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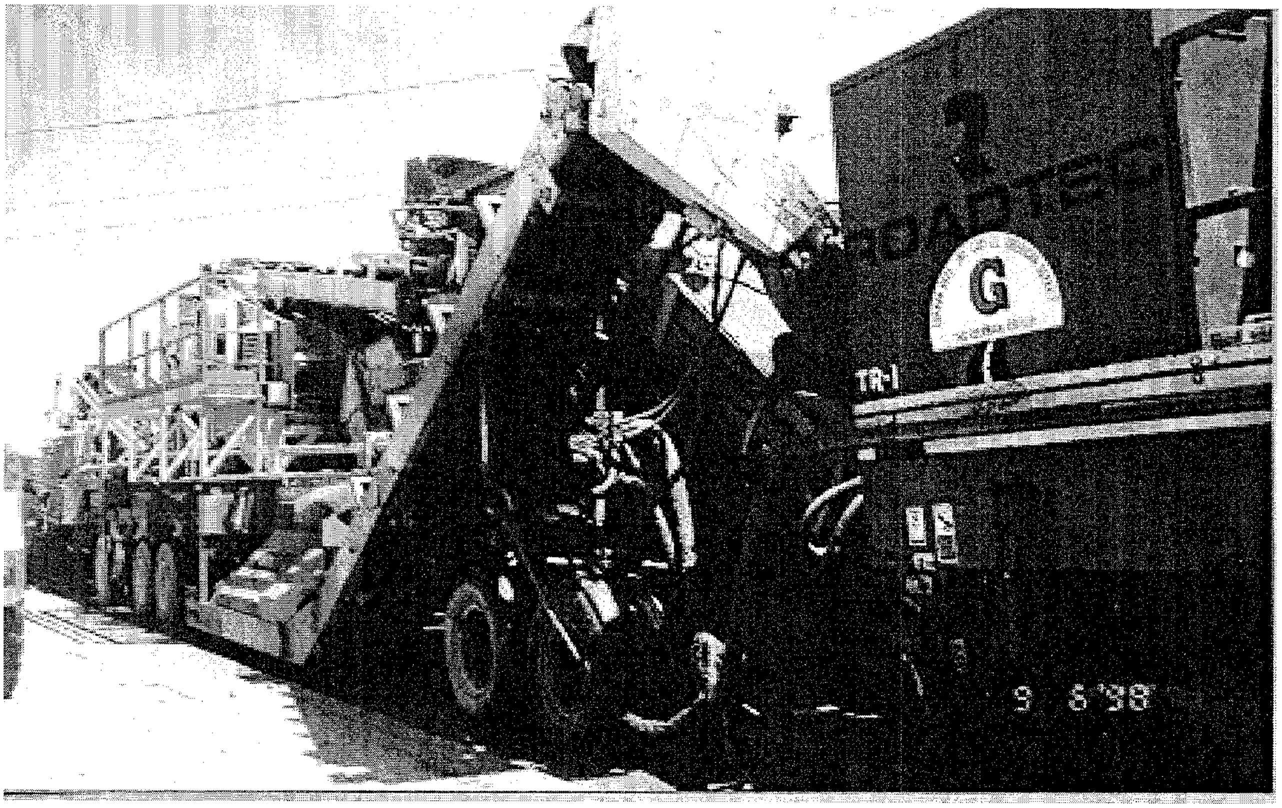
Development of Performance Based Mix Design for Cold In-Place Recycling (CIR) of Bituminous Pavements Based on Fundamental Properties



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16. Abstract

The high cost and environmental impact of traditional pavement rehabilitation has led to an increase in the use of Cold In-Place Recycling (CIR) as an effective alternative to other rehabilitation strategies. However, currently there is not a universally accepted or standard mix-design for CIR. Therefore, this research has been undertaken with the objective to develop a new mix-design procedure for CIR through laboratory evaluation and limited field verification. The project focuses on partial-depth CIR using asphalt emulsions as the recycling agent. The modified Marshall mix-design recommended by the AASHTO Task Force No. 38 was evaluated and found to be inefficient. Therefore, a new volumetric mix-design has been developed utilizing the Superpave gyratory compactor and technology. It requires that specimens be prepared at densities similar to those found in the field. The performance of CIR mixtures prepared and constructed in accordance with the new mix-design has been evaluated in the laboratory as well as in the field. Creep compliance and strength of the mixtures have been determined using the Indirect Tensile Test (IDT) in an effort to evaluate the resistance against low-temperature cracking.

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Cold In-Place Recycling (CIR), Mix-Design, Bituminous
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FOREWARD

The objective of this research program was to develop a performance based mix-design for the cold in-place recycling (CIR) asphalt mixtures.

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Chapter 1. Introduction

Agencies have been recycling pavement materials for road rehabilitation since 1915. Pavement recycling has greatly increased since the mid-1970's, largely due to the oil embargo as well as a decrease in the availability of quality aggregates. Several benefits arise from pavement recycling, including conservation of materials and energy, preservation of the environment, and reduction in cost. Because of these benefits, many agencies such as the Federal Highway Administration (FHWA) and State Highway Agencies (SHAs) began to promote recycling (Epps 1990).

It has been recognized by transportation officials that there is a vast amount of aggregate and asphalt materials already in place that can supply materials for future highway construction. This recognition, in addition to the potential energy savings from not manufacturing new virgin materials and the reduction of environmental impact, has led to an increase in the use of Cold In-Place Recycling (CIR) as an effective alternative to other rehabilitation strategies by transportation agencies. States such as Kansas (Maag and Fager 1990), Oregon (Rogge et al. 1992), California (Kuennen 1988), and New Mexico (McKeen et al. 1997) have successfully performed CIR on projects since the early 1980's. Some projects, however, have not performed as well as expected, which may be due to the wide variation in mix-design procedures, tests, and quality control of the overall process. This suggests that more consistent results can be obtained in the field with the development of a standard mix-design. Moreover, once a standard mix-design is produced, the CIR technology can be used on a more regular basis. Consequently, the American Association of State Highway and Transportation Officials (AASHTO), the American Road and Transportation Builders

Association (ARTBA), and the Associated General Contractors of America (AGC) formed the Special Joint Task Force No. 38. The group produced guidelines for CIR design, but they did not develop a standard mix-design (Task Force No. 38, 1998). Thus, this research project seeks to develop a performance-based mix-design that can be used as a standard for the CIR industry. To accomplish this objective, the following tasks were performed:

- Formed an Expert Task Group (ETG),
- Literature has been reviewed,
- Conducted Survey Questionnaire,
- Development of a Work Plan to Develop a Performance-Base Mix-Design,
- Evaluation of Modified Marshall Mix-Design, and
- Development of Performance-Based Mix-Design Utilizing Superpave Technology.

Chapter 2. Current Status of Knowledge

2.1 Cold In-Place Recycling Process

There are two methods by which agencies perform Cold Recycling: Cold In-Place Recycling (CIR) and Cold Central Plant Recycling (CCPR). Agencies generally prefer CIR because trucking is reduced, which saves time, money, energy, and the environment. The CIR process is completed on grade and typically consists of milling the existing pavement to the specified depth, usually 50 – 100 mm (2 – 4 in). The Reclaimed Asphalt Pavement (RAP) is then screened and crushed to meet specifications, typically 25 – 37.5 mm (1 – 1.5 in), mixed with additives (emulsions, recycling agents, fly ash/cements, lime slurry), and finally spread and compacted. CIR can be accomplished using a single-unit train or a multi-unit train. The single-unit train consists of a milling machine that does the cutting, RAP sizing and blending at the cutting head (Kearney 1997). The recycled mix is then placed either in a windrow or directly into a paver hopper. The multi-unit train consists of a milling machine, a trailer mounted screening/crushing unit and a trailer mounted pugmill mixer.

Once the windrow has been placed, a conventional asphalt paver is usually used to place the recycled mixture, which is typically 50 – 100 mm (2 – 4 in) thick. After placement, the emulsion breaks and compaction begins. Breaking is the evaporation of water from the mixture and can be seen visually as a change in color of the mix from brown to black. Compaction is then performed, first by a large 23-ton or larger pneumatic-tired roller and then by an 10 –12 ton steel double drum vibratory roller. A new surface course is placed on the CIR mixture after curing, which typically requires one to two weeks, or sometimes less. This surface course is usually a hot mix asphalt

(HMA) overlay, but can also be a surface treatment such as a chip seal for lower volume roads.

The most important aspect to consider for successful CIR mixtures is project selection. When CIR projects fail, it is most often because agencies fail to evaluate and select the appropriate rehabilitation process for the project. A proper selection process should include an assessment of the existing pavement conditions, mode of failure, causes of distress, and sampling and testing of the pavement materials, including the base, subbase, and subgrade. In addition, evaluation of the history of the pavement maintenance and its past and expected traffic volumes is necessary. Environmental consideration can also be a limiting factor on using CIR technology. Minimum construction air temperature in the range from 10 to 16°C (50 to 60°F) is recommended. In addition, CIR should not be performed in the presence of high humidity such as rain or fog.

Most pavement distresses, such as fatigue cracking, transverse thermal cracking, reflective cracking, and raveling, can be successfully corrected using CIR. CIR eliminates the existing damaged layers, thus producing a crack-free layer in the pavement structure. However, not all pavements are ideal candidates for CIR. Pavement distresses that are less successfully corrected include (Task Force No. 38, 1998):

- Rutted pavements caused by excessively high asphalt content,
- Failures caused by a wet, unstable base, subbase, or subgrade,
- Failures caused by heaving or swelling in underlying soils, and
- Stripped pavements.

Pavements with weak bases, subbases, or subgrades can be recycled full-depth using additives such as fly ash or portland cement, which produce higher early strengths. Also, CIR can be used in a stage construction process where the surface is milled off and windrowed to the shoulder, the base is stabilized, and the RAP is returned to the roadway where CIR operation continues as normal. Alternatively, CCPR can be used after the underlying materials are replaced or stabilized, by using a recycled mix produced at a central plant from the original pavement. Rutted pavements can also be recycled using CIR, if the rutting is in the asphalt and not in the underlying materials, by adding new aggregate. Also, the addition of some additives, including cement, lime, and fly ash, can allow for stripped pavements to be recycled.

Pavement distress is not the only factor that might make CIR impractical. Other conditions that could cause excessive difficulty in recycling include (Task Force No. 38, 1998):

- Presence of numerous manhole or drainage outlets,
- Excessive steep grades, 5% and 760 m (2,316 ft), which reduce production,
- Heavily shaded areas, which increase curing times,
- Asphalt pavements with a thickness less than 50 mm (2 in), and
- Excessive roadway accesses such as driveways.

Additional factors such as project size, pavement width, traffic volumes, traffic congestion, and excessive curves also need to be considered when determining the possible use of CIR.

2.2 Survey Questionnaire

A survey questionnaire was developed to determine the mix-design procedures, tests, and criteria agencies currently use for CIR projects. Due to the limitation of the project timeframe, the survey was designed to obtain answers primarily for partial-depth CIR using asphalt emulsions. The survey was conducted in the spring of 1998. Table 2.1 shows the use of CIR by state agencies. All 50 states and two provinces were asked to fill out the questionnaire. Of these, 46 states responded and 24 states currently use, have used or will use CIR. It should be noted that CIR is more popular for county and local agencies than SHAs because CIR has typically been used for lower volume roads, which are usually in the jurisdiction of the county and local agencies. However, some state agencies have recently begun to perform more CIR projects on higher volume roadways, including interstates. A few selected contractors and suppliers were also asked to complete the questionnaire for 29 respondents who use CIR. Of the respondents, 13 use partial-depth CIR, four use full-depth, and seven use both.

The Marshall mix-design is the most common method practiced, but other mix-designs are utilized including Hveem, Gyratory Compaction, and the Oregon Method (Table 2.2). In addition, 24 of the 46 respondents use emulsions as an additive, with most using high-float type emulsions. Some use slow setting and medium setting cationic emulsions. Lime, fly ash, and Portland cement are also used as additives by eight, four, and three respondents, respectively. For sampling, eight respondents use cores and millings, ten use only cores, five use only millings, and three do not use RAP samples. The maximum RAP size allowed in the mixture ranges from 19 to 75 mm (0.75 to 3 in), with 31.75 mm (1.25 in) being the most common. Four agencies do not

Table 2.1. CIR Use For State-Maintained Highways by SHAs (1998)

STATE	USE CIR	DON'T USE CIR	HAVE USED CIR IN THE PAST	PLAN TO USE CIR IN THE FUTURE
ALABAMA			X (RESEARCH)	
ALASKA		X		
ARIZONA	X			
ARKANSAS		X		
CALIFORNIA			X	
COLORADO	X			
CONNECTICUT				X
DELAWARE				
DIST/COLUMBIA		X		
FLORIDA		X		
GEORGIA		X		
HAWAII		X		
IDAHO	X			
ILLINOIS		X		
INDIANA		X		
IOWA				
KANSAS	X			
KENTUCKY		X		
LOUISIANA		X		
MAINE		X		
MARYLAND		X		
MASSACHUSETTS				
MICHIGAN		X		
MINNESOTA				
MISSISSIPPI		X		
MISSOURI		X		
MONTANA	X			
NEBRASKA			X	
NEVADA				
NEW HAMPSHIRE	X			
NEW JERSEY	X			
NEW MEXICO	X			
NEW YORK	X			
NORTH CAROLINA	X			
NORTH DAKOTA		X		
OHIO		X		
OKLAHOMA	X			
OREGON	X			
PENNSYLVANIA	X			
PUERTO RICO		X		
RHODE ISLAND		X		
SOUTH CAROLINA		X		
SOUTH DAKOTA	X			
TENNESSEE		X		
TEXAS	X			
UTAH	X			
VERMONT	X			
VIRGINIA		X		
WASHINGTON	X			
WEST VIRGINIA				
WISCONSIN			X	
WYOMING				X

have a maximum size limit. The testing performed on the RAP is shown in Table 2.3. All agencies perform standard testing on the emulsion with the exception of one.

Table 2.2. Mix-Design Methods Currently Specified by SHA's

Mix-Design Method	**No. of Respondents**
Marshall	11
Hveem	3
Gyratory Compactor	4
Other	7
None	4

Ten respondents allow the addition of new aggregate and nine respondents do not allow new aggregate. The reasons specified for using additional aggregate are to correct gradation, improve thickness, and to increase mixture strength. The amount of new aggregate allowed to be added to CIR mixtures ranged from 15 to 50%.

Table 2.3. RAP Testing Currently Performed By SHA's

Test	**No. of Respondents**
Asphalt Content	13
Extracted Gradation	12
RAP Gradation	3
Viscosity	7
Penetration	6
Visual	2
None	1

The specifications for the amounts of added water and emulsion are too numerous to list, but are usually based on total liquids content and are often determined using density curves. Considerable variability also exists in the curing temperatures and times that are used for mix-designs. Most agencies use either 60^0C (140^0F) or room temperature for curing. The curing times range from two hours to three days. No state agencies considered humidity.

Numerous tests are performed on the mix-design specimens in addition to the Marshall and Hveem stability. These tests include direct and unconfined compression, dynamic modulus, cohesion, retained resilient modulus, and indirect tension.

The pavement distresses considered when designing mixes include cracking (fatigue, low-temperature, transverse, and reflective), rutting, stripping, and flushing.

2.3 *Existing Mix-Design Methods*

A careful review of the mix-design methods that are currently being used or have been used in the past for CIR of asphalt pavements has been completed. These methods are briefly reviewed in the following sections.

2.3.1 Oregon Method

The Oregon Method (Rogge et al. 1990) estimates the initial emulsion content to be added to a recycled mixture. The procedure begins with a base emulsion content to which adjustments are made based upon test results on the milled RAP samples. The estimated emulsion content (EC_{EST}), in percent, is determined using Eq. 2.1,

$$EC_{EST} = 1.2 + A_G + A_{AC} + A_{P/V} \tag{2.1}$$

1.2 = base emulsion content (%),

A_G = adjustment for gradation (%),

A_{AC} = adjustment for residual asphalt content (%),

$A_{P/V}$ = adjustment for penetration or viscosity (%).

The amount of water to be added is determined by subtracting the emulsion content from the total liquids content. The total liquids content is determined by using the modified Oregon State Highway Division test method, OSHD TM-126. Adjustments are then made in the field based upon observation, e.g., less emulsion is used if the mixture seems to have too much asphalt. The recycling agent used before 1988 was CMS-2SD, and HFE-150 emulsion has been used since 1988.

Oregon conducted research to evaluate the mix properties (resilient modulus, fatigue, Marshall stability and flow, and Hveem stability) to determine mix-design criteria. Results indicated that none of the mix property tests accurately predicted the same emulsion content as the estimation procedure presented earlier, (Eq. 2.1). Therefore, it was concluded that the estimation procedure was the most efficient procedure.

2.3.2 California Method

California (Epps 1990) uses the Hveem stabilometer for determination of the optimum binder content. RAP samples are tested for asphalt content, aggregate gradation, and asphalt viscosity. An aggregate surface area equation applied to the extracted aggregate of the RAP is used to determine asphalt content. The viscosity of the reclaimed asphalt and the base asphalt is used to determine the grade of recycling agent. Laboratory samples are prepared by adding 2% water and varying emulsion contents. The samples are cured at 60°C (140°F) for 16 hours and compacted with a kneading compactor at 60°C (140°F). Hveem stability values at 60°C (140°F) are determined and air voids calculated. The recommended asphalt content for the mix is selected as the highest emulsion content that shows no signs of bleeding, has a minimum of 4% air voids and minimum Hveem stability value of 30 for travel lanes and 25 for shoulders.

2.3.3 Chevron Method

Chevron ("Cold" 1982) uses resilient modulus, Hveem stabilometer, Hveem cohesionmeter, and mix workability to determine the optimum binder content. RAP gradation is adjusted, if necessary, by the addition of new aggregate to accommodate new binder or to increase the stability of the CIR. The asphalt demand of the RAP is determined by the centrifuge kerosene equivalent (CKE) test and Hveem aggregate surface area formula. A minimum asphalt emulsion content of 2% is specified. If less than 2% is indicated, the mix-design calls for adding new aggregate. The binder content is based on a final cure resilient modulus in the range of 150,000 to 600,000 psi at 23°C (73°F), minimum Hveem stability of 30 at 60°C (140°F) and minimum cohesionmeter value of 100 at 60°C (140°F).

2.3.4 Asphalt Institute Method

The Asphalt Institute (AI) method is summarized in MS-19, *A Basic Asphalt Emulsion Manual* (*Basic* 1979) and is the same method as their emulsified asphalt method. The CKE test is used to determine the range of optimum binder content. Samples are prepared and the optimum fluids content determined. Strength and modulus, and retained strength after moisture conditioning are also determined. AI recommends the use of the heaviest asphalt that can be worked. In addition, AI stresses the use of lower-viscosity asphalt cements for mixes with high fines and higher-viscosity asphalt cements for mixes with low fines.

2.3.5 US Army Corps Of Engineers Method

The Corps of Engineers Method ("Guide" 1989) is essentially a Marshall mix-design using 50 blows for compaction. The RAP and any additives are treated as hot mix and the mix requirements are the same as HMA for low traffic pavements.

2.3.6 University of Kansas Research

Researchers at the University of Kansas (Cross and Ramaya 1995) performed a study to evaluate three mix-design methods. The first method to be evaluated was the US Army Corps of Engineers Method, the second was a modification of the Corps of Engineers Method using samples compacted at 60°C (140°F), and the third method utilized the Corps of Engineers Gyratory Testing Machine. Based on the conclusions obtained from this evaluation, the study recommends the following: (a) CIR mix-design samples should be compacted at 135°C (275°F) with a gyration angle of 1° for 150 revolutions at 620 kPa ram pressure, (b) CIR mixes should have a maximum GEPI of 1.54 and a minimum shear strength of 100 kPa, (c) Millings should be used for testing instead of cores, and (d) mixtures indicating unacceptable rutting should be redesigned with additional aggregate or possibly chemical stabilization.

2.3.7 Pennsylvania Method

Pennsylvania DOT (Epps 1990) uses the resilient modulus test for its mix-design, which was developed based on the results of more than 90 CIR projects constructed in the state. Marshall tests are run for informational purposes only. New aggregate can be added if the RAP consists of a sand mix, contains excessive binder or does not have an acceptable aggregate gradation. The emulsion content is developed using Hveem's aggregate surface area formula applied to the RAP after extraction. CMS-2 emulsion with an asphalt residue of 100 to 250 penetration is used when the penetration of the recovered asphalt is between 15 to 20. CSS-1h emulsions with an asphalt residue of 40 to 90 penetration are used for softer recovered asphalt.

Pennsylvania DOT (Kandhal and Koehler 1987) determines the optimum compaction moisture content by keeping a constant emulsion content of 2.5% and varying the initial moisture in increments of 1%. Hand mixing is performed for 2 minutes. The RAP is maintained at 23°C (73°F) and the emulsion heated to 60°C (140°F). 75-blow Marshall compaction at 23°C (73°F) is used for the samples. The optimum emulsion content is determined by considering the bulk specific gravity, initial resilient modulus, soaked resilient modulus, and percent-retained resilient modulus. No design values were established for these test parameters. The optimum compaction moisture and emulsion content are the starting point and field adjustments are made as necessary.

2.3.8 New Mexico Method

In 1986 New Mexico did not use a specific mix-design method (Hanson and Williams 1986). The New Mexico State Highway and Transportation Department used high float polymer-modified emulsion to overcome pavement problems such as rutting, reflective cracking and moisture damage that occurred when using SS1 and CMS-2S emulsions. Hanson and Williams reported that high float emulsions worked better with their high fines aggregates.

The review of these various mix-design methods verifies that there is not a mix-design method being used as a standard for the CIR industry.

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Chapter 3. Expert Task Group and Work Plan

3.1 Expert Task Group

In order to develop a performance-based mix-design that will be useful to the entire CIR industry, a broadly represented Expert Task Group (ETG) was formed to help guide the research. The ETG is comprised of experts from all areas of the CIR industry as well as different areas of the United States and even Canada. The ETG includes emulsion chemists and suppliers, CIR contractors, federal, state and county engineering personnel, academia, and researchers (Table 3.1).

Table 3.1. Expert Task Group

ETG Member	Affiliation
John Huffman	Brown & Brown, Inc.
Alan James	Akzo Nobel Chemicals
Robert Joubert	Asphalt Institute
Ed Kearney	Gorman Bros., Inc.
Larry Ostermeyer	Mcconnaughay Technologies, Inc.
Todd Thomas	Koch Materials Co.
Steve Cross	University of Kansas
Gary Hicks	Oregon State University
Gerhard Kennepohl	Ministry of Transportation Ontario
Robert McGennis	Navajo Western Asphalt Co.
Charley Johnson	Dept. Of Land & Water Resources
Francis Manning	Rhode Island DOT
Dan Schact	Ramsey County Public Works, Minn.
Dean Steward	Kansas DOT
James Stokes	New Mexico State Highway & Tran.
John Bukowski	FHWA
Jason Harrington	FHWA
Tim Lewis	FHWA
Jim Sorenson	FHWA
Taylor Eighmy	University of New Hampshire
David Gress	University of New Hampshire

3.2 Experimental Work Plan

The ETG's first assignment was to refine the project framework. The ETG decided that the focus of the project needed to be limited due to the limited funds and time. Therefore, the mix-design was developed for partial-depth CIR with emulsions as the binding agent, which is defined as a rehabilitation technique that reuses a portion of the existing asphalt-bound materials (Epps 1990). In addition, the ETG decided that evaluation of additives would be limited to asphalt emulsions with the Superpave Gyratory Compactor (SGC) being used for the volumetric mix-design.

A work plan was formulated for the experimental work of developing a mix-design, and consists of five phases (Table 3.2). The first phase was the identification of sensitivities for CIR mixtures. The ETG determined that the important distress modes to consider in the mix-design are rutting, fatigue cracking, thermal cracking and water sensitivity. The second phase was the procurement of the test samples, including the RAP and emulsions. In order to have representative samples, the RAP would need to be obtained from different regions. Thus, RAP was obtained from Kansas, Connecticut, Ontario, Arizona and New Mexico, as these localities represent different conditions that can be found in North America. For the third phase of the work plan, the ETG decided

Table 3.2. Experimental Work Plan for CIR Project

	Tasks
I.	Identify Sensitivities
II.	Procure and Test RAP & Emulsion
III.	Evaluation of Modified Marshall Mix-Design (AASHTO Task Force No. 38)
IV.	Development of Performance Based Mix-Design
V.	Limited Field Evaluation of Developed Mix-Design

that the Modified Marshall mix-design method recommended by the AASHTO Task Force No. 38 should be evaluated. The fourth phase was the development of a new performance based mix-design method. The final phase was a limited field evaluation.

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Chapter 4. Evaluation of Existing Mix-Design Methods

4.1 Material Properties

The existing mix-design methods have been evaluated to determine the processes that are currently being used for CIR, as well as to determine if there are any faults, or deficiencies, which are present in these methods.

In order to properly evaluate the existing mix-design methods, one must first characterize the materials that will be used. To accomplish this step, several tests were performed on the two materials, Kansas and Ontario, to be used for these evaluations. These tests include sieve analyses of the RAP, determination of the RAP asphalt content and sieve analysis of the extracted aggregate.

RAP was received from roads that were under construction or were soon to undergo construction using CIR pavement rehabilitation. It was specified that the samples would be millings obtained from milling machines as part of the CIR recycling train. Material from Kansas was taken from a RAP stockpile that was created from US-70 in Kansas, which was undergoing CIR. Ontario material was obtained directly from the millings of a CIR project in Ontario, Canada. RAP material from both sites was deposited into 55 gallon barrels and shipped to the University of Rhode Island.

Once the RAP was received, sieve analyses were performed on the RAP following the procedures of AASHTO T27-93 and ASTM C136-93 in order to obtain representative samples. After analyzing the gradations of the materials, it was found that some of the particles in the RAP were larger than 31.75 mm (1.25 in.). Therefore, the materials were processed to meet the sizing requirements of the Modified Marshall Mix-Design. In order to avoid producing excessively fine materials, a heavy hammer was used to crush these large particles. Gradations of the two processed materials were obtained through this process and are shown in Table 4.1.

Table 4.1. RAP Gradation (Processed)

Sieve Size	Kansas RAP % Passing	Ontario RAP % Passing
31.8 mm (1 ¼")	100	100
25 mm (1")	100	100
19.1 mm (¾")	90.4	96.1
12.5 mm (½")	76.1	86.0
9.5 mm (3/8")	65.5	74.7
4.75 mm (# 4)	42.6	48.3
2.36 mm (# 8)	23.3	27.1
1.18 mm (#16)	15.8	12.1
0.6 mm (# 30)	8.7	4.1
0.3 mm (# 50)	3.5	1.1
0.15 mm (# 100)	1.5	0.3
0.075 mm (#200)	0.4	0.1

Two methods were used to determine the asphalt contents of the RAP materials. The first method was the extraction of the asphalt using AASHTO T164-93. The second method utilized an asphalt ignition oven to burn off the asphalt leaving the aggregate behind and thus allowing for calculation of the asphalt content. It was determined that the asphalt content was 4.4% for the Kansas RAP. The gradation of the extracted aggregate was then obtained through sieve analyses, AASHTO T30-93, as is shown in Table 4.2.

Table 4.2. Extracted Aggregate Gradation

Sieve Size	Kansas RAP % Passing
19.1 mm (¾")	100
12.5 mm (½")	97.6
9.5 mm (3/8")	92.5
4.75 mm (# 4)	73.5
2.36 mm (# 8)	55.8
1.18 mm (#16)	42.6
0.6 mm (# 30)	30.8
0.3 mm (# 50)	16.4
0.15 mm (# 100)	8.5
0.075 mm (#200)	5.2

In addition to the RAP, emulsion was also obtained for use in the laboratory experiments. It was specified that the emulsion should be what each project would typically use for CIR for that particular site. Koch Materials Co. in Wichita, Kansas sent CSS-1h emulsion with the Kansas RAP. HF150P emulsion accompanied the Ontario RAP. The emulsion suppliers tested the supplied emulsion and they were found to meet all ASTM specifications.

4.2 Modified Marshall Mix-Design

The modified Marshall mix-design, recommended by AASHTO Task Force No. 38, was evaluated using the Kansas and Ontario materials. The procedure is summarized below. However, for the complete detailed procedure, refer to the Task Force No. 38 report. The mix-design consists of two parts.

The first part is the determination of the optimum emulsion content and the second part is the determination of the optimum water content. Steps for the first part are indicated as follows:

1. Weigh sufficient RAP to fabricate 62.5 mm (2.5 in) specimens into individual pans and let stand at mixing temperature at 25°C (77°F) for one hour. Prepare three specimens for each emulsion content.
2. Add sufficient water to obtain 3% total liquids content and mix for one minute.
3. Add emulsion heated to 60°C (140°F) and mix until evenly dispersed but less than two minutes.
4. Fabricate specimens by applying 50 blows of the Marshall hammer to each face at 25°C (77°F).

5. Cure specimens in their molds for 6 hours at 60°C (140°F).
6. Remove molds from the oven and allow specimens to cool on their side overnight and extrude.
7. Test specimens for bulk specific gravity at 25°C (77°F).
8. Bring specimens to 25°C (77°F) for two hours and test for stability and flow (AASHTO T245).
9. Determine maximum specific gravity for each emulsion content.

The data obtained from the above procedure was analyzed to determine the optimum emulsion content (OEC), as described below.

In the second part, three specimens each at varying water contents below and above 3% were fabricated at the OEC. A step-by-step procedure similar to that cited previously was used to determine the optimum water content (OWC).

Tables 4.3 and 4.4 show the tabulated results for part one and two, respectively.

Table 4.3. Modified Marshall Mix-Design Data for Cold In-Place Recycling
To Determine the Optimum Emulsion Content (OEC)

<table>
<tr><th colspan="6">Mix No. 1 – Varying Emulsion Contents</th></tr>
<tr><th colspan="6">Kansas RAP w/ CSS-1h Emulsion</th></tr>
<tr><td>Emulsion %</td><td>0.5</td><td>1.0</td><td>1.5</td><td>2.0</td><td>2.5</td></tr>
<tr><td>Water %</td><td>3.0</td><td>3.0</td><td>3.0</td><td>3.0</td><td>3.0</td></tr>
<tr><td>Bulk SG</td><td>2.042</td><td>2.019</td><td>2.011</td><td>1.991</td><td>1.991</td></tr>
<tr><td>Max. SG</td><td>2.453</td><td>2.444</td><td>2.434</td><td>2.413</td><td>2.405</td></tr>
<tr><td>Air Voids (%)</td><td>16.8</td><td>17.4</td><td>17.4</td><td>17.5</td><td>17.2</td></tr>
<tr><td>Unit Weight</td><td>127.1</td><td>125.6</td><td>125.2</td><td>123.9</td><td>123.9</td></tr>
<tr><td>Stability (lbs)</td><td>1733</td><td>1675</td><td>1833</td><td>1667</td><td>1664</td></tr>
<tr><td>Flow (1/100 in)</td><td>12.0</td><td>15.0</td><td>17.0</td><td>19.8</td><td>20.7</td></tr>
<tr><th colspan="6">Ontario RAP w/ HF150P Emulsion</th></tr>
<tr><td>Emulsion %</td><td>0.5</td><td>1.0</td><td>1.5</td><td>2.0</td><td>2.5</td></tr>
<tr><td>Water %</td><td>2.0</td><td>2.0</td><td>2.0</td><td>2.0</td><td>2.0</td></tr>
<tr><td>Bulk SG</td><td>2.093</td><td>2.108</td><td>2.092</td><td>2.114</td><td>2.100</td></tr>
<tr><td>Max. SG</td><td>2.469</td><td>2.450</td><td>2.431</td><td>2.417</td><td>2.402</td></tr>
<tr><td>Air Voids (%)</td><td>15.2</td><td>14.0</td><td>13.9</td><td>12.6</td><td>12.6</td></tr>
<tr><td>Unit Weight</td><td>130.2</td><td>131.2</td><td>130.2</td><td>131.6</td><td>130.7</td></tr>
<tr><td>Stability (lbs)</td><td>1499</td><td>1581</td><td>1390</td><td>1254</td><td>1222</td></tr>
<tr><td>Flow (1/100 in)</td><td>14.5</td><td>13</td><td>16</td><td>11</td><td>19</td></tr>
</table>

The OEC for the Kansas RAP was determined to be 1.2% based on the highest stability value. The OWC was found to be 3.0% based on the highest stability and optimum air voids. The optimum air void content that was used was 11%, since this was the approximate mid-point of the 9 – 14% air voids suggested by AASHTO Task Force No. 38. The OEC for the Ontario RAP was determined to be 1.2% based on the maximum stability value. The OWC was found to be 2.2% based on the maximum stability and optimum air voids.

Table 4.4. Modified Marshall Mix-Design Data for Cold In-Place Recycling To Determine the Optimum Emulsion Content (OEC)

Mix No. 2 – Varying Water Contents					
Kansas RAP w/ CSS-1h Emulsion					
Emulsion %	1.2	1.2	1.2	1.2	1.2
Water %	2.0	2.5	3.0	3.5	4.0
Bulk SG	2.014	2.033	2.038	2.034	2.019
Max. SG	2.415	2.418	2.419	2.418	2.413
Air Voids (%)	16.6	15.9	15.7	15.9	16.3
Unit Weight	125.3	126.6	126.9	126.6	125.7
Stability (lbs)	1758	1867	2107	1942	1725
Flow (1/100 in)	19.7	20.0	17.7	17.3	18.3
Ontario RAP w/ HF150P Emulsion					
Emulsion %	1.2	1.2	1.2	1.2	1.2
Water %	1.5	2.0	2.5	3.0	3.5
Bulk SG	2.056	2.061	2.074	2.082	2.078
Max. SG	2.485	2.486	2.483	2.487	2.490
Air Voids (%)	17.3	17.1	16.5	16.3	16.5
Unit Weight	128.0	128.3	129.1	129.6	129.4
Stability (lbs)	1378	1274	1300	1300	1144
Flow (1/100 in)	16.5	15	15	13	10.5

However, there was one noticeable problem with the mixtures. The air voids in the mixes were higher than the design parameter of 9 – 14% air voids suggested by Task Force No. 38. The densities obtained through field-testing using a nuclear gauge are also higher than those found using this method. One possible reason for this problem is the gradation of the RAP, which has a very small amount of fine material. The coarse RAP does not allow for proper compaction. In addition, CSS-1h is usually best used with dense-graded mixtures. However, it is felt that the best explanation for these differences lies in the inability of this Marshall procedure to accurately simulate field conditions.

During the evaluation, the following problems and disadvantages were identified with the Modified Marshall procedure:

1. The first disadvantage with this procedure is the amount of time needed to complete the entire procedure. The procedure can take upwards of 8 days to perform, where as a typical HMA mix design can be performed in 2 days. This amount of time may be more than most contractors and DOT engineers would be willing to allocate for one mix-design.
2. The procedure does not give any specifications for when new aggregate should be added to the mixture. There should be some specification for the gradation of the mixture, either a general specification or an agency specification.
3. The amount of material needed to fabricate 62.5 mm (2.5 in) specimens was about 1,000 g, which was less than that suggested in the procedure, i.e. 1,150g. The unit weight of the mix will determine the amount of material that is needed.
4. The procedure does not mention how long to cure the specimen to allow the mixture to break.
5. The procedure does not state how long to heat the emulsion in the oven, and also does not address the temperature differences for different emulsions.

6. For the determination of bulk specific gravity, the procedure states to directly immerse the specimens in the water. Due to the higher air voids found in CIR mixes, however, it may be necessary to wrap the specimens in parafilm before their immersion in the water, or to use another suitable method such as the CoreLok system.
7. The procedure does not clearly state how to determine the optimum values for the emulsion and water contents.
8. The procedure does not accurately simulate field densities.
9. The design has no bearing on how well the mix will perform. The critical need of the industry is to show performance of the mix.

These observations suggest that this procedure is not the best mix-design method for CIR. In addition, since the use of the Superpave mix-design has had considerable success for HMA, it was decided to modify the Superpave mix-design for use in this project. In the process of developing the performance-based mix-design method, the disadvantages of the modified Marshall mix-design are addressed and corrected wherever possible.

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Chapter 5. Development of Mix-Design For Cold In-Place Recycling (CIR) Using Superpave Apparatus

5.1 Pilot Study

The first step in developing a new mix-design was to perform a pilot volumetric mix-design on the RAP materials from Kansas, Ontario, and Connecticut using the Superpave Gyratory Compactor (SGC). The purpose of this pilot study was to determine how the different materials react to the compaction of the SGC. Density values obtained from this study were used to help determine the amount of compaction that was needed for the remainder of the experimental testing, as well as for the development of the new mix-design. The modified Marshall mix-design procedure was used for the pilot modified Superpave mix-design with some adjustments. They are as follows:

1. Weigh 4,000 grams of previously sieved RAP into individual pans and let stand at the mixing temperature of 25°C (77°F) for one hour. Also, heat emulsion and molds at 60°C (140°F) for one hour. Prepare two specimens for each emulsion content.
2. Add sufficient water to obtain 3% total liquids content by weight and mix for one minute.
3. Add emulsion and mix until evenly dispersed but for less than two minutes.
4. Allow the mixture to cure for one hour. This will allow the emulsion to break before compaction.
5. Fabricate 150 mm specimens using the SGC by applying 52 gyrations at 600 kPa at an angle of gyration of 1.25° at 25°C (77°F). 52 gyrations were used

as a starting point for compaction, which was half of that specified for HMA, since no previous research had been done using the SGC.

6. Extrude specimens from the molds and cure for 6 hours at 60°C (140°F).
7. Remove specimens from the oven and allow specimens to cool on their sides overnight.
8. Test specimens for bulk specific gravity at 25°C (77°F).
9. Determine maximum specific gravity for each emulsion content.

Using the data from the procedure above, the OEC was determined, as described below. At this OEC, two specimens each at varying water contents below and above 3% were fabricated. A procedure similar to the one mentioned above was used to determine the OWC.

Table 5.1 and Table 5.2 show the tabulated results for part one and two of the mix-design, respectively. The OEC for the Kansas RAP was determined to be 1.4% at air voids of 11%. The OWC was found to be 2.9% at 11% air voids.

Air voids for the Ontario RAP was in the range of 6% to 9%, which indicates that the compactive effort was too high. However, the SGC measures the height of each specimen after every gyration, which can be used in conjunction with the measured bulk specific gravity to determine the number of gyrations where the specimens are at the optimum 11% air voids. The point where the four varying emulsion contents average 11% air voids is then taken to be the proper number of gyrations. For this mixture, it was determined that 25 gyrations would be necessary. Therefore, the OEC for the Ontario RAP was determined to be 1.2%, and the OWC was found to be 2.1%.

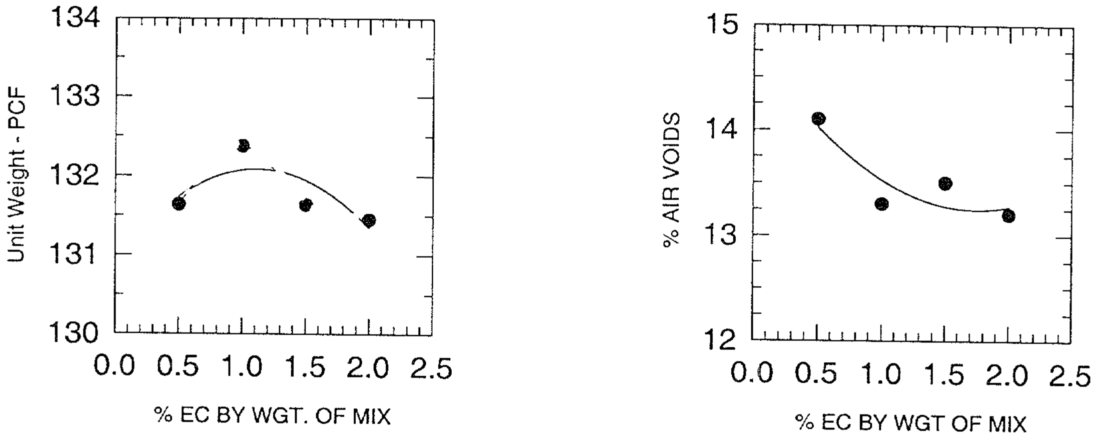
Table 5.1. Pilot Study Mix-Design Data to Determine OEC

Kansas RAP w/CSS-1h Emulsion				
Emulsion %	0.5	1.0	1.5	2.0
Water %	3.0	3.0	3.0	3.0
Bulk SG	2.157	2.155	2.155	2.141
Max. SG	2.436	2.429	2.422	2.414
Air Voids (%)	11.5	11.3	11.0	11.3
Unit Weight (pcf)	134.2	134.2	134.2	133.2
Ontario RAP w/HF150P Emulsion				
Emulsion %	0.5	1.0	1.5	2.0
Water %	3.0	3.0	3.0	3.0
Bulk SG	2.287	2.307	2.311	2.315
Max. SG	2.506	2.495	2.486	2.479
Air Voids (%)	8.8	7.6	7.0	6.6
Unit Weight (pcf)	142.3	143.6	143.8	144.1
Connecticut RAP w/HFMS-2T Emulsion				
Emulsion %	0.5	1.0	1.5	2.0
Water %	3.0	3.0	3.0	3.0
Bulk SG	2.115	2.127	2.115	2.112
Max. SG	2.462	2.453	2.446	2.434
Air Voids (%)	14.1	13.3	13.5	13.2
Unit Weight (pcf)	131.6	132.4	131.6	131.5

The OEC for the Connecticut RAP was determined to be 1.2% at the maximum unit weight of 132.1 pcf, which resulted in air voids of 13.4% (Figure 5.1a). The OWC was found to be 2.3% at the maximum unit weight of 133.4 pcf, which resulted in air voids of 12.6% (Figure 5.1b).

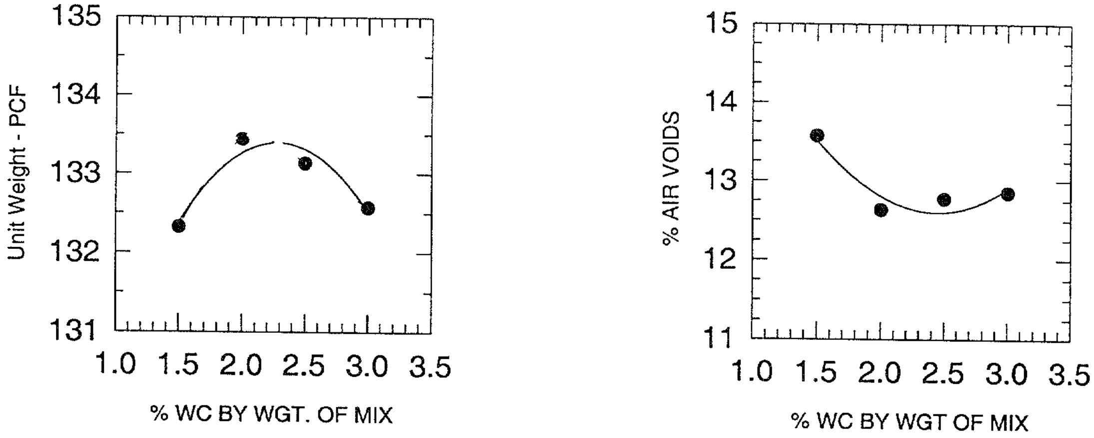
Table 5.2. Pilot Study Mix-Design Data to Determine OWC

Kansas RAP w/CSS-1h Emulsion				
Emulsion %	1.4	1.4	1.4	1.4
Water %	2.0	2.5	3.0	3.5
Bulk SG	2.196	2.170	2.153	2.146
Max. SG	2.418	2.420	2.421	2.422
Air Voids (%)	9.2	10.4	11.1	11.4
Unit Weight (pcf)	136.7	135.0	134.0	133.6
Ontario RAP w/HF150P Emulsion				
Emulsion %	1.2	1.2	1.2	1.2
Water %	1.5	2.0	2.5	3.0
Bulk SG	2.319	2.272	2.259	2.251
Max. SG	2.474	2.468	2.464	2.461
Air Voids (%)	6.3	7.9	8.3	8.5
Unit Weight (pcf)	144.3	141.4	140.6	140.1
Connecticut RAP w/HFMS-2T Emulsion				
Emulsion %	1.2	1.2	1.2	1.2
Water %	1.5	2.0	2.5	3.0
Bulk SG	2.126	2.144	2.139	2.130
Max. SG	2.457	2.454	2.452	2.444
Air Voids (%)	13.6	12.6	12.8	12.9
Unit Weight (pcf)	132.3	133.4	133.1	132.6



OEC = 1.2%

(a) Determination of Optimum Emulsion Content (OEC)



OWC = 2.3%

(b) Determination of Optimum Water Content (OWC)

Figure 5.1. Pilot Mix-Design for CIR Mixture using Connecticut RAP

5.2 *Experimental Program to Develop New Mix-Design*

After several pilot trials, an experimental program was undertaken in order to consider the effects certain important variables had on the CIR mix-design. The Connecticut RAP and HFMS-2T emulsion were used for this investigation. Since unit weight is the most important factor to consider for new CIR pavements, it was the response chosen for this analysis. Variables under study include emulsion content (EC), total liquid content (TLC), curing time, and curing temperature (Table 5.3). The emulsion content had four levels ranging from 0.5% to 2.0% of total mix by weight, in 0.5% increments. This range has two emulsion contents above and below the optimum emulsion content of 1.2% by weight that was determined in the pilot study. This range also covers most emulsion contents that would be found in the field.

Table 5.3. Experimental Design – Connecticut RAP w/HFMS-2T Emulsion

	Emulsion Content, %	0.5		1.0		1.5		2.0	
	Total Liquid Content, %	3.5	4.0	3.5	4.0	3.5	4.0	3.5	4.0
Curing Temp., F	Curing Time, Hours								
140	24	2	2	2	2	2	2	2	2
	6	2	2	2	2	2	2	2	2
77	24	2	2	2	2	2	2	2	2
	6	2	2	2	2	2	2	2	2

Note: 2 Specimens Prepared for Each Cell

Two levels were used for TLC, 3.5% and 4.0%. TLC was used as a parameter instead of water content due to its high use as a parameter for mix-designs. In addition, TLC is a more fundamental measure of the moisture in the mixtures, rather than water content, since the emulsion also contains some water. The total liquid content of 3.5% was chosen because this is the optimum content that was found from the pilot study for the Connecticut material, i.e., 1.2% EC + 2.3% WC = 3.5% TLC. The total liquid content of 4.0% was chosen because it is a typical field value.

Review of the literature and the results from the survey questionnaire show that there is a wide range of curing times for mix-design specimens, usually anywhere from two hours to three days. In addition, many mix-designs use a combination of curing times and temperatures. Therefore, the curing times of 6 hours and 24 hours were chosen for this study because these curing times can be used to simulate two stages of the CIR construction. The early strength of the CIR pavements, immediately after compaction, can be simulated using the curing time of 6 hours. Similarly, the long-term strength of the CIR pavements before overlay or surface treatment can be simulated using the curing time of 24 hours. In addition, these times seem to be the most appropriate for the working schedule of laboratory personnel.

The two most common temperatures for curing of specimens after compaction are 60°C (140°F) and room temperature, which is approximately 25°C (77°F). Furthermore, these temperatures most accurately simulate field conditions, 60°C (140°F) being a typical value for the highest temperature that pavement reaches during a summer day and 25°C (77°F) a typical pavement temperature during summer nights, or during early season construction. Therefore, these two temperatures were chosen for the experimental program.

5.2.1 Compaction Level

In order to investigate the effects of the above parameters on CIR mixtures, it was imperative that the densities of the laboratory specimens simulate field densities. Therefore, actual field densities were obtained for the project. The unit weight that was obtained for the project for the sampling date was 130 pcf. Therefore, 130 pcf was the desired unit weight for the laboratory specimens. To achieve this density, one or more of the parameters of the SGC needed to be changed from the HMA specifications. The possible parameters to change are the number of gyrations, the vertical compaction pressure, the angle of gyration, and the speed of gyration. A study performed on the SGC at the Asphalt Institute during SHRP (Huber 1999), however, indicated that the speed of gyration had little effect and vertical pressure has only a small effect on density. The angle of gyration was found to have the greatest influence on the density. However, the angle of gyration of 1.25° was shown to be the best angle for proper densification (Huber 1999). Therefore, the number of gyrations was chosen as the parameter to change in the present study.

The SGC collects the height data of the specimen for each gyration during the compaction process. This information, along with the mass of the mix, can be used to estimate the specific gravity of the specimen after every gyration. This is accomplished by measuring the bulk specific gravity of the compacted specimen and comparing it to the estimated specific gravity after the last gyration. A correction factor, a ratio of the measured to estimated bulk specific gravity, is then applied to the estimated specific gravity to arrive at the corrected specific gravity for each gyration (McGennis et al. 1995). This procedure was used on the data obtained in the pilot study, and 37 gyrations were found to be necessary to achieve a density of 130 pcf for the Connecticut material, as shown in Appendix A. Thus, 37 gyrations were applied to compact the specimens for the experimental program.

5.2.2 Test Results and Data Analysis

The bulk specific gravity of each specimen was measured twice. The first measurement took place two hours after the end of the curing period. This delay was employed to allow the specimens heated to 60°C (140°F) to cool to room temperature. Specimens that were cured at 25°C (77°F) were also left at room temperature for two hours after the curing period to maintain consistency for all specimens. The second measurement was performed one week after compaction to allow all water to leave the specimen. Unit weight data for the first and the second measurement are shown in Table 5.4a and 5.4b, respectively. The raw data for the determination of unit weights can be found in Appendix B.

Table 5.4. Unit Weights (pcf) for Experimental Program
Using Connecticut RAP w/HFMS-2T Emulsion

(a) 2 Hours after Curing

Curing Temperature								
	25°C (77°F)				**60°C (140°F)**			
	Curing Time (Hours)							
	24		6		24		6	
	Total Liquid Content (%)							
Emul. Content (%)	**3.5**	**4.0**	**3.5**	**4.0**	**3.5**	**4.0**	**3.5**	**4.0**
0.5	132.6	131.9	132.5	130.3	129.9	129.6	132.5	131.3
1.0	129.0	131.6	132.4	133.2	129.8	129.5	131.6	131.2
1.5	131.0	131.8	135.1	135.2	134.4	131.4	130.3	130.4
2.0	131.0	130.6	132.2	131.4	133.6	133.5	132.5	131.4

Table 5.4. Unit Weights (pcf) for Experimental Program
Using Connecticut RAP w/HFMS-2T Emulsion

(b) 1 Week After Curing

Curing Temperature								
	25°C (77°F)				**60°C (140°F)**			
	Curing Time (Hours)							
	24		**6**		**24**		**6**	
	Total Liquid Content (%)							
Emul. Content (%)	**3.5**	**4.0**	**3.5**	**4.0**	**3.5**	**4.0**	**3.5**	**4.0**
0.5	132.0	130.9	130.2	132.8	130.2	130.1	131.3	130.6
1.0	128.5	130.3	131.1	131.1	129.8	129.7	131.0	131.0
1.5	130.6	130.8	133.6	133.1	134.6	131.6	129.9	130.0
2.0	130.4	129.8	131.7	131.0	133.8	133.8	132.3	131.0

With the use of the Minitab statistical software, an analysis of variance (ANOVA) was performed on this data to investigate the effects of the four variables (Emulsion Content, Total Liquid Content, Cure Time, and Cure Temp.). Based on the low p-values, it was found that all of the main effects were statistically significant at a level of significance of 0.05 as shown in Table 5.5. All of the two-way interactions of the variables were also found significant, except for the interaction of curing time and total liquid content. All of the three-way and four-way interactions were found significant as well. These results indicate that all four of the variables are essential to the preparation of CIR mixtures and need to be taken into consideration in the new mix-design method.

Further analysis of the data was performed through the application of two-sample t-tests. The values for the two unit weight measurements, i.e., 2 hours and 1 week after curing, were analyzed to determine if there is a difference between them. The null hypothesis is that the mean of the unit weight values two hours after curing are

Table 5.5. ANOVA

Analysis of Variance (Balanced Designs)

Factor	Type	Levels	Values
Curing Time (CTI)	fixed	2	6 hrs., 24 hrs.
Emulsion Content (EC)	fixed	4	0.5%, 1.0%, 1.5%, 2.0%
Total Liquids Content (TLC)	fixed	2	3.5%, 4.0%
Curing Temperature (CTE)	fixed	2	25°C (77°), 60°C (140°F)

Analysis of Variance for Unit Weight – 2-Hour Cure

Source	**DF**	**SS**	**MS**	**F**	**P**
Main Effects:					
Curing Time	1	10.0014	10.0014	31.40	0.000
Emulsion Content	3	20.5340	6.8847	21.49	0.000
Total Liquids Content	1	1.8225	1.8225	5.72	0.023
Curing Temperature	1	5.0963	5.0963	16.00	0.000
Interactions:					
CTI*EC	3	11.1894	3.7298	11.71	0.000
CTI*TLC	1	0.5077	0.5077	1.59	0.216
CTI*CTE	1	11.5600	11.5600	36.30	0.000
EC*TLC	3	6.6810	2.2270	6.99	0.001
EC*CTE	3	21.2470	7.0823	22.24	0.000
TLC*CTE	1	2.7806	2.7806	8.73	0.006
CTI*EC*TLC	3	3.3718	1.1239	3.53	0.026
CTI*EC*CTE	3	45.5577	15.1859	47.68	0.000
CTI*TLC*CTE	1	1.5876	1.5876	4.98	0.033
EC*TLC*CTE	3	5.1775	1.7258	5.42	0.004
CTI*EC*TLC*CTE	3	2.9817	0.9939	3.12	0.040
Error	32	10.1917	0.3185		
Total	63	160.2878			

equal to the mean of the unit weight values one week after curing. The low p-values obtained prove the alternate hypothesis that the mean of the unit weights just two hours after curing are not equal to the unit weights after one week for some of the factors as seen in Table 5.6. Closer inspection of the data shows the largest difference between the two measurements occurs for the specimens that were cured for 6 hours and the specimens that were cured at 25°C (77°F). The obvious reason for this is that the short time and cooler temperature does not allow all the mixing water to leave the specimen.

One week would allow most, if not all, of the water to leave the specimen. The 24 hour curing time and the 60°C (140°F) curing temperature would more easily allow the water to be removed from the specimen, thus resulting in less difference between values.

Table 5.6. Two Sample t-Tests

		N	Mean	St. Dev.	SE Mean	T	P
24 Hour Cure	UW_1	32	131.33	1.62	0.29	0.68	0.500
	UW_2	32	131.04	1.72	0.30		
6 Hour Cure	UW_1	32	132.12	1.49	0.26	2.30	0.025
	UW_2	32	131.35	1.16	0.21		
140°F	UW_1	32	131.44	1.53	0.27	0.41	0.680
	UW_2	32	131.28	1.60	0.28		
77°F	UW_1	32	132.00	1.63	0.29	2.39	0.020
	UW_2	32	131.11	1.34	0.24		
24 & 140°F	UW_1	16	131.47	2.05	0.51	-0.28	0.780
	UW_2	16	131.68	2.07	0.52		
24 & 77°F	UW_1	16	131.18	1.08	0.27	2.13	0.042
	UW_2	16	130.40	0.99	0.25		
6 & 140°F	UW_1	16	131.41	0.79	0.20	1.87	0.071
	UW_2	16	130.88	0.81	0.20		
6 & 77°F	UW_1	16	132.82	1.70	0.43	1.88	0.070
	UW_2	16	131.82	1.30	0.32		

UW_1 = Unit weight of specimens 2 hours after curing
UW_2 = Unit weight of specimens 1 week after curing

Based on the above analysis, specimen preparation specifications have been formulated for the new mix-design method for CIR, which are as follows:

1. The specimens are cured for 24 hours at 60°C (140°F) after compaction.
2. A minimum of four emulsion contents are used.
3. The number of gyrations used to compact the specimens should be adjusted to achieve densities similar to those found in the field.

The final mix-design procedure has been included in the next section.

5.3 Mix-Design Method for Cold In-Place Recycling of Asphalt Mixtures

5.3.1. Scope

This method covers the design of mixtures for cold in-place recycling (CIR) using the Superpave Gyratory Compactor. The procedures presented are applicable only for mixtures containing asphalt emulsion and reclaimed asphalt pavement (RAP). This method consists of two parts. The first is the determination of the optimum emulsion content and the second is the determination of the optimum mixing water content. A stand-alone version of this mix-design, following ASTM format, can be found in Appendix C.

5.3.2 Apparatus

5.3.2.1 See AASHTO TP4

5.3.3 Test Specimens

5.3.3.1 Preparation of RAP

- RAP samples shall be obtained from the roadway that will be recycled by taking cores to the specified depth. These cores will then be crushed in order to have representative samples.
- Dry a portion of the RAP to a constant mass at 110°C (230°F) to determine the moisture content. Dry the remainder of the RAP to a constant mass at 60°C (140°F) to remove the existing water.
- Separate the RAP into the following particle sizes, by screening through a series of sieves.

+ 31.75 mm (1 ¼”)
+ 25.0 mm (1”)
+ 19.1 mm (¾”)
+ 12.5 mm (½”)
+ 9.5 mm (3/8”)
+ 4.75 mm (# 4)
+ 2.36 mm (# 8)
+ 1.18 mm (# 16)
- 1.18 mm (# 16)

- Eliminate the material retained on the 31.75 mm (1.25 in) sieve either by removing or crushing the material such that excess fines are not produced.

5.3.3.2 Mixing and Compacting Temperatures

- The mixing temperatures shall be 25°C ± 2°C (77°F ± 4°F) for the RAP and mixing water. The mixing temperature for the emulsion varies depending on the emulsion. Obtain the correct mixing temperature from the emulsion manufacturer.
- The compaction temperature shall be 25°C ± 2°C (77°F ± 4°F).

5.3.3.3 Preparation of Mixtures

- The first part of the mix-design involves determining the optimum emulsion content, while keeping the mixing water content constant. A minimum of two specimens shall be prepared at each of a minimum of four emulsion contents by weight in 0.5% increments. All specimens will be prepared with 3.0% mixing water by weight (different water contents can be used based on experience). In addition, one loose sample shall be prepared for each additive content for determining the maximum theoretical specific gravity.

- Weigh into individual pans a sufficient amount of RAP (~ 4000 grams) based on the gradation determined in section 5.3.3.1 to fabricate specimens 150mm (6 in) in diameter and 115 mm (4.5 in) in height.
- Let RAP samples stand at 25°C ± 2°C (77°F ± 4°F) for a minimum of one hour. In addition, heat emulsion at the specified temperature (Section 5.3.3.2) for one hour.
- Add mixing water to each sample and mix thoroughly for one minute. Mixing may be performed either by hand or through the use of a mechanical mixer.
- Add emulsion to each sample according to section 5.3.3.3 and mix thoroughly until the emulsion is uniformly dispersed but for no longer than one minute. If the sample is not uniformly mixed after one minute, additional mixing water may be required to improve emulsion dispersion. Otherwise, another emulsion type may be required.

5.3.3.4 Compaction of Specimens

- Apply load immediately after mixing using the Superpave Gyratory Compactor (SGC). The loading pressure shall be 600 kPa (87 psi) at an angle of gyration of 1.25 degrees. The load shall be applied for the number of gyrations that will result in achieving densities similar to those found in the field.
- Remove specimens from their molds immediately after compaction.

- Oven cure the specimens at 60°C (140°F) for 24 hours.
- Remove the specimens from the oven and allow to cool to room temperature.

5.3.3.5 Bulk Specific Gravity, G_{mb}

5.3.3.5.1 (ASTM D2726 or AASHTO T166)

This test method should be used when the samples absorb less than 2% of water by volume as determined by section 10.4 of ASTM D2726. Otherwise, use ASTM D1188 (Section 5.3.3.5.2).

- Record the dry mass, A, of the specimen.
- Immerse the specimen in water at 25°C (77°F) for five minutes and record the immersed mass, C.
- Remove the specimen from the water, surface dry with a damp towel and record the surface-dry mass, B.
- Calculate the bulk specific gravity as follows:

$$G_{mb} = \frac{A}{(B - C)}$$

5.3.3.5.2 (ASTM D1188)

This test method should be used when the samples absorb more than 2% of water by volume as determined by section 10.4 of ASTM D2726. Otherwise, use ASTM D2726 (Section 5.3.3.5.1). The CoreLok system can also be used if the samples absorb more than 2%.

- Record the dry mass, A, of the specimen
- Coat specimen with parafilm and record the coated mass, D.

- Immerse the specimen in water at 25°C (77°F) and record the immersed mass, E.
- Determine the specific gravity of the parafilm at 25°C (77°F), F.
- Calculate the bulk specific gravity as follows:

$$G_{mb} = \frac{A}{(D - E - \frac{D - A}{F})}$$

5.3.3.5.3 Determine maximum theoretical specific gravity for each emulsion content using AASHTO T209.

5.3.3.6 Determine Optimum Emulsion Content (OEC)

- Plot unit weight versus percent emulsion content for each emulsion content.
- Plot percent air voids versus percent emulsion content for each emulsion content.
- OEC is the emulsion content at which the unit weight is at its maximum value.
- If a maximum unit weight is not achieved, the OEC should be the emulsion content at which the unit weight is similar to those found in the field.

5.3.3.7 Determine Optimum Mixing Water Content (OWC)

The OWC is determined by following steps 5.3.3.1 through 5.3.3.5, with the following exceptions.

- A minimum of two specimens will be prepared at the Optimum Emulsion Content (OEC) with each of a minimum of four varying water contents, surrounding the mixing water content used in step 5.3.3.3.
- Plot unit weight versus percent water content for each water content.
- Plot percent air voids versus percent water content for each water content.
- OWC is the water content at which the unit weight is at its maximum value.
- If a maximum unit weight is not achieved, the OWC should be the water content at which the unit weight is similar to those found in the field.
- If the OWC is more than 1.0% above or below the mixing water content used to determine the OEC, the procedure to determine the OEC in sections 5.3.3.3 through 5.3.3.6 shall be repeated. Preparing specimens using mixing water content equal to the OWC obtained above. If the new OEC is different from the first OEC, section 5.3.3.7 shall then be repeated using this new OEC to determine the OWC. If there is no change in the value of the OEC, section 5.3.3.7 does not need to be repeated.

5.3.3.8 Moisture Sensitivity

- Prepare six specimens at OEC and OWC, three for dry testing and three for conditioned testing, and determine moisture sensitivity of the specimens in accordance with AASHTO T283.

5.3.4 Report

5.3.4.1 The report shall include the following:

5.3.4.1.1 Type of Emulsion Used

5.3.4.1.2 RAP Gradation

5.3.4.1.3 Specimen Height

5.3.4.1.4 Specimen Mass

5.3.4.1.5 Specimen Bulk Specific Gravity

5.3.4.1.6 Specimen Unit Weight

5.3.4.1.7 Specimen Air Void Content

5.3.4.1.8 Optimum Emulsion Content

5.3.4.1.9 Optimum Mixing Water Content

5.3.4.1.10 Moisture Sensitivity Results

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Chapter 6. Application of New Mix-Design Method and Performance Prediction

6.1 Application of New Mix-Design

Once the new mix-design procedure was developed, the next step was to apply the mix-design. In order to be representative of the different types of materials that are being used for CIR, the mix-design should be performed using materials from various locations throughout North America. Therefore, the new mix-design was applied using materials from five geographically varied locations, i.e., Connecticut, Kansas, Ontario, Arizona, and New Mexico. Reclaimed Asphalt Pavement (RAP) was received from roads that were under construction or were soon to undergo construction using CIR pavement rehabilitation techniques. At the time that the samples were obtained, it was specified that the samples would be obtained from milling machines as part of the CIR recycling train. Subsequent discussions with the Expert Task Group were held and it was decided that the use of cores for the mix-design method would be a more appropriate sampling method in the future. However, the milled samples that were received were appropriate for this study. Thus, the application of the new mix-design method took place with the milled samples.

Material obtained from Connecticut was taken directly from the recycling train on a CIR project of the asphalt shoulders of Interstate 695 by graduate students from the University of Rhode Island (URI) and stored in several 10-gallon barrels. Material from Kansas was secured from a RAP stockpile that was created from US-70 in Kansas, which was undergoing CIR. Ontario material was obtained directly from the millings of a CIR project in Ontario, Canada. The Arizona material was obtained from a project for the Bureau of Indian Affairs and was shipped to URI in several buckets. Material from New Mexico was taken directly from millings on a CIR project. RAP materials from the Kansas, Ontario, and New Mexico sites were deposited into 55-gallon drums and shipped to URI. Sieve analyses were performed on all the RAP materials and the results are shown in Appendix D. The RAP was processed by removing the material retained on the 31.8 mm (1 ¼") sieve and combining the material passing the 1.18 mm (# 16) sieve. The processed gradations are shown in Appendix D.

The first step necessary to perform the new mix-design on the obtained materials was to determine the compactive effort of the Superpave Gyratory Compactor (SGC) to simulate field density for each material. Field density was measured for each CIR project and the unit weights obtained are listed in Table 6.1.

Table 6.1. Field Unit Weights and Gyrations Required to Simulate Field Density

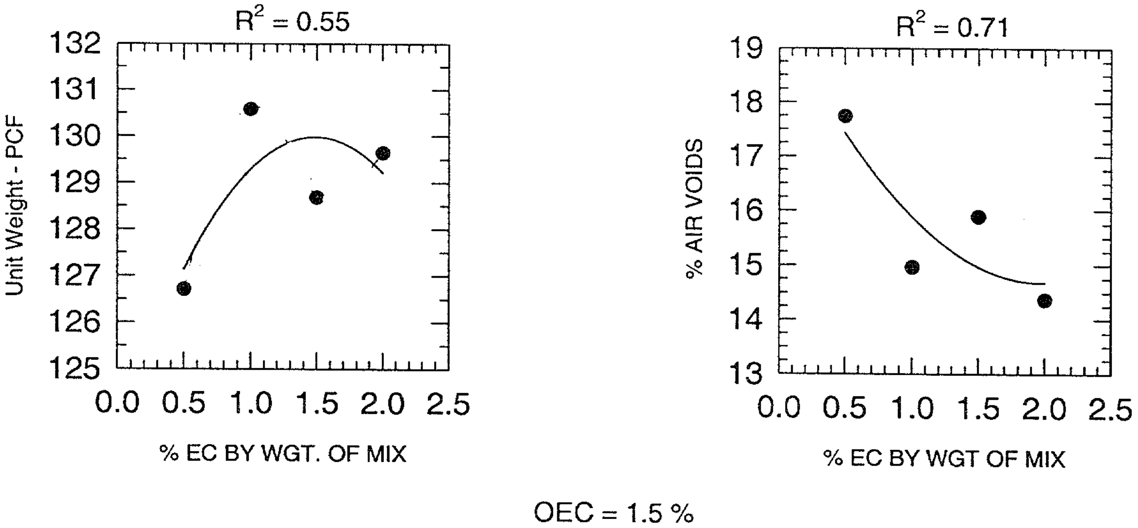
RAP Material	Field Unit Weight (pcf)	Number of Gyrations To Simulate Field Density
Connecticut	130	37
Kansas	130	33
Ontario	140	90
Arizona	127.5	48
New Mexico	131.5	97

Specimens were prepared for each RAP in order to determine the number of gyrations necessary to simulate the unit weights listed in Table 6.1. The number of gyrations to be applied to achieve the field unit weights were determined from the height data collected from the SGC as explained in Section 5.2.1. Table 6.1 also lists the number of gyrations for each RAP material.

6.1.1 Connecticut

The first application of the new mix-design for CIR materials was performed on the RAP material from Connecticut. HFMS-2T emulsion was sent with the RAP, and was used in the mix-design.

In order to determine the optimum emulsion content (OEC) two specimens were prepared, according to the procedure outlined in Section 5.3, at each of the following emulsion contents: 0.5%, 1.0%, 1.5%, and 2.0%. The initial mixing water content used to prepare these specimens was 3.0%. Based on data obtained in the pilot study, thirty-seven gyrations of the SGC were applied to simulate the field density of 130 pcf. Results obtained from this portion of the mix-design are presented in Figure 6.1a.

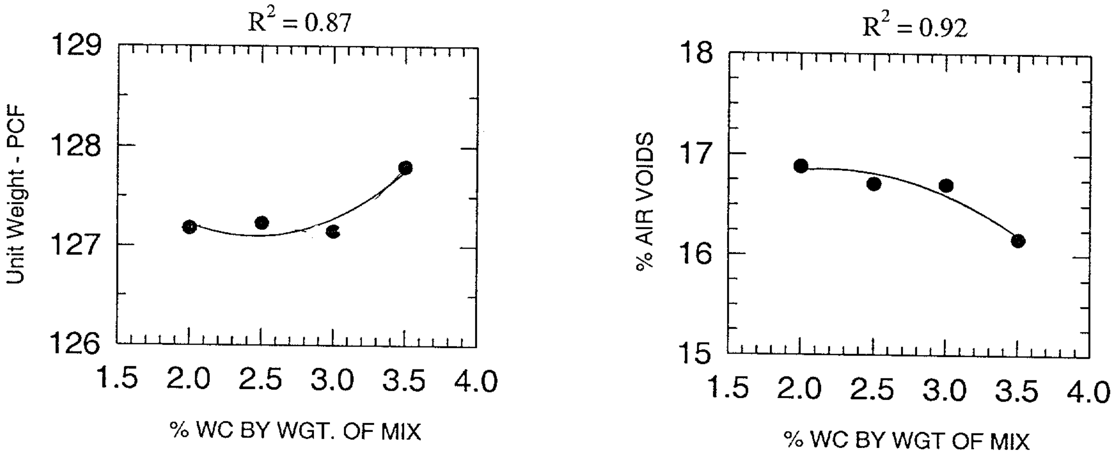


(a) Determination of OEC at 3.0% Water Content

Figure 6.1. Mix-Design for CIR using Connecticut RAP and HFMS-2T Emulsion

As the emulsion content increases, the unit weight increases until it reaches a maximum. Then as the emulsion content increases, the unit weight decreases. This occurs because the asphalt in the emulsion fills the pockets of air between the RAP particles, which lubricates the particles allowing the compactive effort to force them closer together. The density begins to decrease because the additional asphalt produces thicker films around the individual particles, thereby pushing the particles further apart and resulting in lower density (Roberts et. al. 1996). The emulsion content at the peak of the curve in the unit weight versus emulsion content graph, or the maximum density, as shown in Figure 6.1a, was chosen as the optimum. The OEC was determined to be 1.5% at the maximum unit weight as shown in Figure 6.1a.

The second part of the mix-design was performed by preparing specimens at the OEC with varying water contents. Two specimens were prepared at 2.0%, 2.5%, 3.0%, and 3.5% water content. Results obtained from these specimens are shown in Figure 6.1b. The optimum water content (OWC) was determined to be 2.9%. Please refer to Appendix E for the mix-design data.



OWC = 2.9 %

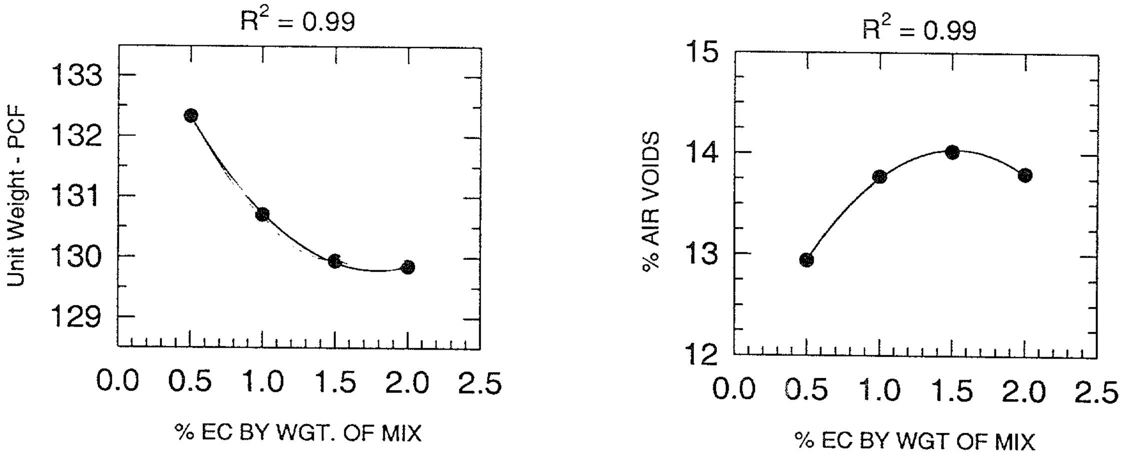
(b) Determination of OWC at 1.5% Emulsion Content (OEC)

Figure 6.1. Mix-Design for CIR using Connecticut RAP and HFMS-2T Emulsion

6.1.2 Kansas

The next material used in the application of the new mix-design was the RAP material from Kansas. CSS-1h emulsion was sent with the RAP, and was used in the mix-design.

The OEC was determined by preparing two specimens, in accordance with the procedure outlined in Section 5.3, at each of the following emulsion contents: 0.5%, 1.0%, 1.5%, and 2.0%. The mixing water content used to prepare these specimens was 3.0%. Based on data obtained in the pilot study, thirty-three gyrations of the SGC were applied to simulate the field density of 130 pcf, as shown in Appendix A. Results obtained from this portion of the mix-design are presented in Figure 6.2a.



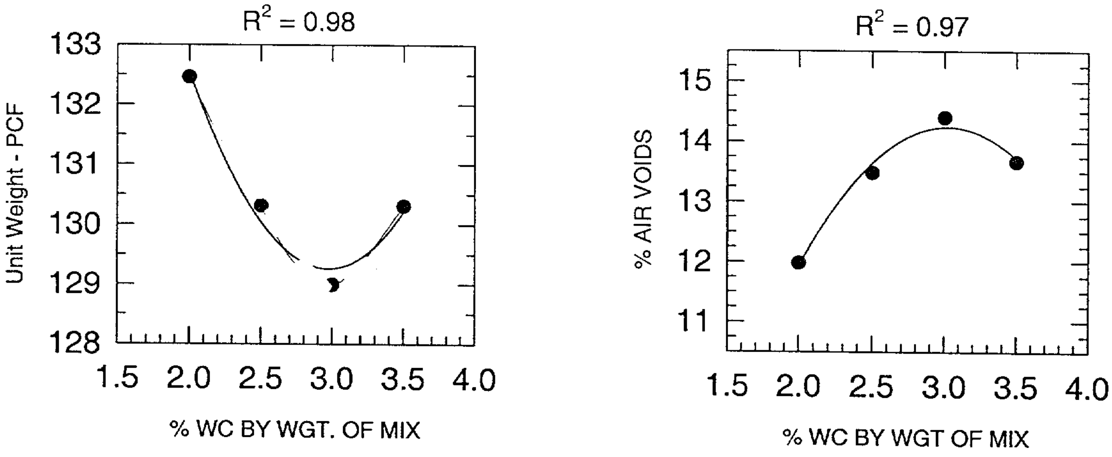
OEC = 1.4%

(a) Determination of OEC at 3.0% Water Content

Figure 6.2. Mix-Design for CIR using Kansas RAP and CSS-1h Emulsion

Due to the highly variable nature of RAP materials and their mixture with emulsion and water, the relationship between unit weight and emulsion content, as described earlier, occasionally does not hold true for CIR mixtures. Such a case occurred with the Kansas mixture. The highest unit weight was achieved at the lowest emulsion content of 0.5 %. However, 0.5% emulsion does not supply enough asphalt to properly coat the RAP particles. Under such conditions, the OEC should be selected at the emulsion content that produces the same unit weight as found in the field. For this mixture, the OEC was determined to be 1.4% at the field unit weight of 130 pcf.

The second portion of the mix-design was performed by fabricating specimens at the OEC with varying water contents. Two specimens were prepared at 2.0%, 2.5%, 3.0%, and 3.5% water content. Results obtained from these specimens are shown in Figure 6.2b.



OWC = 2.5%

(b) Determination of OWC at 1.4% Emulsion Content (OEC)

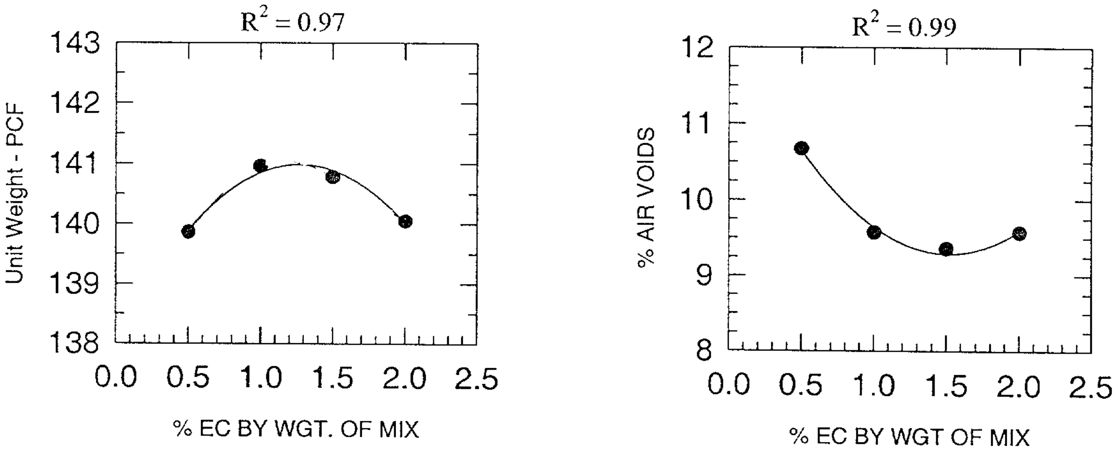
Figure 6.2. Mix-Design for CIR using Kansas RAP and CSS-1h Emulsion

Since varying the water content added to the CIR mixtures does not produce a change in the asphalt in the mixture, the emulsion-density relationship described earlier does not apply. In fact, the results obtained in this project seem to indicate that the density of the mixtures decreases with added water. This may be caused by the additional water in the mixture filling the voids and making it more difficult for the SGC to properly compact the specimens. However, some mixing water is required in the mix to allow the emulsion to properly adhere to the RAP particles. Thus, the optimum water content is selected at the point where the unit weight equals the field unit weight. The OWC for the Kansas mixture was determined to be 2.5% at the field unit weight of 130 pcf. Please refer to Appendix E for the mix-design data.

6.1.3 Ontario

The third material used in the application of the new mix-design was the RAP material from Ontario. HF150P emulsion was sent with the RAP, and was used in the mix-design.

The OEC was determined by preparing two specimens, according to the procedure outlined in Section 5.3, at each of the following emulsion contents: 0.5%, 1.0%, 1.5%, and 2.0%. The mixing water content used to prepare these specimens was 2.5%, based on experience gained working with the material, earlier in this study. Since the specimens prepared during the pilot study did not reach field density, it was necessary to prepare two additional specimens to determine the number of gyrations required to simulate field density. The two specimens were prepared at the OEC and OWC obtained in the pilot study and compacted for two hundred gyrations. Based on analysis of unit weights versus gyrations as described in Section 5.2.1, it was determined that ninety gyrations of the SGC were necessary to simulate the field unit weight of 140 pcf, as is shown in Appendix A. Thus, ninety gyrations were applied to prepare the mix-design specimens. Results obtained from this portion of the mix-design are presented in Figure 6.3a. The OEC was determined to be 1.3% at the maximum unit weight as determined from Figure 6.3a.

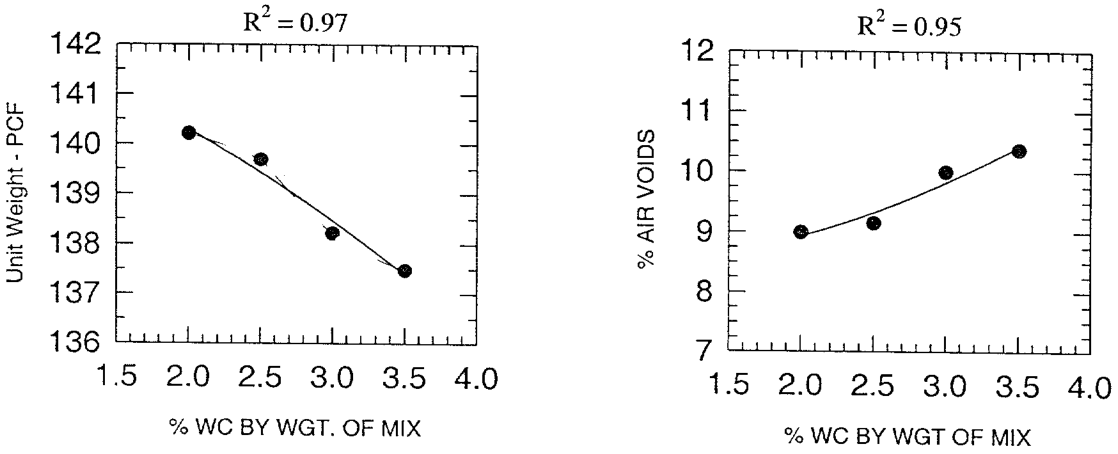


OEC = 1.3%

(a) Determination of OEC at 3.0% Water Content

Figure 6.3. Mix-Design for CIR using Ontario RAP and HF150P Emulsion

The second portion of the mix-design was performed by preparing specimens at the OEC with varying water contents. Two specimens were prepared at 2.0%, 2.5%, 3.0%, and 3.5% water content. Results obtained from these specimens are shown in Figure 6.3b. The OWC was determined to be 2.2% at the field unit weight of 140 pcf. Please refer to Appendix E for the mix-design data.



OWC = 2.2%

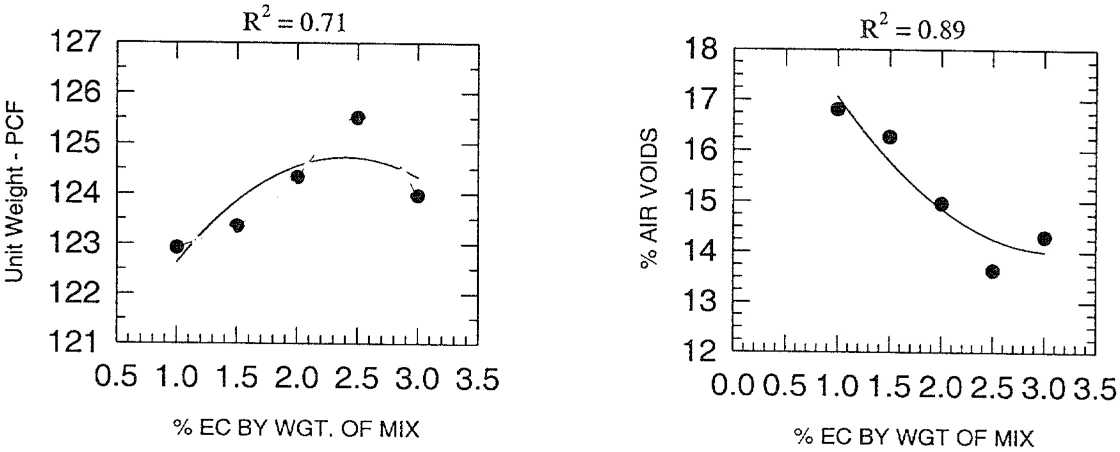
(b) Determination of OWC at 1.3% Emulsion Content (OEC)

Figure 6.3. Mix-Design for CIR using Ontario RAP and HF150P Emulsion

6.1.4 Arizona

The fourth material used in the application of the new mix-design was the RAP material from Arizona. The recycling agent that was sent with the RAP, and used in the mix-design, was Cyclogen ME.

The OEC was determined by preparing two specimens, in accordance with the procedure outlined in Section 5.3, at each of the following emulsion contents: 1.0%, 1.5%, 2.0%, 2.5%, and 3.0%. The mixing water content used to prepare these specimens was 3.0%. Using height data, bulk specific gravity, and the procedure described in Section 5.2.1, it was determined that forty-eight gyrations of the SGC were necessary to simulate the field density of 127.5 pcf. Thus, the specimens were prepared with the application of forty-eight gyrations. Results obtained from this portion of the mix-design are presented in Figure 6.4a. The OEC was determined to be 2.6% at the maximum unit weight as determined from Figure 6.4a.

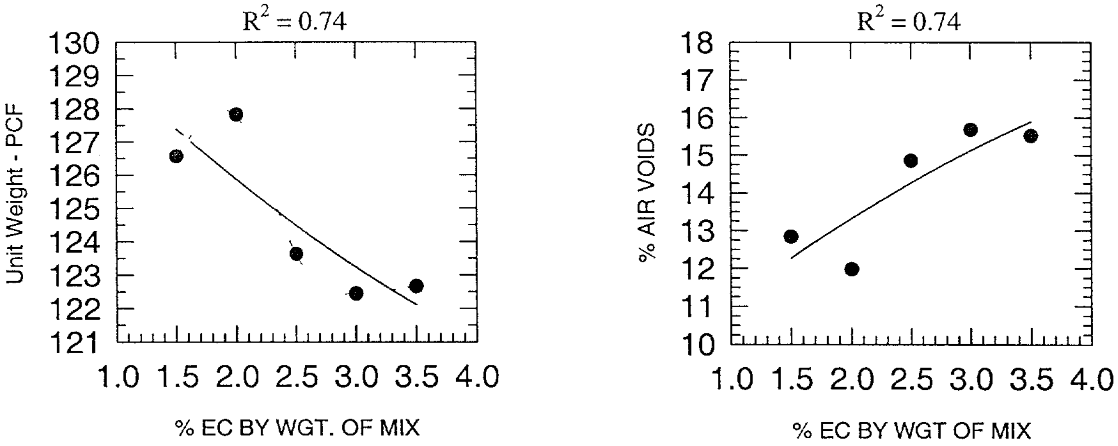


OEC = 2.6%

(a) Determination of OEC at 3.0% Water Content

Figure 6.4. Mix-Design for CIR using Arizona RAP and Cyclogen ME

The second part of the mix-design was performed by fabricating specimens at the OEC with varying water contents. Two specimens were prepared at 1.5%, 2.0%, 2.5%, 3.0%, and 3.5% water content. Results obtained from these specimens are presented in Figure 6.4b. The optimum water content (OWC) was determined to be 1.8% at the field unit weight of 127.5 pcf. Please refer to Appendix E for the mix-design data.



OWC = 1.8%

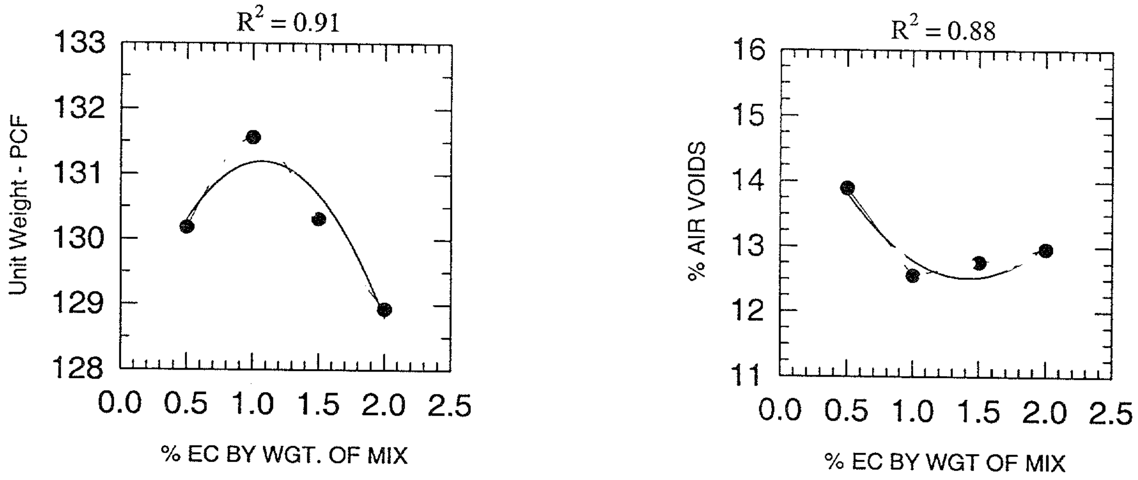
(b) Determination of OWC at 2.6% Emulsion Content (OEC)

Figure 6.4. Mix-Design for CIR using Arizona RAP and Cyclogen ME

6.1.5 New Mexico

The fifth material used in the application of the new mix-design was the RAP material from New Mexico. HFE150-P emulsion was sent with the RAP, and was used in the mix-design.

The OEC was determined by preparing two specimens, according to the procedure outlined in Section 5.3, at each of the following emulsion contents: 0.5%, 1.0%, 1.5%, and 2.0%. Based on experience gathered during preparation of sample specimens, the mixing water content used to prepare these specimens was 2.0%. Specimens were prepared in order to determine the number of gyrations required to simulate field density. The two specimens were compacted for two hundred gyrations using the SGC. Analysis of unit weights versus gyrations as described in Section 5.2.1, indicated that ninety-seven gyrations of the SGC were necessary to simulate the field unit weight of 131.5 pcf, as is shown in Appendix A. Thus, ninety-seven gyrations of the SGC were applied in the preparation of the mix-design specimens. Results obtained from this portion of the mix-design are presented in Figure 6.5a. The OEC was determined to be 1.1% at the maximum unit weight as determined from Figure 6.5a.

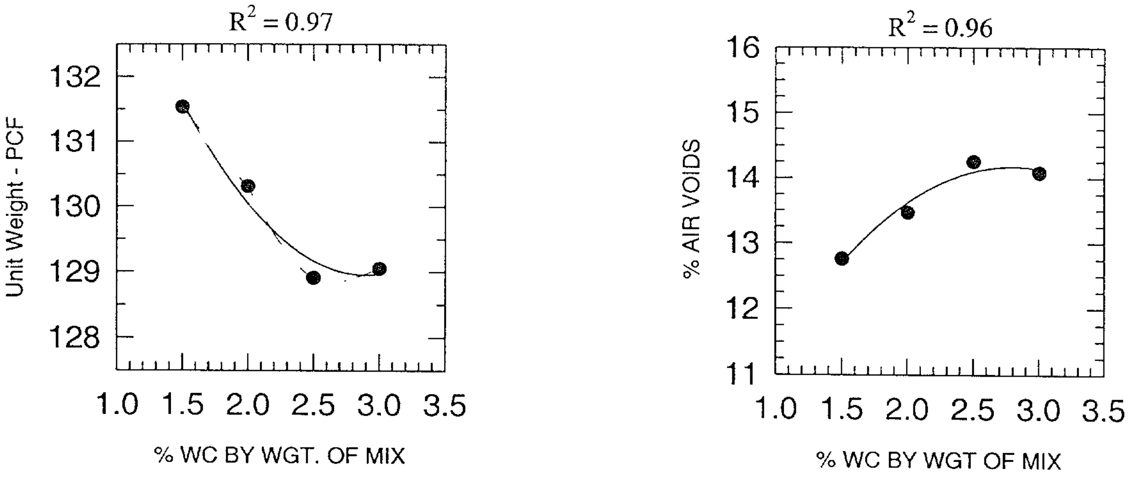


OEC = 1.1 %

(a) Determination of OEC at 2.0% Water Content

Figure 6.5. Mix-Design for CIR using New Mexico RAP and HFE150-P

The second part of the mix-design was performed by preparing specimens at the OEC with varying water contents. Two specimens were prepared at 1.5%, 2.0%, 2.5%, and 3.0%, water content. Results obtained from these specimens are presented in Figure 6.5b. The OWC was determined to be 1.8% at the field density as shown in Figure 6.5b. Please refer to Appendix E for the mix-design data.



OWC = 1.8 %

(b) Determination of OWC at 1.1% Emulsion Content (OEC)

Figure 6.5. Mix-Design for CIR using New Mexico RAP and HFE150-P

6.2 Performance Prediction

An attempt was made to predict the performance of the CIR mixtures prepared using the new volumetric mix-design. The distress modes that were investigated for performance analysis in this report were rutting, fatigue cracking, and low-temperature cracking.

6.2.1 Rutting and Fatigue Cracking

The distress modes of rutting and fatigue cracking were investigated using the computer program VESYS. The Incremental Static Dynamic Creep Test (ISDCT) was performed to obtain material properties for rutting analysis using VESYS. More detailed information on the ISDCT, VESYS, and rutting prediction can be found in Appendix F.

Fatigue cracking was to be investigated by also using VESYS. Please refer to Appendix G for information pertaining to the fatigue beam testing. Results for the prediction of fatigue cracking have not yet been obtained due to difficulties with the fatigue beam test apparatus.

6.2.2 Thermal Cracking

6.2.2.1 Low-Temperature Cracking Mechanism

Low-temperature, or thermal, cracking is a distress type that is caused, as its name would indicate, by adverse environmental conditions, namely low temperatures. Low-temperature cracking is characterized by transverse cracks that occur at a consistent spacing in the pavement. Formation of these transverse cracks takes place when the asphalt shrinks in cold temperatures. Tensile stresses build in the pavement until they exceed the tensile strength of the pavement, causing the pavement to crack.

6.2.2.2 Superpave System

Beginning in the fall of 1987 and continuing for over 5 years, a $50 million research effort was conducted to develop new and more effective ways to specify, test, and design asphalt materials. This effort was performed under the Strategic Highway Research Program (SHRP) and the final product of this research is referred to as Superpave™, which stands for SUperior PERforming PAVEments. Superpave represents an improved system for specifying component materials, mix-design and analysis, and performance prediction, including test equipment, methods, and criteria (McGennis 1995). Superpave is composed of two parts: Superpave asphalt binder specifications and Superpave asphalt mixture design and analysis.

The Superpave mix-design system initially consisted of three levels of testing; Level 1, Level 2 and Level 3. However, recently it has been recommended that

Superpave no longer be referred to as level 1, 2, and 3 due to the misinterpretation as three different mix-design procedures. The current terminology refers to the former Level 1 mix-design as the Superpave volumetric mix-design. Likewise, the former Level 2 and Level 3 analyses are now known as the Superpave models and analysis procedures or additional mix testing and analysis.

The Superpave volumetric mix-design consists of four sections as follows: selection of materials, selection of design aggregate structure, selection of design asphalt binder content, and the evaluation of moisture sensitivity of the design asphalt mixture. For low volume roads, no additional testing is required. Additional testing and analysis is required, however, when designing for medium and high traffic levels.

The additional testing and analysis are performance-based, allowing the use of prediction models to estimate the future performance of the Superpave mixes. The three pavement distress types investigated are rutting (permanent deformation), fatigue cracking, and low-temperature cracking (thermal cracking).

Prediction of future pavement performance was developed with the use of two new performance based testing procedures, the Superpave Shear Tester (SST) and the Indirect Tensile Tester (IDT). The SST performs six tests that are used to predict rutting and fatigue cracking. The IDT is used to design against fatigue cracking and low-temperature cracking, through the measurement of creep compliance and tensile strength of the mixes. Results are input prediction models that allow the user to decide if the mixes should be used as they are or if they need to be redesigned.

Essential aspects of the performance testing for the Superpave system are the performance models developed for prediction. They are prediction algorithms that use performance test results as inputs and give an output of the predicted pavement performance. This represents a new tool for designing pavements with a mechanistic approach instead of previous empirical procedures.

Four components make up the Superpave performance prediction software: material property model, environmental effects model, pavement response model, and pavement distress model. Used together with the performance test results, these models estimate rutting, fatigue cracking, and low-temperature (thermal) cracking. Only low temperature cracking was predicted, however, due to the incomplete rutting and fatigue model when this study was conducted.

6.2.2.3 Indirect Tensile Tester (IDT)

The IDT measures the creep compliance and strength of asphalt mixtures using indirect tensile loading techniques at intermediate to low temperatures, i.e. lower than 20°C (68°F). The testing involves the application of a compressive load across the diametrical axis of a cylinder specimen as can be seen in Figure 6.6. A nearly uniform state of tensile stress is achieved across the diametral plane. The IDT includes the testing apparatus, the test control and data acquisition system, load measuring device, and the environmental control chamber.

Testing apparatus consists of a closed-loop electromechanical system. A rigid loading frame is used to ensure precise displacement measurements. Measurements of the specimens are recorded by an analog to digital data acquisition device.

Loads are measured and controlled with an electronic load cell which is placed between the loading piston and loading platen. The environmental chamber controls the test temperature.

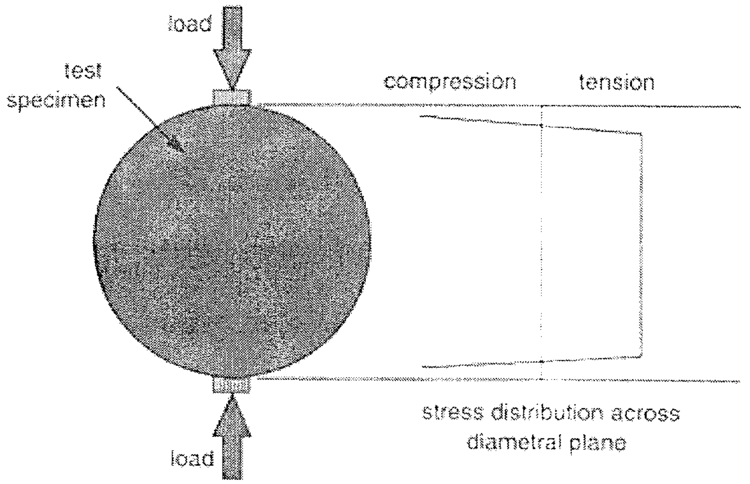


Figure 6.6. Loading of IDT Specimen

Specimens used in the IDT have a thickness to diameter ratio of at least 0.33 with smooth, parallel surfaces for the mounting of the Linear Variable Differential Transducers (LVDTs). The LVDTs are mounted as shown in Figure 6.7, with two LVDTs on each side of the specimen.

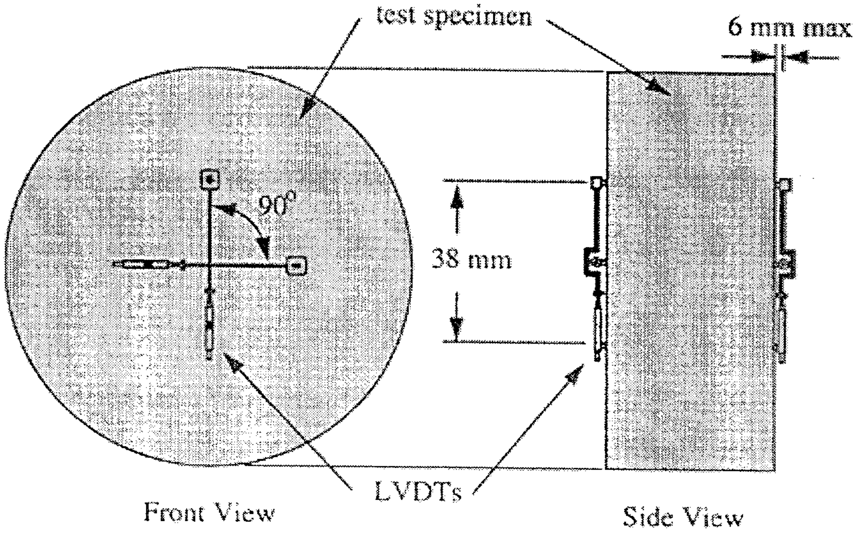


Figure 6.7. LVDT Mounting on IDT Specimen

Two tests can be performed with the IDT:

- IDT Creep Compliance and Strength at Low Temperatures and
- IDT Strength at Intermediate Temperatures.

The IDT creep compliance and strength tests are used to analyze mixtures for low-temperature cracking and are performed at 0°C (32°F), -10°C (14°F), and -20°C (-4°F). The first phase of the test has a static creep load placed on the specimen (Figure 6.8), which produces between 30 – 500 microstrain for the 100-second duration of the test. Vertical and horizontal displacements are measured. The second phase of the test has the load increased at a rate of 12.5 mm (0.5 in)/minute until specimen failure occurs as seen in Figure 6.9. Vertical and horizontal displacements are again measured.

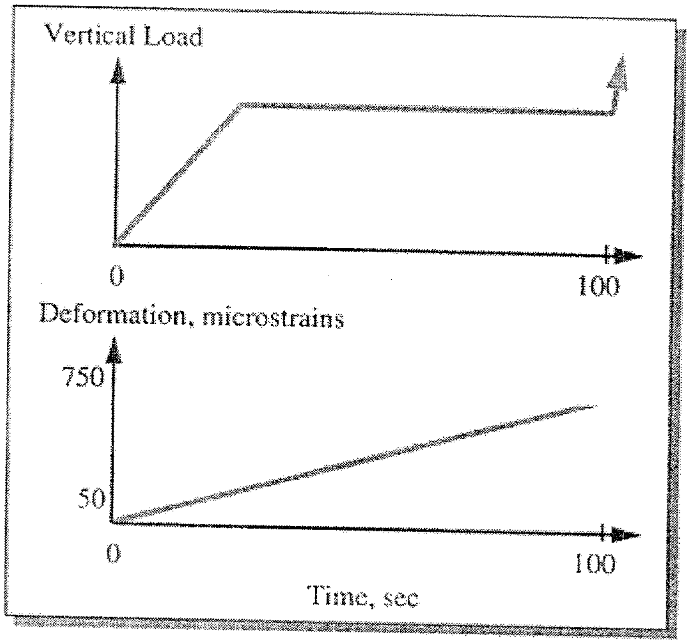


Figure 6.8. Static Creep Phase of IDT Test for Thermal Cracking Prediction

The IDT strength test for fatigue cracking analysis is performed between –10°C (14°F) and 20°C (68°F). The specimen is loaded at a rate of 50 mm (2 in)/minute until failure occurs. Load and deformations are measured.

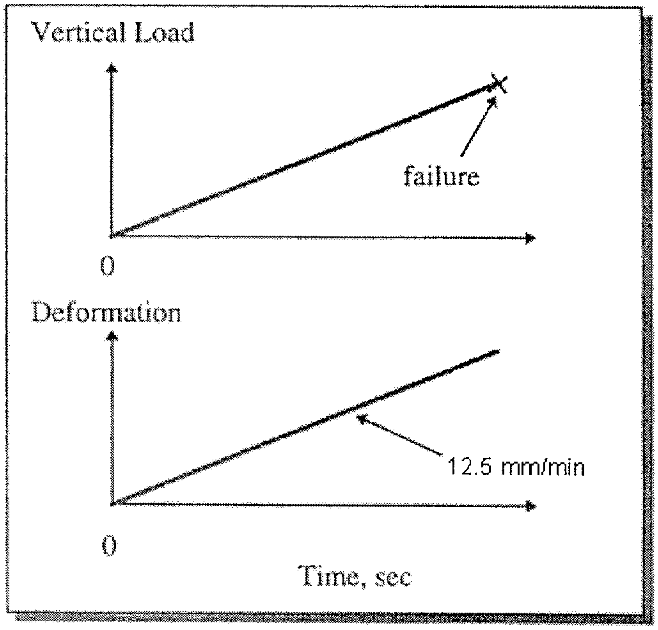


Figure 6.9. Loading of IDT Strength Test for Thermal Cracking Prediction

6.2.2.4 IDT Research

Research projects have been conducted with the IDT by Pennsylvania State University, the University of Florida, and the University of Illinois at Urbana-Champaign.

Research by Christensen at Pennsylvania State University was performed to develop reference standards for the IDT (Christensen and Mehta 1998). Reference standards are specimens or materials with known properties that are used to verify the proper operation of a system used to characterize these known properties. From this research it was determined that high density polyethylene (HDPE) can be used as a reference standard for the IDT and when used in combination with proficiency testing and good lab management, variability in the IDT test and data analysis can be minimized.

Another study was performed to determine if the IDT could predict thermal cracking (Buttlar and Roque 1994). In order to accomplish this, some enhancements to the test equipment and methods were needed, which included modifications to the gauges, loading frame, mounting system as well as the use of a transducer diagnostic program. Enhancements to the testing method include the establishment of strain limits to ensure linearity, and consistent conditioning of the specimens and the test temperature. In addition, the analysis procedures were simplified.

Using this new system it was determined that reasonable values were obtained for creep compliance. In addition, these creep compliance values were used successfully to predict low-temperature cracking performance, using the Superpave model, reference materials from the SHRP Materials Reference Library (MRL), and a comprehensive field-testing program.

Another study was performed to develop techniques to analyze creep data obtained from the IDT (Christensen 1998). The study recommended new techniques that can be applied within the framework of the Superpave IDT test to produce simpler analyses that can be practically implemented using any spreadsheet program.

6.2.2.5 Superpave IDT Test

For the CIR mixtures, creep compliance and the strength at low temperature tests (AASHTO TP9-94) were performed using the Indirect Tensile Tester (IDT) to evaluate the resistance against low temperature cracking. The test was performed at three temperatures for creep compliance, i.e., 0°C (32°F), -10°C (14°F), and -20°C (-4°F), and tensile strength as shown in Table 6.2. Step by step details of the test are provided in Appendix H.

Table 6.2. IDT Experimental Design

	Temperature		
Material	**0°C**	**-10°C**	**-20°C**
Connecticut	2	2	2
Kansas	2	2	2
Ontario	2	2	2
Arizona	2	2	2
New Mexico	2	2	2

Note: All Specimens prepared at Optimum Emulsion and Water Contents

Connecticut

The IDT test was performed using the Connecticut RAP and HFMS-2T emulsion. The OEC of 1.5% and OWC of 2.9%, as determined in Section 6.1.1, were used to prepare the specimens. To ensure that the specimens would be representative of those prepared in section 6.1.1, the specimens were compacted by applying the SGC for 37 gyrations to achieve a similar specimen thickness of approximately 115 mm (4.5 in). Since the specimen thickness needed to perform the tests is 50 mm (2 in), the specimens were cut to the proper size using a diamond-blade saw. Both sides of all specimens were cut to get smooth faces for mounting of the LVDTs on the brass gauge points.

The tensile strength test was performed for the Connecticut mixture at 0°C (32°F), -10°C (14°F), and -20°C (-4°F). The tensile strength was determined by use of the following equation:

$$S = \frac{2P}{\Pi b D} \qquad (6.1)$$

where,

P = failure load,
Π = Pi (3.14)
b = specimen thickness, and
D = specimen diameter.

The results from the tensile strength test are shown in Table 6.3. The tensile strengths of the Connecticut mixture were calculated to be 90.6, 94.9, and 199.9 psi at 0°C (32°F), -10°C (14°F), and -20°C (-4°F), respectively as shown in Figure 6.10.

Table 6.3. Tensile Strengths (psi)

RAP Source	**0°C (32°F)**	**-10°C (14°F)**	**-20°C (-4°F)**
Connecticut	90.6	94.9	199.9
Kansas	126.5	179.3	252.2
Ontario	59.6	85.1	120.3
Arizona	95.4	109.8	193.5
New Mexico	97.5	129.3	197.0

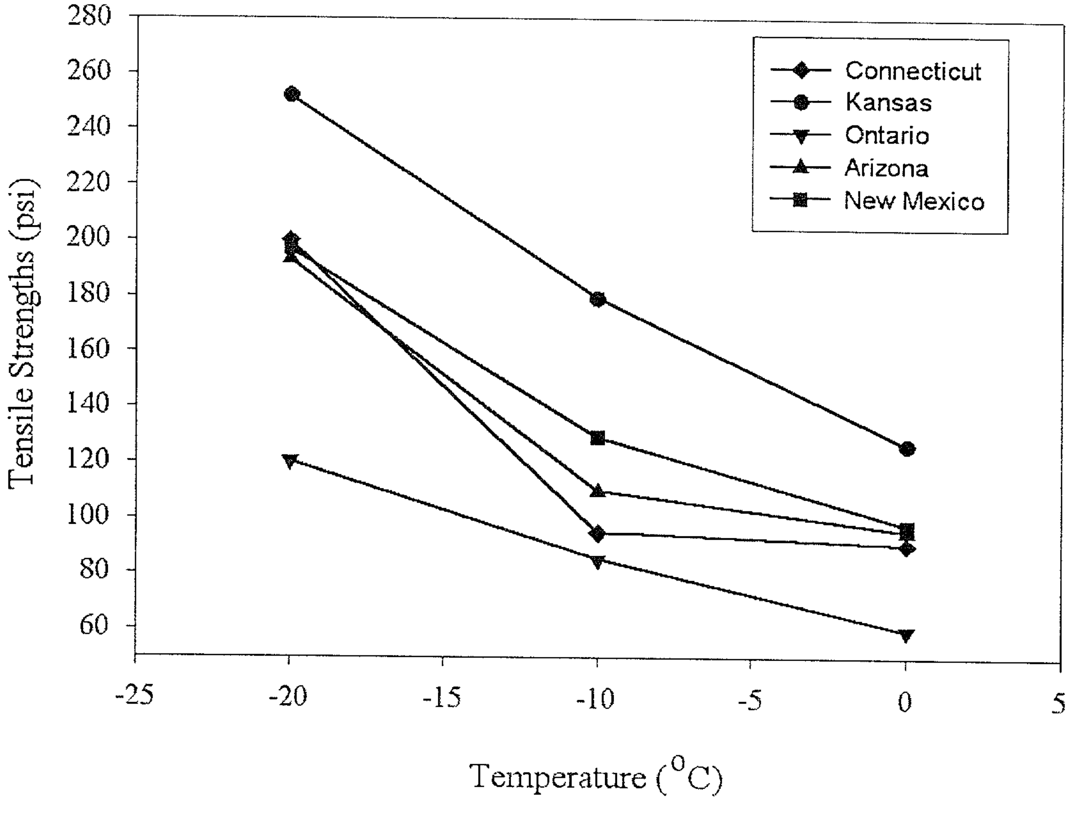


Figure 6.10. Temperature Variation of Tensile Strengths for CIR Mixtures

Kansas

The IDT test was also performed using the Kansas RAP and CSS-1h emulsion. The OEC of 1.4% and OWC of 2.5%, as determined in Section 6.1.2, were used to prepare the specimens. To ensure that the specimens would be representative of those prepared in Section 6.1.2, the specimens were compacted by applying the SGC for 33 gyrations to achieve a similar specimen thickness of approximately 115 mm (4.5 in). Since the specimen thickness needed to perform the tests is 50 mm (2 in), the specimens were cut to the proper size using a diamond-blade saw. As with the Connecticut specimens, both sides of all specimens were cut to get smooth faces for mounting of the LVDTs.

The tensile strength test was performed for the Kansas mixture at 0°C (32°F), -10°C (14°F), and -20°C (-4°F). The tensile strength was determined by use of Equation 6.1 and the results are shown in Table 6.3. The tensile strength of the Kansas mixture was calculated to be 126.5 psi at 0°C (32°F), 179.3 psi at -10°C (14°F), and 252.2 psi at -20°C (-4°F) as shown in Figure 6.10.

Ontario

The IDT test was next performed using the Ontario RAP and HF150P emulsion. The OEC of 1.3% and OWC of 2.2%, as determined in Section 6.1.3, were used to prepare the specimens. To ensure that the specimens would be representative of those prepared in Section 6.1.3, the specimens were compacted by applying the SGC for 90 gyrations to achieve a similar specimen thickness of approximately 115 mm (4.5 in). Since the specimen thickness needed to perform the tests is 50 mm (2 in), the specimens were cut to the proper size using a diamond-blade saw. As with the other mixtures, both sides of all specimens were cut to get smooth faces for mounting of the LVDTs.

The tensile strength test was performed for the Ontario mixture at 0°C (32°F), -10°C (14°F), and -20°C (-4°F). The tensile strength was determined by use of Equation

6.1 and the results are shown in Table 6.3. The tensile strength of the Ontario mixture was calculated to be 59.6 psi at 0°C (32°F), 85.1 psi at -10°C (14°F), and 120.3 psi at -20°C (-4°F) as depicted in Figure 6.10.

Arizona

The IDT test was also performed using the Arizona RAP and Cyclogen ME recycling agent. The OEC of 2.6% and OWC of 1.8%, as determined in Section 6.1.4, were used to prepare the specimens. To ensure that the specimens would be representative of those prepared in Section 6.1.4, the specimens were compacted by applying the SGC for 48 gyrations to achieve a similar specimen thickness of approximately 115 mm (4.5 in). Since the specimen thickness needed to perform the tests is 50 mm (2 in), the specimens were cut to the proper size using a diamond-blade saw. As with the other mixtures, both sides of all specimens were cut to get smooth faces for mounting of the LVDTs.

The tensile strength test was performed for the Arizona mixture at 0°C (32°F), -10°C (14°F), and -20°C (-4°F). The tensile strength was determined by use of Equation 6.1 and the results are shown in Table 6.3. The tensile strength of the Arizona mixture was calculated to be 95.4 psi at 0°C (32°F), 109.8 psi at -10°C (14°F), and 193.5 psi at -20°C (-4°F) as shown in Figure 6.10.

New Mexico

The final material that was used for performance of the IDT test was the New Mexico RAP and HFE150-P emulsion. The OEC of 1.1% and OWC of 1.8%, as determined in Section 6.1.5, were used to prepare the specimens. To ensure that the specimens would be representative of those prepared in section 6.1.5, the specimens were compacted by applying the SGC for 97 gyrations to achieve a similar specimen thickness of approximately 115 mm (4.5 in). Since the specimen thickness needed to perform the tests is 50 mm (2 in), the specimens were cut to the proper size using a diamond-blade saw. As with the other mixtures, both sides of all specimens were cut to get smooth faces for mounting of the LVDTs.

The tensile strength test was performed for the New Mexico mixture at 0°C (32°F), -10°C (14°F), and -20°C (-4°F). The tensile strength was determined by use of Equation 6.1 and the results are shown in Table 6.3. The tensile strength of the New Mexico mixture was calculated to be 97.5 psi at 0°C (32°F), 129.3 psi at -10°C (14°F), and 197.0 at -20°C (-4°F) as illustrated in Figure 6.10.

The creep compliance test was also performed on the Connecticut, Kansas, Ontario, Arizona, and New Mexico mixtures. An attempt was made to analyze the mixtures for thermal cracking by using the Superpave thermal cracking model TCMODEL. This model, however, was still under development, and was not successfully applied for thermal cracking prediction at this point.

6.3 Field Verification

A test section using the new mix-design was constructed on Route 94 in the Gila Indian Reservation in Arizona on October 2, 2000. This test section is in a desert environment. The road is a two-lane highway with moderate vehicular traffic. The mix-design for the test section was performed by Law Engineering using RAP millings that were taken from the test site. The OEC was determined to be 2.5% and the OWC was determined to be 2.0%.

The existing 2 inches of broken asphalt pavement was recycled to result in a new 2-inch CIR layer. The original plan for the roadway called for application of a chip seal to serve as a surface treatment for the CIR layer. Due to weather related difficulties, however, the chip seal was delayed, and approximately two months after construction, a 1-½ inch hot mix asphalt overlay was placed.

Observations taken in March of 2002, approximately 18 months after construction, which included two winters, showed no distresses in the roadway. Further periodic observations will be taken in the coming months and years to document the performance of the CIR mix-design. Photographs taken during construction are included in Appendix I.

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Chapter 7. Conclusions and Recommendations

7.1 Conclusions

This study has been undertaken to develop a new mix-design method for use with Cold In-Place Recycling (CIR) of asphalt pavements. Evaluation of the Modified Marshall Mix-Design method from the AASHTO Task Force No. 38 has suggested that this method is not the future for CIR mix-designs. Expanding use of the Superpave system deems it vitally necessary to provide a mix-design for CIR similar to that for HMA with modifications for the nature of cold mixes. Therefore, a volumetric mix-design using the Superpave Gyratory Compactor (SGC) has been developed for use with CIR materials. This mix-design was developed primarily for partial-depth CIR, using emulsion as the recycling additive.

The new mix-design was evaluated using materials from five geographically varied locations in North America, i.e., Connecticut, Kansas, Ontario, Arizona, and New Mexico. The results from these mix-designs are summarized as follows:

	OEC	OWC
• Connecticut:	1.5%	2.9%
• Kansas:	1.4%	2.5%
• Ontario:	1.3%	2.2%
• Arizona:	2.6%	1.8%
• New Mexico:	1.1%	1.8%

After completing the mix-designs, the mixtures were tested for resistance to low temperature cracking using the Superpave InDirect Tensile Tester (IDT). Creep compliance and strength tests were performed at 0°C (32°F), -10°C (14°F), and –20°C (-

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Appendix A – Compaction Level: Gyration and Unit Weight Data

Table A.1. Gyration and Unit Weight Data for Connecticut RAP and HFMS-2T Emulsion to Determine No. of Gyrations Required to Simulate Field Density (130 pcf)

3.0% WC

1 OF 4

Emul. Cont.	0.5%						
Specimen #	1			2			**Unit Weight**
Gyrations	Ht, mm	G_{mb} (est)	G_{mb} (corr)	Ht, mm	G_{mb} (est)	G_{mb} (corr)	
0	131.0	1.748	1.773	130.2	1.760	1.777	**110.81**
1	128.2	1.786	1.811	127.5	1.797	1.815	**113.19**
2	126.4	1.812	1.837	125.7	1.823	1.841	**114.81**
3	124.9	1.834	1.859	124.2	1.845	1.863	**116.19**
4	123.6	1.853	1.879	123.0	1.863	1.881	**117.37**
5	122.5	1.870	1.896	121.9	1.880	1.898	**118.42**
6	121.7	1.882	1.908	121.0	1.894	1.912	**119.25**
7	120.9	1.894	1.921	120.2	1.907	1.925	**120.04**
8	120.2	1.905	1.932	119.5	1.918	1.936	**120.75**
9	119.6	1.915	1.941	118.9	1.927	1.946	**121.35**
10	119.0	1.925	1.951	118.3	1.937	1.956	**121.97**
11	118.5	1.933	1.960	117.8	1.945	1.964	**122.48**
12	118.1	1.939	1.966	117.3	1.954	1.973	**122.95**
13	117.6	1.947	1.974	116.8	1.962	1.981	**123.48**
14	117.2	1.954	1.981	116.4	1.969	1.988	**123.90**
15	116.9	1.959	1.986	116.0	1.976	1.995	**124.27**
16	116.5	1.966	1.993	115.6	1.983	2.002	**124.70**
17	116.2	1.971	1.998	115.3	1.988	2.007	**125.02**
18	115.9	1.976	2.003	115.0	1.993	2.012	**125.35**
19	115.6	1.981	2.009	114.7	1.998	2.017	**125.67**
20	115.3	1.986	2.014	114.4	2.003	2.023	**126.00**
21	115.0	1.991	2.019	114.1	2.009	2.028	**126.33**
22	114.8	1.995	2.023	113.8	2.014	2.033	**126.61**
23	114.5	2.000	2.028	113.6	2.017	2.037	**126.89**
24	114.3	2.004	2.032	113.4	2.021	2.041	**127.11**
25	114.1	2.007	2.035	113.1	2.026	2.046	**127.39**
26	113.9	2.011	2.039	112.9	2.030	2.050	**127.61**
27	113.7	2.014	2.042	112.7	2.034	2.053	**127.84**
28	113.5	2.018	2.046	112.5	2.037	2.057	**128.07**
29	113.3	2.021	2.049	112.3	2.041	2.061	**128.29**
30	113.1	2.025	2.053	112.1	2.044	2.064	**128.52**
31	112.9	2.029	2.057	112.0	2.046	2.066	**128.69**
32	112.7	2.032	2.060	111.8	2.050	2.070	**128.92**
33	112.6	2.034	2.062	111.6	2.054	2.073	**129.09**
34	112.4	2.038	2.066	111.5	2.055	2.075	**129.27**
35	112.3	2.039	2.068	111.3	2.059	2.079	**129.44**
36	112.1	2.043	2.071	111.2	2.061	2.081	**129.61**
37	112.0	2.045	2.073	111.0	2.065	2.085	**129.79**
38	111.8	2.048	2.077	110.9	2.067	2.087	**129.96**
39	111.7	2.050	2.079	110.7	2.070	2.090	**130.14**
40	111.6	2.052	2.081	110.6	2.072	2.092	**130.26**
41	111.4	2.056	2.084	110.5	2.074	2.094	**130.43**
42	111.3	2.058	2.086	110.3	2.078	2.098	**130.61**
43	111.2	2.060	2.088	110.2	2.080	2.100	**130.73**
44	111.1	2.061	2.090	110.1	2.082	2.102	**130.85**
45	111.0	2.063	2.092	110.0	2.083	2.104	**130.96**
46	110.9	2.065	2.094	109.9	2.085	2.106	**131.08**
47	110.8	2.067	2.096	109.8	2.087	2.107	**131.20**
48	110.6	2.071	2.099	109.7	2.089	2.109	**131.38**
49	110.5	2.073	2.101	109.6	2.091	2.111	**131.50**
50	110.4	2.074	2.103	109.5	2.093	2.113	**131.62**
51	110.3	2.076	2.105	109.3	2.097	2.117	**131.80**
52	110.1	2.080	2.109	109.1	2.101	2.121	**132.04**
G_{mb} (meas)		2.109			2.121		
Mass, g	4033.7			4036.5			

3.0% WC

2 OF 4

Emul. Cont.	1.0%						
Specimen #	1			2			**Unit Weight**
Gyrations	Ht, mm	G_{mb} (est)	G_{mb} (corr)	Ht, mm	G_{mb} (est)	G_{mb} (corr)	
0	132.5	1.735	1.779	132.0	1.742	1.790	**111.40**
1	129.9	1.770	1.815	129.3	1.778	1.827	**113.68**
2	128.1	1.795	1.840	127.5	1.803	1.853	**115.28**
3	126.6	1.816	1.862	126.0	1.825	1.875	**116.65**
4	125.4	1.833	1.880	124.7	1.844	1.894	**117.82**
5	124.4	1.848	1.895	123.6	1.860	1.911	**118.81**
6	123.4	1.863	1.910	122.7	1.874	1.925	**119.73**
7	122.6	1.875	1.923	121.9	1.886	1.938	**120.51**
8	121.9	1.886	1.934	121.2	1.897	1.949	**121.21**
9	121.3	1.895	1.943	120.5	1.908	1.960	**121.86**
10	120.7	1.905	1.953	120.0	1.916	1.969	**122.42**
11	120.1	1.914	1.963	119.4	1.926	1.979	**123.03**
12	119.6	1.922	1.971	119.0	1.932	1.985	**123.49**
13	119.2	1.929	1.978	118.5	1.940	1.994	**123.96**
14	118.7	1.937	1.986	118.1	1.947	2.000	**124.43**
15	118.3	1.943	1.993	117.7	1.954	2.007	**124.86**
16	118.0	1.948	1.998	117.3	1.960	2.014	**125.23**
17	117.6	1.955	2.005	117.0	1.965	2.019	**125.60**
18	117.3	1.960	2.010	116.6	1.972	2.026	**125.98**
19	117.0	1.965	2.015	116.3	1.977	2.031	**126.30**
20	116.7	1.970	2.020	116.0	1.982	2.036	**126.63**
21	116.4	1.975	2.025	115.8	1.986	2.040	**126.90**
22	116.1	1.980	2.031	115.5	1.991	2.045	**127.23**
23	115.9	1.984	2.034	115.2	1.996	2.051	**127.50**
24	115.6	1.989	2.039	115.0	1.999	2.054	**127.78**
25	115.4	1.992	2.043	114.8	2.003	2.058	**128.00**
26	115.2	1.996	2.046	114.6	2.006	2.061	**128.22**
27	115.0	1.999	2.050	114.4	2.010	2.065	**128.45**
28	114.8	2.003	2.054	114.2	2.013	2.069	**128.67**
29	114.6	2.006	2.057	114.0	2.017	2.072	**128.90**
30	114.4	2.010	2.061	113.8	2.021	2.076	**129.12**
31	114.2	2.013	2.064	113.6	2.024	2.080	**129.35**
32	114.0	2.017	2.068	113.4	2.028	2.083	**129.58**
33	113.8	2.020	2.072	113.3	2.029	2.085	**129.75**
34	113.7	2.022	2.073	113.1	2.033	2.089	**129.92**
35	113.5	2.025	2.077	113.0	2.035	2.091	**130.09**
36	113.4	2.027	2.079	112.8	2.038	2.094	**130.26**
37	113.2	2.031	2.083	112.7	2.040	2.096	**130.44**
38	113.1	2.033	2.084	112.5	2.044	2.100	**130.61**
39	112.9	2.036	2.088	112.4	2.046	2.102	**130.78**
40	112.8	2.038	2.090	112.2	2.049	2.105	**130.96**
41	112.7	2.040	2.092	112.1	2.051	2.107	**131.08**
42	112.5	2.044	2.096	112.0	2.053	2.109	**131.25**
43	112.4	2.045	2.097	111.9	2.055	2.111	**131.37**
44	112.3	2.047	2.099	111.7	2.058	2.115	**131.54**
45	112.2	2.049	2.101	111.6	2.060	2.117	**131.66**
46	112.0	2.053	2.105	111.5	2.062	2.119	**131.84**
47	111.9	2.054	2.107	111.4	2.064	2.121	**131.96**
48	111.8	2.056	2.109	111.3	2.066	2.122	**132.07**
49	111.7	2.058	2.111	111.2	2.068	2.124	**132.19**
50	111.6	2.060	2.112	111.1	2.070	2.126	**132.31**
51	111.5	2.062	2.114	111.0	2.071	2.128	**132.43**
52	111.2	2.067	2.120	110.7	2.077	2.134	**132.79**
G_{mb} (meas)		2.120			2.134		
Mass, g	4049.1			4049.8			

3.0% WC

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Emul. Cont.	1.5%						
Specimen #	1			2			Unit Weight
Gyrations	Ht, mm	G_{mb} (est)	G_{mb} (corr)	Ht, mm	G_{mb} (est)	G_{mb} (corr)	
0	132.0	1.748	1.771	132.1	1.747	1.767	**110.44**
1	129.2	1.786	1.810	129.3	1.785	1.805	**112.83**
2	127.4	1.811	1.835	127.5	1.810	1.830	**114.43**
3	125.8	1.834	1.859	126.0	1.832	1.852	**115.84**
4	124.6	1.852	1.877	124.7	1.851	1.871	**117.00**
5	123.5	1.868	1.893	123.6	1.867	1.888	**118.04**
6	122.5	1.884	1.909	122.7	1.881	1.902	**118.95**
7	121.7	1.896	1.921	121.9	1.893	1.914	**119.74**
8	121.0	1.907	1.932	121.1	1.906	1.927	**120.48**
9	120.3	1.918	1.944	120.5	1.915	1.937	**121.13**
10	119.7	1.928	1.953	119.9	1.925	1.946	**121.73**
11	119.2	1.936	1.962	119.4	1.933	1.955	**122.24**
12	118.7	1.944	1.970	118.9	1.941	1.963	**122.76**
13	118.2	1.952	1.978	118.4	1.949	1.971	**123.28**
14	117.8	1.959	1.985	118.0	1.956	1.978	**123.70**
15	117.4	1.966	1.992	117.6	1.963	1.984	**124.12**
16	117.0	1.972	1.999	117.2	1.969	1.991	**124.54**
17	116.7	1.977	2.004	116.8	1.976	1.998	**124.91**
18	116.3	1.984	2.011	116.5	1.981	2.003	**125.29**
19	116.0	1.989	2.016	116.2	1.986	2.008	**125.61**
20	115.7	1.994	2.021	115.9	1.991	2.014	**125.94**
21	115.4	2.000	2.026	115.6	1.997	2.019	**126.27**
22	115.2	2.003	2.030	115.3	2.002	2.024	**126.54**
23	114.9	2.008	2.035	115.1	2.005	2.028	**126.82**
24	114.7	2.012	2.039	114.8	2.011	2.033	**127.09**
25	114.5	2.015	2.042	114.6	2.014	2.036	**127.31**
26	114.2	2.021	2.048	114.4	2.018	2.040	**127.59**
27	114.0	2.024	2.051	114.2	2.021	2.044	**127.82**
28	113.8	2.028	2.055	114.0	2.025	2.047	**128.04**
29	113.6	2.031	2.058	113.8	2.028	2.051	**128.27**
30	113.4	2.035	2.062	113.6	2.032	2.054	**128.49**
31	113.3	2.037	2.064	113.4	2.035	2.058	**128.66**
32	113.1	2.040	2.067	113.2	2.039	2.062	**128.89**
33	112.9	2.044	2.071	113.1	2.041	2.063	**129.06**
34	112.7	2.048	2.075	112.9	2.044	2.067	**129.29**
35	112.6	2.049	2.077	112.7	2.048	2.071	**129.46**
36	112.4	2.053	2.080	112.6	2.050	2.073	**129.63**
37	112.3	2.055	2.082	112.4	2.054	2.076	**129.81**
38	112.2	2.057	2.084	112.3	2.055	2.078	**129.92**
39	112.0	2.060	2.088	112.2	2.057	2.080	**130.10**
40	111.9	2.062	2.090	112.0	2.061	2.084	**130.27**
41	111.8	2.064	2.091	111.9	2.063	2.086	**130.39**
42	111.6	2.068	2.095	111.8	2.065	2.087	**130.56**
43	111.5	2.070	2.097	111.6	2.068	2.091	**130.74**
44	111.4	2.071	2.099	111.5	2.070	2.093	**130.85**
45	111.3	2.073	2.101	111.4	2.072	2.095	**130.97**
46	111.2	2.075	2.103	111.3	2.074	2.097	**131.09**
47	111.1	2.077	2.105	111.2	2.076	2.099	**131.21**
48	110.9	2.081	2.108	111.1	2.078	2.101	**131.39**
49	110.8	2.083	2.110	111.0	2.079	2.102	**131.50**
50	110.7	2.085	2.112	110.9	2.081	2.104	**131.62**
51	110.6	2.086	2.114	110.8	2.083	2.106	**131.74**
52	110.4	2.090	2.118	110.5	2.089	2.112	**132.04**
G_{mb} (meas)		2.118			2.112		
Mass, g	4064.3			4065.3			

3.0% WC

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Emul. Cont.	2.0%							All Specimens
Specimen #	1			2			Unit Weight	AVG Unit Weight
Gyrations	Ht, mm	G_{mb} (est)	G_{mb} (corr)	Ht, mm	G_{mb} (est)	G_{mb} (corr)		
0	132.0	1.751	1.758	132.0	1.755	1.760	109.83	110.62
1	129.3	1.788	1.795	129.3	1.792	1.797	112.12	112.96
2	127.4	1.814	1.822	127.4	1.819	1.824	113.79	114.58
3	125.9	1.836	1.843	125.9	1.840	1.845	115.15	115.96
4	124.7	1.854	1.861	124.6	1.860	1.865	116.30	117.12
5	123.6	1.870	1.878	123.5	1.876	1.881	117.34	118.15
6	122.6	1.885	1.893	122.5	1.892	1.897	118.30	119.06
7	121.8	1.898	1.906	121.7	1.904	1.909	119.07	119.84
8	121.1	1.909	1.917	121.0	1.915	1.920	119.76	120.55
9	120.4	1.920	1.928	120.3	1.926	1.931	120.46	121.20
10	119.8	1.929	1.937	119.7	1.936	1.941	121.06	121.80
11	119.2	1.939	1.947	119.2	1.944	1.949	121.62	122.34
12	118.7	1.947	1.955	118.7	1.952	1.957	122.13	122.83
13	118.3	1.954	1.962	118.2	1.960	1.966	122.60	123.33
14	117.8	1.962	1.970	117.8	1.967	1.972	123.07	123.77
15	117.4	1.969	1.977	117.4	1.974	1.979	123.48	124.18
16	117.0	1.976	1.984	117.0	1.980	1.986	123.91	124.59
17	116.7	1.981	1.989	116.6	1.987	1.993	124.28	124.95
18	116.4	1.986	1.994	116.3	1.992	1.998	124.60	125.30
19	116.0	1.993	2.001	116.0	1.998	2.003	124.98	125.64
20	115.7	1.998	2.006	115.7	2.003	2.008	125.30	125.97
21	115.5	2.001	2.009	115.4	2.008	2.013	125.57	126.27
22	115.2	2.006	2.015	115.1	2.013	2.019	125.90	126.57
23	114.9	2.012	2.020	114.8	2.018	2.024	126.23	126.86
24	114.7	2.015	2.023	114.6	2.022	2.027	126.45	127.11
25	114.5	2.019	2.027	114.4	2.025	2.031	126.67	127.34
26	114.2	2.024	2.032	114.1	2.031	2.036	127.00	127.61
27	114.0	2.028	2.036	113.9	2.034	2.040	127.22	127.83
28	113.8	2.031	2.039	113.7	2.038	2.043	127.45	128.06
29	113.6	2.035	2.043	113.5	2.042	2.047	127.67	128.28
30	113.4	2.038	2.047	113.3	2.045	2.051	127.90	128.51
31	113.2	2.042	2.050	113.2	2.047	2.052	128.07	128.69
32	113.1	2.044	2.052	113.0	2.051	2.056	128.24	128.91
33	112.9	2.047	2.056	112.7	2.056	2.062	128.52	129.11
34	112.6	2.053	2.061	112.4	2.061	2.067	128.86	129.33
35	112.4	2.056	2.065	112.1	2.067	2.073	129.15	129.54
36	112.2	2.060	2.069	111.8	2.073	2.078	129.44	129.74
37	111.9	2.066	2.074	111.6	2.076	2.082	129.73	**129.94**
38	111.8	2.067	2.076	111.5	2.078	2.084	129.84	130.09
39	111.7	2.069	2.078	111.4	2.080	2.086	129.96	130.25
40	111.6	2.071	2.080	111.2	2.084	2.089	130.14	130.41
41	111.4	2.075	2.083	111.1	2.086	2.091	130.31	130.55
42	111.3	2.077	2.085	111.0	2.087	2.093	130.43	130.71
43	111.2	2.079	2.087	110.9	2.089	2.095	130.55	130.84
44	111.0	2.082	2.091	110.8	2.091	2.097	130.72	130.99
45	110.9	2.084	2.093	110.6	2.095	2.101	130.90	131.12
46	110.8	2.086	2.095	110.5	2.097	2.103	131.02	131.26
47	110.7	2.088	2.097	110.4	2.099	2.105	131.14	131.38
48	110.6	2.090	2.098	110.3	2.101	2.106	131.26	131.52
49	110.5	2.092	2.100	110.2	2.103	2.108	131.37	131.64
50	110.4	2.094	2.102	110.1	2.105	2.110	131.49	131.76
51	110.3	2.096	2.104	110.0	2.106	2.112	131.61	131.90
52	110.1	2.099	2.108	109.8	2.110	2.116	131.85	132.18
G_{mb} (meas)		2.108			2.116			
Mass, g	4071.1			4081.1				

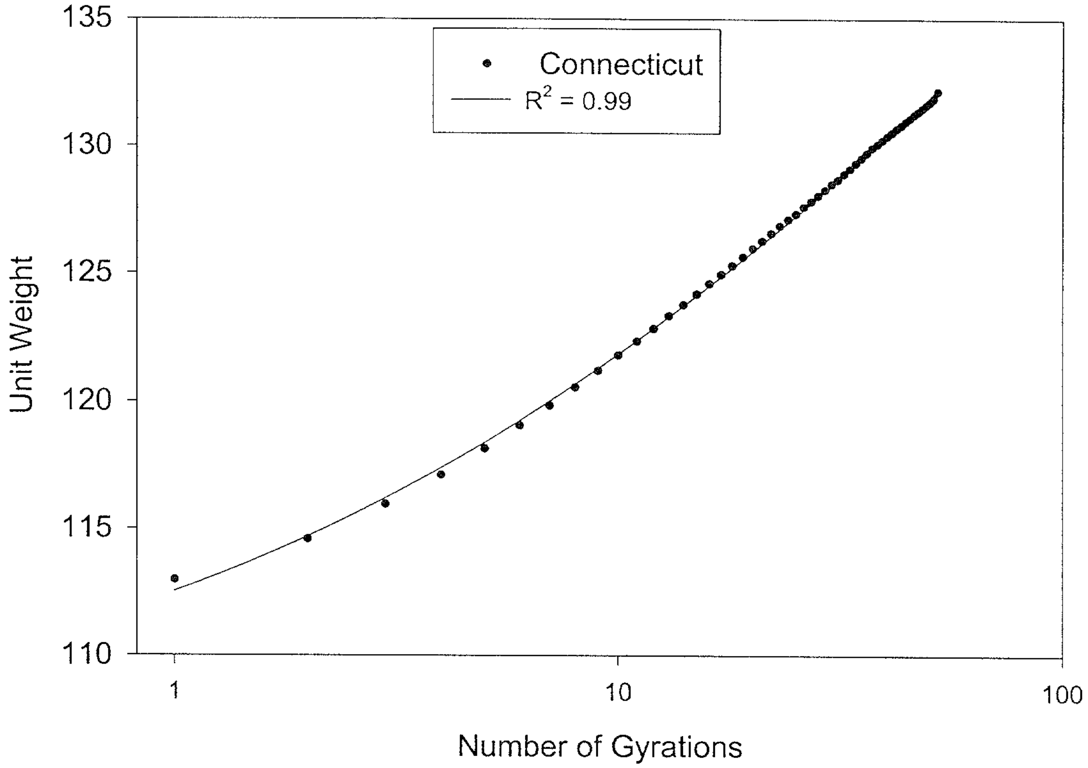

Figure A.1. Number of Gyrations vs. Unit Weight for Connecticut RAP and HFMS-2T Emulsion - Pilot Study

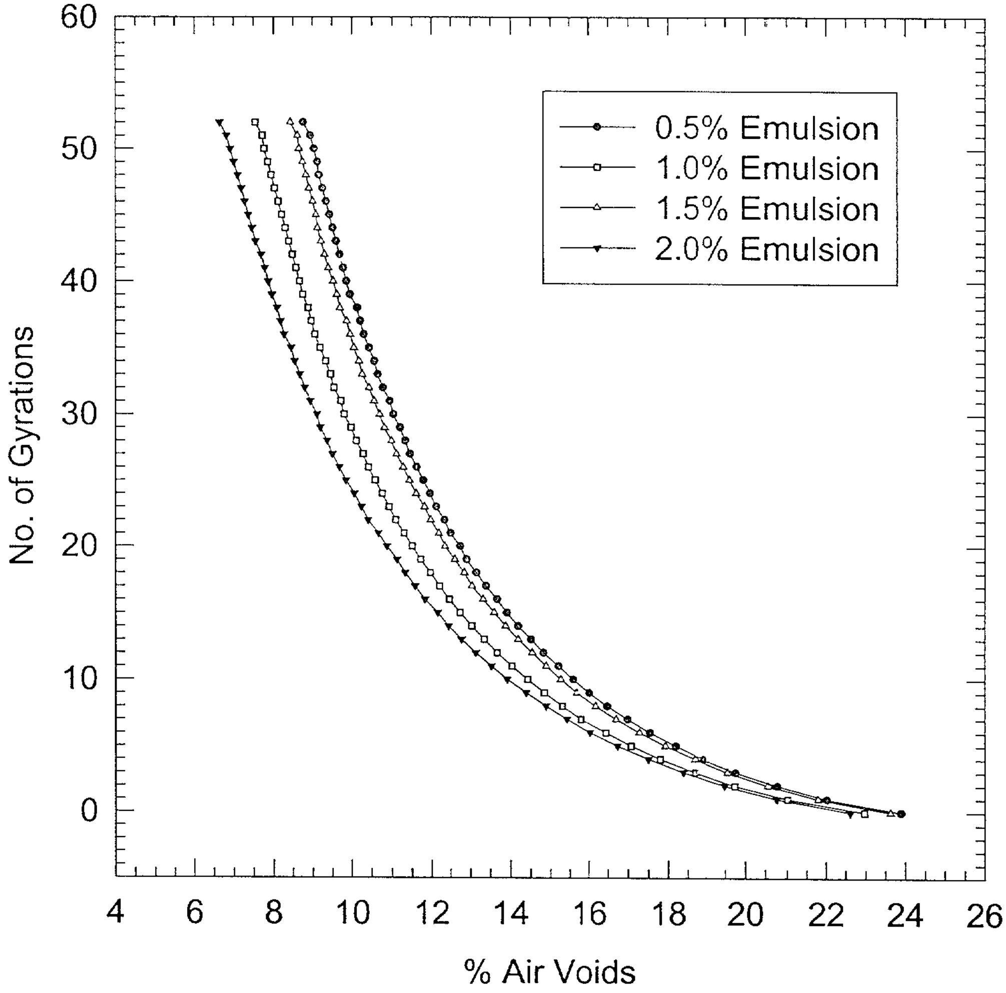

Figure A.2. Number of Gyrations vs. % Air Voids for Ontario RAP and HF150P Emulsion at Varying Emulsion Contents (3.0%) – Pilot Study

Table A.2. Gyration and Unit Weight Data for Kansas RAP and CSS-1h Emulsion to Determine No. of Gyrations Required to Simulate Field Density (130 pcf)

3.0% WC

1 OF 4

Emul. Cont.	0.5%						
Specimen #	1			2			Unit Weight
Gyrations	Ht, mm	G_{mb} (est)	G_{mb} (corr)	Ht, mm	G_{mb} (est)	G_{mb} (corr)	
0	132.7	1.726	1.769	131.4	1.744	1.778	**110.72**
1	129.6	1.767	1.812	128.2	1.788	1.822	**113.43**
2	127.4	1.798	1.843	126.2	1.816	1.851	**115.31**
3	125.7	1.822	1.868	124.5	1.841	1.876	**116.87**
4	124.3	1.842	1.889	123.3	1.859	1.895	**118.10**
5	123.2	1.859	1.906	122.3	1.874	1.910	**119.11**
6	122.0	1.877	1.924	121.2	1.891	1.927	**120.24**
7	121.3	1.888	1.936	120.4	1.903	1.940	**120.98**
8	120.7	1.897	1.945	119.6	1.916	1.953	**121.69**
9	120.2	1.905	1.953	118.9	1.927	1.965	**122.30**
10	119.7	1.913	1.961	118.3	1.937	1.975	**122.86**
11	119.3	1.920	1.968	117.8	1.945	1.983	**123.33**
12	118.9	1.926	1.975	117.4	1.952	1.990	**123.75**
13	118.5	1.933	1.981	117.0	1.959	1.997	**124.17**
14	118.1	1.939	1.988	116.7	1.964	2.002	**124.54**
15	117.7	1.946	1.995	116.4	1.969	2.007	**124.91**
16	117.4	1.951	2.000	116.1	1.974	2.012	**125.23**
17	117.1	1.956	2.005	115.8	1.979	2.017	**125.55**
18	116.8	1.961	2.010	115.5	1.984	2.023	**125.88**
19	116.5	1.966	2.015	115.2	1.989	2.028	**126.21**
20	116.2	1.971	2.020	114.9	1.995	2.033	**126.53**
21	115.9	1.976	2.026	114.6	2.000	2.038	**126.86**
22	115.6	1.981	2.031	114.3	2.005	2.044	**127.19**
23	115.3	1.986	2.036	114.0	2.010	2.049	**127.53**
24	115.0	1.991	2.042	113.7	2.016	2.055	**127.86**
25	114.7	1.997	2.047	113.4	2.021	2.060	**128.20**
26	114.4	2.002	2.052	113.1	2.026	2.065	**128.54**
27	114.1	2.007	2.058	112.8	2.032	2.071	**128.88**
28	113.8	2.012	2.063	112.5	2.037	2.076	**129.22**
29	113.5	2.018	2.069	112.2	2.043	2.082	**129.56**
30	113.2	2.023	2.074	112.0	2.046	2.086	**129.85**
31	113.0	2.027	2.078	111.9	2.048	2.088	**130.02**
32	112.9	2.029	2.080	111.7	2.052	2.091	**130.19**
33	112.8	2.030	2.081	111.6	2.054	2.093	**130.31**
34	112.7	2.032	2.083	111.4	2.057	2.097	**130.49**
35	112.5	2.036	2.087	111.2	2.061	2.101	**130.72**
36	112.3	2.039	2.091	111.1	2.063	2.103	**130.89**
37	112.1	2.043	2.094	111.0	2.065	2.105	**131.07**
38	111.9	2.047	2.098	110.8	2.068	2.108	**131.30**
39	111.8	2.048	2.100	110.5	2.074	2.114	**131.54**
40	111.6	2.052	2.104	110.3	2.078	2.118	**131.78**
41	111.4	2.056	2.108	110.1	2.082	2.122	**132.02**
42	111.2	2.060	2.111	109.9	2.085	2.126	**132.26**
43	111.0	2.063	2.115	109.7	2.089	2.129	**132.50**
44	110.8	2.067	2.119	109.5	2.093	2.133	**132.74**
45	110.6	2.071	2.123	109.3	2.097	2.137	**132.98**
46	110.3	2.076	2.129	109.1	2.101	2.141	**133.28**
47	110.1	2.080	2.132	108.9	2.104	2.145	**133.52**
48	109.9	2.084	2.136	108.6	2.110	2.151	**133.83**
49	109.7	2.088	2.140	108.4	2.114	2.155	**134.08**
50	109.5	2.092	2.144	108.3	2.116	2.157	**134.26**
51	109.4	2.093	2.146	108.2	2.118	2.159	**134.38**
52	109.2	2.097	2.150	108.0	2.122	2.163	**134.63**
G_{mb} (meas)		2.150			2.163		
Mass, g	4033.7			4036.5			

3.0% WC

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Emul. Cont.	1.0%						
Specimen #	1			2			Unit Weight
Gyrations	Ht, mm	G_{mb} (est)	G_{mb} (corr)	Ht, mm	G_{mb} (est)	G_{mb} (corr)	
0	131.6	1.747	1.780	131.6	1.747	1.782	**111.20**
1	128.6	1.788	1.822	128.6	1.788	1.824	**113.80**
2	126.6	1.816	1.850	126.6	1.816	1.853	**115.59**
3	125.0	1.839	1.874	125.0	1.839	1.877	**117.07**
4	123.9	1.855	1.891	123.8	1.857	1.895	**118.16**
5	123.0	1.869	1.904	122.9	1.871	1.909	**119.03**
6	122.1	1.883	1.918	121.8	1.888	1.926	**120.00**
7	121.2	1.897	1.933	121.1	1.899	1.937	**120.79**
8	120.4	1.909	1.946	120.5	1.908	1.947	**121.50**
9	119.8	1.919	1.955	119.9	1.918	1.956	**122.10**
10	119.3	1.927	1.964	119.3	1.927	1.966	**122.67**
11	118.8	1.935	1.972	118.8	1.935	1.975	**123.18**
12	118.4	1.942	1.978	118.3	1.944	1.983	**123.65**
13	118.0	1.948	1.985	117.9	1.950	1.990	**124.07**
14	117.6	1.955	1.992	117.5	1.957	1.996	**124.49**
15	117.2	1.962	1.999	117.1	1.964	2.003	**124.92**
16	116.9	1.967	2.004	116.8	1.969	2.008	**125.24**
17	116.6	1.972	2.009	116.5	1.974	2.014	**125.56**
18	116.3	1.977	2.014	116.2	1.979	2.019	**125.89**
19	116.0	1.982	2.019	115.9	1.984	2.024	**126.21**
20	115.7	1.987	2.025	115.6	1.989	2.029	**126.54**
21	115.4	1.992	2.030	115.3	1.994	2.034	**126.87**
22	115.1	1.997	2.035	115.0	1.999	2.040	**127.20**
23	114.8	2.003	2.040	114.7	2.005	2.045	**127.53**
24	114.5	2.008	2.046	114.4	2.010	2.050	**127.87**
25	114.2	2.013	2.051	114.1	2.015	2.056	**128.20**
26	113.9	2.018	2.057	113.8	2.021	2.061	**128.54**
27	113.6	2.024	2.062	113.6	2.024	2.065	**128.82**
28	113.3	2.029	2.067	113.4	2.028	2.069	**129.11**
29	113.1	2.033	2.071	113.3	2.029	2.070	**129.28**
30	112.9	2.036	2.075	113.2	2.031	2.072	**129.45**
31	112.7	2.040	2.078	113.0	2.035	2.076	**129.68**
32	112.5	2.044	2.082	112.9	2.037	2.078	**129.85**
33	112.4	2.045	2.084	112.8	2.038	2.080	**129.97**
34	112.2	2.049	2.088	112.6	2.042	2.083	**130.20**
35	112.0	2.053	2.091	112.4	2.046	2.087	**130.43**
36	112.1	2.051	2.090	112.2	2.049	2.091	**130.49**
37	111.8	2.056	2.095	112.0	2.053	2.094	**130.78**
38	111.6	2.060	2.099	111.8	2.057	2.098	**131.01**
39	111.4	2.064	2.103	111.7	2.058	2.100	**131.19**
40	111.2	2.067	2.107	111.5	2.062	2.104	**131.43**
41	111.0	2.071	2.110	111.3	2.066	2.108	**131.66**
42	110.8	2.075	2.114	111.1	2.070	2.111	**131.90**
43	110.6	2.079	2.118	110.8	2.075	2.117	**132.20**
44	110.4	2.082	2.122	110.6	2.079	2.121	**132.44**
45	110.2	2.086	2.126	110.4	2.083	2.125	**132.68**
46	110.0	2.090	2.130	110.2	2.087	2.129	**132.92**
47	109.8	2.094	2.133	110.0	2.090	2.132	**133.16**
48	109.6	2.098	2.137	109.7	2.096	2.138	**133.46**
49	109.3	2.103	2.143	109.4	2.102	2.144	**133.83**
50	109.2	2.105	2.145	109.1	2.108	2.150	**134.07**
51	109.1	2.107	2.147	108.9	2.111	2.154	**134.26**
52	108.8	2.113	2.153	108.7	2.115	2.158	**134.57**
G_{mb} (meas)		2.153			2.158		
Mass, g	4049.1			4049.8			

3.0% WC

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Emul. Cont.	1.5%						
Specimen #	1			2			Unit Weight
Gyrations	Ht, mm	G_{mb} (est)	G_{mb} (corr)	Ht, mm	G_{mb} (est)	G_{mb} (corr)	
0	132.8	1.738	1.778	131.7	1.753	1.788	**111.32**
1	129.9	1.776	1.817	128.8	1.792	1.829	**113.81**
2	127.9	1.804	1.846	126.9	1.819	1.856	**115.56**
3	126.3	1.827	1.869	125.4	1.841	1.878	**116.98**
4	125.1	1.845	1.887	124.3	1.857	1.895	**118.06**
5	124.1	1.859	1.902	123.2	1.873	1.912	**119.06**
6	123.2	1.873	1.916	122.4	1.886	1.924	**119.88**
7	122.3	1.887	1.930	121.7	1.897	1.935	**120.67**
8	121.5	1.899	1.943	121.0	1.908	1.947	**121.42**
9	120.8	1.910	1.954	120.4	1.917	1.956	**122.07**
10	120.3	1.918	1.962	119.8	1.927	1.966	**122.63**
11	119.9	1.925	1.969	119.3	1.935	1.974	**123.09**
12	119.5	1.931	1.976	118.8	1.943	1.983	**123.56**
13	119.1	1.938	1.982	118.4	1.949	1.989	**123.97**
14	118.7	1.944	1.989	118.0	1.956	1.996	**124.39**
15	118.3	1.951	1.996	117.6	1.963	2.003	**124.81**
16	118.0	1.956	2.001	117.3	1.968	2.008	**125.13**
17	117.7	1.961	2.006	117.0	1.973	2.013	**125.45**
18	117.4	1.966	2.011	116.7	1.978	2.018	**125.77**
19	117.1	1.971	2.016	116.4	1.983	2.024	**126.10**
20	116.8	1.976	2.021	116.1	1.988	2.029	**126.42**
21	116.5	1.981	2.026	115.8	1.993	2.034	**126.75**
22	116.2	1.986	2.032	115.5	1.998	2.039	**127.08**
23	115.9	1.991	2.037	115.2	2.004	2.045	**127.41**
24	115.6	1.996	2.042	114.9	2.009	2.050	**127.74**
25	115.3	2.001	2.048	114.6	2.014	2.055	**128.07**
26	115.0	2.007	2.053	114.3	2.019	2.061	**128.41**
27	114.7	2.012	2.058	114.0	2.025	2.066	**128.74**
28	114.4	2.017	2.064	113.7	2.030	2.072	**129.08**
29	114.1	2.022	2.069	113.4	2.035	2.077	**129.42**
30	113.8	2.028	2.075	113.2	2.039	2.081	**129.71**
31	113.6	2.031	2.078	113.0	2.043	2.084	**129.94**
32	113.4	2.035	2.082	112.9	2.044	2.086	**130.11**
33	113.3	2.037	2.084	112.8	2.046	2.088	**130.22**
34	113.1	2.040	2.087	112.6	2.050	2.092	**130.45**
35	113.0	2.042	2.089	112.5	2.052	2.094	**130.57**
36	112.8	2.046	2.093	112.3	2.055	2.097	**130.80**
37	112.6	2.049	2.097	112.1	2.059	2.101	**131.03**
38	112.4	2.053	2.100	111.9	2.063	2.105	**131.27**
39	112.2	2.057	2.104	111.7	2.066	2.109	**131.50**
40	112.0	2.060	2.108	111.5	2.070	2.113	**131.74**
41	111.8	2.064	2.112	111.3	2.074	2.116	**131.97**
42	111.7	2.066	2.114	111.1	2.078	2.120	**132.15**
43	111.5	2.070	2.117	110.9	2.081	2.124	**132.39**
44	111.3	2.073	2.121	110.7	2.085	2.128	**132.63**
45	111.1	2.077	2.125	110.5	2.089	2.132	**132.87**
46	110.9	2.081	2.129	110.3	2.093	2.135	**133.11**
47	110.7	2.085	2.133	110.0	2.098	2.141	**133.41**
48	110.5	2.088	2.136	109.8	2.102	2.145	**133.65**
49	110.3	2.092	2.140	109.7	2.104	2.147	**133.83**
50	111.1	2.077	2.125	109.6	2.106	2.149	**133.41**
51	109.9	2.100	2.148	109.5	2.108	2.151	**134.20**
52	109.6	2.105	2.154	109.2	2.114	2.157	**134.57**
G_{mb} (meas)		2.154			2.157		
Mass, g	4064.3			4065.3			

3.0% WC

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All Specimens

Emul. Cont.	2.0%							
Specimen #	1			2			Unit Weight	AVG Unit Weight
Gyrations	Ht, mm	G_{mb} (est)	G_{mb} (corr)	Ht, mm	G_{mb} (est)	G_{mb} (corr)		
0	133.0	1.740	1.774	134.5	1.723	1.762	**110.38**	**110.91**
1	130.2	1.777	1.812	131.7	1.759	1.799	**112.74**	**113.44**
2	128.2	1.805	1.841	129.8	1.785	1.826	**114.44**	**115.22**
3	126.6	1.828	1.864	128.2	1.807	1.848	**115.88**	**116.70**
4	125.4	1.845	1.882	127.0	1.824	1.866	**116.98**	**117.83**
5	124.4	1.860	1.897	126.0	1.839	1.881	**117.92**	**118.78**
6	123.5	1.874	1.911	124.9	1.855	1.897	**118.86**	**119.75**
7	122.7	1.886	1.923	123.9	1.870	1.913	**119.73**	**120.54**
8	121.9	1.898	1.936	123.2	1.881	1.924	**120.46**	**121.27**
9	121.3	1.908	1.945	122.6	1.890	1.933	**121.06**	**121.88**
10	120.7	1.917	1.955	122.1	1.898	1.941	**121.61**	**122.44**
11	120.2	1.925	1.963	121.6	1.906	1.949	**122.11**	**122.93**
12	119.7	1.933	1.971	121.2	1.912	1.955	**122.57**	**123.38**
13	119.3	1.940	1.978	120.8	1.918	1.962	**122.97**	**123.80**
14	118.9	1.946	1.985	120.4	1.925	1.968	**123.39**	**124.20**
15	118.5	1.953	1.991	120.0	1.931	1.975	**123.80**	**124.61**
16	118.2	1.958	1.996	119.7	1.936	1.980	**124.11**	**124.93**
17	117.9	1.963	2.001	119.4	1.941	1.985	**124.43**	**125.25**
18	117.6	1.968	2.006	119.1	1.946	1.990	**124.74**	**125.57**
19	117.3	1.973	2.012	118.8	1.950	1.995	**125.06**	**125.89**
20	117.0	1.978	2.017	118.5	1.955	2.000	**125.38**	**126.22**
21	116.7	1.983	2.022	118.2	1.960	2.005	**125.70**	**126.54**
22	116.4	1.988	2.027	117.9	1.965	2.010	**126.02**	**126.87**
23	116.1	1.993	2.032	117.6	1.970	2.015	**126.34**	**127.20**
24	115.8	1.998	2.038	117.3	1.975	2.020	**126.67**	**127.53**
25	115.5	2.003	2.043	117.0	1.980	2.025	**126.99**	**127.87**
26	115.2	2.009	2.048	116.7	1.986	2.031	**127.32**	**128.20**
27	114.9	2.014	2.054	116.4	1.991	2.036	**127.65**	**128.52**
28	114.6	2.019	2.059	116.1	1.996	2.041	**127.99**	**128.85**
29	114.3	2.024	2.064	115.8	2.001	2.046	**128.32**	**129.14**
30	114.0	2.030	2.070	115.5	2.006	2.052	**128.65**	**129.41**
31	113.8	2.033	2.073	115.3	2.010	2.055	**128.88**	**129.63**
32	113.6	2.037	2.077	115.1	2.013	2.059	**129.10**	**129.81**
33	113.5	2.039	2.079	114.9	2.017	2.062	**129.27**	129.94
34	113.3	2.042	2.083	114.7	2.020	2.066	**129.50**	**130.16**
35	113.2	2.044	2.084	114.5	2.024	2.070	**129.67**	**130.35**
36	113.0	2.048	2.088	114.4	2.025	2.071	**129.84**	**130.51**
37	112.8	2.051	2.092	114.2	2.029	2.075	**130.07**	**130.74**
38	112.6	2.055	2.096	114.0	2.033	2.079	**130.30**	**130.97**
39	112.4	2.059	2.099	113.8	2.036	2.082	**130.53**	**131.19**
40	112.2	2.062	2.103	113.7	2.038	2.084	**130.71**	**131.41**
41	112.0	2.066	2.107	113.5	2.042	2.088	**130.94**	**131.65**
42	111.7	2.072	2.112	113.2	2.047	2.093	**131.29**	**131.90**
43	111.5	2.075	2.116	113.0	2.051	2.097	**131.52**	**132.15**
44	111.3	2.079	2.120	112.8	2.054	2.101	**131.76**	**132.39**
45	111.1	2.083	2.124	112.6	2.058	2.105	**131.99**	**132.63**
46	110.9	2.086	2.128	112.4	2.061	2.108	**132.23**	**132.88**
47	110.7	2.090	2.132	112.2	2.065	2.112	**132.46**	**133.14**
48	110.5	2.094	2.135	112.0	2.069	2.116	**132.70**	**133.41**
49	110.3	2.098	2.139	111.8	2.073	2.120	**132.94**	**133.67**
50	110.2	2.100	2.141	111.6	2.076	2.123	**133.12**	**133.72**
51	110.1	2.102	2.143	111.4	2.080	2.127	**133.30**	**134.04**
52	109.8	2.107	2.149	111.1	2.086	2.133	**133.66**	**134.36**
G_{mb} (meas)		2.149			2.133			
Mass, g	4075.5			4081.1				

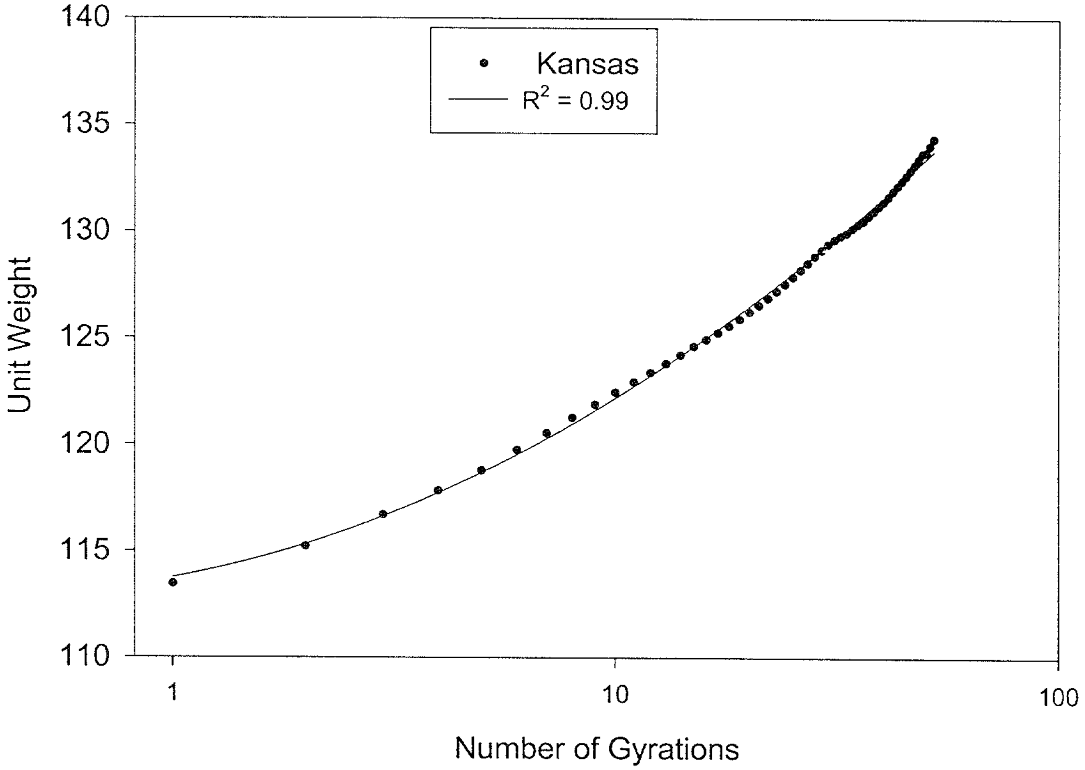

Figure A.3. Number of Gyrations vs. Unit Weight for Kansas RAP and CSS-1h Emulsion - Pilot Study

Table A.3. Gyration and Unit Weight Data for Ontario RAP and HF150P Emulsion to Determine No. of Gyrations Required to Simulate Field Density (140 pcf)

		Specimen # 1 Mass, g	2.5% WC 4049.7	1.2 % EC		Specimen # 2 Mass, g	2.5% WC 4042.8	1.2 % EC	
Gyration #	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Avg Unit Weight
0	128.3	1.788	1.811	113.08	127.8	1.791	1.815	113.28	**113.18**
1	125.4	1.829	1.853	115.69	124.8	1.835	1.858	116.01	**115.85**
2	123.5	1.857	1.882	117.47	122.9	1.863	1.887	117.80	**117.64**
3	122.0	1.880	1.905	118.92	121.3	1.887	1.912	119.35	**119.14**
4	120.6	1.902	1.927	120.30	120.0	1.908	1.933	120.65	**120.47**
5	119.5	1.919	1.945	121.40	118.8	1.927	1.952	121.87	**121.64**
6	118.6	1.934	1.959	122.33	117.9	1.942	1.967	122.80	**122.56**
7	117.7	1.948	1.974	123.26	117.0	1.957	1.982	123.74	**123.50**
8	117.0	1.960	1.986	124.00	116.2	1.970	1.996	124.59	**124.30**
9	116.3	1.972	1.998	124.75	115.5	1.982	2.008	125.35	**125.05**
10	115.7	1.982	2.009	125.39	114.9	1.993	2.018	126.00	**125.70**
11	115.1	1.993	2.019	126.05	114.4	2.001	2.027	126.55	**126.30**
12	114.6	2.001	2.028	126.60	113.8	2.012	2.038	127.22	**126.91**
13	114.2	2.008	2.035	127.04	113.4	2.019	2.045	127.67	**127.35**
14	113.7	2.017	2.044	127.60	112.9	2.028	2.054	128.23	**127.92**
15	113.3	2.024	2.051	128.05	112.5	2.035	2.061	128.69	**128.37**
16	112.9	2.031	2.058	128.50	112.1	2.042	2.069	129.15	**128.83**
17	112.6	2.037	2.064	128.84	111.8	2.048	2.074	129.50	**129.17**
18	112.2	2.044	2.071	129.30	111.4	2.055	2.082	129.96	**129.63**
19	111.9	2.049	2.077	129.65	111.1	2.061	2.087	130.31	**129.98**
20	111.6	2.055	2.082	130.00	110.8	2.066	2.093	130.66	**130.33**
21	111.3	2.061	2.088	130.35	110.6	2.070	2.097	130.90	**130.63**
22	111.1	2.064	2.092	130.58	110.3	2.076	2.102	131.26	**130.92**
23	110.8	2.070	2.097	130.94	110.0	2.081	2.108	131.62	**131.28**
24	110.6	2.074	2.101	131.17	109.8	2.085	2.112	131.85	**131.51**
25	110.4	2.077	2.105	131.41	109.6	2.089	2.116	132.10	**131.75**
26	110.2	2.081	2.109	131.65	109.4	2.093	2.120	132.34	**131.99**
27	109.9	2.087	2.115	132.01	109.1	2.099	2.126	132.70	**132.36**
28	109.7	2.091	2.118	132.25	108.9	2.102	2.129	132.94	**132.60**
29	109.5	2.094	2.122	132.49	108.8	2.104	2.131	133.07	**132.78**
30	109.4	2.096	2.124	132.61	108.6	2.108	2.135	133.31	**132.96**
31	109.2	2.100	2.128	132.86	108.4	2.112	2.139	133.56	**133.21**
32	109.0	2.104	2.132	133.10	108.2	2.116	2.143	133.80	**133.45**
33	108.9	2.106	2.134	133.22	108.1	2.118	2.145	133.93	**133.58**
34	108.7	2.110	2.138	133.47	107.9	2.122	2.149	134.18	**133.82**
35	108.5	2.114	2.142	133.71	107.8	2.124	2.151	134.30	**134.01**
36	108.4	2.116	2.144	133.84	107.6	2.128	2.155	134.55	**134.19**
37	108.3	2.118	2.146	133.96	107.5	2.130	2.157	134.68	**134.32**
38	108.1	2.122	2.150	134.21	107.3	2.134	2.161	134.93	**134.57**
39	108.0	2.124	2.152	134.33	107.2	2.136	2.163	135.05	**134.69**
40	107.9	2.125	2.154	134.46	107.1	2.138	2.165	135.18	**134.82**
41	107.7	2.129	2.158	134.71	106.9	2.142	2.169	135.43	**135.07**
42	107.6	2.131	2.160	134.83	106.8	2.144	2.171	135.56	**135.19**
43	107.5	2.133	2.162	134.96	106.7	2.146	2.173	135.69	**135.32**
44	107.4	2.135	2.164	135.08	106.6	2.148	2.175	135.81	**135.45**
45	107.3	2.137	2.166	135.21	106.5	2.150	2.177	135.94	**135.57**
46	107.1	2.141	2.170	135.46	106.3	2.154	2.182	136.20	**135.83**
47	107.0	2.143	2.172	135.59	106.2	2.156	2.184	136.32	**135.96**
48	106.9	2.145	2.174	135.71	106.1	2.158	2.186	136.45	**136.08**
49	106.8	2.147	2.176	135.84	106.0	2.160	2.188	136.58	**136.21**
50	106.7	2.149	2.178	135.97	105.9	2.162	2.190	136.71	**136.34**
51	106.6	2.151	2.180	136.10	105.8	2.164	2.192	136.84	**136.47**
52	106.5	2.153	2.182	136.22	105.7	2.166	2.194	136.97	**136.60**
53	106.4	2.155	2.184	136.35	105.6	2.168	2.196	137.10	**136.73**
54	106.3	2.157	2.186	136.48	105.5	2.170	2.198	137.23	**136.85**
55	106.2	2.159	2.188	136.61	105.4	2.172	2.200	137.36	**136.98**

		Specimen # 1	2.5% WC	1.2 % EC		Specimen # 2	2.5% WC	1.2 % EC	
		Mass, g	4049.7			Mass, g	4042.8		
Gyration #	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Avg Unit Weight
56	106.1	2.162	2.190	136.74	105.3	2.174	2.202	137.49	**137.11**
57	106.1	2.162	2.190	136.74	105.3	2.174	2.202	137.49	**137.11**
58	106.0	2.164	2.192	136.87	105.2	2.176	2.204	137.62	**137.24**
59	105.9	2.166	2.194	137.00	105.1	2.178	2.206	137.75	**137.37**
60	105.8	2.168	2.196	137.13	105.0	2.180	2.209	137.88	**137.50**
61	105.7	2.170	2.199	137.26	104.9	2.183	2.211	138.01	**137.63**
62	105.7	2.170	2.199	137.26	104.8	2.185	2.213	138.15	**137.70**
63	105.6	2.172	2.201	137.39	104.8	2.185	2.213	138.15	**137.77**
64	105.5	2.174	2.203	137.52	104.7	2.187	2.215	138.28	**137.90**
65	105.4	2.176	2.205	137.65	104.6	2.189	2.217	138.41	**138.03**
66	105.4	2.176	2.205	137.65	104.5	2.191	2.219	138.54	**138.09**
67	105.3	2.178	2.207	137.78	104.5	2.191	2.219	138.54	**138.16**
68	105.2	2.180	2.209	137.91	104.4	2.193	2.221	138.67	**138.29**
69	105.1	2.182	2.211	138.04	104.3	2.195	2.223	138.81	**138.42**
70	105.1	2.182	2.211	138.04	104.3	2.195	2.223	138.81	**138.42**
71	105.0	2.184	2.213	138.17	104.2	2.197	2.226	138.94	**138.56**
72	104.9	2.186	2.215	138.30	104.1	2.199	2.228	139.07	**138.69**
73	104.9	2.186	2.215	138.30	104.1	2.199	2.228	139.07	**138.69**
74	104.8	2.188	2.217	138.43	104.0	2.201	2.230	139.21	**138.82**
75	104.8	2.188	2.217	138.43	103.9	2.204	2.232	139.34	**138.89**
76	104.7	2.190	2.220	138.57	103.9	2.204	2.232	139.34	**138.95**
77	104.6	2.193	2.222	138.70	103.8	2.206	2.234	139.48	**139.09**
78	104.6	2.193	2.222	138.70	103.7	2.208	2.236	139.61	**139.15**
79	104.5	2.195	2.224	138.83	103.7	2.208	2.236	139.61	**139.22**
80	104.5	2.195	2.224	138.83	103.6	2.210	2.238	139.75	**139.29**
81	104.4	2.197	2.226	138.96	103.6	2.210	2.238	139.75	**139.35**
82	104.3	2.199	2.228	139.10	103.5	2.212	2.241	139.88	**139.49**
83	104.3	2.199	2.228	139.10	103.5	2.212	2.241	139.88	**139.49**
84	104.2	2.201	2.230	139.23	103.4	2.214	2.243	140.02	**139.62**
85	104.2	2.201	2.230	139.23	103.3	2.216	2.245	140.15	**139.69**
86	104.1	2.203	2.232	139.36	103.3	2.216	2.245	140.15	**139.76**
87	104.1	2.203	2.232	139.36	103.2	2.218	2.247	140.29	**139.83**
88	104.0	2.205	2.234	139.50	103.2	2.218	2.247	140.29	**139.89**
89	104.0	2.205	2.234	139.50	103.1	2.221	2.249	140.42	**139.96**
90	103.9	2.207	2.237	139.63	103.1	2.221	2.249	140.42	**140.03**
91	103.9	2.207	2.237	139.63	103.0	2.223	2.251	140.56	**140.10**
92	103.8	2.209	2.239	139.77	103.0	2.223	2.251	140.56	**140.16**
93	103.8	2.209	2.239	139.77	102.9	2.225	2.254	140.70	**140.23**
94	103.7	2.212	2.241	139.90	102.9	2.225	2.254	140.70	**140.30**
95	103.7	2.212	2.241	139.90	102.8	2.227	2.256	140.83	**140.37**
96	103.6	2.214	2.243	140.04	102.8	2.227	2.256	140.83	**140.44**
97	103.6	2.214	2.243	140.04	102.8	2.227	2.256	140.83	**140.44**
98	103.6	2.214	2.243	140.04	102.7	2.229	2.258	140.97	**140.50**
99	103.5	2.216	2.245	140.17	102.7	2.229	2.258	140.97	**140.57**
100	103.5	2.216	2.245	140.17	102.6	2.231	2.260	141.11	**140.64**
101	103.4	2.218	2.247	140.31	102.6	2.231	2.260	141.11	**140.71**
102	103.4	2.218	2.247	140.31	102.5	2.234	2.262	141.25	**140.78**
103	103.3	2.220	2.250	140.44	102.5	2.234	2.262	141.25	**140.84**
104	103.3	2.220	2.250	140.44	102.4	2.236	2.265	141.38	**140.91**
105	103.3	2.220	2.250	140.44	102.4	2.236	2.265	141.38	**140.91**
106	103.2	2.222	2.252	140.58	102.4	2.236	2.265	141.38	**140.98**
107	103.2	2.222	2.252	140.58	102.3	2.238	2.267	141.52	**141.05**
108	103.1	2.224	2.254	140.72	102.3	2.238	2.267	141.52	**141.12**
109	103.1	2.224	2.254	140.72	102.2	2.240	2.269	141.66	**141.19**
110	103.1	2.224	2.254	140.72	102.2	2.240	2.269	141.66	**141.19**
111	103.0	2.227	2.256	140.85	102.2	2.240	2.269	141.66	**141.26**
112	103.0	2.227	2.256	140.85	102.1	2.242	2.271	141.80	**141.33**
113	102.9	2.229	2.258	140.99	102.1	2.242	2.271	141.80	**141.39**
114	102.9	2.229	2.258	140.99	102.0	2.245	2.274	141.94	**141.46**
115	102.9	2.229	2.258	140.99	102.0	2.245	2.274	141.94	**141.46**

		Specimen # 1 Mass, g	2.5% WC 4049.7	1.2 % EC		Specimen # 2 Mass, g	2.5% WC 4042.8	1.2 % EC	
Gyration #	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Avg Unit Weight
116	102.8	2.231	2.261	141.13	102.0	2.245	2.274	141.94	**141.53**
117	102.8	2.231	2.261	141.13	101.9	2.247	2.276	142.08	**141.60**
118	102.8	2.231	2.261	141.13	101.9	2.247	2.276	142.08	**141.60**
119	102.7	2.233	2.263	141.26	101.9	2.247	2.276	142.08	**141.67**
120	102.7	2.233	2.263	141.26	101.8	2.249	2.278	142.22	**141.74**
121	102.7	2.233	2.263	141.26	101.8	2.249	2.278	142.22	**141.74**
122	102.6	2.235	2.265	141.40	101.7	2.251	2.280	142.36	**141.88**
123	102.6	2.235	2.265	141.40	101.7	2.251	2.280	142.36	**141.88**
124	102.6	2.235	2.265	141.40	101.7	2.251	2.280	142.36	**141.88**
125	102.5	2.237	2.267	141.54	101.6	2.253	2.283	142.50	**142.02**
126	102.5	2.237	2.267	141.54	101.6	2.253	2.283	142.50	**142.02**
127	102.5	2.237	2.267	141.54	101.6	2.253	2.283	142.50	**142.02**
128	102.4	2.240	2.269	141.68	101.5	2.256	2.285	142.64	**142.16**
129	102.4	2.240	2.269	141.68	101.5	2.256	2.285	142.64	**142.16**
130	102.4	2.240	2.269	141.68	101.5	2.256	2.285	142.64	**142.16**
131	102.3	2.242	2.272	141.82	101.4	2.258	2.287	142.78	**142.30**
132	102.3	2.242	2.272	141.82	101.4	2.258	2.287	142.78	**142.30**
133	102.3	2.242	2.272	141.82	101.4	2.258	2.287	142.78	**142.30**
134	102.2	2.244	2.274	141.96	101.3	2.260	2.289	142.92	**142.44**
135	102.2	2.244	2.274	141.96	101.3	2.260	2.289	142.92	**142.44**
136	102.2	2.244	2.274	141.96	101.3	2.260	2.289	142.92	**142.44**
137	102.2	2.244	2.274	141.96	101.3	2.260	2.289	142.92	**142.44**
138	102.1	2.246	2.276	142.09	101.2	2.262	2.292	143.06	**142.58**
139	102.1	2.246	2.276	142.09	101.2	2.262	2.292	143.06	**142.58**
140	102.1	2.246	2.276	142.09	101.2	2.262	2.292	143.06	**142.58**
141	102.0	2.248	2.278	142.23	101.1	2.265	2.294	143.20	**142.72**
142	102.0	2.248	2.278	142.23	101.1	2.265	2.294	143.20	**142.72**
143	102.0	2.248	2.278	142.23	101.1	2.265	2.294	143.20	**142.72**
144	101.9	2.251	2.281	142.37	101.0	2.267	2.296	143.34	**142.86**
145	101.9	2.251	2.281	142.37	101.0	2.267	2.296	143.34	**142.86**
146	101.9	2.251	2.281	142.37	101.0	2.267	2.296	143.34	**142.86**
147	101.9	2.251	2.281	142.37	101.0	2.267	2.296	143.34	**142.86**
148	101.8	2.253	2.283	142.51	100.9	2.269	2.298	143.49	**143.00**
149	101.8	2.253	2.283	142.51	100.9	2.269	2.298	143.49	**143.00**
150	101.8	2.253	2.283	142.51	100.9	2.269	2.298	143.49	**143.00**
151	101.8	2.253	2.283	142.51	100.8	2.271	2.301	143.63	**143.07**
152	101.7	2.255	2.285	142.65	100.8	2.271	2.301	143.63	**143.14**
153	101.7	2.255	2.285	142.65	100.8	2.271	2.301	143.63	**143.14**
154	101.7	2.255	2.285	142.65	100.8	2.271	2.301	143.63	**143.14**
155	101.6	2.257	2.287	142.79	100.7	2.274	2.303	143.77	**143.28**
156	101.6	2.257	2.287	142.79	100.7	2.274	2.303	143.77	**143.28**
157	101.6	2.257	2.287	142.79	100.7	2.274	2.303	143.77	**143.28**
158	101.6	2.257	2.287	142.79	100.7	2.274	2.303	143.77	**143.28**
159	101.5	2.259	2.290	142.93	100.6	2.276	2.305	143.91	**143.42**
160	101.5	2.259	2.290	142.93	100.6	2.276	2.305	143.91	**143.42**
161	101.5	2.259	2.290	142.93	100.6	2.276	2.305	143.91	**143.42**
162	101.5	2.259	2.290	142.93	100.6	2.276	2.305	143.91	**143.42**
163	101.4	2.262	2.292	143.08	100.5	2.278	2.307	144.06	**143.57**
164	101.4	2.262	2.292	143.08	100.5	2.278	2.307	144.06	**143.57**
165	101.4	2.262	2.292	143.08	100.5	2.278	2.307	144.06	**143.57**
166	101.4	2.262	2.292	143.08	100.5	2.278	2.307	144.06	**143.57**
167	101.4	2.262	2.292	143.08	100.4	2.280	2.310	144.20	**143.64**
168	101.3	2.264	2.294	143.22	100.4	2.280	2.310	144.20	**143.71**
169	101.3	2.264	2.294	143.22	100.4	2.280	2.310	144.20	**143.71**
170	101.3	2.264	2.294	143.22	100.4	2.280	2.310	144.20	**143.71**
171	101.3	2.264	2.294	143.22	100.3	2.283	2.312	144.34	**143.78**
172	101.2	2.266	2.296	143.36	100.3	2.283	2.312	144.34	**143.85**
173	101.2	2.266	2.296	143.36	100.3	2.283	2.312	144.34	**143.85**
174	101.2	2.266	2.296	143.36	100.3	2.283	2.312	144.34	**143.85**
175	101.2	2.266	2.296	143.36	100.2	2.285	2.314	144.49	**143.92**

		Specimen # 1 Mass, g	2.5% WC 4049.7	1.2 % EC		Specimen # 2 Mass, g	2.5% WC 4042.8	1.2 % EC	
Gyration #	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Avg Unit Weight
176	101.1	2.268	2.299	143.50	100.2	2.285	2.314	144.49	**143.99**
177	101.1	2.268	2.299	143.50	100.2	2.285	2.314	144.49	**143.99**
178	101.1	2.268	2.299	143.50	100.2	2.285	2.314	144.49	**143.99**
179	101.1	2.268	2.299	143.50	100.1	2.287	2.317	144.63	**144.07**
180	101.1	2.268	2.299	143.50	100.1	2.287	2.317	144.63	**144.07**
181	101.0	2.271	2.301	143.64	100.1	2.287	2.317	144.63	**144.14**
182	101.0	2.271	2.301	143.64	100.1	2.287	2.317	144.63	**144.14**
183	101.0	2.271	2.301	143.64	100.1	2.287	2.317	144.63	**144.14**
184	101.0	2.271	2.301	143.64	100.0	2.289	2.319	144.78	**144.21**
185	101.0	2.271	2.301	143.64	100.0	2.289	2.319	144.78	**144.21**
186	100.9	2.273	2.303	143.78	100.0	2.289	2.319	144.78	**144.28**
187	100.9	2.273	2.303	143.78	100.0	2.289	2.319	144.78	**144.28**
188	100.9	2.273	2.303	143.78	100.0	2.289	2.319	144.78	**144.28**
189	100.9	2.273	2.303	143.78	99.9	2.292	2.321	144.92	**144.35**
190	100.9	2.273	2.303	143.78	99.9	2.292	2.321	144.92	**144.35**
191	100.8	2.275	2.305	143.93	99.9	2.292	2.321	144.92	**144.42**
192	100.8	2.275	2.305	143.93	99.9	2.292	2.321	144.92	**144.42**
193	100.8	2.275	2.305	143.93	99.8	2.294	2.324	145.07	**144.50**
194	100.8	2.275	2.305	143.93	99.8	2.294	2.324	145.07	**144.50**
195	100.8	2.275	2.305	143.93	99.8	2.294	2.324	145.07	**144.50**
196	100.7	2.277	2.308	144.07	99.8	2.294	2.324	145.07	**144.57**
197	100.7	2.277	2.308	144.07	99.8	2.294	2.324	145.07	**144.57**
198	100.7	2.277	2.308	144.07	99.7	2.296	2.326	145.21	**144.64**
199	100.7	2.277	2.308	144.07	99.7	2.296	2.326	145.21	**144.64**
200	100.6	2.280	2.310	144.21	99.7	2.296	2.326	145.21	**144.71**

G_{mb} (meas) 2.310 2.326

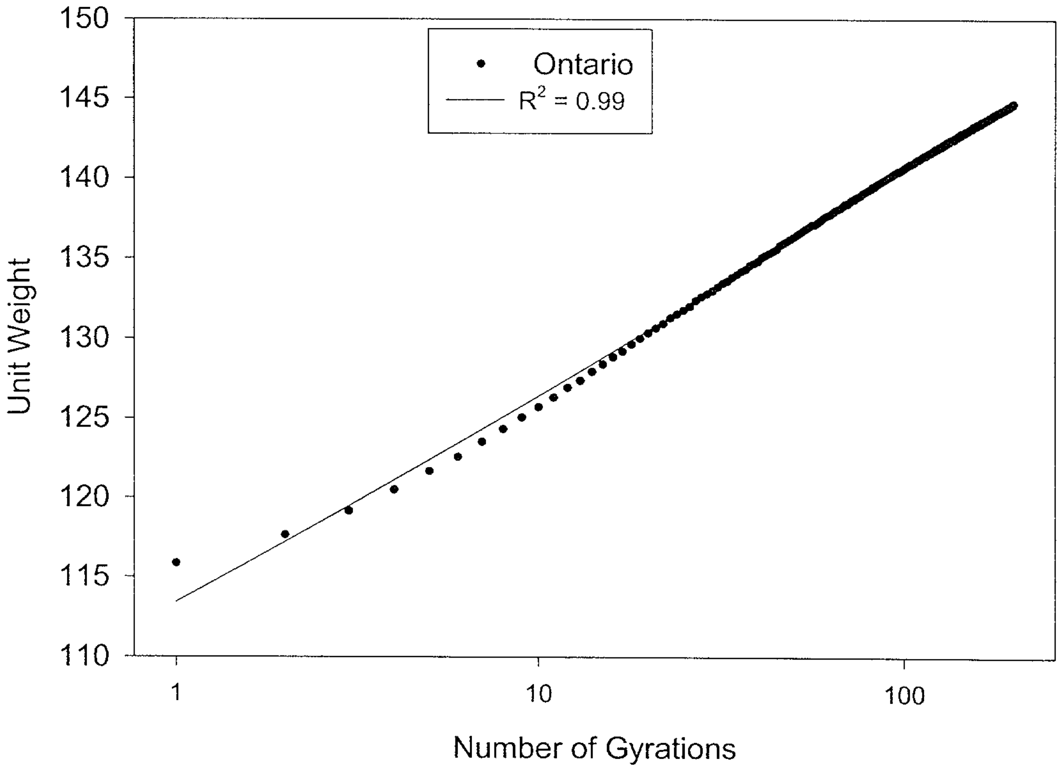

Figure A.4. Number of Gyrations vs. Unit Weight for Ontario RAP and HF150P Emulsion – Determination of No. of Gyrations to Simulate Field Density

Table A.4. Gyration and Unit Weight Data for New Mexico RAP and HFE150-P to Determine No. of Gyrations Required to Simulate Field Density (131.5 pcf)

		Specimen # 1	2.0% WC	1.5 % EC		Specimen # 2	2.0% WC	1.5 % EC	
		Mass, g	4067.4			Mass, g	4073.8		Avg
Gyration #	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Unit Weight
0	142.5	1.616	1.640	102.37	142.0	1.625	1.645	102.67	**102.52**
1	139.1	1.656	1.680	104.88	138.7	1.663	1.684	105.12	**105.00**
2	136.7	1.685	1.709	106.72	136.5	1.690	1.711	106.81	**106.76**
3	134.8	1.709	1.733	108.22	134.6	1.714	1.735	108.32	**108.27**
4	133.1	1.731	1.756	109.60	133.0	1.735	1.756	109.62	**109.61**
5	131.8	1.748	1.773	110.68	131.6	1.753	1.775	110.79	**110.74**
6	130.6	1.764	1.789	111.70	130.4	1.769	1.791	111.81	**111.75**
7	129.6	1.777	1.803	112.56	129.3	1.784	1.806	112.76	**112.66**
8	128.7	1.790	1.816	113.35	128.4	1.797	1.819	113.55	**113.45**
9	127.9	1.801	1.827	114.06	127.6	1.808	1.830	114.26	**114.16**
10	127.1	1.812	1.838	114.78	126.8	1.819	1.842	114.98	**114.88**
11	126.4	1.822	1.849	115.41	126.1	1.830	1.852	115.62	**115.52**
12	125.8	1.831	1.857	115.96	125.5	1.838	1.861	116.17	**116.07**
13	125.3	1.838	1.865	116.43	124.9	1.847	1.870	116.73	**116.58**
14	124.7	1.847	1.874	116.99	124.3	1.856	1.879	117.29	**117.14**
15	124.2	1.855	1.881	117.46	123.8	1.864	1.886	117.77	**117.61**
16	123.7	1.862	1.889	117.93	123.3	1.871	1.894	118.24	**118.09**
17	123.3	1.868	1.895	118.31	122.9	1.877	1.900	118.63	**118.47**
18	122.9	1.874	1.901	118.70	122.4	1.885	1.908	119.11	**118.91**
19	122.5	1.880	1.908	119.09	122.0	1.891	1.914	119.50	**119.30**
20	122.1	1.886	1.914	119.48	121.6	1.897	1.921	119.90	**119.69**
21	121.8	1.891	1.918	119.77	121.3	1.902	1.925	120.19	**119.98**
22	121.4	1.897	1.925	120.17	120.9	1.908	1.932	120.59	**120.38**
23	121.1	1.902	1.930	120.46	120.6	1.913	1.936	120.89	**120.68**
24	120.8	1.907	1.934	120.76	120.3	1.918	1.941	121.19	**120.98**
25	120.5	1.912	1.939	121.06	120.0	1.923	1.946	121.50	**121.28**
26	120.2	1.916	1.944	121.37	119.7	1.927	1.951	121.80	**121.58**
27	119.9	1.921	1.949	121.67	119.4	1.932	1.956	122.11	**121.89**
28	119.7	1.924	1.952	121.87	119.2	1.935	1.959	122.31	**122.09**
29	119.4	1.929	1.957	122.18	118.9	1.940	1.964	122.62	**122.40**
30	119.2	1.932	1.960	122.38	118.6	1.945	1.969	122.93	**122.66**
31	118.9	1.937	1.965	122.69	118.4	1.949	1.972	123.14	**122.92**
32	118.7	1.941	1.969	122.90	118.2	1.952	1.976	123.35	**123.12**
33	118.5	1.944	1.972	123.11	117.9	1.957	1.981	123.66	**123.38**
34	118.3	1.947	1.975	123.32	117.7	1.960	1.984	123.87	**123.59**
35	118.1	1.950	1.979	123.52	117.5	1.963	1.988	124.08	**123.80**
36	117.9	1.954	1.982	123.73	117.3	1.967	1.991	124.29	**124.01**
37	117.7	1.957	1.985	123.94	117.1	1.970	1.994	124.50	**124.22**
38	117.5	1.960	1.989	124.15	116.9	1.974	1.998	124.72	**124.44**
39	117.3	1.964	1.992	124.37	116.7	1.977	2.001	124.93	**124.65**
40	117.1	1.967	1.995	124.58	116.6	1.979	2.003	125.04	**124.81**
41	116.9	1.970	1.999	124.79	116.4	1.982	2.006	125.25	**125.02**
42	116.8	1.972	2.001	124.90	116.2	1.985	2.010	125.47	**125.18**
43	116.6	1.975	2.004	125.11	116.0	1.989	2.013	125.69	**125.40**
44	116.4	1.979	2.008	125.33	115.9	1.991	2.015	125.79	**125.56**
45	116.3	1.981	2.009	125.44	115.7	1.994	2.018	126.01	**125.72**
46	116.1	1.984	2.013	125.65	115.6	1.996	2.020	126.12	**125.89**
47	116.0	1.986	2.014	125.76	115.4	1.999	2.024	126.34	**126.05**
48	115.8	1.989	2.018	125.98	115.3	2.001	2.025	126.45	**126.21**
49	115.7	1.991	2.020	126.09	115.1	2.004	2.029	126.67	**126.38**
50	115.6	1.993	2.021	126.20	115.0	2.006	2.031	126.78	**126.49**
51	115.4	1.996	2.025	126.41	114.8	2.010	2.034	127.00	**126.71**
52	115.3	1.998	2.027	126.52	114.7	2.011	2.036	127.11	**126.82**
53	115.1	2.001	2.030	126.74	114.6	2.013	2.038	127.22	**126.98**
54	115.0	2.003	2.032	126.85	114.5	2.015	2.040	127.33	**127.09**
55	114.9	2.005	2.034	126.96	114.3	2.018	2.043	127.55	**127.26**

		Specimen # 1	2.0% WC	1.5 % EC		Specimen # 2	2.0% WC	1.5 % EC	
		Mass, g	4067.4			Mass, g	4073.8		Avg
Gyration #	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Unit Weight
56	114.8	2.006	2.035	127.07	114.2	2.020	2.045	127.67	**127.37**
57	114.7	2.008	2.037	127.19	114.1	2.022	2.047	127.78	**127.48**
58	114.5	2.012	2.041	127.41	114.0	2.024	2.049	127.89	**127.65**
59	114.4	2.013	2.043	127.52	113.9	2.025	2.050	128.00	**127.76**
60	114.3	2.015	2.044	127.63	113.7	2.029	2.054	128.23	**127.93**
61	114.2	2.017	2.046	127.74	113.6	2.031	2.056	128.34	**128.04**
62	114.1	2.019	2.048	127.85	113.5	2.033	2.058	128.45	**128.15**
63	114.0	2.021	2.050	127.97	113.4	2.034	2.059	128.57	**128.27**
64	113.9	2.022	2.052	128.08	113.3	2.036	2.061	128.68	**128.38**
65	113.8	2.024	2.053	128.19	113.2	2.038	2.063	128.79	**128.49**
66	113.7	2.026	2.055	128.30	113.1	2.040	2.065	128.91	**128.61**
67	113.6	2.028	2.057	128.42	113.0	2.042	2.067	129.02	**128.72**
68	113.5	2.029	2.059	128.53	112.9	2.043	2.069	129.14	**128.83**
69	113.4	2.031	2.061	128.64	112.8	2.045	2.070	129.25	**128.95**
70	113.3	2.033	2.062	128.76	112.7	2.047	2.072	129.37	**129.06**
71	113.2	2.035	2.064	128.87	112.6	2.049	2.074	129.48	**129.18**
72	113.1	2.037	2.066	128.99	112.5	2.051	2.076	129.60	**129.29**
73	113.0	2.038	2.068	129.10	112.4	2.053	2.078	129.71	**129.41**
74	112.9	2.040	2.070	129.21	112.4	2.053	2.078	129.71	**129.46**
75	112.8	2.042	2.072	129.33	112.3	2.054	2.080	129.83	**129.58**
76	112.7	2.044	2.073	129.44	112.2	2.056	2.081	129.94	**129.69**
77	112.6	2.046	2.075	129.56	112.1	2.058	2.083	130.06	**129.81**
78	112.6	2.046	2.075	129.56	112.0	2.060	2.085	130.17	**129.87**
79	112.5	2.047	2.077	129.67	111.9	2.062	2.087	130.29	**129.98**
80	112.4	2.049	2.079	129.79	111.8	2.064	2.089	130.41	**130.10**
81	112.3	2.051	2.081	129.90	111.8	2.064	2.089	130.41	**130.16**
82	112.2	2.053	2.083	130.02	111.7	2.065	2.091	130.52	**130.27**
83	112.2	2.053	2.083	130.02	111.6	2.067	2.093	130.64	**130.33**
84	112.1	2.055	2.085	130.14	111.5	2.069	2.094	130.76	**130.45**
85	112.0	2.057	2.086	130.25	111.5	2.069	2.094	130.76	**130.50**
86	111.9	2.058	2.088	130.37	111.4	2.071	2.096	130.88	**130.62**
87	111.9	2.058	2.088	130.37	111.3	2.073	2.098	130.99	**130.68**
88	111.8	2.060	2.090	130.48	111.2	2.075	2.100	131.11	**130.80**
89	111.7	2.062	2.092	130.60	111.2	2.075	2.100	131.11	**130.86**
90	111.6	2.064	2.094	130.72	111.1	2.077	2.102	131.23	**130.97**
91	111.6	2.064	2.094	130.72	111.0	2.078	2.104	131.35	**131.03**
92	111.5	2.066	2.096	130.84	111.0	2.078	2.104	131.35	**131.09**
93	111.4	2.068	2.098	130.95	110.9	2.080	2.106	131.47	**131.21**
94	111.4	2.068	2.098	130.95	110.8	2.082	2.108	131.58	**131.27**
95	111.3	2.070	2.099	131.07	110.8	2.082	2.108	131.58	**131.33**
96	111.2	2.071	2.101	131.19	110.7	2.084	2.110	131.70	**131.45**
97	111.2	2.071	2.101	131.19	110.6	2.086	2.112	131.82	**131.51**
98	111.1	2.073	2.103	131.31	110.6	2.086	2.112	131.82	**131.56**
99	111.0	2.075	2.105	131.43	110.5	2.088	2.113	131.94	**131.68**
100	111.0	2.075	2.105	131.43	110.4	2.090	2.115	132.06	**131.74**
101	110.9	2.077	2.107	131.54	110.4	2.090	2.115	132.06	**131.80**
102	110.9	2.077	2.107	131.54	110.3	2.092	2.117	132.18	**131.86**
103	110.8	2.079	2.109	131.66	110.3	2.092	2.117	132.18	**131.92**
104	110.7	2.081	2.111	131.78	110.2	2.093	2.119	132.30	**132.04**
105	110.7	2.081	2.111	131.78	110.1	2.095	2.121	132.42	**132.10**
106	110.6	2.083	2.113	131.90	110.1	2.095	2.121	132.42	**132.16**
107	110.6	2.083	2.113	131.90	110.0	2.097	2.123	132.54	**132.22**
108	110.5	2.085	2.115	132.02	110.0	2.097	2.123	132.54	**132.28**
109	110.4	2.086	2.117	132.14	109.9	2.099	2.125	132.66	**132.40**
110	110.4	2.086	2.117	132.14	109.9	2.099	2.125	132.66	**132.40**
111	110.3	2.088	2.119	132.26	109.8	2.101	2.127	132.78	**132.52**
112	110.3	2.088	2.119	132.26	109.7	2.103	2.129	132.90	**132.58**
113	110.2	2.090	2.120	132.38	109.7	2.103	2.129	132.90	**132.64**
114	110.2	2.090	2.120	132.38	109.6	2.105	2.131	133.02	**132.70**
115	110.1	2.092	2.122	132.50	109.6	2.105	2.131	133.02	**132.76**

		Specimen # 1	2.0% WC	1.5 % EC		Specimen # 2	2.0% WC	1.5 % EC	
		Mass, g	4067.4			Mass, g	4073.8		
Gyration #	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Avg Unit Weight
116	110.1	2.092	2.122	132.50	109.5	2.107	2.133	133.15	**132.82**
117	110.0	2.094	2.124	132.62	109.5	2.107	2.133	133.15	**132.88**
118	110.0	2.094	2.124	132.62	109.4	2.109	2.135	133.27	**132.94**
119	109.9	2.096	2.126	132.74	109.4	2.109	2.135	133.27	**133.00**
120	109.9	2.096	2.126	132.74	109.3	2.111	2.137	133.39	**133.07**
121	109.8	2.098	2.128	132.86	109.3	2.111	2.137	133.39	**133.13**
122	109.8	2.098	2.128	132.86	109.2	2.113	2.139	133.51	**133.19**
123	109.7	2.100	2.130	132.98	109.2	2.113	2.139	133.51	**133.25**
124	109.7	2.100	2.130	132.98	109.1	2.115	2.141	133.63	**133.31**
125	109.6	2.102	2.132	133.10	109.1	2.115	2.141	133.63	**133.37**
126	109.6	2.102	2.132	133.10	109.0	2.117	2.143	133.76	**133.43**
127	109.5	2.104	2.134	133.23	109.0	2.117	2.143	133.76	**133.49**
128	109.5	2.104	2.134	133.23	108.9	2.118	2.144	133.88	**133.55**
129	109.4	2.105	2.136	133.35	108.9	2.118	2.144	133.88	**133.61**
130	109.4	2.105	2.136	133.35	108.8	2.120	2.146	134.00	**133.68**
131	109.3	2.107	2.138	133.47	108.8	2.120	2.146	134.00	**133.74**
132	109.3	2.107	2.138	133.47	108.7	2.122	2.148	134.13	**133.80**
133	109.2	2.109	2.140	133.59	108.7	2.122	2.148	134.13	**133.86**
134	109.2	2.109	2.140	133.59	108.7	2.122	2.148	134.13	**133.86**
135	109.2	2.109	2.140	133.59	108.6	2.124	2.150	134.25	**133.92**
136	109.1	2.111	2.142	133.71	108.6	2.124	2.150	134.25	**133.98**
137	109.1	2.111	2.142	133.71	108.5	2.126	2.152	134.37	**134.04**
138	109.0	2.113	2.144	133.84	108.5	2.126	2.152	134.37	**134.11**
139	109.0	2.113	2.144	133.84	108.4	2.128	2.154	134.50	**134.17**
140	108.9	2.115	2.146	133.96	108.4	2.128	2.154	134.50	**134.23**
141	108.9	2.115	2.146	133.96	108.3	2.130	2.156	134.62	**134.29**
142	108.8	2.117	2.148	134.08	108.3	2.130	2.156	134.62	**134.35**
143	108.8	2.117	2.148	134.08	108.3	2.130	2.156	134.62	**134.35**
144	108.8	2.117	2.148	134.08	108.2	2.132	2.158	134.75	**134.41**
145	108.7	2.119	2.150	134.21	108.2	2.132	2.158	134.75	**134.48**
146	108.7	2.119	2.150	134.21	108.1	2.134	2.160	134.87	**134.54**
147	108.6	2.121	2.152	134.33	108.1	2.134	2.160	134.87	**134.60**
148	108.6	2.121	2.152	134.33	108.1	2.134	2.160	134.87	**134.60**
149	108.6	2.121	2.152	134.33	108.0	2.136	2.162	135.00	**134.66**
150	108.5	2.123	2.154	134.45	108.0	2.136	2.162	135.00	**134.72**
151	108.5	2.123	2.154	134.45	107.9	2.138	2.164	135.12	**134.79**
152	108.4	2.125	2.156	134.58	107.9	2.138	2.164	135.12	**134.85**
153	108.4	2.125	2.156	134.58	107.9	2.138	2.164	135.12	**134.85**
154	108.4	2.125	2.156	134.58	107.8	2.140	2.166	135.25	**134.91**
155	108.3	2.127	2.158	134.70	107.8	2.140	2.166	135.25	**134.97**
156	108.3	2.127	2.158	134.70	107.7	2.142	2.168	135.37	**135.04**
157	108.2	2.129	2.160	134.83	107.7	2.142	2.168	135.37	**135.10**
158	108.2	2.129	2.160	134.83	107.7	2.142	2.168	135.37	**135.10**
159	108.2	2.129	2.160	134.83	107.6	2.144	2.170	135.50	**135.16**
160	108.1	2.131	2.162	134.95	107.6	2.144	2.170	135.50	**135.22**
161	108.1	2.131	2.162	134.95	107.6	2.144	2.170	135.50	**135.22**
162	108.1	2.131	2.162	134.95	107.5	2.146	2.172	135.62	**135.29**
163	108.0	2.133	2.164	135.08	107.5	2.146	2.172	135.62	**135.35**
164	108.0	2.133	2.164	135.08	107.4	2.148	2.174	135.75	**135.41**
165	108.0	2.133	2.164	135.08	107.4	2.148	2.174	135.75	**135.41**
166	107.9	2.135	2.166	135.20	107.4	2.148	2.174	135.75	**135.48**
167	107.9	2.135	2.166	135.20	107.3	2.150	2.176	135.88	**135.54**
168	107.8	2.137	2.168	135.33	107.3	2.150	2.176	135.88	**135.60**
169	107.8	2.137	2.168	135.33	107.3	2.150	2.176	135.88	**135.60**
170	107.8	2.137	2.168	135.33	107.2	2.152	2.178	136.00	**135.66**
171	107.7	2.139	2.170	135.45	107.2	2.152	2.178	136.00	**135.73**
172	107.7	2.139	2.170	135.45	107.2	2.152	2.178	136.00	**135.73**
173	107.7	2.139	2.170	135.45	107.1	2.154	2.181	136.13	**135.79**
174	107.6	2.141	2.172	135.58	107.1	2.154	2.181	136.13	**135.85**
175	107.6	2.141	2.172	135.58	107.1	2.154	2.181	136.13	**135.85**

		Specimen # 1	2.0% WC	1.5 % EC		Specimen # 2	2.0% WC	1.5 % EC	
		Mass, g	4067.4			Mass, g	4073.8		Avg
Gyration #	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Height	G_{mb} (est)	G_{mb} (Corr)	Unit Weight	Unit Weight
176	107.6	2.141	2.172	135.58	107.0	2.156	2.183	136.26	**135.92**
177	107.5	2.143	2.174	135.70	107.0	2.156	2.183	136.26	**135.98**
178	107.5	2.143	2.174	135.70	107.0	2.156	2.183	136.26	**135.98**
179	107.5	2.143	2.174	135.70	106.9	2.158	2.185	136.38	**136.04**
180	107.4	2.145	2.176	135.83	106.9	2.158	2.185	136.38	**136.11**
181	107.4	2.145	2.176	135.83	106.9	2.158	2.185	136.38	**136.11**
182	107.4	2.145	2.176	135.83	106.8	2.160	2.187	136.51	**136.17**
183	107.3	2.147	2.178	135.96	106.8	2.160	2.187	136.51	**136.23**
184	107.3	2.147	2.178	135.96	106.8	2.160	2.187	136.51	**136.23**
185	107.3	2.147	2.178	135.96	106.7	2.162	2.189	136.64	**136.30**
186	107.2	2.149	2.180	136.08	106.7	2.162	2.189	136.64	**136.36**
187	107.2	2.149	2.180	136.08	106.7	2.162	2.189	136.64	**136.36**
188	107.2	2.149	2.180	136.08	106.6	2.164	2.191	136.77	**136.43**
189	107.2	2.149	2.180	136.08	106.6	2.164	2.191	136.77	**136.43**
190	107.1	2.151	2.182	136.21	106.6	2.164	2.191	136.77	**136.49**
191	107.1	2.151	2.182	136.21	106.5	2.166	2.193	136.90	**136.55**
192	107.1	2.151	2.182	136.21	106.5	2.166	2.193	136.90	**136.55**
193	107.0	2.153	2.184	136.34	106.5	2.166	2.193	136.90	**136.62**
194	107.0	2.153	2.184	136.34	106.4	2.168	2.195	137.03	**136.68**
195	107.0	2.153	2.184	136.34	106.4	2.168	2.195	137.03	**136.68**
196	106.9	2.155	2.186	136.47	106.4	2.168	2.195	137.03	**136.75**
197	106.9	2.155	2.186	136.47	106.4	2.168	2.195	137.03	**136.75**
198	106.9	2.155	2.186	136.47	106.3	2.170	2.197	137.15	**136.81**
199	106.9	2.155	2.186	136.47	106.3	2.170	2.197	137.15	**136.81**
200	106.7	2.159	2.190	136.72	106.2	2.172	2.199	137.28	**137.00**

G_{mb} (meas) 2.190 2.199

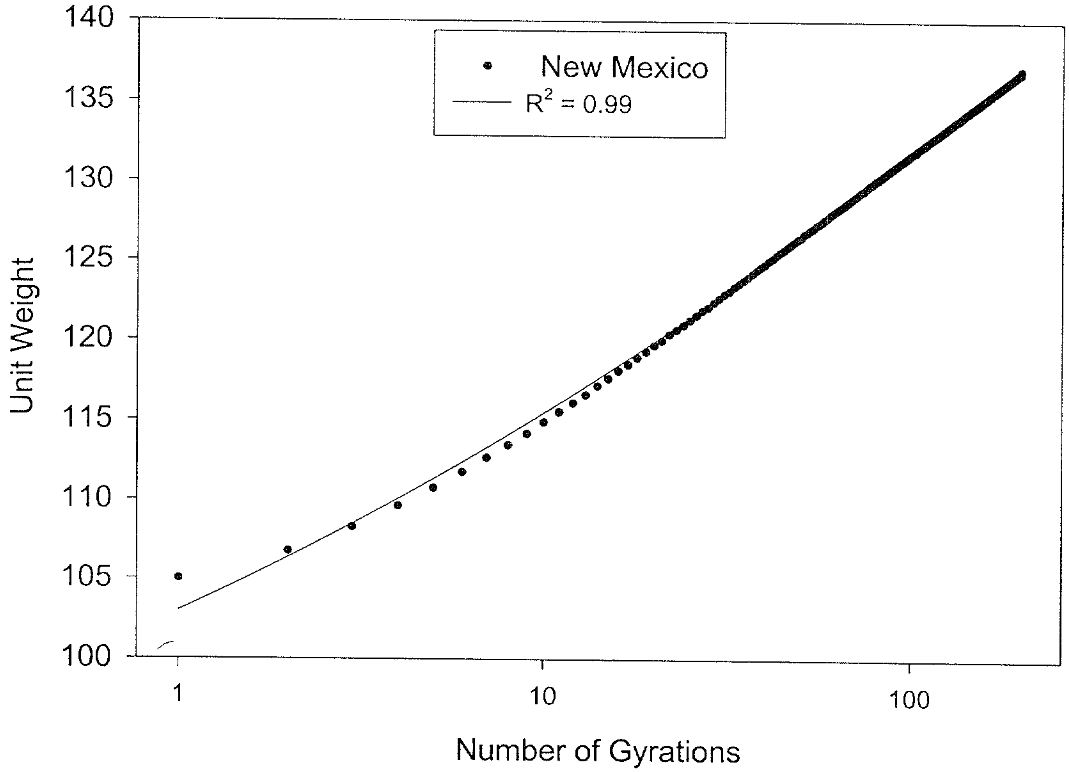

Figure A.5. Number of Gyrations vs. Unit Weight for New Mexico RAP and HFE150-P Emulsion – Determination of No. of Gyrations to Simulate Field Density

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Appendix B - Experimental Program to Develop New Mix-Design

Table B.1. 24 Hours Curing Time, 0.5% EC, 3.5% TLC,
77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 24053577 (2 Hours)	1	4059.5	2257.9	4165.5	2.128	132.45
	2	4056.3	2250.5	4152.5	2.133	132.74
	AVG				**2.130**	**132.59**
CN 240535140 (2 Hours)	1	4019.2	2172.0	4103.4	2.081	129.52
	2	4020.6	2175.1	4096.1	2.093	130.27
	AVG				**2.087**	**129.89**
CN 24053577 (1 Week)	1	4034.2	2231.6	4139.7	2.114	131.59
	2	4043.9	2237.2	4139.2	2.126	132.33
	AVG				**2.120**	**131.96**
CN 240535140 (1 Week)	1	4022.5	2180.0	4109.7	2.085	129.74
	2	4025.7	2199.7	4117.3	2.099	130.66
	AVG				**2.092**	**130.20**

Connecticut RAP w/HFMS-2T Emulsion

Table B.2. 24 Hours Curing Time, 0.5% EC, 4.0% TLC, 77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 24054077 (2 Hours)	1	4074.2	2261.7	4184.4	2.119	131.89
	2	4071.1	2256.1	4177.4	2.119	131.88
	AVG				**2.119**	**131.88**
CN 240540140 (2 Hours)	1	4024.2	2187.2	4106.8	2.096	130.48
	2	4018.9	2168.4	4112.5	2.067	128.66
	AVG				**2.082**	**129.57**
CN 24054077 (1 Week)	1	4037.4	2217.3	4139.5	2.100	130.73
	2	4042.9	2217.4	4138.7	2.104	130.97
	AVG				**2.102**	**130.85**
CN 240540140 (1 Week)	1	4029.8	2206.0	4119.1	2.106	131.10
	2	4025.7	2185.5	4127.0	2.073	129.05
	AVG				**2.090**	**130.08**

Connecticut RAP w/HFMS-2T Emulsion

Table B.3. 24 Hours Curing Time, 1.0% EC, 3.5% TLC, 77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 241035140 (2 Hours)	1	4038.9	2171.6	4109.5	2.084	129.72
	2	4039.4	2181.4	4117.3	2.087	129.87
	AVG				**2.085**	**129.79**
CN 24103577 (2 Hours)	1	4057.1	2215.4	4182.9	2.062	128.34
	2	4056.4	2216.1	4162.9	2.084	129.68
	AVG				**2.073**	**129.01**
CN 241035140 (1 Week)	1	4034.6	2164.0	4099.8	2.084	129.72
	2	4035.1	2170.4	4104.2	2.087	129.87
	AVG				**2.085**	**129.80**
CN 24103577 (1 Week)		4040.3	2175.9	4141.1	2.056	127.96
		4039.4	2176.9	4124.6	2.074	129.08
	AVG				**2.065**	**128.52**

Connecticut RAP w/HFMS-2T Emulsion

Table B.4. 24 Hours Curing Time, 1.0% EC, 4.0% TLC, 77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 241040140	1	4041.9	2167.2	4121.4	2.068	128.73
(2 Hours)	2	4046.2	2189.0	4120.9	2.094	130.36
	AVG				**2.081**	**129.54**
CN 24104077	1	4091.0	2256.1	4188.6	2.117	131.76
(2 Hours)	2	4090.8	2260.7	4197.1	2.113	131.49
	AVG				**2.115**	**131.62**
CN 241040140	1	4036.1	2160.4	4113.8	2.066	128.60
(1 Week)	2	4054.0	2199.0	4129.0	2.101	130.74
	AVG				**2.083**	**129.67**
CN 24104077	1	4054.6	2217.3	4151.0	2.097	130.51
(1 Week)	2	4052.2	2223.4	4162.4	2.090	130.07
	AVG				**2.093**	**130.29**

Connecticut RAP w/HFMS-2T Emulsion

Table B.5. 24 Hours Curing Time, 1.5% EC, 3.5% TLC, 77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS IN AIR	MASS GRAMS IN WATER	MASS GRAMS SSD IN AIR	BULK SG COMP. MIX	UNIT WGT. PCF
CN 24153577 (2 Hours)	1	4090.4	2227.7	4166.6	2.110	131.30
	2	4087.1	2224.9	4170.3	2.101	130.76
	AVG				**2.105**	**131.03**
CN 241535140 (2 Hours)	1	4066.4	2230.0	4114.8	2.157	134.28
	2	4067.9	2223.0	4105.4	2.161	134.50
	AVG				**2.159**	**134.39**
CN 24153577 (1 Week)	1	4073.7	2205.7	4144.7	2.101	130.76
	2	4075.0	2208.9	4153.6	2.095	130.42
	AVG				**2.098**	**130.59**
CN 241535140 (1 Week)	1	4071.3	2232.7	4117.2	2.160	134.46
	2	4069.7	2224.6	4105.8	2.163	134.65
	AVG				**2.162**	**134.56**

Connecticut RAP w/HFMS-2T Emulsion

Table B.6. 24 Hours Curing Time, 1.5% EC, 4.0% TLC, 77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 241540140 (2 Hours)	1	4068.9	2217.2	4139.9	2.116	131.71
	2	4070.5	2195.7	4127.1	2.108	131.17
	AVG				**2.112**	**131.44**
CN 24154077 (2 Hours)	1	4102.9	2252.2	4192.7	2.114	131.60
	2	4102.1	2248.8	4183.7	2.120	131.95
	AVG				**2.117**	**131.77**
CN 241540140 (1 Week)	1	4079.1	2217.9	4142.7	2.119	131.90
	2	4076.2	2194.6	4128.3	2.108	131.20
	AVG				**2.114**	**131.55**
CN 24154077 (1 Week)	1	4068.5	2224.8	4165.1	2.097	130.51
	2	4075.2	2227.0	4162.7	2.105	131.03
	AVG				**2.101**	**130.77**

Connecticut RAP w/HFMS-2T Emulsion

Table B.7. 24 Hours Curing Time, 2.0% EC, 3.5% TLC, 77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS IN AIR	MASS GRAMS IN WATER	MASS GRAMS SSD IN AIR	BULK SG COMP. MIX	UNIT WGT. PCF
CN 242035140 (2 Hours)	1	4080.1	2229.3	4133.7	2.142	133.35
	2	4078.6	2229.3	4126.5	2.150	133.80
	AVG				**2.146**	**133.58**
CN 24203577 (2 Hours)	1	4099.3	2237.0	4185.1	2.104	130.97
	2	4100.9	2242.3	4191.7	2.104	130.93
	AVG				**2.104**	**130.95**
CN 242035140 (1 Week)	1	4086.2	2233.1	4136.4	2.147	133.62
	2	4083.3	2235.1	4132.5	2.152	133.94
	AVG				**2.149**	**133.78**
CN 24203577 (1 Week)	1	4089.8	2228.0	4180.0	2.095	130.40
	2	4089.1	2228.9	4179.7	2.096	130.46
	AVG				**2.096**	**130.43**

Connecticut RAP w/HFMS-2T Emulsion

Table B.8. 24 Hours Curing Time, 2.0% EC, 4.0% TLC, 77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 242040140 (2 Hours)	1	4082.6	2227.8	4128.2	2.148	133.71
	2	4078.1	2225.0	4128.3	2.143	133.36
	AVG				**2.145**	**133.53**
CN 24204077 (2 Hours)	1	4115.5	2237.6	4199.1	2.098	130.59
	2	4110.4	2237.7	4196.7	2.098	130.59
	AVG				**2.098**	**130.59**
CN 242040140 (1 Week)	1	4088.6	2232.6	4131.6	2.153	134.00
	2	4085.0	2228.3	4132.1	2.146	133.55
	AVG				**2.149**	**133.78**
CN 24204077 (1 Week)	1	4091.0	2217.7	4177.3	2.088	129.94
	2	4082.5	2209.4	4168.5	2.084	129.70
	AVG				**2.086**	**129.82**

Connecticut RAP w/HFMS-2T Emulsion

Table B.9. 6 Hours Curing Time, 0.5% EC, 3.5% TLC, 77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 6053577 (2 Hours)	1	4089.2	2293.3	4215.0	2.128	132.44
	2	4089.2	2287.4	4208.8	2.128	132.46
	AVG				**2.128**	**132.45**
CN 6053540 (2 Hours)	1	4050.3	2256.3	4158.2	2.130	132.55
	2	4049.7	2248.2	4152.6	2.126	132.35
	AVG				**2.128**	**132.45**
CN 6053577 (1 Week)	1	4020.9	2226.1	4155.0	2.085	129.74
	2	4020.3	2225.9	4142.4	2.098	130.56
	AVG				**2.091**	**130.15**
CN 6053540 (1 Week)	1	4033.6	2235.6	4137.7	2.121	131.99
	2	4024.2	2204.3	4123.4	2.097	130.51
	AVG				**2.109**	**131.25**

Connecticut RAP w/HFMS-2T Emulsion

Table B.10. 6 Hours Curing Time, 0.5% EC, 4.0% TLC,
77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 6054077 (2 Hours)	1	4032.7	2232.0	4144.1	2.109	131.27
	2	4016.8	2221.8	4154.2	2.079	129.38
	AVG				**2.094**	**130.32**
CN 60540140 (2 Hours)	1	4052.7	2243.0	4162.1	2.112	131.44
	2	4049.8	2235.1	4156.2	2.108	131.21
	AVG				**2.110**	**131.32**
CN 6054077 (1 Week)	1	4110.0	2286.0	4201.4	2.146	133.55
	2	4101.7	2278.5	4213.4	2.120	131.94
	AVG				**2.133**	**132.75**
CN 60540140 (1 Week)	1	4029.1	2214.9	4133.7	2.100	130.69
	2	4024.2	2204.3	4123.4	2.097	130.51
	AVG				**2.098**	**130.60**

Connecticut RAP w/HFMS-2T Emulsion

Table B.11. 6 Hours Curing Time, 1.0% EC, 3.5% TLC, 77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 6103577 (2 Hours)	1	4090.5	2259.0	4179.7	2.130	132.55
	2	4092.3	2258.2	4185.3	2.124	132.17
	AVG				**2.127**	**132.36**
CN 61035140 (2 Hours)	1	4065.1	2243.2	4161.3	2.119	131.91
	2	4060.3	2239.1	4163.2	2.110	131.34
	AVG				**2.115**	**131.62**
CN 6103577 (1 Week)	1	4047.9	2212.8	4131.6	2.110	131.30
	2	4046.8	2205.2	4129.1	2.103	130.92
	AVG				**2.107**	**131.11**
CN 61035140 (1 Week)	1	4047.6	2227.3	4145.8	2.110	131.31
	2	4042.1	2221.4	4145.5	2.101	130.75
	AVG				**2.105**	**131.03**

Connecticut RAP w/HFMS-2T Emulsion

Table B.12. 6 Hours Curing Time, 1.0% EC, 4.0% TLC,
77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 6104077 (2 Hours)	1	4108.8	2271.9	4192.8	2.139	133.13
	2	4110.6	2279.3	4199.2	2.141	133.26
	AVG				**2.140**	**133.20**
CN 61040140 (2 Hours)	1	4066.9	2235.3	4165.0	2.108	131.17
	2	4070.2	2237.9	4167.2	2.110	131.31
	AVG				**2.109**	**131.24**
CN 6104077 (1 Week)	1	4043.5	2200.8	4121.6	2.105	131.02
	2	4047.5	2220.5	4142.4	2.106	131.08
	AVG				**2.106**	**131.05**
CN 61040140 (1 Week)	1	4050.9	2223.4	4142.9	2.110	131.35
	2	4047.9	2215.3	4143.2	2.100	130.68
	AVG				**2.105**	**131.02**

Connecticut RAP w/HFMS-2T Emulsion

Table B.13. 6 Hours Curing Time, 1.5% EC, 3.5% TLC, 77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 61535140 (2 Hours)	1	4077.3	2235.4	4183.3	2.093	130.28
	2	4076.6	2238.0	4184.7	2.094	130.34
	AVG				**2.094**	**130.31**
CN 6153577 (2 Hours)	1	4109.8	2279.3	4174.0	2.169	135.00
	2	4106.6	2275.2	4164.7	2.173	135.27
	AVG				**2.171**	**135.14**
CN 61535140 (1 Week)	1	4067.3	2223.2	4173.2	2.086	129.82
	2	4065.2	2229.9	4176.3	2.089	129.99
	AVG				**2.087**	**129.91**
CN 6153577 (1 Week)	1	4058.9	2229.8	4122.9	2.144	133.45
	2	4062.1	2230.2	4120.4	2.149	133.76
	AVG				**2.147**	**133.60**

Connecticut RAP w/HFMS-2T Emulsion

Table B.14. 6 Hours Curing Time, 1.5% EC, 4.0% TLC, 77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 61540140 (2 Hours)	1	4084.7	2235.9	4184.8	2.096	130.45
	2	4083.7	2240.7	4189.4	2.096	130.43
	AVG				**2.096**	**130.44**
CN 6154077 (2 Hours)	1	4125.4	2293.2	4178.0	2.189	136.23
	2	4126.0	2276.1	4190.4	2.155	134.15
	AVG				**2.172**	**135.19**
CN 61540140 (1 Week)	1	4067.8	2220.3	4169.5	2.087	129.89
	2	4066.5	2233.4	4179.7	2.089	130.04
	AVG				**2.088**	**129.97**
CN 6154077 (1 Week)	1	4054.9	2218.1	4100.1	2.155	134.10
	2	4059.0	2217.2	4129.0	2.123	132.14
	AVG				**2.139**	**133.12**

Connecticut RAP w/HFMS-2T Emulsion

Table B.15. 6 Hours Curing Time, 2.0% EC, 3.5% TLC, 77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 62035140 (2 Hours)	1	4097.7	2247.9	4170.1	2.132	132.68
	2	4092.6	2265.1	4190.6	2.125	132.29
	AVG				**2.129**	**132.49**
CN 6203577 (2 Hours)	1	4109.2	2258.2	4183.7	2.134	132.83
	2	4108.4	2251.9	4196.2	2.113	131.52
	AVG				**2.124**	**132.17**
CN 62035140 (1 Week)	1	4089.0	2242.0	4163.9	2.128	132.42
	2	4083.5	2259.8	4182.5	2.124	132.19
	AVG				**2.126**	**132.30**
CN 6203577 (1 Week)	1	4089.4	2245.0	4167.2	2.127	132.41
	2	4085.9	2234.9	4175.2	2.106	131.07
	AVG				**2.117**	**131.74**

Connecticut RAP w/HFMS-2T Emulsion

Table B.16. 6 Hours Curing Time, 2.0% EC, 4.0% TLC,
77°F and 140°F Curing Temps.

EXPERIMENTAL PROGRAM DATA FORM
CIR SPECIMENS USING SGC

SPECIMEN ID	SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	UNIT WGT. PCF
		IN AIR	IN WATER	SSD IN AIR		
CN 62040140	1	4104.8	2241.1	4188.5	2.108	131.19
(2 Hours)	2	4103.2	2242.4	4183.0	2.114	131.60
	AVG				**2.111**	**131.40**
CN 6204077	1	4124.3	2246.0	4191.1	2.120	131.97
(2 Hours)	2	4123.3	2257.3	4208.3	2.113	131.54
	AVG				**2.117**	**131.76**
CN 62040140	1	4094.4	2234.4	4180.5	2.104	130.95
(1 Week)	2	4088.2	2232.9	4175.1	2.105	131.01
	AVG				**2.104**	**130.98**
CN 6204077	1	4094.6	2221.4	4165.3	2.106	131.10
(1 Week)	2	4091.3	2237.3	4182.6	2.103	130.90
	AVG				**2.105**	**131.00**

Connecticut RAP w/HFMS-2T Emulsion

Appendix C - New Mix-Design Method For Cold In-Place Recycling of Asphalt Mixtures

1. *Scope*

1.1 This method covers the design of mixtures for cold in-place recycling (CIR) using the Superpave Gyratory Compactor. The procedures presented are applicable only for mixtures containing asphalt emulsion and reclaimed asphalt pavement (RAP). This method consists of two parts. The first is the determination of the optimum emulsion content and the second is the determination of the optimum mixing water content.

2. *Apparatus*

2.1 See AASHTO TP4

3. *Test Specimens*

3.1 Preparation of RAP

3.1.1 RAP samples shall be obtained from the roadway that will be recycled by taking cores to the specified depth. These cores will then be crushed in order to have representative samples.

3.1.2 Dry a portion of the RAP to a constant mass at 110^0 C (230^0 F) to determine the moisture content. Dry the remainder of the RAP to a constant mass at 60^0 C (140^0F) to remove the existing water.

3.1.3 Separate the RAP into the following particle sizes, by screening through a series of sieves. Eliminate the material retained on the 31.75 mm (1 ¼”) sieve either by removing or crushing the material such that excess fines are not produced.

+ 31.75 mm (1 ¼”)
+ 25.0 mm (1”)
+ 19.1 mm (¾”)
+ 12.5 mm (½”)
+ 9.5 mm (3/8”)
+ 4.75 mm (# 4)
+ 2.36 mm (# 8)
+ 1.18 mm (# 16)
- 1.18 mm (# 16)

3.2 Mixing and Compacting Temperatures

3.2.1 The mixing temperatures shall be 25^0 C +/- 2^0 C (77^0 F +/- 4^0 F) for the RAP and mixing water. The mixing temperature for the emulsion varies depending on the emulsion. Obtain the correct mixing temperature from the emulsion manufacturer.

3.2.2 The compaction temperature shall be 25^0 C +/- 2^0 C (77^0 F +/- 4^0 F).

3.3 Preparation of Mixtures

3.3.1 The first part of the mix design involves the determination of the optimum emulsion content, while keeping the mixing water content constant. A minimum of two specimens shall be prepared for a minimum of four emulsion contents by weight in 0.5 % increments. All specimens will be prepared with 3.0% mixing water. (A different water content can be used based on experience.) In addition, one loose sample shall be prepared for each additive content for determination of maximum theoretical specific gravity

3.3.2 Weigh into individual pans a sufficient amount of RAP (~ 4000 grams) based on the gradation determined in section 3.1.3 to fabricate specimens 150mm (6 in) in diameter and 115 mm (4.5 in) in height.

3.3.3 Let RAP samples stand at 25^0 C +/- 2^0 C (77^0 F +/- 4^0 F) for a minimum of one hour. In addition, heat emulsion at the specified temperature (Section 3.2.1) for one hour.

3.3.4 Add mixing water to each sample and mix thoroughly for one minute. Mixing may be performed either by hand or through the use of a mechanical mixer.

3.3.5 Add emulsion to each sample according to section 3.3.1 and mix thoroughly until the emulsion is uniformly dispersed but for no longer than one minute. If the sample is not uniformly mixed after one minute, additional mixing water may be required to improve emulsion dispersion. Otherwise, another emulsion type may be required.

3.4 Compaction of Specimens

3.4.1 Apply load immediately after mixing using the Superpave Gyratory Compactor (SGC). The loading pressure shall be 600 kPa (87 psi) at an angle of gyration of 1 ¼ degrees. The load shall be applied for the number of gyrations that will result in achieving densities similar to those found in the field.

3.4.2 Remove specimens from their molds immediately after compaction.

3.4.3 Oven cure the specimens at 60^0 C (140^0 F) for 24 hours.

3.4.4 Remove the specimens from the oven and allow to cool to room temperature.

3.5 Bulk Specific Gravity, G_{mb}

3.5.1 (ASTM D2726 or AASHTO T166)

This test method should be used when the samples absorb less than 2 % of water by volume as determined by section 10.4 of ASTM D2726. Otherwise use ASTM D1188 (Section 3.5.2).

3.5.1.1 Record the dry mass, A, of the specimen.
3.5.1.2 Immerse the specimen in water at 25^0 C (77^0 F) for five minutes and record the immersed mass, C.
3.5.1.3 Remove the specimen from the water, surface dry with a damp towel and record the surface-dry mass, B.
3.5.1.4 Calculate the bulk specific gravity as follows:

$$G_{mb} = \frac{A}{(B - C)}$$

3.5.2 (ASTM D1188)

This test method should be used when the samples absorb more than 2 % of water by volume as determined by section 10.4 of ASTM D2726. Otherwise use ASTM D2726 (Section 3.5.1). The CoreLok system can also be used if the samples absorb more than 2%.

3.5.2.1 Record the dry mass, A, of the specimen
3.5.2.2 Coat specimen with parafilm and record the coated mass, D.
3.5.2.3 Immerse the specimen in water at 25^0 C (77^0 F) and record the immersed mass, E.
3.5.2.4 Determine the specific gravity of the parafilm at 25^0 C (77^0 F), F.
3.5.2.5 Calculate the bulk specific gravity as follows:

$$G_{mb} = \frac{A}{(D - E - \frac{D - A}{F})}$$

3.5.3 Determine maximum theoretical specific gravity for each emulsion content using AASHTO T209.

3.6 Determine Optimum Emulsion Content (OEC)

3.6.1 Plot unit weight versus percent emulsion content for each emulsion content.
3.6.2 Plot percent air voids versus percent emulsion content for each emulsion content.
3.6.3 OEC is the emulsion content at which the unit weight is at its maximum value.
3.6.4 If a maximum unit weight is not achieved, the OEC should be the emulsion content at which the unit weight is similar to those found in the field.

3.7 Determine Optimum Mixing Water Content (OWC)

3.7.1 OWC is determined by following steps 3.1 through 3.5, with the following exceptions.
3.7.2 A minimum of two specimens will be prepared at the Optimum Emulsion Content (OEC) with each of four varying water contents, 0.5 % and 1.0 % above and below the mixing water content used in step 3.3.1.
3.7.3 Plot unit weight versus percent water content for each water content.
3.7.4 Plot percent air voids versus percent water content for each water content.
3.7.5 OWC is the water content at which the unit weight is at its maximum value.
3.7.6 If a maximum unit weight is not achieved, the OWC should be the water content at which the unit weight is similar to those found in the field.
3.7.7 If the OWC is more than 1.0% above or below the mixing water content used to determine the OEC, the procedure to determine the OEC in sections 3.3 through 3.6 shall be repeated. Prepare specimens using mixing water content equal to the OWC obtained above. If the new OEC is different from the first OEC, section 3.7 shall then be repeated using this new OEC to determine the OWC. If there is no change in the value of the OEC, section 3.7 does not need to be repeated.

3.8 Moisture Sensitivity

3.8.1 Prepare six specimens at OEC and OWC, three for dry testing and three for conditioned testing and determine moisture sensitivity of the specimens in accordance with AASHTO T283.

4 Report

4.1 The report shall include the following:

4.1.1 Type of Emulsion Used
4.1.2 RAP Gradation
4.1.3 Specimen Height
4.1.4 Specimen Mass
4.1.5 Specimen Bulk Specific Gravity
4.1.6 Specimen Unit Weight
4.1.7 Specimen Air Void Content
4.1.8 Optimum Emulsion Content
4.1.9 Optimum Mixing Water Content
4.1.10 Moisture Sensitivity Results

Appendix D – Gradations of Processed RAP to Apply New Mix-Design

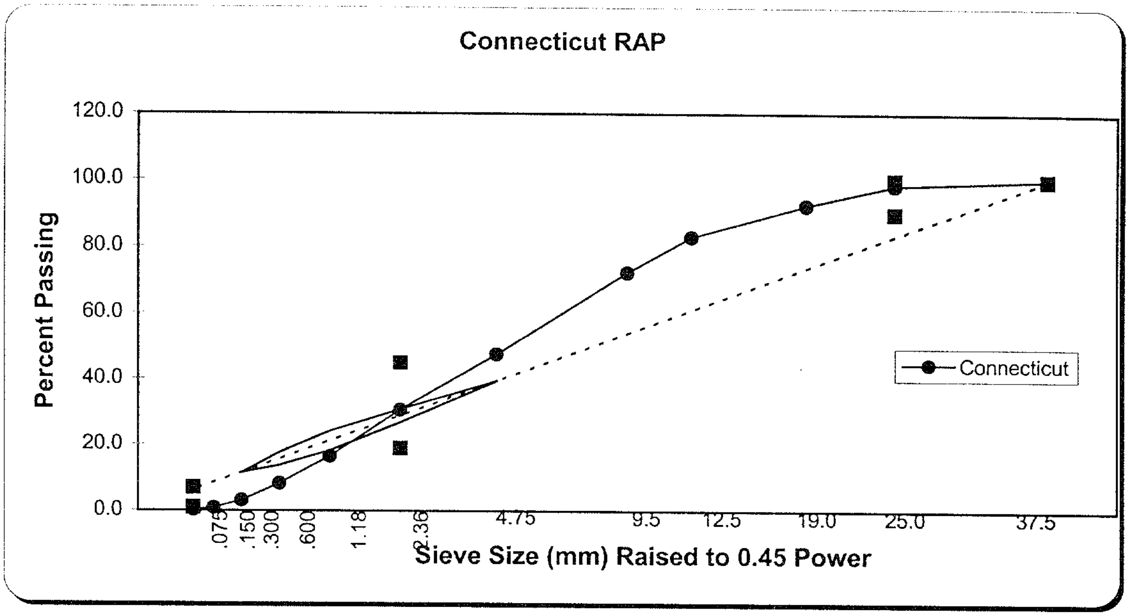


Figure D.1. Sieve Analysis of Connecticut RAP

Table D.1. Processed Gradation of Connecticut RAP
For Application of New Mix Design

	Connecticut RAP
Sieve Size	**% Passing**
31.8 mm (1 ¼”)	100
25 mm (1”)	97.4
19.1 mm (¾”)	91.8
12.5 mm (½”)	74.9
9.5 mm (3/8”)	61.6
4.75 mm (# 4)	33.9
2.36 mm (# 8)	17.6
1.18 mm (#16)	8.2

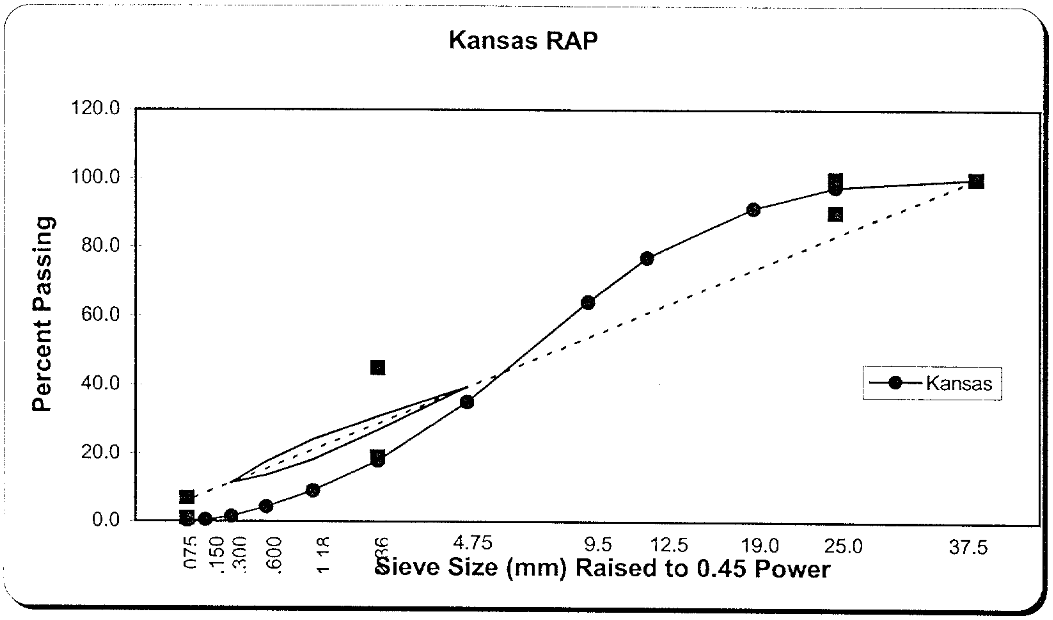


Figure D.2. Sieve Analysis of Kansas RAP

Table D.2. Processed Gradation of Kansas RAP For Application of New Mix Design

	Kansas RAP
Sieve Size	**% Passing**
31.8 mm (1 ¼")	100
25 mm (1")	95.5
19.1 mm (¾")	87.0
12.5 mm (½")	74.0
9.5 mm (3/8")	63.1
4.75 mm (# 4)	39.8
2.36 mm (# 8)	23.5
1.18 mm (#16)	14.1

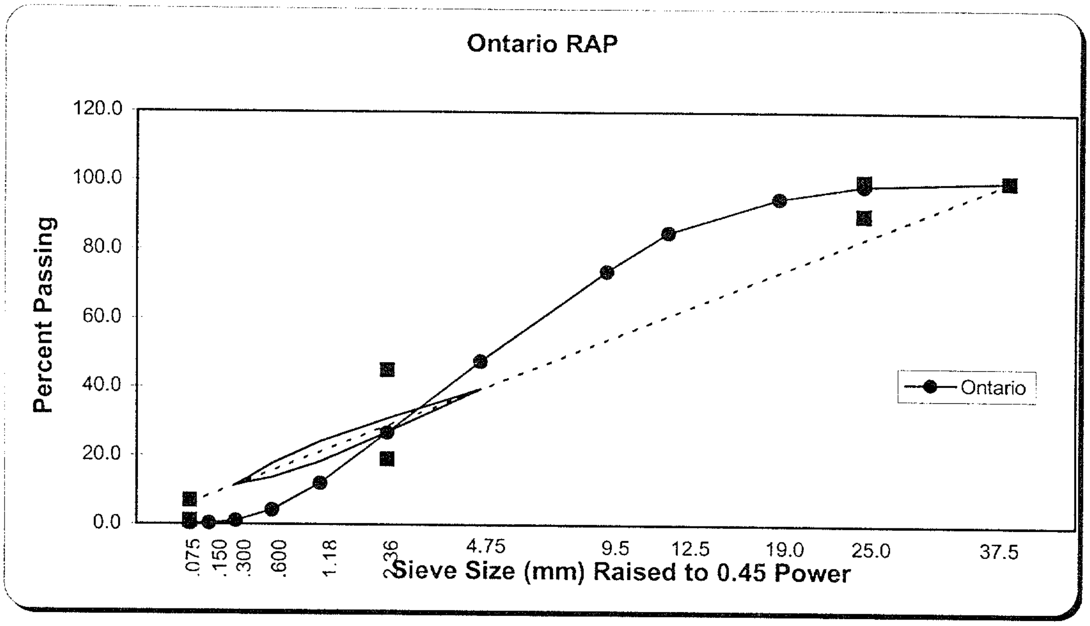


Figure D.3. Sieve Analysis of Ontario RAP

Table D.3. Processed Gradation of Ontario RAP
For Application of New Mix Design

	Ontario RAP
Sieve Size	**% Passing**
31.8 mm (1 ¼")	100
25 mm (1")	98.6
19.1 mm (¾")	94.7
12.5 mm (½")	84.8
9.5 mm (3/8")	73.6
4.75 mm (# 4)	47.6
2.36 mm (# 8)	26.7
1.18 mm (#16)	11.9

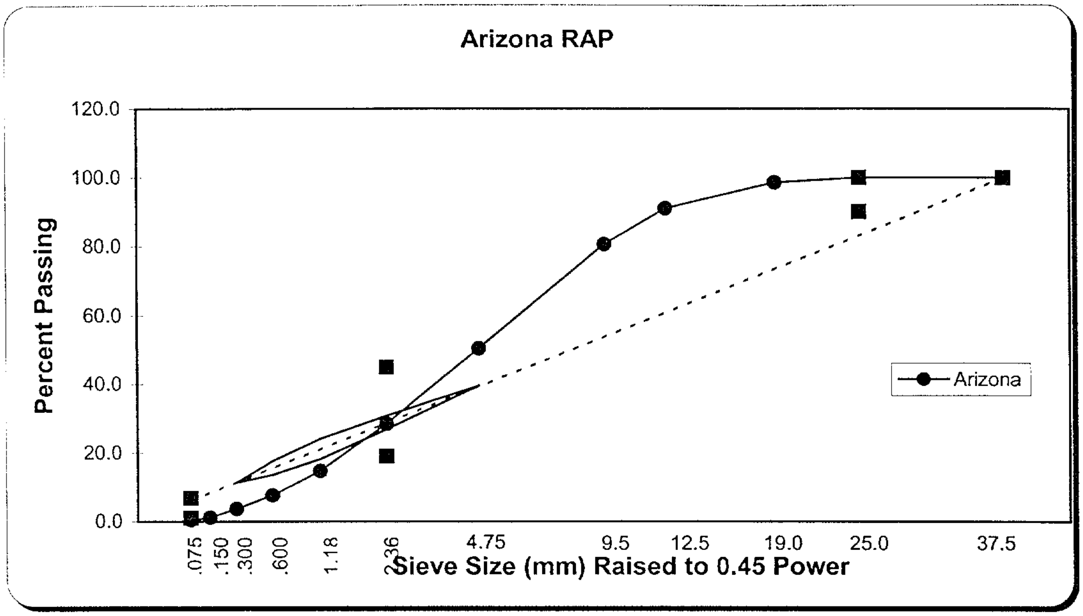


Figure D.4. Sieve Analysis of Arizona RAP

Table D.4. Processed Gradation of Arizona RAP
For Application of New Mix Design

Sieve Size	Arizona RAP % Passing
31.8 mm (1 ¼”)	100
25 mm (1”)	100
19.1 mm (¾”)	98.5
12.5 mm (½”)	90.9
9.5 mm (3/8”)	80.6
4.75 mm (# 4)	50.4
2.36 mm (# 8)	28.5
1.18 mm (#16)	14.7

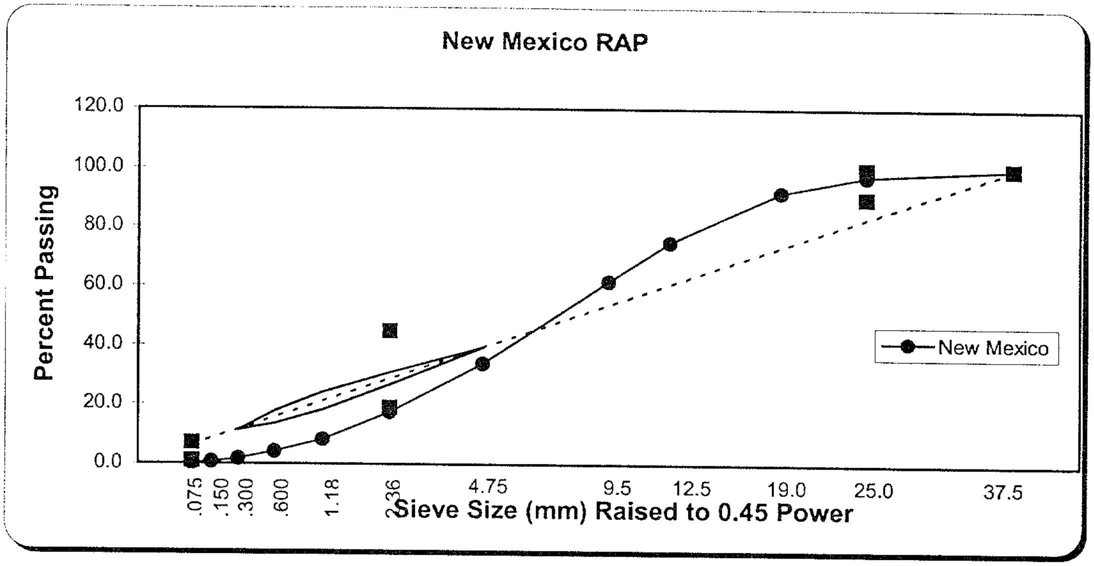


Figure D.5. Sieve Analysis of New Mexico RAP

Table D.5. Processed Gradation of New Mexico RAP
For Application of New Mix Design

Sieve Size	New Mexico RAP % Passing
31.8 mm (1 ¼")	100
25 mm (1")	97.4
19.1 mm (¾")	91.8
12.5 mm (½")	74.9
9.5 mm (3/8")	61.6
4.75 mm (# 4)	33.9
2.36 mm (# 8)	17.6
1.18 mm (#16)	8.2

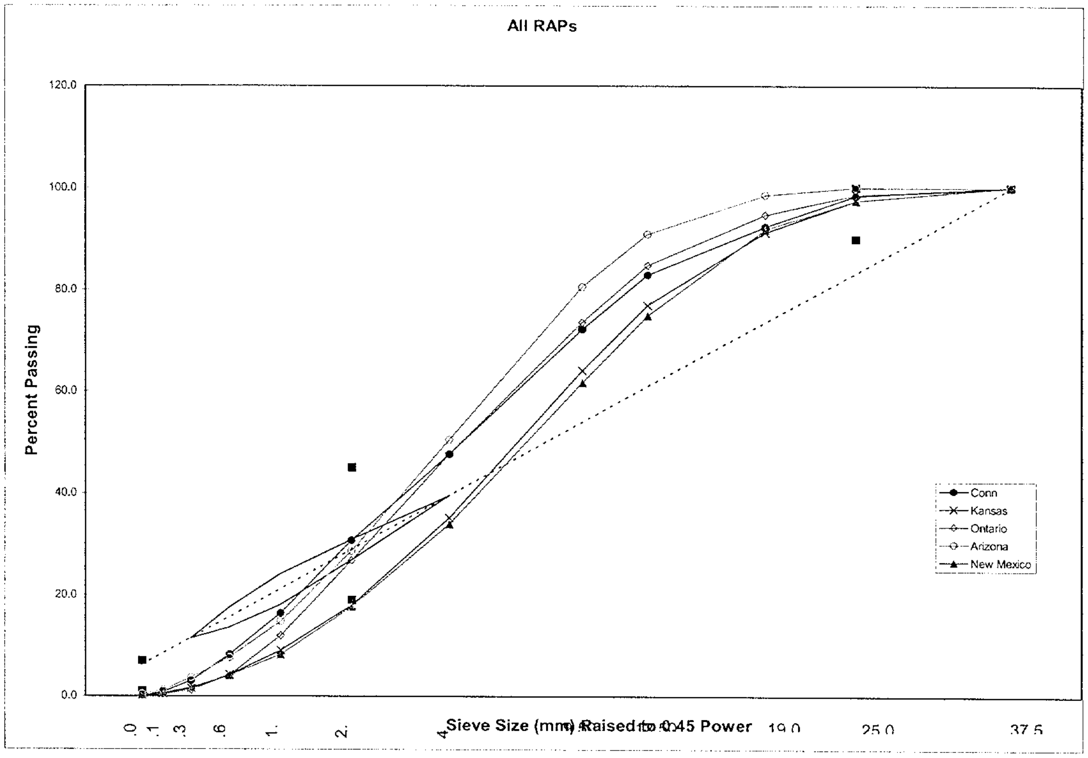


Figure D.6. Sieve Analysis of All RAP Materials

Appendix E – Results of the Application of the New Mix-Design

Table E.1. CIR Mix-Design (Varying Emulsion Content)
Connecticut RAP with HFMS-2T Emulsion

3.0% WC

% EC SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	Gmm	% AIR VOIDS	UNIT WGT. PCF
	IN AIR	IN WATER	SSD IN AIR				
1	4015.7	2136.4	4112.8	2.032			
0.5 2	4013.5	2140.9	4108.4	2.040			
AVG				**2.036**	**2.475**	**17.74**	**126.71**
3	4035.4	2154.0	4085.2	2.090			
1.0 4	4037.8	2173.9	4090.8	2.106			
AVG				**2.098**	**2.467**	**14.96**	**130.58**
5	4058.9	2166.6	4127.6	2.070			
1.5 6	4058.7	2171.6	4136.9	2.065			
AVG				**2.067**	**2.458**	**15.89**	**128.68**
7	4077.8	2192.4	4149.4	2.084			
2.0 8	4072.3	2172.4	4128.4	2.082			
AVG				**2.083**	**2.451**	**15.02**	**129.64**

Table E.2. CIR Mix-Design (Varying Water Content)
Connecticut RAP with HFMS-2T Emulsion

1.5% EC

% WC SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	Gmm	% AIR VOIDS	UNIT WGT. PCF
	IN AIR	IN WATER	SSD IN AIR				
1	4037.4	2136.5	4127.8	2.028			
2.0 2	4045.0	2144.9	4119.3	2.049			
AVG				**2.038**	**2.452**	**16.88**	**127.18**
3	4036.9	2138.7	4120.3	2.037			
2.5 4	4034.2	2133.8	4110.7	2.041			
AVG				**2.039**	**2.448**	**16.71**	**127.23**
5	4032.1	2126.2	4107.4	2.035			
3.0 6	4036.6	2135.7	4114.4	2.040			
AVG				**2.038**	**2.446**	**16.70**	**127.15**
7	4035.9	2142.4	4112.2	2.049			
3.5 8	4037.4	2131.0	4103.0	2.047			
AVG				**2.048**	**2.443**	**16.16**	**127.80**

Table E.3. CIR Mix-Design (Varying Emulsion Content)
Kansas RAP with CSS-1h Emulsion

3.0% WC

% EC SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	Gmm	% AIR VOIDS	UNIT WGT. PCF
	IN AIR	IN WATER	SSD IN AIR				
1	4004.9	2162.7	4051.7	2.120			
0.5 2	4009.2	2175.4	4065.4	2.121			
AVG				**2.121**	**2.436**	**12.94**	**132.33**
3	4029.1	2175.3	4099.2	2.094			
1.0 4	4027.0	2159.7	4082.0	2.095			
AVG				**2.095**	**2.429**	**13.77**	**130.70**
5	4042.7	2166.2	4114.5	2.075			
1.5 6	4041.9	2185.9	4120.0	2.090			
AVG				**2.082**	**2.422**	**14.02**	**129.94**
7	4059.1	2191.6	4142.2	2.081			
2.0 8	4061.1	2191.7	4143.3	2.081			
AVG				**2.081**	**2.414**	**13.80**	**129.85**

Table E.4. CIR Mix-Design (Varying Water Content)
Kansas RAP with CSS-1h Emulsion

1.4% EC

% WC SPEC. NO.	MASS GRAMS IN AIR	MASS GRAMS IN WATER	MASS GRAMS SSD IN AIR	BULK SG COMP. MIX	Gmm	% AIR VOIDS	UNIT WGT. PCF
1	4045.0	2205.0	4112.3	2.121			
2.0% 2	4047.4	2209.4	4104.5	2.136			
AVG				**2.128**	**2.418**	**11.98**	**132.46**
3	4045.6	2186.4	4120.9	2.091			
2.5% 4	4041.6	2173.7	4101.8	2.096			
AVG				**2.094**	**2.420**	**13.48**	**130.31**
5	4042.5	2159.3	4109.1	2.073			
3.0% 6	4035.9	2166.0	4114.2	2.072			
AVG				**2.072**	**2.421**	**14.40**	**128.99**
7	4042.6	2172.0	4110.8	2.085			
3.5% 8	4054.4	2187.4	4121.3	2.096			
AVG				**2.091**	**2.422**	**13.67**	**130.13**

Table E.5. CIR Mix-Design (Varying Emulsion Content)
Ontario RAP with HF150P Emulsion

2.5% WC

% EC SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	Gmm	% AIR VOIDS	UNIT WGT. PCF
	IN AIR	IN WATER	SSD IN AIR				
1	4041.8	2261.9	4066.9	2.239			
0.5 2	4039.0	2268.8	4069.1	2.244			
AVG				**2.241**	**2.509**	**10.67**	**139.86**
3	4028.7	2271.2	4059.4	2.253			
1.0 4	4019.9	2277.1	4051.9	2.265			
AVG				**2.259**	**2.498**	**9.57**	**140.96**
5	4047.6	2272.8	4072.9	2.249			
1.5 6	4051.8	2283.3	4073.3	2.264			
AVG				**2.256**	**2.489**	**9.36**	**140.78**
7	4067.3	2280.3	4093.9	2.243			
2.0 8	4064.2	2281.7	4091.2	2.246			
AVG				**2.244**	**2.482**	**9.57**	**140.05**

Table E.6. CIR Mix-Design (Varying Water Content)
Ontario RAP with HF150P Emulsion

1.3% OEC

% WC SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	Gmm	% AIR VOIDS	UNIT WGT. PCF
	IN AIR	IN WATER	SSD IN AIR				
1	4056.9	2269.2	4085.7	2.233			
2.0% 2	4062.5	2280.9	4078.0	2.261			
AVG				**2.247**	**2.469**	**8.99**	**140.21**
3	4049.8	2263.3	4071.3	2.240			
2.5% 4	4054.8	2263.7	4076.1	2.237			
AVG				**2.239**	**2.464**	**9.15**	**139.69**
5	4050.8	2249.9	4077.1	2.217			
3.0% 6	4047.9	2250.4	4079.5	2.213			
AVG				**2.215**	**2.461**	**10.00**	**138.22**
7	4044.4	2248.1	4078.7	2.209			
3.5% 8	4043.5	2244.7	4085.1	2.197			
AVG				**2.203**	**2.458**	**10.37**	**137.48**

Table E.7. CIR Mix-Design (Varying Emulsion Content)
Arizona RAP with Cyclogen ME

3.0% WC

% EC SPEC. NO.	MASS GRAMS IN AIR	IN WATER	SSD IN AIR	BULK SG COMP. MIX	Gmm	% AIR VOIDS	UNIT WGT. PCF
1	4035.7	2107.9	4148.2	1.978			
1.0% 2	4032.4	2103.6	4148.5	1.972			
AVG				**1.975**	**2.374**	**16.81**	**122.92**
3	4049.0	2108.6	4147.0	1.986			
1.5% 4	4049.5	2105.2	4153.2	1.977			
AVG				**1.982**	**2.367**	**16.27**	**123.35**
5	4074.1	2119.7	4162.1	1.995			
2.0% 6	4066.5	2124.5	4157.3	2.000			
AVG				**1.998**	**2.349**	**14.96**	**124.33**
7	4105.1	2150.1	4187.2	2.015			
2.5% 8	4109.5	2152.4	4188.8	2.018			
AVG				**2.017**	**2.335**	**13.64**	**125.51**
9	4132.4	2155.4	4232.9	1.989			
3.0% 10	4135.1	2156.4	4229.8	1.994			
AVG				**1.992**	**2.324**	**14.30**	**123.97**

Table E.8. CIR Mix-Design (Varying Water Content)
Arizona RAP with Cyclogen ME

2.6% EC

% WC SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	Gmm	% AIR VOIDS	UNIT WGT. PCF
	IN AIR	IN WATER	SSD IN AIR				
1	4051.6	2162.9	4150.6	2.038			
1.5% 2	4153.6	2235.3	4283.0	2.028			
AVG				**2.033**	**2.333**	**12.84**	**126.56**
3	4061.6	2162.9	4130.6	2.064			
2.0% 4	4183.6	2235.3	4283.0	2.043			
AVG				**2.054**	**2.333**	**11.98**	**127.82**
5	4099.1	2196.3	4266.1	1.980			
2.0% 6	4052.3	2159.6	4193.8	1.992			
AVG				**1.986**	**2.333**	**14.86**	**123.62**
7	4040.0	2189.1	4245.3	1.965			
2.5% 8	4046.0	2190.6	4244.7	1.970			
AVG				**1.967**	**2.333**	**15.68**	**122.44**
9	4067.3	2196.0	4264.4	1.966			
3.0% 10	4068.4	2197.0	4256.7	1.975			
AVG				**1.971**	**2.333**	**15.52**	**122.66**

Table E.9. CIR Mix-Design (Varying Emulsion Content)
New Mexico RAP with HFE150-P

2.0% WC

% EC SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	Gmm	% AIR VOIDS	UNIT WGT. PCF
	IN AIR	IN WATER	SSD IN AIR				
1	4020.3	2141.0	4066.0	2.088			
0.5% 2	4022.0	2135.0	4055.2	2.095			
AVG				**2.092**	**2.429**	**13.89**	**130.18**
3	4013.7	2145.1	4052.4	2.104			
1.0% 4	4017.2	2148.5	4040.7	2.123			
AVG				**2.114**	**2.417**	**12.55**	**131.56**
5	4063.3	2173.4	4122.0	2.085			
1.5% 6	4064.9	2184.0	4117.6	2.102			
AVG				**2.094**	**2.400**	**12.76**	**130.31**
7	4009.5	2141.0	4078.7	2.069			
2.0% 8	4048.0	2166.6	4118.6	2.074			
AVG				**2.071**	**2.380**	**12.96**	**128.93**

Table E.10. CIR Mix-Design (Varying Water Content)
New Mexico RAP with HFE150-P

1.1% EC

% EC SPEC. NO.	MASS GRAMS			BULK SG COMP. MIX	Gmm	% AIR VOIDS	UNIT WGT. PCF
	IN AIR	IN WATER	SSD IN AIR				
1	4041.8	2167.9	4087.8	2.105			
1.5% 2	4044.3	2166.9	4083.3	2.110			
AVG				**2.108**	**2.416**	**12.76**	**131.53**
3	4044.1	2146.0	4093.5	2.077			
2.0% 4	4056.9	2167.1	4099.0	2.100			
AVG				**2.088**	**2.413**	**13.46**	**130.31**
5	4038.7	2137.2	4097.3	2.060			
2.5% 6	4039.4	2147.3	4097.6	2.071			
AVG				**2.066**	**2.409**	**14.25**	**128.91**
7	4053.2	2160.5	4102.2	2.087			
3.0% 8	4040.0	2150.9	4122.8	2.049			
AVG				**2.068**	**2.407**	**14.08**	**129.05**

Appendix F - Incremental Static Dynamic Creep Test and Input Parameters for Rutting Prediction

F.1 Cold In-place Recycled (CIR) Materials

Originally five different RAP materials were secured from different regions of North America. However, some materials were exhausted during the development of the Modified Superpave Mix-Design Method. Thus, only three out of five CIR materials were used to perform the Incremental Static Dynamic Creep Test (ISDCT): Ontario, New Mexico, and Arizona.

Before testing CIR materials, Hot Mix Asphalt (HMA) specimens were tested. This enabled us to calibrate testing equipment and procedures, to validate our test results, and to relatively compare the RAP material's performance to HMA performance. It was necessary, because information needed for the VESYS analysis could not be provided for some CIR project sites.

F.2 Specimen Preparation with CIR Materials

The ISDCT produces input data for the computer program VESYS. It generates both primary properties (creep or elastic compliance) and the distress (permanent deformation) properties of 100 mm (4 in.) diameter and 200 mm (8 in.) high specimen.

The specimens used for this test were prepared in accordance with the procedure of ASTM Method D 1561 with the exception that the height to diameter ratio should be 2 to 1. The specimen diameter should be at least 6 times the maximum nominal size of the aggregate particles. The CIR specimens were prepared at the Optimum Emulsion Content (OEC) and Optimum Water Content (OWC) as determined in Chapter 6. The specimens were prepared with the same unit weight as that found in the field to simulate field conditions.

A reliable compaction procedure had been developed in the research project to investigate the Use of Crumb Rubber Modifier at URI (Lee et al. 1996). The compaction takes place in 4 layers, which will be described in detail later, to ensure that homogenous specimens would be obtained.

To assure a satisfying compaction under laboratory conditions the asphalt emulsion is heated to a temperature of 60°C (140°F) for approximately one hour before mixing.

The aggregates were dried and weighed out to 3,800 grams according to the gradations in Appendix D (the actual mass to weigh out can vary according to the field density required for each material). First the necessary amount of water to reach the OWC for the specific material was added and mixed thoroughly with the aggregate. Then, the necessary amount of emulsion was added and also mixed thoroughly with the aggregate. The mixture was oven-cured at 60°C (140°F) for one hour before the compaction, to allow for the specimens to be compacted to field density. The compacting device used was the California Kneading Compactor, or Hveem compactor, which allowed the fabrication of specimens 4 inches in diameter and 8 inches in height.

The compaction was conducted in four layers, equal in mass of material. The molds for this compacting device have to be heated up to the same temperature as the mixture, 60°C (140θF), to ensure good compacting conditions. If possible, depending upon the type of kneading compactor, it has been recommended to detach and preheat the compaction foot prior to compacting. Care should be taken to minimize the loss of heat during compacting, which can be achieved by putting the remaining mixture back into the oven while compacting each layer.

After preheating the mold, a thin film of regular machine oil was used to cover the inside surface of the mold to ease the extraction of the specimen later on. The compaction mold was placed in position in the mold holder, and a waxed or oiled paper disk, 4 inches in diameter to cover the base plate in the mold holder, was inserted. Then, the first layer was filled into the mold. Each layer was pre-compacted with a heated metal rod; 10 times in the center of mass and 10 times around the edge by means of the round nose rod. This procedure was repeated for every layer placed in the mold.

The actual compacting blows of the kneading compactor were applied: 10, 20, 30, and 40 blows per layer, respectively. A static load of 500 - 600 psi is applied to compact the specimen to its final degree of compaction. The static load had to be adjusted for the different compaction degrees of the different materials used.

After compaction, the mold was released from the compactor, and the paper disc was removed from its bottom. Compacted specimens should be brought to the room temperature before extraction. A push-out device for removing the specimens described in AASHTO T 246 was used. After removing the specimens from the molds, they were cooled down to the room temperature, and then tested for the bulk specific gravity to determine the unit weight.

The testing for the bulk specific gravity was performed after the specimens were cooled down to room temperature after the 24-hour oven curing. The unit weight was the control parameter for the specimens and indicated whether the compaction procedure was successful or not, in terms of under-compaction as well as over-compaction.

F.3 Test Equipment and Settings

F.3.1 Equipment

The ISDCT instrumentation, as specified in the VESYS User Manual has to conform to the following:

- An electro-hydraulic testing machine capable of applying up to 1,361kg (3,000 lbs) and producing either haversine or ramp hold waveforms. The machine should have the capability of attaining the ramp peak load through frequency control in 0.03 second or the haversine load for at least 0.1 second duration of loading. The machine should have the capability of applying any number of load repetitions (frequency control between 1 and 50 cps minimum), however, with additional controls for eliminating intermediate pulses to provide rest periods (time of no load) between pulses.
- An old consolidation device capable of applying up to 136.1 kg (300 lbs) and which has been modified with a quick release lever arm may be equally suitable for determination of the primary response property (creep test) and the permanent deformation properties (incremental creep test) of those materials exhibiting predominant amounts of flow such as asphalt bound materials.
- The temperature control system should be capable maintaining the sample at the required test temperature range of 0θC (32θF) to 50θC (120θF) ρ 0.5θC (1θF). An insulated test chamber should be constructed around the test setup for asphalt

concrete specimens (Figure F.1). It is not necessary to test asphalt concrete in the triaxial cell.

The VESYS user manual describes the following criteria for the measurement system: The measurement system consists of three-channel recorder, load and deformation measuring devices, and suitable signal amplification and excitation equipment. The measuring system should have the capability of measuring and recording loads up to 1,361 kg (3,000 lbs). This system should also be capable of measuring and recording deformations from 300 to 5,000 micro units of strain and have adequate sensitivity setting. It also should be able to display 4 micro strain units or less per millimeter in the recorder chart.

F.3.2 LVDT

The deformation measuring equipment consists of Linear Variable Differential Transformers (LVDT) attached to the specimen by a pair of clamps. The LVDTs are used for the measurement of axial deformation. The load is preferably measured by placing a load cell between the sample and the loading piston.

- ξ The LVDT is an electromechanical device that produces an electrical output proportional to the displacement of a separate, movable magnetic core. It consists of three coils, one of which is the primary of the transformer. The other two coils are usually symmetrical about the primary and in normal operation are connected in series opposing to form the transformer secondary. When the movable transformer core is centered with respect to the two secondary windings, they will have the same magnitude of induced output voltage, but the polarity or phrasing will be opposite. The net output voltage of the secondary will therefore be zero. This position is classically referred to as the electrical null position. When the magnetic core is displaced from the null position, the output of one secondary coil increases, while the output of the other coil decreases, producing a non-zero differential output voltage as a function of core displacement. The phase of this output voltage changes by 180θ as the core is moved from one side of null to the other.

ξ Some form of AC source to drive the primary, and some form of measuring the secondary output voltage needs to be available to operate and use the LVDT. The excitation source is usually a sine wave with an amplitude of a few volts rms and a frequency between 1 kHz and 10 kHz. The output can be measured with an AC voltmeter, or even an oscilloscope, but the usual method is to rectify the signal and measure the resulting DC voltage. More typically, the required functions to provide excitation and a DC output voltage are provided by some from a specialized LVDT signal conditioner.

ξ The output of the LVDT is an AC signal, which must be converted to DC before it can be used in most instrumentation systems. There are numerous means of accomplishing this. The simplest one involves some form of diode rectification, while the more complex one involve synchronous demodulation.

ξ The sensitivity of LVDTs is usually given as millivolts of differential secondary signal per volt of primary excitation voltage per thousandth of an inch displacement, or mV/V/0.001.

ξ Every LVDT conditioner must have a minimum of three sections. A source of excitation, some form of demodulator, and some form of filtering, which usually also includes DC gain. The building blocks, which have been described above, can be configured to optimize the LVDT system.

ξ The LVDTs used in this research project were so called "Miniature LVDTs" (Model Number: 100MHR), fabricated by Schaevitz, NJ. The features of those miniature LVDTs are the following:

(1) For applications where installation space or weight is limited,

(2) Lightweight core,

(3) Calibration certificate supplied with all models,

(4) Compatible with all Schaevitz signal conditioners,

(5) High temperature (220 θC) and high pressure (vented case) available, and

(6) Their specifications are summarized in Table F.1.

F.4 Permanent Deformation Parameters

The determination of the rut depth is an important consideration in flexible pavement design. To evaluate the rut resistance characteristic of the pavement structure, it is necessary to obtain the permanent deformation parameters of the material comprising the pavement section. Several laboratory-testing methods are available for this purpose. However, all rely on some sort of repeated load test, which simulates actual traffic conditions. In such tests, similar to the resilient modulus test, repeated loads are applied up to 100,000 repetitions and permanent deformations are recorded.

The VESYS analysis requires the ISDCT to measure permanent deformation parameters. The parameters of interest are evaluated by using the incremental static series or the dynamic series of the ISDCT. The theoretical basis for evaluating the permanent deformation parameters using either the incremental static or dynamic creep test is described below.

The method used in the VESYS program assumes that the permanent strain is proportional to the resilient strain given by:

$$H_p(N) \quad \Pi H N^{\Delta} \qquad \text{Eq. F-1}$$

where $H_p(N)$= permanent or plastic strain due to a single load application at the Nth application;

H= the elastic or resilient strain at the 200th load repetition;

N = the load application number;

Π= a permanent deformation parameter equal to the proportionality between permanent and elastic strains; and

Δ = a permanent deformation parameter that indicates the rate of decrease in permanent deformation as the number of load application increases.

One may obtain the total permanent deformation by integrating the above equation over the total number of load applications:

$$H_p \quad \int_0^N H_p(N)dN \quad H\Pi\frac{N^{1\ \Delta}}{1\ \ \Delta}$$ Eq. F-2

Where the terms have been defined previously.

Taking the log of both sides of the above equation, we obtain:

$$\log H_p \quad \log\left(\frac{H\Pi}{1\ \ \Delta}\right) \quad 1\ \ \Delta\ \log N$$ Eq. F-3

When one plots of log H_p versus log N, a straight line is obtained that has the slope S, which equals 1-Δ. The intercept, I, of the straight line at N=1 cycle (or a one second of time as the rate of testing is one load application per second) equals HΠ/(1-Δ). Solving for the parameter Π, Π= IS/H

To evaluate the parameters Δ and Π, the procedure in the VESYS manual can be used.

It utilizes the results of the incremental static test series. The log of the total permanent strain, H_p, is plotted versus the log of incremental load duration. The resulting data curve should be a straight line from which the Intercept, I, and the slope, S, are obtained. With the Intercept and the Slope known, the values of Δ and Π are readily obtained based on the equation described above. By definition the slope, S, of the log-log relationship is defined as:

$$S \quad \frac{\log F_{p1} \quad \log F_{p2}}{\log N_1 \quad \log N_2}$$ Eq. F-4

where H_{p1} is the permanent strain occurring at N_1.

F.4.1 Effect of Temperature on Δ and Π

Both parameters change with temperature of the bituminous mixture. To take this aspect into consideration, mix samples were supposed to be tested at different temperatures, e.g. 40, 70 and 105 θF for the Hot Mix Asphalt Mixes. During the first tests being run at the Transportation Engineering Laboratory at the University of Rhode Island (URI), it was found that the CIR material does not endure temperatures over 85 °F without failing the test. Therefore, it was decided that the tests should only be conducted at temperatures below the originally planned ones, i.e. 35, 50, 70, and 80 °F. If information was needed beyond the measured temperatures, either a regression curve or the application of a shift factor was used. At each temperature, H_p was plotted against incremental loading duration, and the values of Δ and Πwere determined.

F.4.2 Seasonal Variation of Δ and Π

The VESYS program requires seasonal values for Δ and Π The seasonal values for Δ and Πwere obtained by plotting each of them versus temperature. Based on these plots seasonal values were interpolated and extrapolated for average temperatures expected during each month. Since Δ and Π versus temperature do not exhibit linear relationships, polynomial or exponential curves were fitted to the data points.

F.5 ISDCT Procedure

In order to obtain the permanent deformation and strains, which are necessary inputs into the VESYS program to compute rut depths, two types of compression tests were utilized. These tests are the incremental static and dynamic tests, otherwise known as the ISDCT when performed back to back. The ISDCT equipment and set up are similar to that used in the resilient modulus test . Strain is measured by two LVDTs mounted opposite each other with a gage distance of 100mm (4 in.), placed in the middle of the specimen (Figure F.2). A load of 113.4 kg (250lbs) is applied using an electro-hydraulic actuator programmed to apply a stress of 138 kPa (20 psi) per load application, in a manner described shortly. The incremental static part of the test is preceded by a preconditioning loading phase which consists of the application of two load ramps of 138 kPa (20 psi) that are held for 10 minutes each with minimum time in between them. A third load is applied and held for another 10 minutes followed by a 10 minutes rest period. Following this preconditioning phase, the incremental static test is performed. The loading sequence and typical shape of the output strain is given in Figure F.3 where it can be seen that five different durations of the same stress, 138 kPa (20 psi), are applied. These durations are 0.1, 1, 10, 100, and 1,000 seconds, with rest periods of 2, 2, 2, 4, and 8 minutes, respectively.

During the fifth part of the incremental; static test, or the 1,000 second part, measurements of the deformation (and therefore strain) are taken at 0.03, 0.1, 1, 3, 10, 30, 100, and 1,000 seconds. The 0.03 second reading creep strain is equivalent to the resilient strain, Ḩ under a dynamic haversine load of 0.1 second duration.

Immediately after the incremental static test is performed, one may start the dynamic testing without further sample conditioning. The test is run with the same loading conditions as the incremental static test. The load duration is 0.1 second with a rest period of 0.9 seconds and continued until 100,000 cycles are completed. At the 200th repetition, both the permanent and the resilient deformations are measured. The entire ISDCT takes about 27 hours from start to finish.

The ISDCT in the URI Transportation Engineering Laboratory uses the equipment of the INSTRON servo hydraulic system and the LABTECH NOTEBOOK software to record the test. Figure F.4 shows strain response to a single stress pulse.

F.6 Data Process

The raw test data consists of voltage measurements recorded by the LVDT's mounted on the specimen. These changes in voltage represent longitudinal displacements of the test specimen. The data was taken every second of the testing time and the labtech notebook output provides a listing of the time with the correlating voltage measurement.

Calculating the voltage differences between the first reading and the last reading and each measurement and multiplying it with a conversion factor unique for each LVDT determined the actual displacement of the specimen. During our testing, one LVDT broke and had to be replaced. In order to ensure proper testing, a second LVDT was purchased and replaced the other old one. To determine the conversion factors for each new LVDT, both had to be calibrated.

F.7 Test Results

The CIR materials were tested at four different temperatures: 35, 50, 70, and 80 °F. These are lower than the ones used for testing HMA specimens, because CIR specimens failed at temperatures above 80 °F. Therefore, it was decided to establish a curve through the measured points, and to extrapolate and interpolate the values of the deformation parameters at the desired temperatures, required by VESYS. Test results are summarized in Table F.2.

Table F.1 LVDT Characteristics

Input Voltage	3 V rms (nominal)
Frequency Range	2 kHz to 20 kHz
Operating Temperature Range	-65 θF to 300 θF (-55 θC to 150 θC)
Null Voltage	<0.5% full scale output
Shock Survival	1,000 *g* for 11 msec
Vibration Tolerance	20 *g* up to 2 kHz
Coil Form Material	High density, glass filled polymer
Housing Material	AISI 400 series stainless steel
Lead Wires	32 AWG, stranded copper, Teflon-insulated, 12 inches (300mm) long (nominal)

Table F.2 Incremental Static-Dynamic Creep Test (ISDCT) Results

a) Ontario

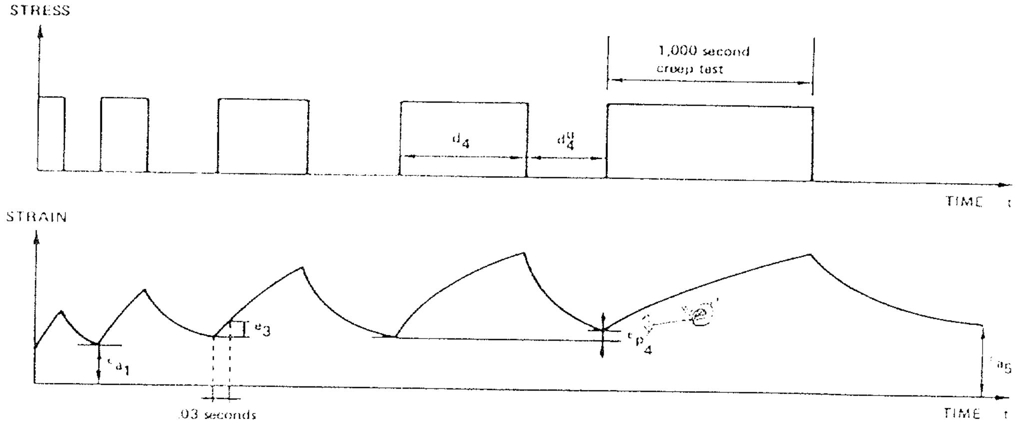
Temp. ° F	Slope	Intercept in./in. 10 e-6	Strain in./in. 10 e-6	Alpha	Gnu
35	0.135	11	25.6	0.866	0.059
50	0.297	4	10.3	0.703	0.115
70	0.419	7.9	14.87	0.581	0.265
80	0.443	8	25.25	0.557	0.315

b) Arizona

Temp °F	Slope	Intercept in./in. 10 e-6	Strain in./in. 10 e-6	Alpha	Gnu
35	0.19	9	41.809	0.81	0.042
50	0.26	15	55.980	0.74	0.0725
70	0.27	23.5	64.807	0.725	0.10
80	0.34	30	87.806	0.66	0.117

c) New Mexico

Temp ° F	Slope	Intercept in./in. 10 e-6	Strain in./in. 10 e-6	Alpha	Gnu
35	0.22	8	22.068	0.78	0.075
50	0.28	12.5	42.642	0.73	0.083
70	0.33	23	64.594	0.67	0.117
80	0.37	12	20.405	0.63	0.210



d_i = duration of the ith load pulse
d_i^u = rest period after the ith load pulse
ϵ_{p_i} = increment in permanent strain due to the ith load pulse
ϵ_{a_n} = total accumulated permanent strain due to n pulses: $\epsilon_{a_n} = \sum_{i=1}^{n} \epsilon_{p_i}$
e_i = strain amplitude measured at .03 seconds due to the ith load pulse

Figure F.1 Incremental Static Test Loading Sequence and Strain Response Sequence

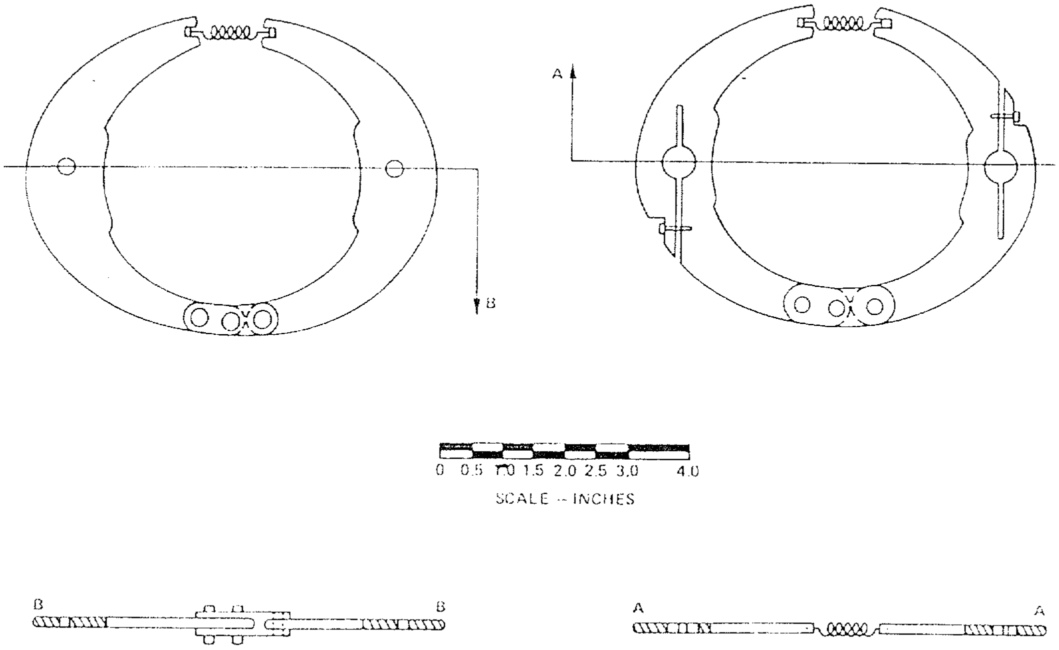


Figure F.2 LVDT Holder Clamps

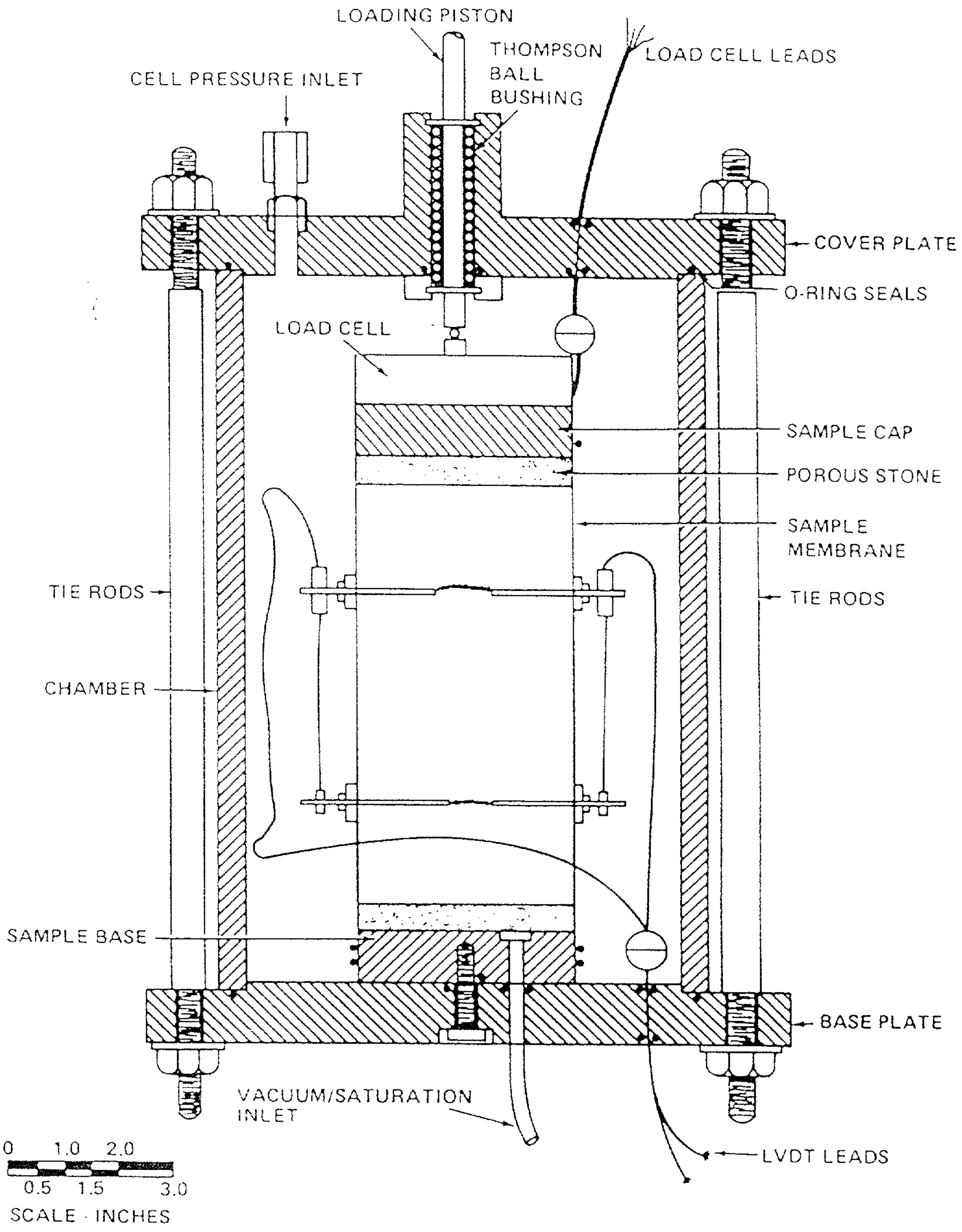


Figure F.3 Triaxial Cell for ISDCT

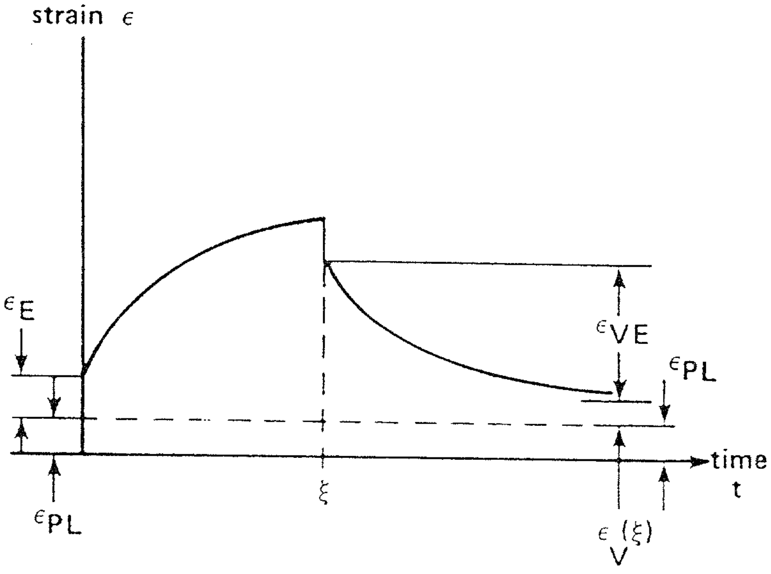


Figure F.4 Viscoelastic Strain Response

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Appendix G - Fatigue Beam Testing and the Input Parameters for the Fatigue Cracking Prediction

The VESYS computer model requires fatigue test data input. It predicts fatigue life as a phenomenological model predicting the extent of cracking based on a probabilistic Miner's hypothesis. The criterion for cracking is based on fatigue resulting from the tensile strain at the bottom of the asphalt concrete layer. It is given as follows:

$$C_q(t) = n_q / N_q \qquad \text{Eq. G-1}$$

where: $C_q(t) =$ increment to the crack index resulting from a repetition of loads in the q^{th} incremental analysis period.

$n_q =$ the number of axle loads applied to the pavement in the q^{th} incremental analysis period

$N_q =$ the number of axle loads to failure under temperature and strain conditions of the q^{th} time interval.

The number of loads for crack initiation in the q_{th} temperature season is given by the following relationship:

$$N_q = K_{1_q}\left(\frac{1}{R_{7_q}}\right)^{K_{2q}} \qquad \text{Eq. G-2}$$

where: $R_{7q} =$ the general radial strain response

K_{1q} and $K_{2q} =$ material fatigue properties

To determine the fatigue properties the VESYS program uses the flexure fatigue test on beams, which will be explained later in this section. The stochastic solutions to the equation for the cracked area are obtained assuming that n_q and N_q are independent (uncorrelated), random variables:

$$E[C(t)] = \sum_{q=1}^{Q} E[n_q] E[1/N_q] \qquad \text{Eq. G-3}$$

Likewise the variance is obtained:

$$Var[C(t)] = \sum_{q=1}^{Q} \left(E[1/N_q] \sigma_{nq}^2 + E[n_q] \sigma_{1/N_q}^2 \right) \qquad \text{Eq. G-4}$$

The variance of the load number is found from the average rate of traffic loads accruing in a Poisson distribution. The expected value and variance of loads to failure are found using second order Taylor series expansion approximations assuming that only K_1 and K_2 are correlated and that strain response is uncorrelated with K_1 and K_2.

The expected cracking damage E[C] is expressed as a dimensionless index. A crack initiated at the bottom of the AC layer when the value of E[C] equals one. In order to express cracking in a more meaningful manner, it is assumed that C takes on a normal distribution with mean E[C] and variance VAR[C].

The probability density function f(c) expressing these quantities can be expressed mathematically as:

$$f(c) = (2\pi Var[C])^{-\frac{1}{2}} \exp\left(-\frac{C - E[C]^2}{2Var[C]} \right) \qquad \text{Eq. G-5}$$

The cumulative distributive function is defined as:

$$F(C_0) = \int_{-\infty}^{C_0} f(c)dc \qquad \text{Eq. G-6}$$

where: f(c) = probability density function

$F(C_0)$ = cumulative distribution function of C at the point C_0 (area under the curve f(c) between C = -∞ and C = C_0.)

This area represents the probability of C being less than C_0. F(1) is the probability that the damage index (C) is less than one (i.e., the pavement does not exhibit cracking distress). The expected area cracked in square feet per 1000 feet is given as:

$$\text{Area cracked} = 1000 * (1-F(1)).$$

G.1 Specimen Preparation with RAP Material and Validation

The CIR specimens were prepared according to the Modified Superpave Mix Design procedure at the Optimum Water Content (OWC) and Optimum Emulsion Content (OEC). The first try of compacting the mixture using a vibratory compactor failed because the desired density was not reached with this method. The mixture was then compacted using a kneading compactor. The mixture was compacted in layers similarly to the way of fabricating ISDCT specimens to assure a continuous density. The size of the specimen was 15 x 3 x 3 inches according to the specifications in the VESYS manual. The molds used were slightly bigger than the final specimen so that sawing was required to obtained the desired dimensions.

G.2 Test Equipment and Settings

The flexure fatigue test on beams is a laboratory test where a simply supported beam is subjected to two symmetrical concentrated loads applied at the one-third points. The test is carried out in the controlled stress mode.

The equipment to conduct flexure fatigue tests requires a 3,000-pound capacity electrohydraulic testing machine capable of applying repeated tension-compression loads in the form of haversine waves for 0.1 second duration with 0.4 second rest periods. The same machine as for conducting the Incremental Static Dynamic Creep Test (ISDCT) can be used with a different testing frame to accommodate a beam specimen. The two-point loading configuration, theoretically, applies a constant bending moment over the center 4 inches of a 15-inch long beam specimen.

A sufficient load, approximately 10 percent of the load deflecting the beam upward, is applied in the opposite direction, forcing the beam to return to its original horizontal position and holding it at that position during the rest period. Adjustable stop nuts installed on the flexure apparatus loading rod prevent the beam from bending below the initial horizontal position during the rest period.

The dynamic deflection of the beam at mid-span is measured with a linear variable differential transformer (LVDT). The LVDT that has been found suitable and is currently used in the URI Transportation Laboratory is Schaevitz type 100 M-H. The LVDT core is attached to a nut bonded with epoxy cement to the center of the specimen. Outputs of the LVDT, and the electric-hydraulic testing machine's load cell through which the loads are applied and controlled, are fed to a suitable recorder. The repeated flexure fatigue apparatus is enclosed in an environmental chamber capable of controlling the temperature with ± 0.5 °F.

Repeated flexure apparatus loading clamps are adjusted to the same deviation as the reaction clamps. The specimen is clamped in the fixture using a jig to position the centers of the two loading clamps 2 inches from beam center. To reduce the friction between the clamps and the beam specimen Teflon sheets are placed between the specimen and the loading points.

After the beams have reached the desired test temperature, repeated loads are applied. Duration is as mentioned above. The applied load should be that which produces an extreme fiber stress level suitable for flexural fatigue test. For fatigue tests on typical bituminous concrete paving mixtures, the VESYS manual recommends the following ranges of extreme fiber stress levels:

55 °F – 150 to 450 psi
70 °F – 75 to 300 psi
85 °F – 35 to 200 psi

The beam center point deflection and applied dynamic load are measured immediately after 200 load applications for calculation of extreme fiber strain. The test is continued at the constant stress level until the specimen fractures. Extreme fiber stress levels for flexural fatigue tests at any temperature should not exceed that which causes specimen fracture before at least 1,000 loads are applied. A set of 8 to 12 fatigue tests should be run for each temperature to adequately describe the relationship between extreme fiber strain and the number of load applications to fracture. The extreme fiber stress should be varied such that the resulting number of load applications to fracture ranges from 1,000 to 1,000,000.

The initial strain amplitude for each specimen can be calculated as follows:

$$e \quad \frac{12td}{3(l^2 \quad 4a^2)} \qquad \text{Eq. G-7}$$

where, e = extreme fiber strain at 200 repetitions
a = ½ (reaction span length – 4), inches
t = specimen depth, inches

d = dynamic deflection of beam center, inches at 200 repetitions

l = reaction span length, inches

The number of repetitions to failure N_f for each specimen is noted down.

To determine the fatigue characteristics, the coefficient and exponent in Miner's fatigue law, K_1 and K_2, the values are plotted versus the number of repetitions to failure N_f on a log-log-scale. Ideally, it should produce a straight line, but most likely a regression line has to be calculated through the plotted points. It will be a descending line, where the highest value of strain is denoted by I (Intercept), and the corresponding lowest number of repetitions to failure is N_0. The absolute value of the slope of the straight line is S.

Having these points, the mean values of the fatigue properties can be calculated:

$$\overline{K}_2 \quad \frac{1}{S} \qquad \text{Eq. G-8}$$

$$\overline{K}_1 \quad N_0(I)^{1/S} \qquad \text{Eq. G-9}$$

These values correspond to STRNEXP = $\overline{K}_2$ and STRNCOEF = $\overline{K}_1$. If all of the points on a plot of e versus N_f lie on the mean line, the probabilistic fatigue parameters to be used in the VESYS program are as follows:

$COEFK_1 = 0$

$COEFK_2 = 0$

$K_1K_2CORL = -1$

If the points exhibit scatter about the mean, the VESYS manual suggests the following procedure to determine $COEFK_1$, $COEFK_2$ and K_1K_2CORL:

Draw a number of lines through the points and calculate a set of fatigue properties (K_{1i} and K_{2i}) for each of the (n) lines. Then, COEFK$_1$, COEFK$_2$ and K$_1$K$_2$CORL can be calculated as:

$$\text{COEFK}_1 = S_{K1} / \overline{K}_1 \qquad \text{Eq. G-10}$$

$$\text{COEFK}_2 = S_{K2} / \overline{K}_2 \qquad \text{Eq. G-11}$$

$$\text{K}_1\text{K}_2\text{CORL} = \frac{1}{n}\sum_{i\ 1}^{n} \frac{K_{1_i}\quad \overline{K}_1}{S_{K_1}} \frac{K_{2_i}\quad \overline{K}_2}{S_{K_2}} \qquad \text{Eq. G-12}$$

Where

$$S_{K_2}^2 \quad \frac{1}{n}\sum_{i\ 1}^{n} K_{1_i}^2 \quad n\overline{K}_1^2 \qquad \text{Eq. G-13}$$

$$S_{K_2}^2 \quad \frac{1}{n}\sum_{i\ 1}^{n} K_{2_i}^2 \quad n\overline{K}_2^2 \qquad \text{Eq. G-14}$$

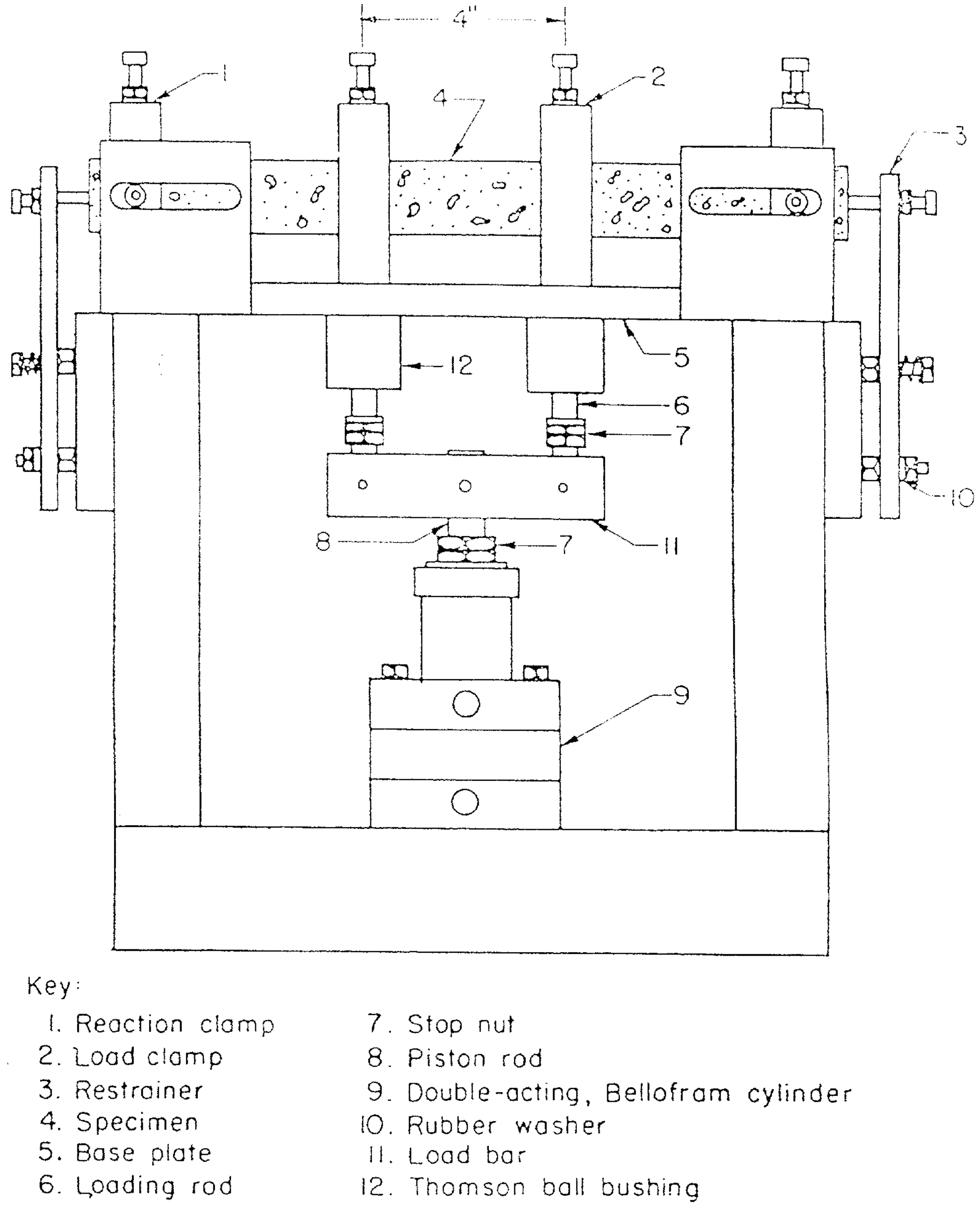

Figure G.1: Repeated Flexure Fatigue Test Apparatus (VESYS)

Appendix H - Creep Compliance and Strength at Low Temperatures Test Using the Indirect Tensile Tester

The following procedure is followed in order to perform the IDT Creep Compliance and Strength at Low Temperatures Test for CIR Mixtures. The Instron Indirect Tensile Test System Operator's Guide ("Indirect") should be referred to for complete instructions and details.

H.1 Specimen Preparation

1. The specimens are prepared for testing by following the compaction procedures described in Section 5.3 and Appendix C. Specimens are prepared at the Optimum Emulsion Content (OEC) and Optimum Water Content (OWC) as determined in Section 6.1. The specimens are compacted by applying the number of gyrations of the Superpave Gyratory Compactor (SGC) required to simulate field density, as described in Section 6.1 and Appendix A.
2. Each specimen prepared using the SGC is cut into two 50 mm (2 in) tests specimens for use in the IDT test. The specimens are cut using a diamond blade saw. Both sides of all specimens are cut to insure smooth surfaces for mounting of the brass mounting pads to hold the Linear Variable Differential Transducers (LVDTs). Since water is required for cutting of the specimens by the diamond blade saw, the specimens are allowed to dry before begin testing. Typically, the specimens are allowed to dry overnight before continuing with this procedure.

H.2 Mounting of Brass Mounting Pads

1. Once the specimens are dry, the brass mounting pads are attached to the specimen. The mounting pad template is placed onto the specimen and a straight line is drawn across the thickness of the specimen to ensure that LVDT axes on the opposite side of the specimen are aligned. Place the template on the specimen such that the notch on the edge of the template is aligned with the line drawn on the edge of the specimen. The mounting pads are then affixed to the test specimens using superglue. The mounting pads are then affixed to the other side using the same procedure. The test specimens are now ready for testing.

H.3 IDT Loading Frame and Environmental Chamber Setup

1. The loading frame is turned on first by flipping the power switch on the side of the frame to the on position.
2. The environmental chamber and subsystem is then turned on by a series of switches on the front control panel of the subsystem. The switches are turned on in sequence from left to right. The temperature set point of the test to be performed is then set on the digital display on the subsystem control panel.
3. The computer and data acquisition system is then turned on.
4. The LVDT conditioners should then be turned on.

H.4 Pre-Test System Preparation

1. The specimens to be tested are placed into the environmental chamber for preconditioning once it has reached the set point. The specimens are to

remain in the chamber for 3 ± 1 hours prior to testing. The specimens are stood on edge to allow good air circulation around the specimen.

2. The Merlin software is started by clicking on the program icon on the computer screen. The computer will then connect to the load frame and environmental chamber subsystem.

3. Select the proper TNCRP.MTM test application for the Tensile Creep Test temperature.

4. The LVDT system is then prepared for mounting onto the specimens. The LVDT coils are first mounted into the coil holders. The LVDT cores are then mounted into the core holders. The set screw on each holder is only tightened to snug, as it will later be necessary to manually zero the LVDTs by adjusting the LVDT cores.

5. The LVDT system is then mounted onto the specimen. The LVDT with the straight core is mounted first. Secure the holders to the brass mounting pads on the face of the specimen by tightening the set screws near the bottom of the holders. The holders should be attached such that the cores are able to move smoothly in and out of the coil. The LVDT with the bent core is then mounted onto the specimen in the same fashion. The LVDTs on the opposite side of the specimen are then mounted.

6. The specimen is then placed into the test fixture inside the environmental chamber. The specimen should be orientated such that the specimen is centered on the lower loading strip and the line drawn on the edge of the specimen is aligned with the upper loading strip.

7. The LVDT cables are then attached to the connectors.

H.5 Transducer Calibration

1. The loadcell is electronically once each time the IDT system is turned on. Select the loadcell icon in the upper right hand corner of the computer screen. Then select "Calibrate" from the dialogue box. Then click "OK".
2. Change the live screen displays so that the LVDT channel outputs (R. Horz., L. Horz., R. Vert., and L. Vert.) are on the screen. Loosen the set screw for the first core and move the core until the display indicates zero ± 0.0025 in. Once the correct position is achieved, snug down the set screw. Repeat for the other three LVDTs. Automatic calibration of the LVDTs is then performed by selecting the multichannel calibration icon in the upper right hand corner of the computer screen. Click on "Calibrate" for any LVDT. At the next screen, click "Calibrate" again. Then click "OK". Repeat for all four LVDTs.
3. Change the live screen displays so "Load" and "Strain 1" are shown, as these displays are more useful during the test.
4. Calibrate the strain channel by selecting the extensometer icon in the upper right hand portion of the screen. Click "Calibrate", and then "OK". This calibration is only required to be performed one time each day.

H.6 Running the IDT Creep Test

1. The event detectors for the creep test should be enabled. To verify this, select the traffic signal icon on the right side of the computer screen. Click

on “Events”. The three events should all be enabled. If any of the events are not enabled, click the check box to enable them. These events ensure that the test proceeds as programmed.

2. The loadcell is balanced before beginning the test. Make sure the specimen is not in contact with the upper loading strip and click on “Balance Load” in the upper left hand corner of the computer screen.

3. The specimen protect feature needs to be turned on so a pre-load can be applied to the specimen. Select the control panel icon in the upper left portion of the computer screen. Click the “Enabled” box under “Specimen Protect” and set the threshold to no higher than 10 lbs. Press the button labeled “SPECIMEN PROTECT” on the loading frame handset. Use the downward jog button on the loadframe handset to apply the pre-load to the specimen. Once the pre-load is applied, turn off “SPECIMEN PROTECT” or the test will not run.

4. Begin the test by pushing the “Start Test” button on the loading frame handset. The software then waits for the temperature set point on the environmental system controller to be achieved. When the temperature set point is achieved, a message will be displayed on the computer screen. The test will start by clicking “OK”. Increasing load will be applied to the specimen until the appropriate strain level is reached, when the system will switch to “Load Hold” and the load will remain constant. Once the test is complete, the loading strip will return to its original position.

5. The two plots of load versus time, and LVDT displacement are rescaled on the computer screen to show all of the test data. These plots can now be printed.
6. Clicking the "End & Save" icon on the computer screen then saves the data for the test. Enter the filename for the specimen, but do not include the filename extension. Then click "OK". The graphs will then be cleared.
7. The tensile strength test is then run on the specimen. Click on "File" in the main menu bar, and select "Open New Method". Select the TNACR.MTM method for the appropriate test temperature.
8. The test is then run by following steps 2 through 6 above.

Appendix I - Test Section Photographs for Field Verification

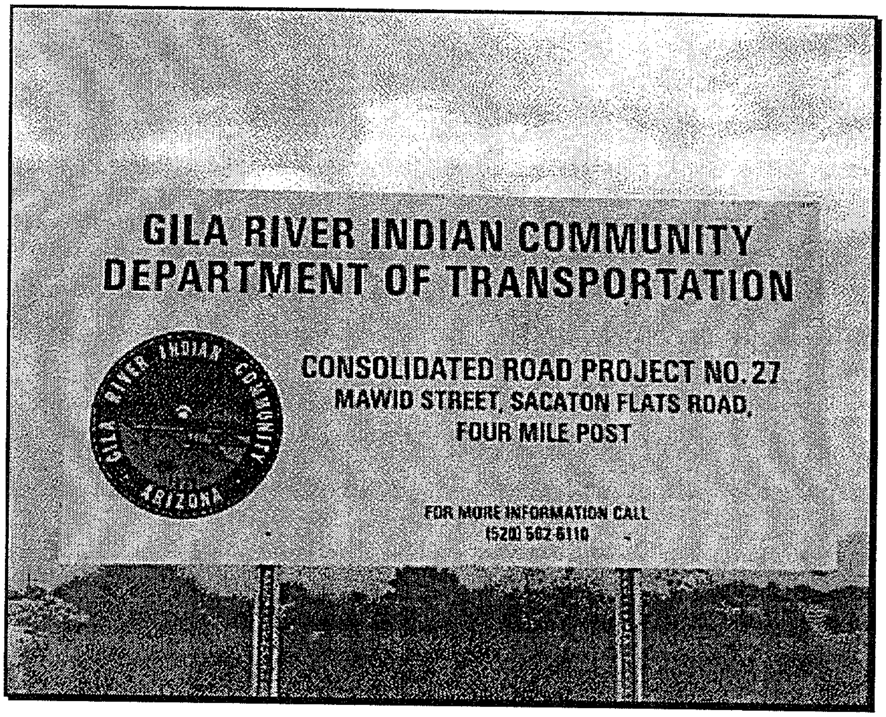

Figure I.1. The Test Section is Located in the Gila River Indian Community

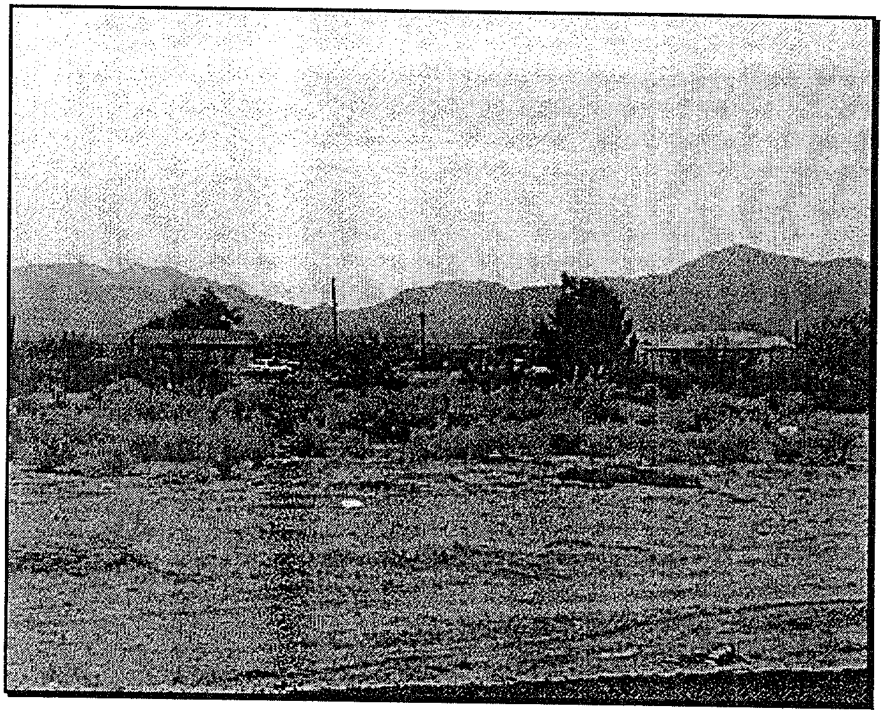

Figure I.2. The Test Section is Located in a Desert Environment in Arizona

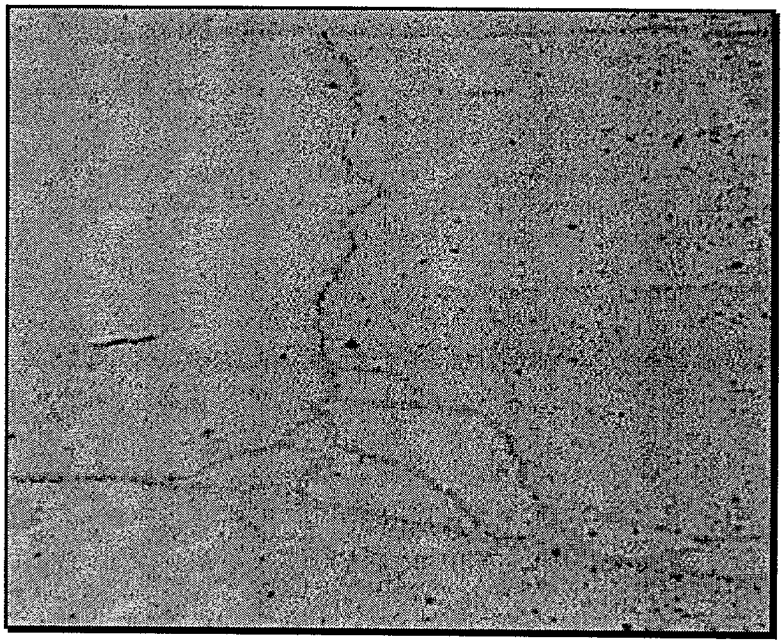

Figure I.3. The Roadway was Experiencing Thermal and Fatigue Cracking

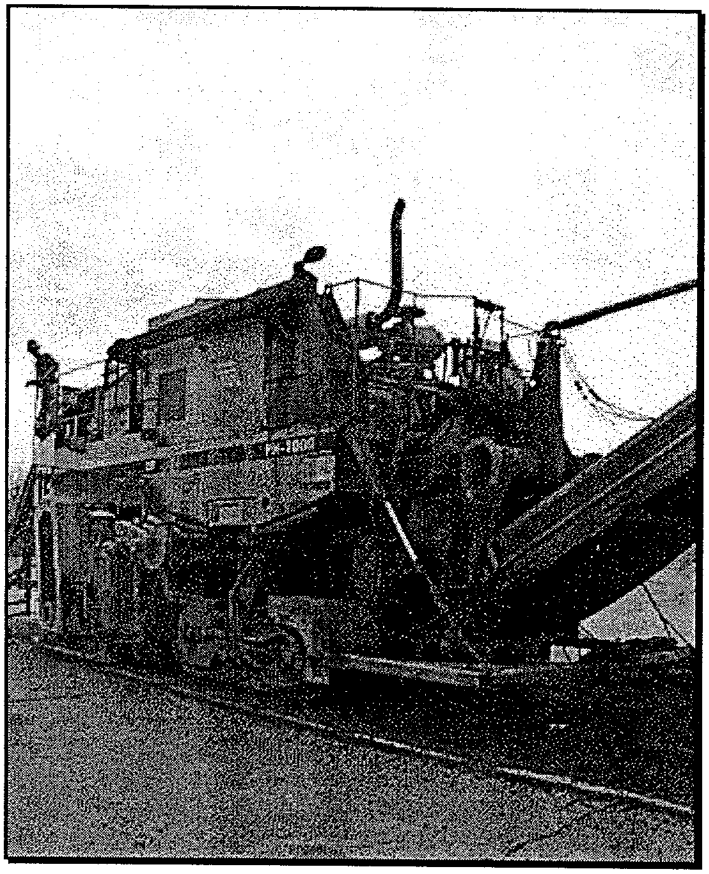

Figure I.4. Milling Portion of the CIR Train

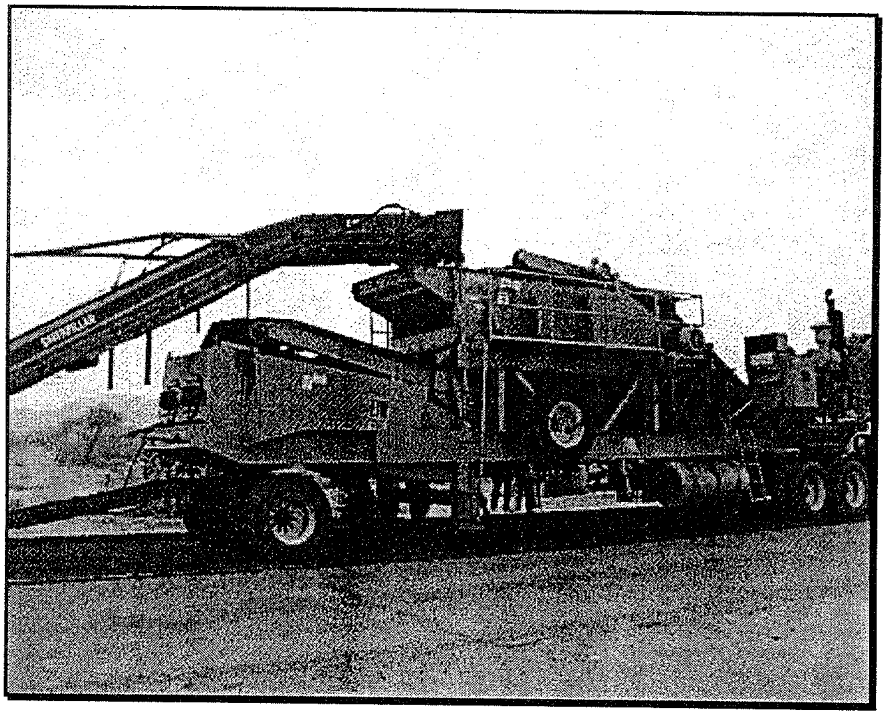

Figure I.5. Screening/Crushing Section of the CIR Train

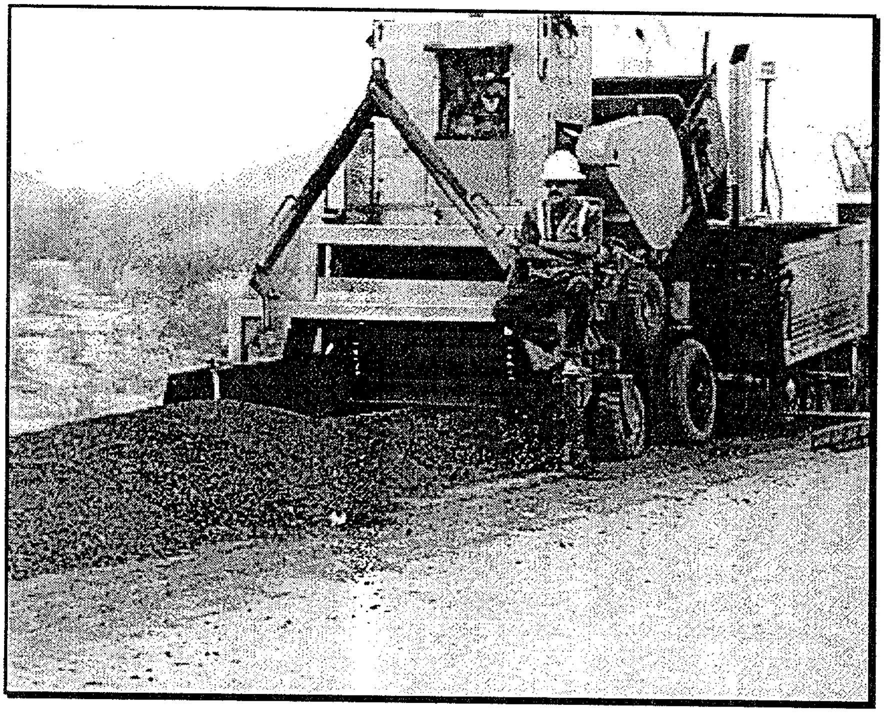

Figure I.6. Cold In-Place Recycled Windrow Behind Paver

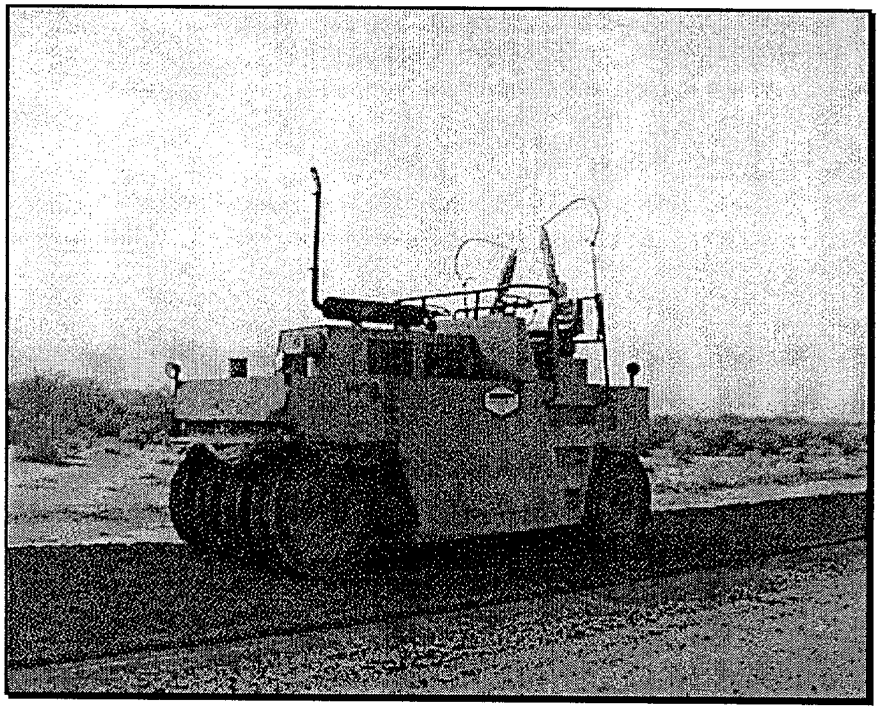

Figure I.7. Pneumatic-Tired Roller

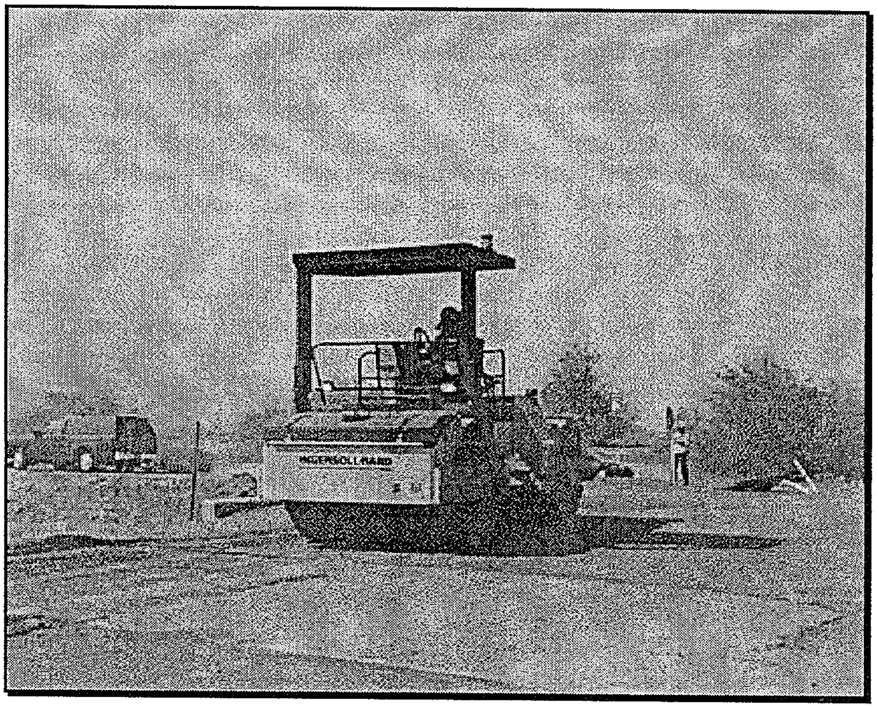

Figure I.8. Steel Double Drum Vibratory Roller

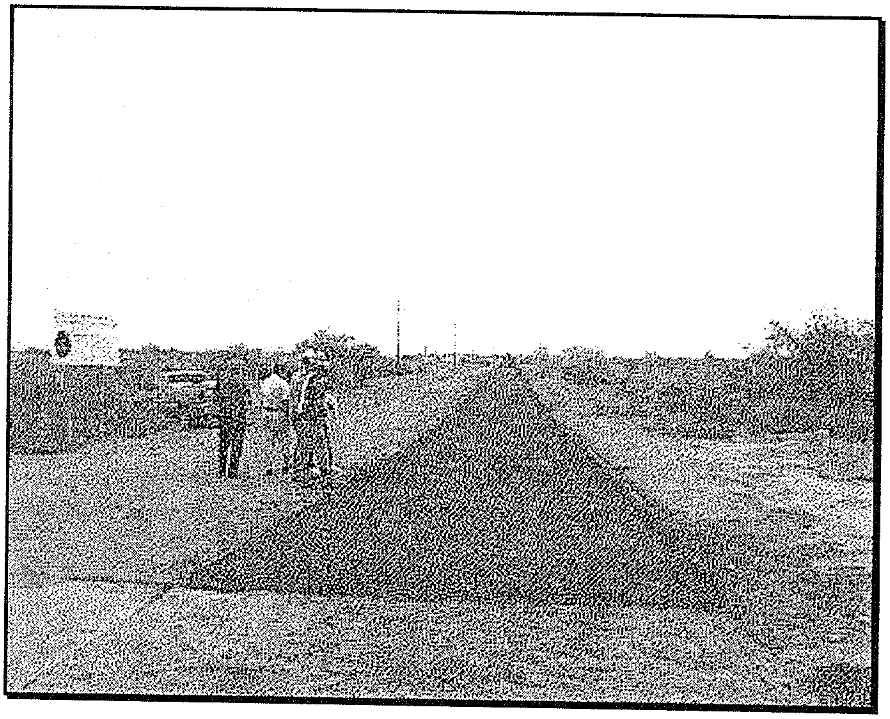

Figure I.9. Final CIR Layer

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