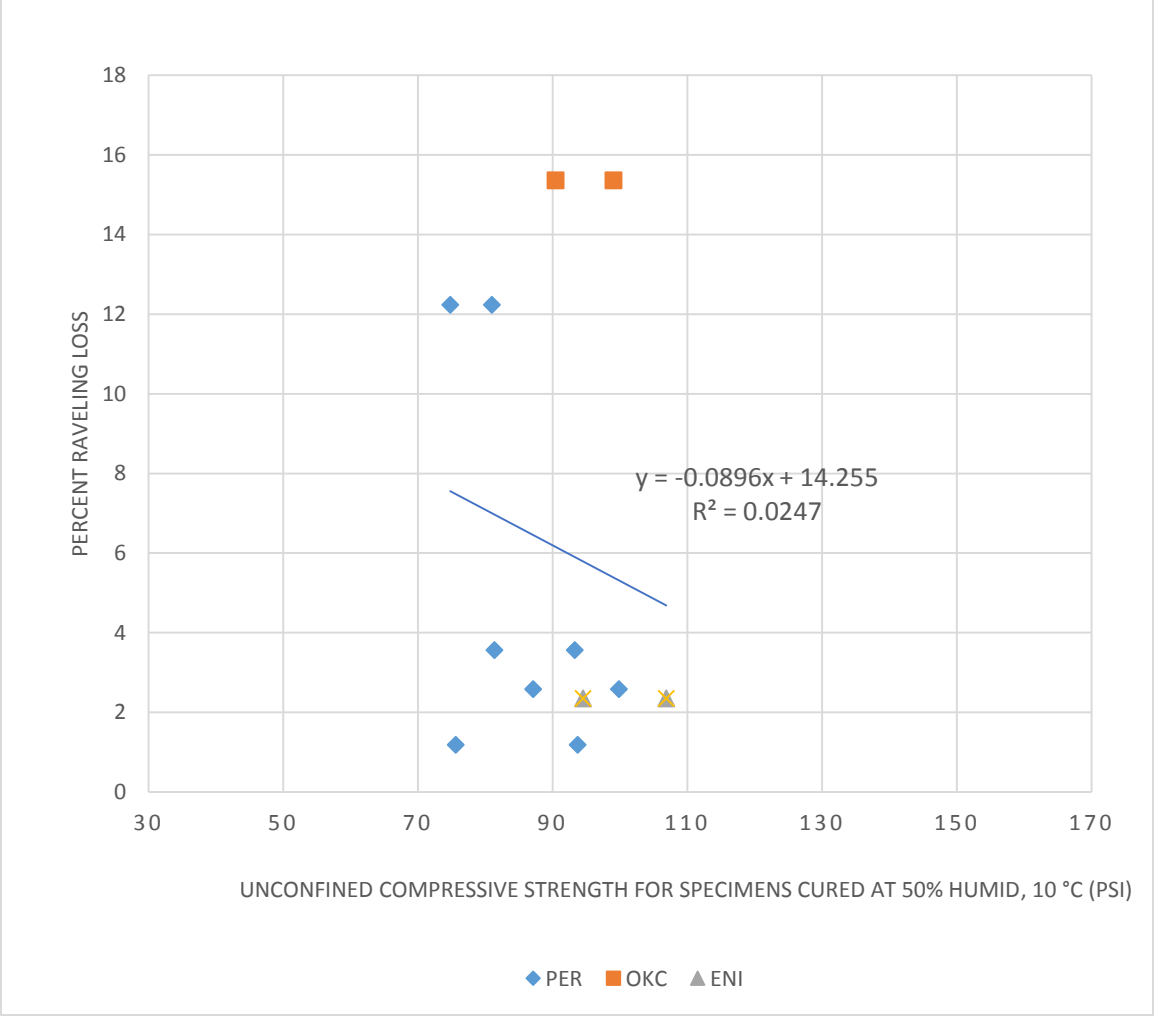

FIGURE 16 Plot of percent raveling loss vs unconfined compressive strength for specimens cured at 50% humidity, 10 °C tested at 10 °C

Tested Immediately

Figure 17 shows the relation between percent raveling loss and unconfined compressive strength of specimens tested immediately after compaction at room temperature. The variability between these points is determined by the R square value of 0.0008 or 0.08 %. It indicates that there was no strong correlation between them.

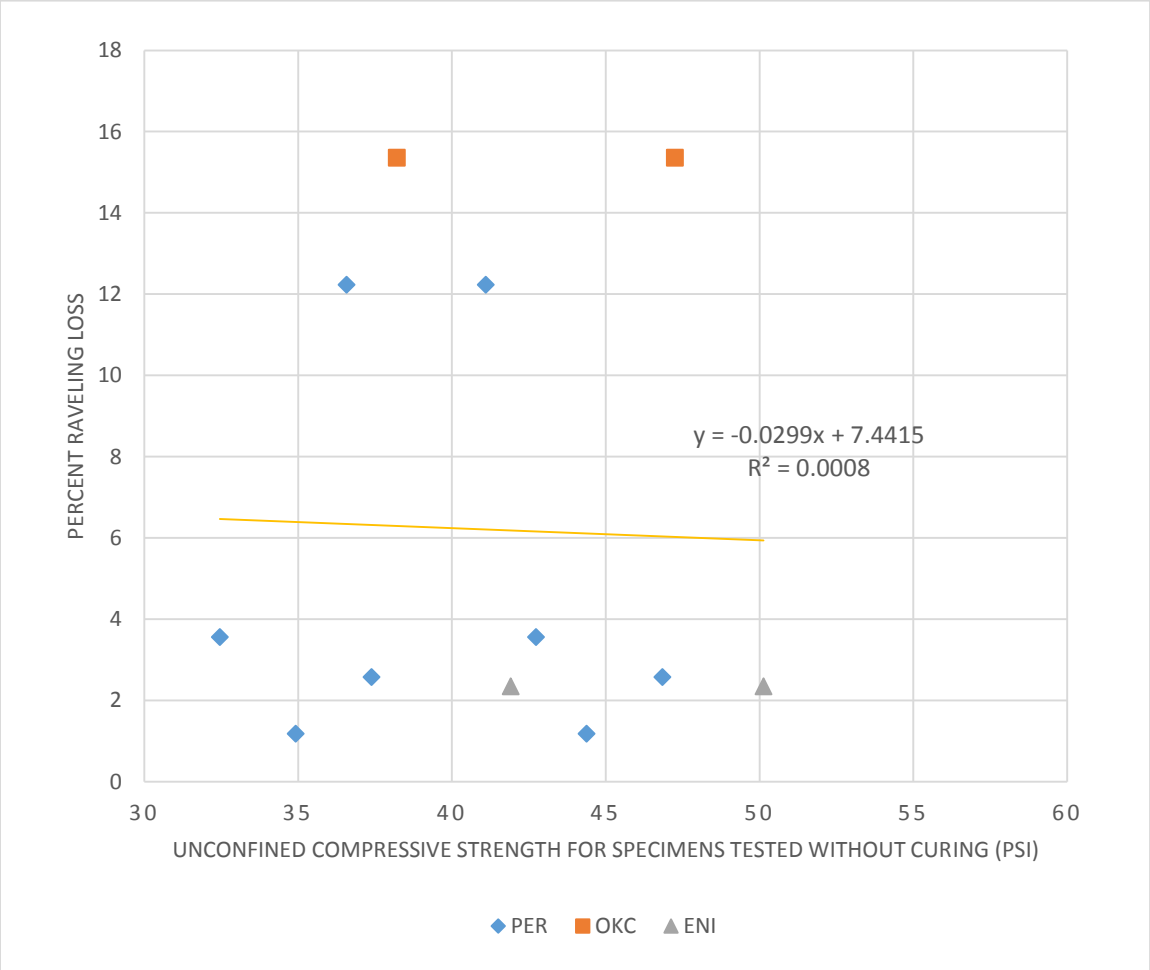

FIGURE 17 Plot of percent raveling loss vs unconfined compressive strength for specimens tested immediately without curing

PERCENT UNCONFINED COMPRESSIVE STRENGTH

Percent unconfined compressive strength is the value obtained by dividing the average value of unconfined compressive strength for specimens cured at 50% relative humidity, 10 °C or the average value of unconfined compressive strength for specimens tested immediately without curing by average value of unconfined compressive strength for specimens tested after fully cured.

Fully Cured

Figure 18 shows the relation between percent raveling loss and percent change in Unconfined Compressive Strength of specimens fully cured with respect to specimens tested immediately. The variability between these points is determined by the R square value of 0.019 or 1.90%. It tells us that there was no strong correlation between them.

50% Relative Humidity Curing

Figure 19 shows the relation between percent raveling loss and percent change in Unconfined Compressive Strength of specimens cured at 50% relative humidity, 10 °C with respect to specimens tested after fully cured. The variability between these points is determined by the R square value of 0.1364 or 13.64 %. It indicates that there was no strong correlation between them.

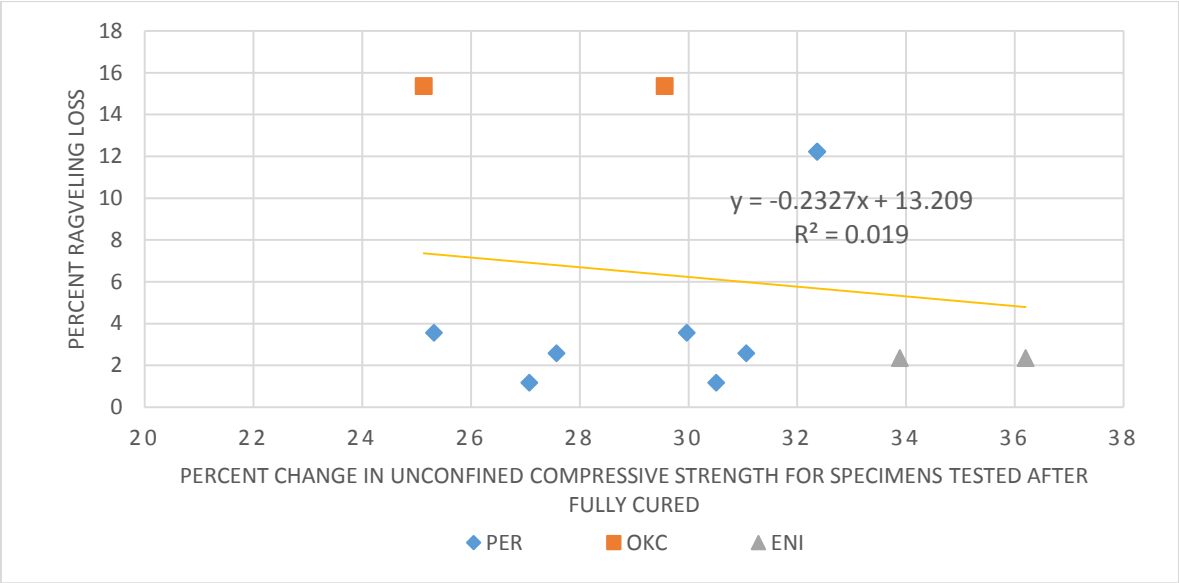

FIGURE 18 Plot of percent raveling loss vs percent change in unconfined compressive strength for specimens tested after fully cured specimens

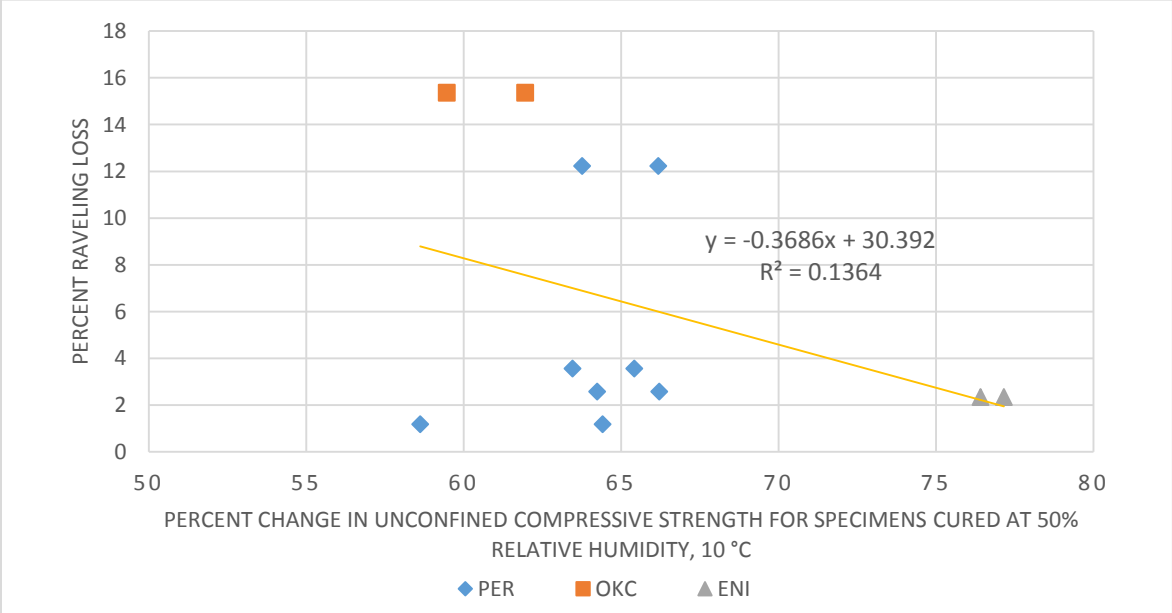

FIGURE 19 Plot of percent raveling loss vs percent change in unconfined compressive strength for specimens cured at 50% relative humidity, 10 °C

THRESHOLD ANALYSIS

From figures 15, 16, 17,18 and 19 it can be observed that there was no clear threshold for unconfined compressive strength, whereas from figures 12, 13 and 14 threshold can be observed for Marshall stability considering 7% raveling loss.

Figure 20 shows the threshold point between percent raveling loss and Marshall stability for specimens tested immediately without curing. A threshold point can be noticed at Marshall stability of 800 pounds considering 7% raveling loss. It is observed that 3 of 10 samples lie below 800 pounds considering less than 7% raveling loss, 7 of 10 samples lie above 800 considering less than 7% raveling loss, whereas 3 of 4 samples lie below 800 pounds considering raveling loss greater than 7% and 1 of 4 samples lie above 800 pounds considering raveling loss greater than 7%.

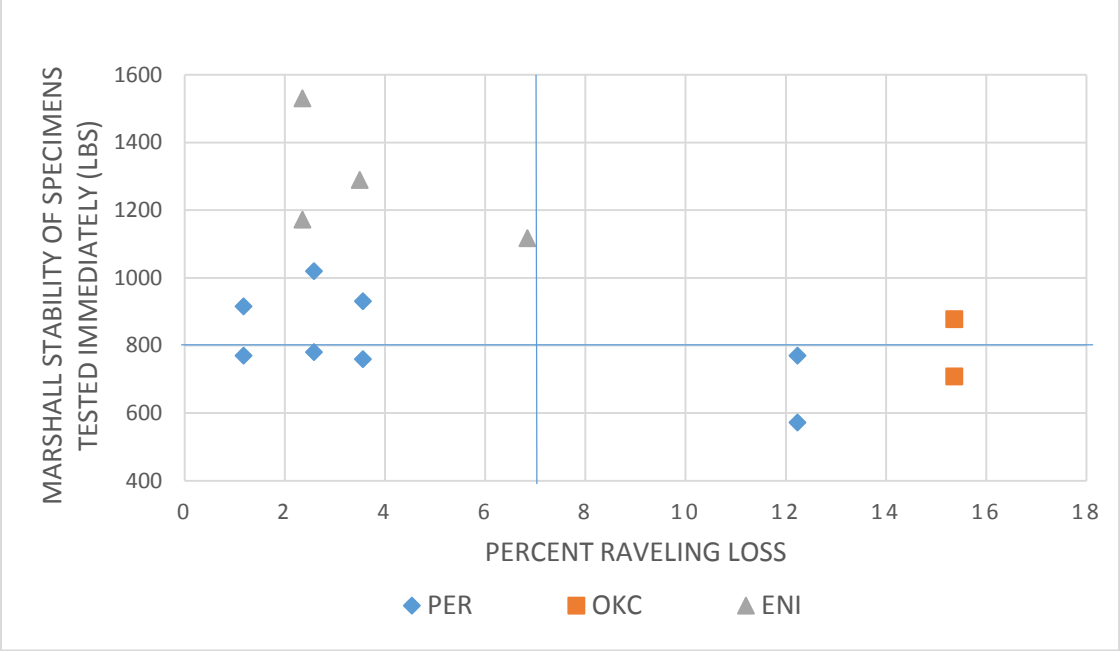

Figure 20 Threshold point between percent raveling loss and Marshall stability for specimens tested immediately without curing

Figure 21 shows the threshold point between percent raveling loss and percent change in Marshall stability for specimens tested immediately after curing at 50% relative humidity, 10 °C with respect to the specimens tested immediately. A threshold point can be noticed at percent change in Marshall stability of 120% considering 7% raveling loss. It is observed that 1 of 8 samples lie below 120% considering less than 7% raveling loss, 7 of 8 samples lie above 120% considering less than 7% raveling loss whereas 2 of 3 samples lie below 120% considering raveling loss greater than 7% and 1 of 3 samples lie above 120% considering raveling loss greater than 7%.

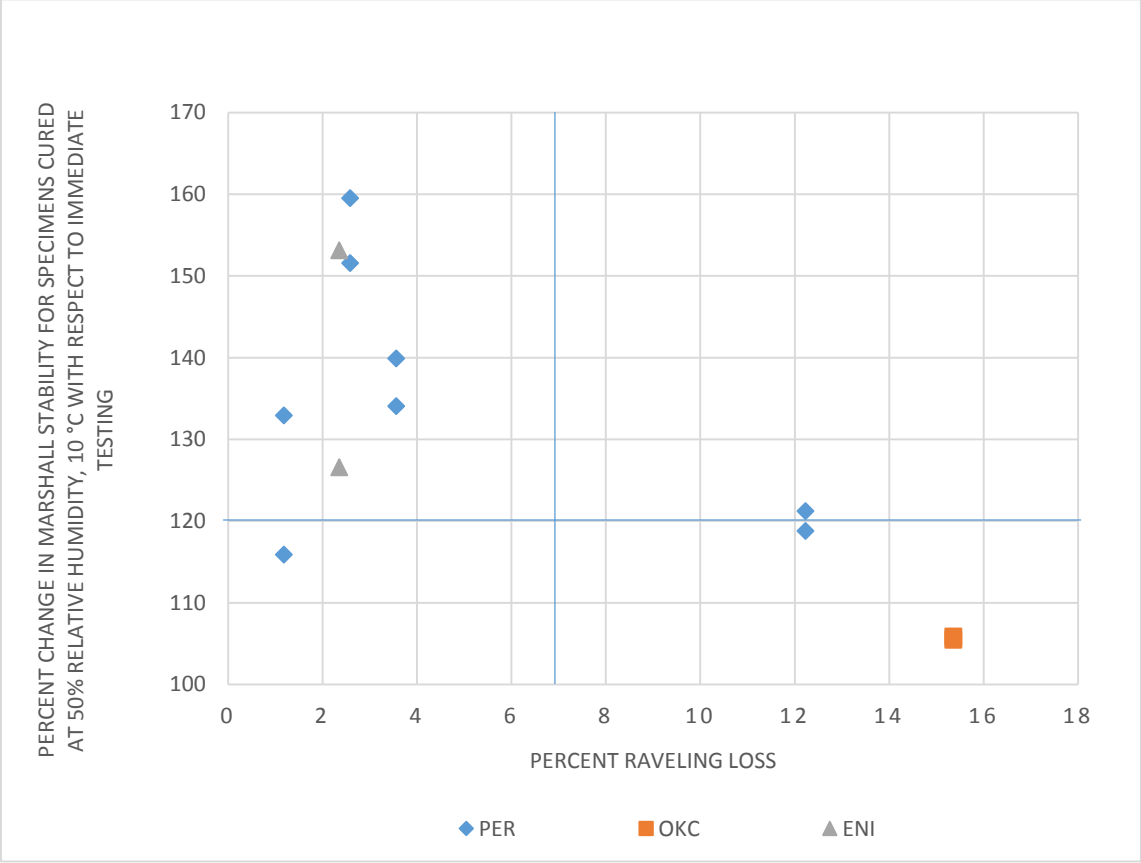

Figure 21 Threshold point between percent raveling loss and percent change in Marshall stability for specimens cured at 50% relative humidity, 10 °C

Figure 22 shows the threshold point between percent raveling loss and percent change in Marshall stability for specimens tested immediately after fully cured with respect to the specimens tested without curing. A threshold point can be noticed at percent change in Marshall stability of 50% considering 7% raveling loss. It is observed that 1 of 9 samples lie below 50% considering less than 7% raveling loss, 8 of 9 samples lie above 50% considering less than 7% raveling loss whereas 4 of 4 samples lie below 50% considering raveling loss greater than 7%.

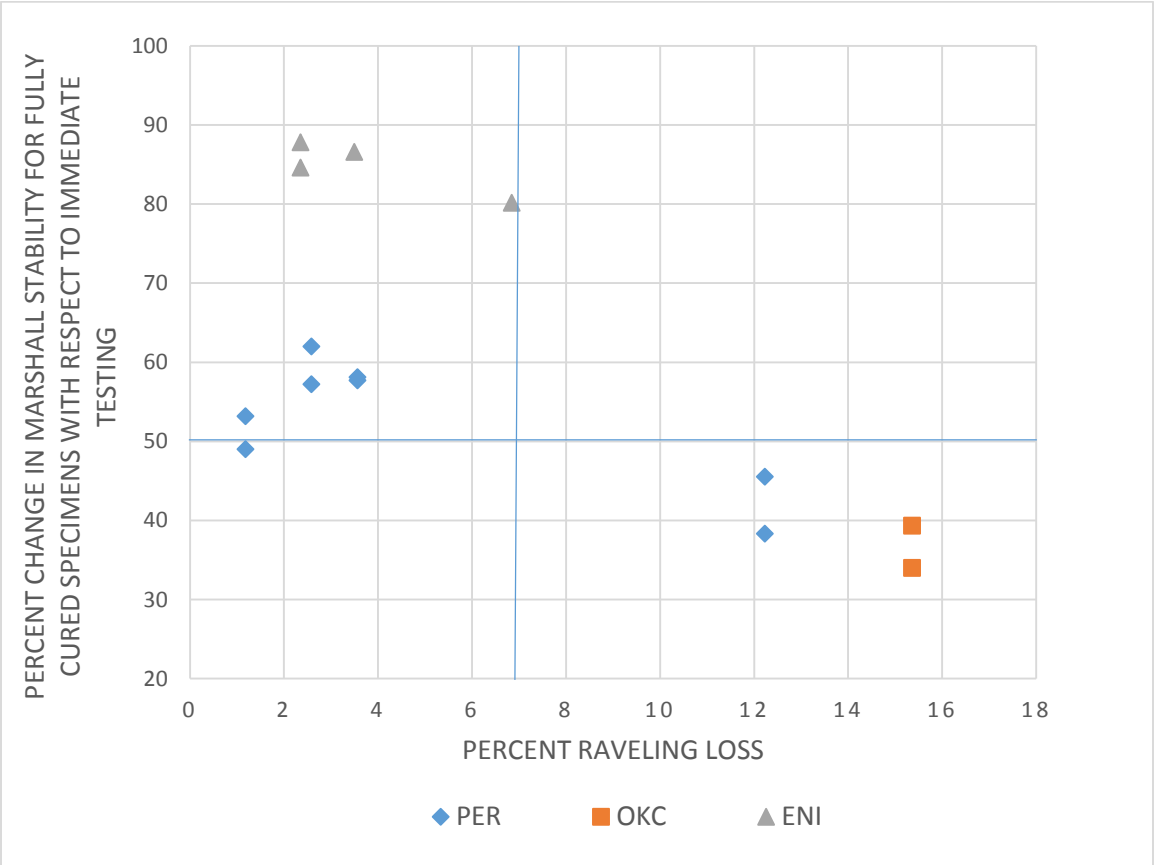

Figure 22 Threshold point between percent raveling loss and percent change in Marshall stability for specimens fully cured

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Based on the test results and analysis performed, the following conclusions are warranted.

CONCLUSIONS

- Raveling test results ranged from a percent mass loss between 1-4% and 12-16%. Specifications have ranged from a maximum of 2 to 7% loss. A maximum percent loss of 7% appears to be a reasonable specification limit.
- Unconfined compressive strength tests (fully cured, moist cured and tested immediately) did not correlate with percent mass loss from the raveling test.
- A threshold value for unconfined compressive strength tests (fully cured, moist cured and tested immediately) was not found.
- Marshall stability tests (fully cured, moist cured and tested immediately) were slightly correlated to percent mass loss from the raveling test and the analysis yielded a threshold value.
- A threshold value of 800 pounds Marshall stability for specimens tested immediately without curing with 7% raveling loss, R square value of 0.20, was observed. A threshold value of 120% change in stability of specimens tested after curing at 50% relative humidity, 10 °C with respect to specimens tested immediately without curing with 7% raveling loss, R square value of 0.50, was observed.

- A threshold value of 50% change in stability of specimens tested after fully cured with respect to specimens tested immediately without curing with 7% raveling loss, R square value of 0.39, was observed.

RECOMMENDATIONS

Based on the test results and analysis performed, the following recommendations are warranted.

- The percent change in Marshall stability from testing immediately compared to fully cured is recommended to replace the Raveling test in CIR mix designs. A minimum of 50% Marshall stability was found to be a pass fail threshold values for 7% loss in the Raveling test.
- Additional testing needs to be conducted with more mixes from different RAP sources and with different emulsified asphalts to verify the results of this study.

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