EVALUATION OF COLD IN-PLACE RECYCLING FOR REHABILITATION OF TRANSVERSE CRACKING ON US 412

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INTRODUCTION

PROBLEM STATEMENT

Cold in-place recycling (CIR) has been shown to be a cost-effective procedure for rehabilitation of hot mix asphalt (HMA) pavements. Recent advances in emulsion formulations and additives have made marked improvement in the performance of CIR pavements. However, one of the drawbacks to the use of CIR reported by some agencies is still unfamiliarity with the process and limited guidelines on the structural support to assign to the CIR layer in overlay thickness design. This problem continues even though many states have significant experience with CIR procedures and experienced contractors are readily available.

With the development of the *Mechanistic-Empirical Pavement Design Guide (M-EPDG)* [1], there is a new emphasis in mechanistic-empirical (M-E) thickness design procedures. Materials input parameters for these M-E procedures are typically either resilient modulus or dynamic modulus, and Poisson's ratio.

In order to ensure CIR's place in pavement maintenance and rehabilitation activities, guidelines on dynamic modulus parameters will need to be developed. There is evidence that the predictive equations provided as default values in the M-EPDG for HMA are not sufficiently accurate, especially with modified asphalts. It is doubtful that the default predictive equations are accurate for CIR mixtures either. A thorough laboratory evaluation of the dynamic modulus properties of CIR pavements is needed to evaluate the input parameters required by the *Mechanistic-Empirical Pavement Design Guide.*

A rehabilitation project using CIR, on US 412 in Beaver County, provided an excellent opportunity to obtain samples for a laboratory evaluation of the dynamic modulus properties of CIR pavements.

OBJECTIVE

The objectives of this thesis were to evaluate the dynamic modulus of CIR mixture made with one reclaimed asphalt pavement (RAP) and four different emulsions and to compare the results with the default values in the M-EPDG.

For bituminous materials, the M-EPDG uses a hierarchical approach with three levels of materials characterization. The first level provides the highest design reliability, using measured values, and each succeeding level is a drop in design reliability. The second and third levels of material characterization use default master curves developed from predictive equations for conventional hot mix asphalt mixtures [1]. The proposed research project would provide an excellent opportunity to investigate the dynamic modulus properties of CIR mixtures and evaluate the appropriateness of the default dynamic modulus values.

SCOPE

During construction of the CIR on the western portion of US 412, samples of RAP were obtained prior to the addition of the recycling agent. Samples of the recycling agent (reflex emulsion) were obtained. The in-place density and mix water content of the compacted CIR were determined immediately after final rolling.

Three additional emulsions were obtained, CSS-1h, CSS-1h with lime and HFE-150P. Laboratory samples of the US-412 RAP mixture were prepared by mixing RAP to the mix water and emulsion contents used in field and compacting to the field unit weight. The Dynamic Modulus (E*) of each sample was determined in accordance with AASHTO TP-62 [2]. The data was analyzed using analysis of variance (ANOVA) procedures. Duncan’s multiple range test was used to determine which means were significantly different when the ANOVA indicated a statistical difference in means. The E* obtained was also used to develop Master Curves for CIR which were compared to the master curves obtained from the Witczak’s predictive equation for HMA which are used as default values in the M-EPDG.

CHAPTER 2

LITERATURE REVIEW

RECYCLING

Recycling of hot mix asphalt (HMA) has increased in popularity since the late 1970s. Many different reasons led to the increased demand and awareness of recycling. Probably the largest single factor was the oil embargo of the early 1970s and the subsequent increase in the price of asphalt. The increase in the price of asphalt made any reclaimed asphalt pavement (RAP) material a valuable asset. Before the oil embargo, the price of asphalt cement was so low that the cost of removing, stockpiling, and recycling old pavements was more than that for purchasing, mixing, and placing new material [3].

A second item that has had a great impact on recycling is the development of the milling machine. Prior to the development of the milling machine, old asphalt pavement had to be ripped from the roadway, and then crushed prior to using. This process often required that the roadway be shut down for extended periods of time. Another process that was used prior to the use of the milling machine was the heater planer. This process required a large amount of fuel to heat the pavement, resulted in air pollution, and damaged the removed HMA by overheating.

The milling machine has solved most of these problems. It can remove any amount of material desired and does not produce appreciable pollution since heat is not required. The material removed with a milling machine does not have to be crushed since it is fine enough immediately after being removed to recycle. A milled surface can also be opened to traffic temporarily until the overlay has been completed [3].

Asphalt recycling is broadly classified into five categories by Asphalt Recycling and Reclaiming Association (ARRA) [4]. These categories are:

- Cold Planning (CP)
- Hot Recycling
- Hot In-Place Recycling (HIR)
- Full Depth Reclamation (FDR)
- Cold Recycling (CR)

Cold Planning (CP)

Cold Planning (CP) is the controlled removal of the surface of the existing HMA pavement to a desired depth, longitudinal profile, and cross-slope, using specially designed equipment (milling machine). CP can be used to remove part or all of the existing pavement layers. The resulting textured pavement can be used immediately as a driving surface. CP is more commonly used as a surface preparation for one of the other rehabilitation techniques such as HIR, CR, FDR or HMA overlays. In addition, CP can be used to roughen or texture pavements to restore low friction numbers and eliminate slipperiness [4].

Hot Recycling

Hot Recycling is the process of combining RAP with new aggregates, new asphalt binder, and/or recycling agents in a central plant to produce a recycled mix. Hot recycling utilizes the heat-transfer method to soften the RAP to permit mixing with virgin aggregates and asphalt binder and/or recycling agent. Hot recycling of RAP currently is the most widely used asphalt recycling method in the world [4].

Hot Inplace Recycling (HIR)

Hot Inplace Recycling consists of heating and softening the existing HMA pavement, permitting it to be scarified or hot rotary milled to a specified depth. The scarified or loosened asphalt pavement is then thoroughly mixed and subsequently placed and compacted with conventional HMA paving equipment. In this process, 100 percent recycling of the existing HMA pavement is completed on site [4].

Full Depth Reclamation (FDR)

Full Depth Reclamation (FDR) is the process in which the full thickness of the HMA pavement and a predetermined portion of the base, subbase and /or subgrade is uniformly pulverized and blended to provide and upgraded, homogenous base material. Often this blend of material alone, without any additional stabilizing additives, is sufficient to act as the base for new surface course. FDR is performed on the roadway without the addition of heat [4].

Cold Recycling (CR)

Cold Recycling consists of recycling HMA pavement without the application of heat during the recycling process. CR is classified into two sub-categories based on the process used. These processes are Cold Central Plant Recycling (CCPR) and Cold In place Recycling (CIR).

Cold Central Plant Recycling (CCPR)

Cold Central Plant Recycling is the process in which the asphalt recycling takes place in a central location using a stationary cold mix plant. The stationary plant could be a specifically designed plant or a CIR train, minus the milling machine, set up in a stationary configuration. The CCPR mix can be used immediately or it can be stockpiled for later use in such applications as maintenance blade patching or pothole repair [4].

Cold Inplace Recycling (CIR)

ARRA defines Cold Inplace Recycling as a partial depth recycling process that rehabilitates the upper portion of an existing pavement, normally between 2 and 4 inches. The RAP material is obtained by milling, planning, or crushing the existing pavement. Virgin aggregate or recycling agent or both are added to the RAP material which is then laid and compacted [4, 5].

In the CIR process, the old pavement is milled, then crushed and screened to size, and ultimately mixed with a liquid recycling agent. New aggregate and other additives can be added, if needed. A paver following the CIR train lays the cold mix, and it is compacted as soon as the emulsion or recycling agent breaks and sets up, releasing the moisture from the mix (usually 15 to 90 minutes after paving) [4, 6, 7, 8]. The process is completed with the laying of a wearing surface over the CIR mix. A minimum HMA thickness of 1.5 inches is recommended, though low traffic volume roads sometimes are treated with chip seals [4, 8].

CIR CONSTRUCTION PROCESS

CIR consists of the following steps [4, 5, 6]:

- Preparation of construction area;
- Reclaiming the old bituminous concrete pavement;
- Crushing the reclaimed pavement and sizing the bituminous aggregate;
- Addition of virgin aggregate if required;

- Addition of new binder;
- Mixing of all the components;
- Laydown of the new mixture;
- Aeration of the mixture;
- Compaction of the mixture;
- Curing of the mixture; and
- Application of wearing course.

CIR EQUIPMENT

CIR equipment can differ in size and sophistication. They generally differ by the way the RAP is removed and sized, how the additives are added and mixed and, finally, how the mix is placed. Generally, CIR is carried out by single or multiple units called trains. The different kinds of CIR trains, which vary depending on their operation and size, are single, two unit and multiple unit trains [4, 6, 9].

Single Unit Trains

The traditional single-unit train consists of a machine that mills the pavement to the specified depth and cross slope and blends the recycling additive. One of the unique features of the single-unit recycler is the use of a down-cutting milling head (most mills cut on the up cycle). The down-cutting milling head lets the operator control RAP size by adjusting the forward speed of the machine [4, 6, 8].

Figures 2-1 and 2-2 show a simple setup of a single unit train. In a single pass the unit is capable of milling, adding recycling agent and paving the surface.

FIGURE 2-1 A Self Contained Single Unit CIR Train [10].

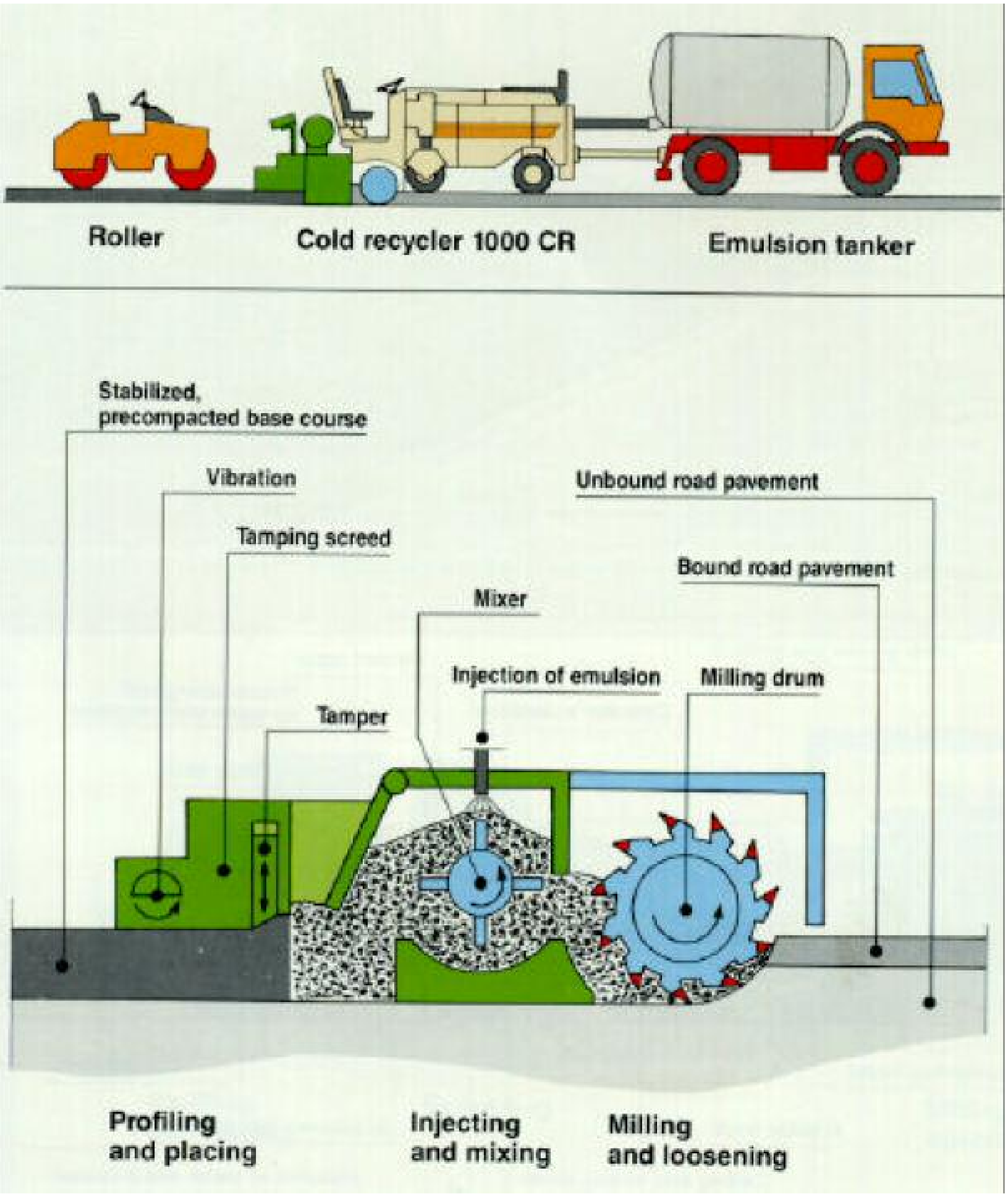

FIGURE 2-2 Traditional Single Unit CIR Train and Sectional View [10].

Some of the single-unit trains are capable of milling the surface to be treated, screening the RAP, crushing any oversized material, blending the RAP with the recycling agent in the pugmill and placing the mixture onto the surface using a screed. Figure 2-3 shows a sectional view of a super single unit CIR train. Figure 2-4 shows a single unit

CIR train depositing the recycled mixture in a windrow, which is being laid by a conventional paver with a windrow pickup attachment.

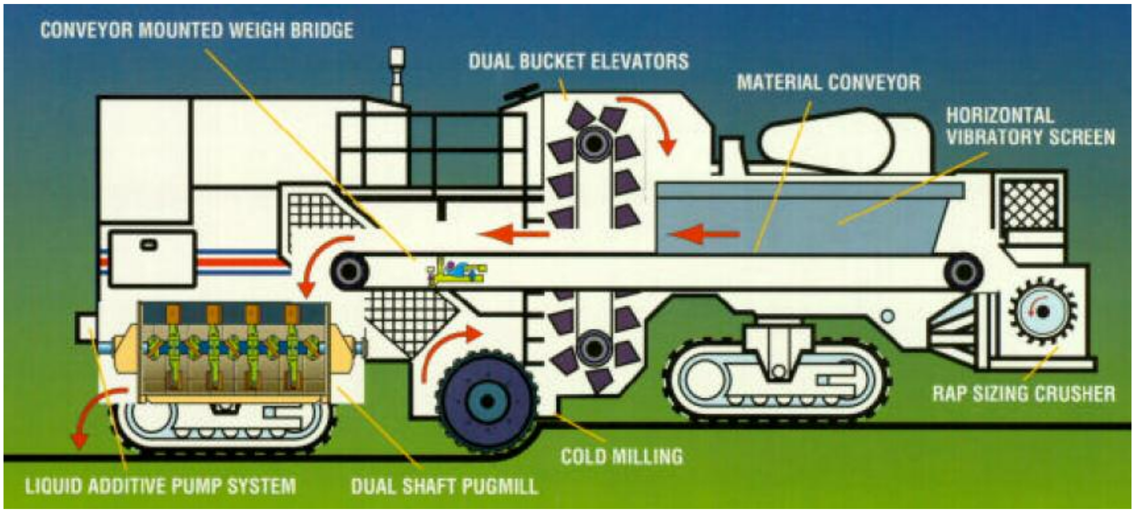

FIGURE 2-3 Super Single Unit CIR Train [10].

FIGURE 2-4 A Single Unit CIR Train Deposits the CIR Mixture in a Windrow [10].

The advantages of the single-unit train are simplicity of operation and high production capacity. The single-unit train may be preferred over a multi-unit train in urban areas and on roads with short turning radius, due to its shorter length. The single-unit CIR trains are less than 70 feet in length when compared to the multiple-unit CIR trains which measure about 150 feet in length. [4].

Two-Unit CIR Train

A two-unit CIR train usually consists of a large, full lane width milling machine, and a mix paver. The milling machine removes the old pavement surfaces and deposits the RAP into a mix paver. A scalping screen can be used to remove oversize RAP. The RAP and the additives are mixed in the mix-paver to form a uniform mixture. The mix paver has an infeed belt with a belt scale and a processing computer to accurately control the amount of recycling additive and modifier being added [4]. The mixture is placed and pre-compacted by a screed which is automatically controlled. Figures 2-5 and 2-6 show a schematic and photograph of a two-unit CIR train, respectively.

The two-unit train provides an intermediate to high degree of process control, with the liquid recycling additive being added based on the weight of the RAP, independent of the treatment volume and forward speed of the train [4].

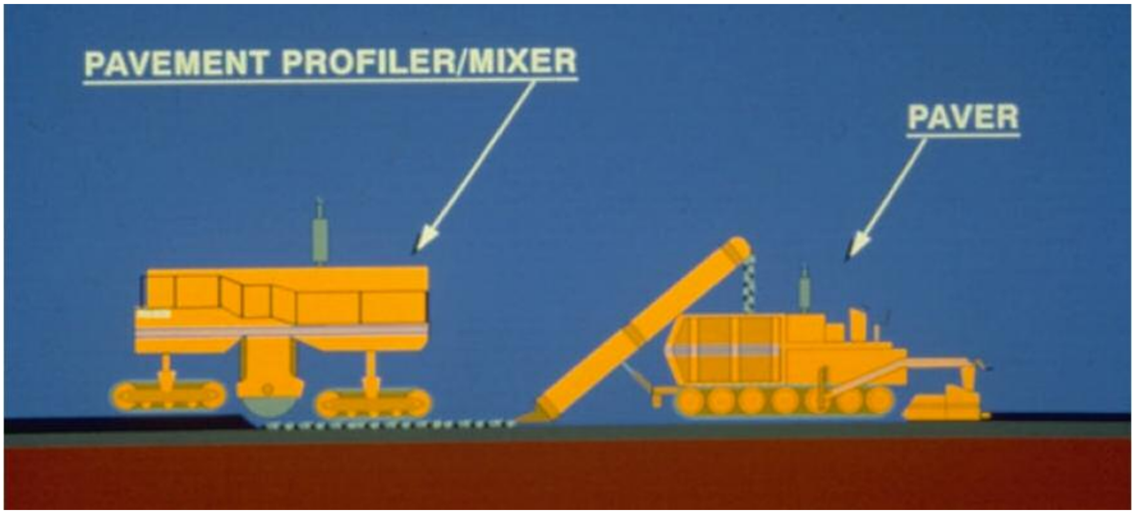

FIGURE 2-5 Schematic View of the Two-Unit CIR Train [10].

FIGURE 2-6 A Paver Mixer Two-Unit CIR Train.

Multi-Unit CIR Trains

Multiple-unit CIR trains consists of a large milling machine which is capable of milling the full lane width, a screening and crushing unit which is mounted on a separate trailer unit, and a trailer mounted pugmill mixer. The milling machine removes the RAP and has conveyer belts which move the millings to the crushing and screening unit.

The sizing and crushing of the oversized RAP is done in a separate screening/crushing unit. The screening unit has a set of vibrating screens which are stacked with larger sieve on the top. The crushed RAP from the milling machine is passed through the set of screens. The oversized pieces of the RAP are retained and put into a crushing machine for further crushing to the desired size.

The graded RAP is mixed with recycling additives in a separate pugmill unit. RAP in the pugmill is mixed uniformly. The amount of additive is calculated by computer, based on the mass of the RAP, and added to the pugmill. The mixture is then laid in a windrow and placed with conventional HMA pavers equipped with a windrow pickup attachment.

CIR mixes are compacted as the mixture begins to “break”, turning from brown to black. Compaction is usually achieved with a large sized heavy pneumatic tired rollers followed by vibrating steel drum rollers in static mode to remove roller marks [4]. In figure 2-7 a schematic of a multi-unit CIR train is shown. The different machines which form the multi-unit CIR train are shown in figures 2-8 – 2-11.

The multi-unit train provides the highest level of process control. The main advantages of the multi-unit train are high productivity and high process control. Most of the highway and interstate work is performed by multi-unit CIR trains. The major disadvantage is the length of the train which can make traffic control difficult in urban locations. Figures 2-12 and 2-13 show the working pictures of multi-unit CIR train.

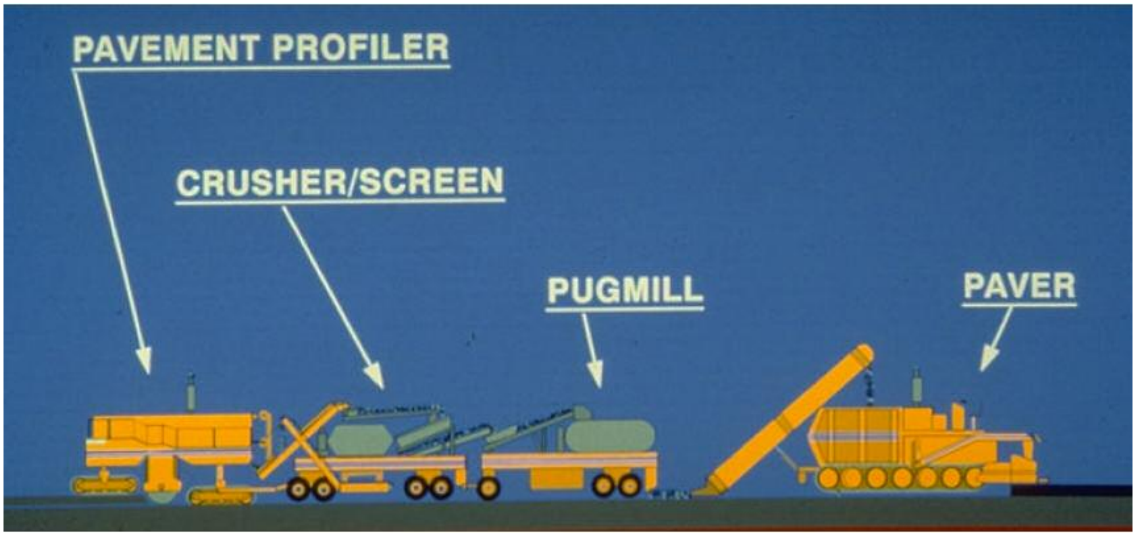

FIGURE 2-7 A Schematic of a Multi-Unit CIR Train [10].

FIGURE 2-8 Portable Crusher Attached to a Cold Milling Machine [10].

FIGURE 2-9 Cold Milling Machine [10].

FIGURE 2-10 Travel Plant Mixer [10].

FIGURE 2-11 Laydown Machine.

FIGURE 2-12 Multi-Unit CIR Train [10].

FIGURE 2-13 Multi-Unit Train Performing CIR [10].

ADDITIVES

The proper selection of additives to the reclaimed asphalt pavement plays a vital role in the proper performance of the CIR project.

Asphalt Emulsions

The most common additives for CIR are asphalt emulsions. The Asphalt Institute's *Asphalt Emulsions Manual* [11] classifies emulsions according to the charge on the droplets and their setting or breaking time. Cationic emulsions have droplets which carry a positive charge. Anionic emulsions have negatively charged droplets. Cationic emulsions have a “C” in front of the setting time anionic emulsions do not have a prefix of “C”. Emulsion classifications for setting times are rapid setting (RS) medium setting (MS), and slow setting (SS). Rapid setting (RS) emulsions are not used with the CIR process because they do not allow for adequate mixing before breaking. Medium setting (MS) asphalt emulsions are designed to mix well with open or coarse graded aggregates. They do not break on contact and remain workable for extended amount of time. High float medium setting (HFMS) asphalt emulsions are a special class of anionic medium setting asphalt emulsions. They have a gel structure in the asphalt residue which allows for thicker films on aggregate particles, giving better coating in some instances, such as under high temperatures. Slow setting (SS) asphalt emulsions work well with dense graded aggregates or aggregates with high fines content. Polymer modified versions of asphalt emulsions are used to improve early strength, resist rutting, and reduce thermal cracking.

Generally, emulsions appear as thick brown liquid when initially applied. When the asphalt cement starts to adhere to the aggregate the color changes from brown to black and the emulsion is said to have “broken”. As water begins to evaporate, the emulsion begins to behave more and more like pure asphalt cement. Once all the water has evaporated, the emulsion is said to have “set”. The time required to break and set depends on the type of emulsion, the application rate, the temperature of the surface onto which it is applied and environmental conditions [4].

Rejuvenators

Rejuvenators are occasionally used as a recycling additive in CIR. According to the ARRA manual [4], rejuvenators are products designed to restore original properties to aged asphalt cement by restoring the original ratio of asphaltenes to maltenes. Many rejuvenators are proprietary, making it difficult to offer a good generic description. However, many rejuvenators contain maltenes because their quantity is reduced by oxidation. Rejuvenators will retard the loss of surface fines and reduce the formation of additional cracks, however they will also reduce pavement skid resistance for up to one year. Because of this, they are appropriate for low volume, low speed roads or parking lots [4].

Chemical Additives

Type C fly ash, lime and Portland cement, have been successfully utilized as a recycling additive in CIR. These chemical additives can be used to improve early strength gain, increase rutting resistance, and improve moisture resistance of CIR mixtures containing rounded coarse aggregates and high percentage of natural sand. Typical hydrated lime and Portland cement contents used have been 1 to 2 percent by weight of RAP. Fly ash contents in the range of 8 to 12 percent have been reported. Type C fly ash is applied dry by spreading in front of the recycling train. Portland cement and hydrated lime can be added dry or as slurry.

Cutback Asphalts

Cutback asphalt cements have been successfully utilized in the past as a recycling agent for CIR but are not currently recommended due to environmental and safety concerns. The flash point of some cutbacks could be at or below the CIR application temperatures [4].

MIX DESIGN

Like HIR and FDR, there is no nationally accepted method for the design of cold recycling mixtures, and most of the agencies which use cold recycling use their own procedures [4]. Several agencies have developed a general design methods for CIR mixes based on modifications to hot-mix asphalt methods. Such methods can serve as a starting point for developing CIR mix design methods.

Mix Design Procedures

Recently, many mix design methods have emerged in an effort to improve the CIR process as a viable method for pavement rehabilitation. A few of the more commonly used methods are reviewed below.

AASHTO-AGC Task Force 38

They reviewed several Mix design procedures and recommended that the Marshall Mix design method for HMA be adopted for CIR with minor modifications. Samples are compacted at lower temperatures and Marshall stabilization is performed at a reduced temperature. Optimum emulsion content is EAC that meets or exceeds minimum stability required [7].

Modified Marshall and Oregon State Mix Design Methods

A cold in-placed recycled asphalt mix design approach has been adopted based on a cold Marshall and Oregon State methods, including the important role of water, on a laboratory scale. A key preliminary step in the mix design is obtaining representative RAP samples of each section and determining the properties of these samples (moisture content, asphalt cement content, gradation and Abson recovery asphalt cement penetration and viscosity) [4, 7].

Modified SuperPave Mix Design Methods

A pilot volumetric mix design using the Superpave Gyratory Compactor (SGC) was performed by Lee [12] using Kansas and Ontario RAPs. The method is based on the AASHTO-AGC-ARTBA Task Force #38 modified Marshall Mix design method [7] with some adjustments. The optimum emulsion content (OEC) can be obtained using this method. The report indicated that SuperPave procedure could be used for CIR if changes in compaction temperature were made.

Two additional studies were performed to determine compaction effort for CIR mix designs using the SGC. The first was mix design guidelines for a CIR project in the Regional Municipality of Ottawa-Carleton (RMOC) of Ontario were developed [13]. The SuperPave Gyratory Compactor (SGC) was used in that study to produce field representative specimens. Cores were obtained and evaluated to project field conditions and adjust the number of Gyrations. The N_{design} or N_{max} for the RMOC study was then determined [13].

In another study [13], the mix design compactive effort (N_{design}) that is needed to match the field density of CIR mixtures using the SGC was determined. The study included RAP from seven CIR projects along with the emulsified asphalt cement for each project. The laboratory testing protocol included testing the RAP and aggregate properties, compaction of samples, permanent deformation, and indirect tensile strength. Moreover, the N_{design} was determined to be between 30 and 35 gyrations.

SemMaterials Reflex CIR Design Method

Reflex is a new mix design protocol that includes a new emulsion formulated for cold recycling, an engineered design procedure and four performance tests for raveling, rutting resistance (strength), thermal cracking resistance, and moisture susceptibility (stripping) [15].

The Reflex system uses the Marshall Stability test for rut resistance; a retained stability test for moisture (or stripping) resistance, a raveling test, and an indirect tensile test for low-temperature cracking. Three different RAP gradations: coarse, medium, and fine are used in the design procedure and optimum asphalt emulsion content is determined by establishing the asphalt emulsion content that passes the four performance tests. The procedure also has a method to adjust asphalt emulsion contents in the field based on changes in the RAP gradation. This mix design procedure, or slight variations, has become the standard for CIR mix design [15].

WHY RECYCLING? [7, 9]

- CIR is not only an effective rehabilitation strategy to mitigate reflective cracking, but also adds structural value to the recycled pavement;
- CIR primarily uses existing asphalt-bound materials and typically recycles 2 to 4 inches in depth. Higher-quality, more uniform paving mixtures are usually produced from the CIR process;
- Cracked pavements with structurally sound, well drained bases and subgrades can be rectified;
- Distress rectified by CIR are:
    - raveling

  - pot holes
  - bleeding
  - skid resistance
  - rutting
  - corrugation
  - shoving
  - fatigue, edge and block cracking
  - slippage, longitudinal and transverse cracking
  - poor ride quality caused by swells, bumps, sags and depressions
- CIR can restore old pavements to the desired profile, rejuvenate aged pavements, correct poor aggregate gradations, eliminate existing wheel ruts, restore the crown and cross slope, and fix irregularities and rough areas;
- CIR can retain overhead clearances, vertical and horizontal geometry, and without reconstructing shoulders;
- CIR is fast, CIR crew's average about two lane miles per day;
- CIR is non-intrusive, recycling trains use the same space as other full lane paving operations, and so most roads can be kept open to traffic during the curing period without having to wait for final wearing course application;
- CIR lasts longer, states and provinces that use CIR are reporting service lives of 15 years or more for CIR base;
- CIR- high production rate and potential of cost savings;
- CIR- minimum traffic disruption;
- CIR- reduction of environmental problems;

- CIR- growing concern for depleting petroleum reserves;
- CIR- recycled pavement can be recycled.

Limitations of CIR [7, 9]

- CIR, being porous in nature, requires a seal coat or HMA overlay;
- CIR is susceptible to rutting caused by high asphalt content;
- CIR is susceptible to failure caused by wet, unstable base, subbase or subgrade;
- CIR is susceptible to failure caused by heaving or swelling occurring in underlying soils;
- Pavements that exhibit stripping of asphalt from aggregates are not good CIR candidates;
- The minimum asphalt pavement thickness to be removed should be 2 inches;
- Addition of new aggregate to RAP to obtain the minimum treatment depth should not exceed 25 percent by weight of the RAP. Otherwise, a significant increase in the emulsion content thus higher associated cost will occur;
- Weather Limitations - CIR cannot be applied if there is a possibility of the temperature falling below freezing within 24 hours;
- Site conditions that limit the effectiveness of CIR are;
    - the presence of several manholes or drainage inlets within the pavement area;
    - long steep grades or those exceeding 5 percent and 2500 feet in length will reduce production and may require extended traffic control;
    - extensive heavily shaded areas where little or no sunlight reaches then the section will require longer curing time.

MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE (M-EPDG)

Need for the Design Guide

The various editions of the *AASHTO Guide for Design of Pavement Structures* have served well for several decades; nevertheless, many serious limitations exist for their continued use as the nation's primary pavement design procedures. Listed below are some of the major deficiencies of the existing design guide [1]:

- Traffic loading deficiencies
- Rehabilitation deficiencies.
- Climatic effects deficiencies
- Subgrade deficiencies
- Surface materials deficiencies
- Base course deficiencies
- Truck characterization deficiencies
- Construction and drainage deficiencies
- Design life deficiencies
- Performance deficiencies
- Reliability deficiencies

M-EPDG

The guide for the Mechanistic-Empirical Design of New and Rehabilitated pavement Structures (referred to hereinafter as M-EPDG) was developed to provide the highway community with the a state-of-the-practice tool for design of new and rehabilitated pavement structures. The M-EPDG is a result of a large study sponsored by the AASHTO in cooperation with the Federal Highway Administration and was conducted through the National Cooperative Highway Research Program (NCHRP) [NCHRP-1-37A]. The final product is design software and a user guide. The M-EPDG is based on a comprehensive pavement design procedures that uses existing mechanistic-empirical technologies. M-EPDG software is temporarily available on the web for trial use which can be downloaded from www.trb.org/mepdg. It is a user oriented computational software package and contains documentation based on the Design Guide procedure. The Guide employs common design parameters for traffic, subgrade, environment, and reliability for all pavement types [1].

CHAPTER 3

MATERIALS AND TESTING PLAN

INTRODUCTION

The objective of the study was to determine the dynamic modulus of CIR mixes and compare the laboratory values with the default values in the M-EPDG. In this project one RAP and three emulsions were used. In this project one RAP was mixed with three emulsions and the dynamic modulus obtained. The dynamic modulus values were compared based on emulsion type to determine if emulsion had a significant effect on dynamic modulus. The values were also compared to the default values calculated from mix parameters by the M-EPDG. Finally, the effect of the emulsion type on pavement performance was evaluated using the M-EPDG.

MATERIALS

RAP

RAP was obtained from a CIR project on US-412 in the Beaver County, OK. The pavement was being rehabilitated to correct transverse cracking. During the construction of the CIR on the western portion of US-412, samples of RAP were obtained prior to the addition of any recycling agent.

Asphalt Emulsion

Three asphalt emulsions were used in the research project, the asphalt emulsion from the US 412 project and two other asphalt emulsions. The emulsion from the job site was a specially formulated CSS-1 emulsion (Reflex) supplied by SemMaterials. The other two emulsions were a cationic slow set (CSS-1h); CSS-1h with lime, which is often used with CSS-1 h and a polymer, modified high float emulsion (HFE-150P). The emulsions were provided by Vance Brothers and the New Mexico Department of Transportation (NMDOT), respectively.

Lime

Pebble quicklime was obtained from Brown and Brown Contractors Inc. The quicklime was added to the mixtures in the form of slaked lime slurry. Lime is added to the CIR to give initial stiffness and prevent the structure from moisture damage. In practice, lime is routinely used with CSS-1h emulsions.

TEST PLAN

RAP Properties

The as received gradation of the RAP was determined in accordance with AASHTO T 27. Two, 2000 gram RAP samples, batched to the as received gradation, were tested to obtain the asphalt content using an extraction furnace in accordance with ODOT Test Method OHD L – 26. The recovered aggregate was tested for gradation in accordance with AASHTO T 30. The results are shown in Table 3-1 and presented graphically in Figure 3-1.

RAP was batched to the as received gradation to obtain two samples of 2000 grams each. The 2000 gram samples were mixed with reflex emulsion to the emulsion content reported on the US 412 project. The mixed samples were cured and tested for theoretical maximum specific gravity (G_{mm}) in accordance with AASHTO T 209. The average of the two results was used further calculations. The average G_{mm} for the RAP was 2.406.

The RAP contained 6.82% asphalt cement by weight of the total mix. The RAP contained 61% coarse aggregate, retained on the 4.75-mm sieve and 90% was retained on the 0.600-mm sieve. Other physical property tests cannot be run on the extracted aggregate because the numbers obtained are not considered accurate.

TABLE 3-1 Gradation of RAP and Recovered Aggregate from US-412

	RAP "As Received"	Recovered Aggregate
Sieve Size	Percent Passing	
1”	100	100
3/4 “	97	100
1/2 “	80	98
3/8 “	66	94
No.4	39	76
No.8	25	63
No.16	17	52
No.30	10	39
No.50	5	27
No.100	2	16
No.200	0.7	10.4

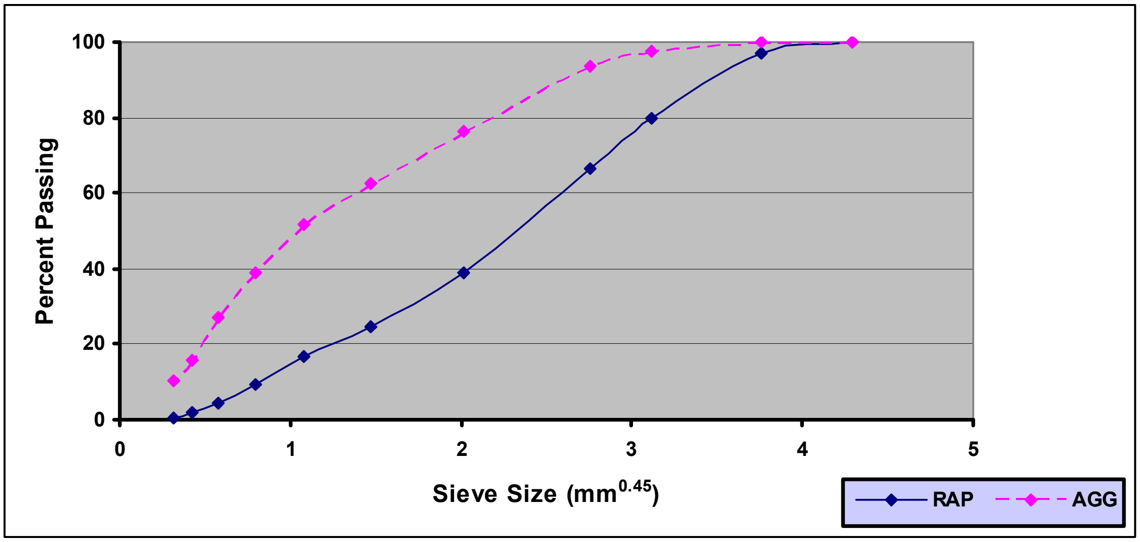

FIGURE 3-1 Gradation of RAP and Recovered Aggregate.

Emulsion Properties

The residual asphalt cement content of Reflex and CSS-1h emulsions was obtained from the supplier. The residual asphalt content of HFE – 150P was determined by using Colorado Department of Transportation quick procedure [16]. The residual asphalt cement content of the emulsions is shown in Table 3-2.

TABLE 3-2 Residual Asphalt Cement Content in Emulsions

Emulsion	Residual AC, %
Reflex	65
CSS - 1h	55
HFE - 150P	72

Hydrated Lime Slurry

To prepare one liter of hydrated lime slurry from quicklime, 277.4 grams of CaO is mixed with 924.6 grams of water. The solids content of the slurry will be between 30%

and 35% depending on the amount of water lost to evaporation during the slaking process.

Preparation of Dynamic Modulus Test Specimen

The samples were prepared according AASHTO TP-62 [2]. The samples tested with different emulsions, and number of replicates are listed in the test matrix shown in table 3-3.

TABLE 3-3 Test Specimen Matrix

Emulsion	Number of Specimen
Reflex	2
CSS - 1h	2
CSS - 1h + Lime	2
HFE - 150P	2

Sample Requirements

AASHTO TP-62 requirements for a dynamic modulus sample are given in table 3-4. Dynamic modulus testing requires a 150 mm high and 100 mm diameter sample of a target air void content to be cored from 175 mm high and 150 mm diameter sample. There is no simple conversion factor for compaction of a 175 mm high, 150 mm diameter SuperPave sample to a cored dynamic modulus (E*) sample with target air void content. They will not have the same VTM. A trial and error procedure is required.

Recommended target void contents for HMA samples are 4-7%. CIR samples can not be treated like HMA samples because of the viscosity and cold temperature of the mixture. In this project, the CIR test samples were compacted to the field unit weight reported by ODOT. This worked out to be a void content of 12 ± 1 % VTM. After several trials it was determined that a 175 mm high and 150 mm diameter sample compacted to 15 ± 1% VTM would yield a dynamic modulus test sample of the target 12 ± 1% void content.

TABLE 3-4 Criteria for Acceptance of Dynamic Modulus Test Specimen

Criterion Items	Requirements
Size	Average diameter between 100 mm and 104 mm Average height between 147.5 mm and 152.5 mm
Gyratory Specimens	Prepare 175 mm high specimens to required air void content (AASHTO T312)
Coring	Core the nominal 100 mm diameter test specimens from the centre of the gyratory specimen. Check the test specimen is cylindrical with sides that are smooth parallel and free from steps, ridges and grooves
Diameter	The standard deviation should not be greater than 2.5 mm
End Preparation	The specimen ends shall have a cut surface waviness height within a tolerance of ± 0.05 mm across diameter The specimen end shall not depart from perpendicular to the axis of the specimen by more than 1 degree
Air Void Content	The test specimen should be within ± 1.0 percent of the target air voids
Replicates	3 LVDT's used number of replicates 2 with a estimated limit of accuracy of 13.1 percent
Sample Storage	Wrap specimens in polyethylene and store in environmentally protected storage between 5 and 26.7° C (40 and 80° F) and be stored no more than two weeks prior to testing

Batching

A 6112.9 gram batch of RAP, batched to the as received gradation was used to prepare a 175 mm high and 150 mm in diameter test specimen. When the compacted sample was cored to 100 mm diameter and sawed to sample height of 150 mm, the required target void content was obtained.

Emulsion Content

The Reflex emulsion and mix water content on US-412, as reported by ODOT, was 3.0% and 2.0%, respectively for a total liquids content of 5.0%. In the lab, the RAP was mixed to this EAC and mix water content. The emulsion content for the CSS–1h and HFE–150P emulsions were determined by keeping the residual asphalt contents the same as the Reflex samples and adjusting the mix water to maintain 5 % total liquids. The percentage of mix water and emulsion required is shown in Table 3-5. Lime slurry is added at 3.3% to result in 1% hydrated lime being added to the mix for the CSS-1h + Lime samples. The mix water was replaced with the 3.3% lime slurry.

TABLE 3-5 Percentages of Water and Emulsions Based on Dry Weight of RAP

	Reflex	CSS - 1h	HFE – 150P
Residual AC %	65	55	72
EAC %	3.00	3.55	2.71
Water %	2.00	1.45	2.29
Total Liquids %	5.00	5.00	5.00

Mixing

The Kansas/ SemMaterials procedure for making CIR samples was followed [17]. The emulsion was stirred and then heated to 54°C for 30 minutes before mixing. All samples were mixed for 2.5 minutes using a mechanical mixer. For mixing, half of the mix water was added to the RAP and mixed for a 1 minute. The remainder of the mix water and the asphalt emulsion was then added and the sample mixed for additional 1.5 minutes. Lime samples were mixed in the same manner except that all of the lime slurry was added and mixed for 1 minute then the EAC was added and mixed for 1.5 minute.

Compaction

The samples were compacted in a 150 mm diameter mold to a height of 175 mm using a Pine gyratory compactor. 6112.9 grams of RAP were required to obtain a sample which was 175 mm high and 150 mm in diameter with a void content of 15 ± 1 %. The compacted samples were then cored and sawed to 150 mm high and 100 mm in diameter which resulted in the target void content of 12 ±1%. The required amount of RAP was more than would fit into the compaction mold. Therefore, it was necessary to lightly tamp down the material with a tapping rod to get the mixture into the mold. Thirty to forty gyrations were typically required to reach a height of 175 mm.

Curing

The samples were extruded immediately after compaction, labeled and placed in a pan. The samples were placed in an oven at 60°C for a minimum of 48 hours. After 1 to 2 hours of curing, the paper discs on the top and bottom of the sample were removed. After 48 hours, the samples were checked every 2 hours until the mass loss was less than 0.05%, up to a maximum of 72 hours of oven curing [17].

Coring & Sawing

After curing, the samples were allowed to cool to room temperature. Next the compacted samples were cored and sawed to obtain a test specimen of 150 mm tall and 100 mm in diameter with 12 ± 1 % voids. The samples were cored using a coring machine to obtain a diameter of 100 mm, as shown in Figure 3-2. The cored samples were sawed to obtain a height of 150 mm, as shown in Figure 3-3. The cored and sawed samples were washed to eliminate all loose debris. After cleaning, the samples were tested to get the submerged and surface saturated mass according to AASHTO T 166. The dry mass was determined by placing the samples at room temperature under a fan over night and allowed to dry to constant mass and the void content was determined.

The dried samples were then checked to the sample requirements of AASHTO TP 62. The criterion for acceptance of the samples is listed in the Table 3-4. Samples which met all criteria were fixed with six steel studs to hold three LVDT's. The LVDT's had a gauge length of 4 inches. Care was taken to precisely position the studs at 4 inches apart from each other and 2 inches from the centre of the sample. Once the epoxy was dry and the studs were firmly attached to the sample, they were ready for testing. Figure 3-4 shows a sample prepared for dynamic modulus testing.

FIGURE 3-2 Sample Being Cored to Required Test Diameter.

FIGURE 3-3 Sample is Sawed to Obtain Parallel Faces.

FIGURE 3-4 Test Specimens for Dynamic Modulus Testing.

Testing

The test specimens were tested for dynamic modulus according to AASHTO TP-62. The procedure is briefly explained in Figure 3-5. The test parameters are given in table 3-6.

The samples could not be tested at -10° C (14°F) due to accumulation of frost in the test chamber. When warm moist air is cooled, moisture collects on the metal surfaces of the test chamber and the test specimen. At -10° C (14°F) the moisture froze and the position of the test specimen shifted under load laterally and eventually fell off the loading plate. The M-EPDG does not require the dynamic modulus at -10°C (14°F) and it is no longer performed even though it is still listed in AASHTO TP-62. The M-EPDG basically requires dynamic modulus at three temperatures to run the analysis with Level 1 inputs, (i) one less than 45°F, (ii) one in-between 45°F - 125°F and (iii) one greater than 125°F [1].

At the high test temperature, 54.4°C (130°F) problems were encountered with repeatability and several test samples were damaged. The problem was due to insufficient sensitivity of the load cell in the test machine at low loads. It was later corrected by the purchase of a smaller load cell. Samples could not be retested due to the limited quantity of RAP available.

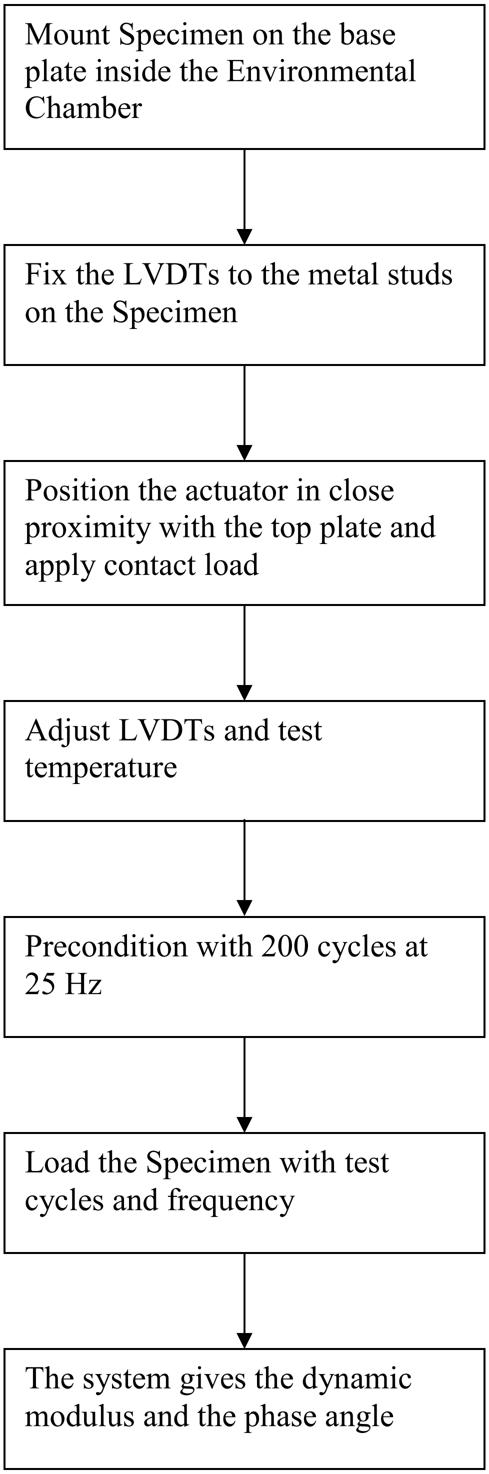

FIGURE 3-5 Test Procedure for Dynamic Modulus of CIR Samples.

TABLE 3-6 Test Parameters for Dynamic Modulus Test [2]

Test Parameters	Values		
Frequencies	25, 10, 5, 1, 0.5, 0.1 Hz		
Temperature	4.4°, 21.1°, 37.8° and 54.4°C (40°, 70°, 100° and 130° F)		
Equilibrium Times	Specimen Temperature,°C (°F)	Time from room temperature, hrs 25°C (77°F)	Time from previous test temperature, hrs
	4.4 (40)	overnight	4 hrs or overnight
	21.1 (70)	1	3
	37.8 (100)	2	2
	54.4 (130)	3	1
Contact Load	5 percent of the test load		
Axial Strains	Between 50 to 150 microstrain		
Dynamic load range	Depends on the specimen stiffness and ranges between 2 and 400 psi		
Load at Test Frequency *	At 4.4° C (40° F): 100 to 200 psi		
	At 21.1° C (70° F): 50 to 100 psi		
	At 37.8° C (100° F): 20 to 50 psi		
	At 54.4° C (130° F): 5 to 10 psi		
Preconditioning	With 200 cycles at 25Hz		
Cycles	At 25Hz: 200 cycles		
	At 10Hz: 200 cycles		
	At 5Hz: 100 cycles		
	At 1Hz: 20 cycles		
	At 0.5Hz: 15 cycles		
	At 0.1Hz: 15 cycles		

* The load should be adjusted to obtain axial strains between 50 and 150 microstrains.

CHAPTER 4

TEST RESULTS

DYNAMIC MODULUS TESTING RESULTS

The main objective of this project was to obtain typical dynamic modulus values for CIR mixture for use in the M-EPDG. RAP and emulsion were obtained from a CIR project on the western portion of US 412, Beaver Co. OK. Two additional emulsions and quick lime were obtained. Test samples were prepared using the RAP from US-412 and four different combinations of the emulsions and lime. Table 4-1 shows the combinations and the number of replicates prepared for testing. The test samples were prepared and tested in accordance with AASHTO TP-62. The dynamic modulus of each sample was obtained and the effect of emulsion on dynamic modulus evaluated. The measured dynamic modulus values were compared to the default values in M-EPDG. Finally, the effect of different emulsions on pavement thickness was evaluated using the M-EPDG. Results from the dynamic modulus testing are provided in Tables 4-2 to 4-5.

As mentioned in chapter 3 the samples were not tested at -10°C (14°F) due to the heavy accumulation of frost in the test chamber. The M-EPDG does not require the dynamic modulus at this temperature. For samples at the high test temperature, 54.4°C (130°F), problems were encountered with repeatability due to the sensitivity of the load cell and several test samples were damaged. A new load cell was purchased to correct the problem. However, only the samples prepared using HFE-150P emulsion were tested with the new load cell.

TABLE 4-1 Matrix of Samples Tested

Emulsion	Number of Specimen
Reflex	2
CSS - 1h	2
CSS - 1h + Lime	2
HFE - 150P	2

TABLE 4-2 Dynamic Modulus for Samples Prepared with Reflex Emulsion

Temperature (°C)	Frequency (Hz)	Dynamic Modulus (psi)		
		Sample 1	Sample 2	Average
4.4	25	863,500	907,981	885,741
	10	793,072	868,540	830,806
	5	719,848	790,864	755,356
	1	549,311	611,389	580,350
	0.5	494,693	550,399	522,546
	0.1	378,596	418,034	398,315
21.1	25	468,193	467,638	467,915
	10	404,601	392,505	398,553
	5	335,638	327,665	331,651
	1	222,871	212,830	217,850
	0.5	187,392	177,024	182,208
	0.1	129,229	124,899	127,064
37.8	25	209,876	240,229	225,052
	10	147,115	148,995	148,055
	5	116,352	111,739	114,046
	1	70,777	78,173	74,475
	0.5	45,131	59,926	52,528

TABLE 4-3 Dynamic Modulus for Samples Prepared with CSS – 1h

Temperature (°C)	Frequency (Hz)	Dynamic Modulus (psi)		
		Sample 1	Sample 2	Average
4.4	25	957,585	1,065,514	1,011,549
	10	877,498	1,023,436	950,467
	5	801,942	917,607	859,774
	1	627,014	715,094	671,054
	0.5	563,247	641,563	602,405
	0.1	436,626	494,033	465,329
21.1	25	547,109	766,988	657,049
	10	458,460	611,676	535,068
	5	386,915	496,709	441,812
	1	250,693	318,907	284,800
	0.5	203,647	253,565	228,606
	0.1	133,546	167,652	150,599
37.8	25	308,067	256,034	282,050
	10	185,093	168,303	176,698
	5	140,080	130,248	135,164
	1	84,859	81,665	83,262
	0.5	66,527	66,517	66,522

TABLE 4-4 Dynamic Modulus for Samples Prepared with CSS – 1h + Lime

Temperature (°C)	Frequency (Hz)	Dynamic Modulus (psi)		
		Sample 1	Sample 2	Average
4.4	25	1,341,448	1,462,943	1,402,196
	10	1,298,784	1,363,747	1,331,266
	5	1,216,269	1,278,824	1,247,547
	1	1,016,050	1,076,058	1,046,054
	0.5	940,586	1,002,879	971,732
	0.1	761,391	816,113	788,752
21.1	25	788,497	954,739	871,618
	10	742,074	871,825	806,949
	5	648,761	762,499	705,630
	1	457,786	554,572	506,179
	0.5	400,590	476,392	438,491
	0.1	296,027	332,223	314,125
37.8	25	657,462	473,953	565,708
	10	364,400	328,642	346,521
	5	274,119	276,368	275,243
	1	170,400	178,529	174,464
	0.5	143,043	146,876	144,960
	0.1	96,228	96,163	96,195

TABLE 4-5 Dynamic Modulus for Samples prepared with HFE – 150P

Temperature (°C)	Frequency (Hz)	Dynamic Modulus (psi)		
		Sample 1	Sample 2	Average
4.4	25	1,373,061	1,029,089	1201075
	10	1,298,416	965,219	1131817
	5	1,169,526	896,088	1032807
	1	919,560	717,806	818683
	0.5	833,857	652,000	742929
	0.1	648,841	513,803	581322
21.1	25	595,883	557,936	576910
	10	492,334	466,930	479632
	5	424,817	390,146	407481
	1	284,121	255,358	269739
	0.5	243,267	218,099	230683
	0.1	176,855	163,468	170161
37.8	25	251,286	224,751	238018
	10	206,213	188,768	197490
	5	173,096	155,597	164346
	1	117,213	99,409	108311
	0.5	98,498	84,583	91540
	0.1	66,157	60,055	63106
54.4	25	110,558	84,378	97468
	10	100,189	69,632	84910
	5	73,385	56,095	64740
	1	39,864	34,734	37299
	0.5	36,090	30,443	33267
	0.1	25,413	22,609	24011

Volumetric Properties

The volumetric and mix design properties from test samples tested in the project are listed in table 4-6. These values are used to determine the predicted dynamic modulus values using Witczak's equation [1] which is explained in chapter 5.

To use Witczak's predictive equation, the following mix properties are required; gradation of the mix, void properties, and effective volume of the binder. These mix properties are all easily available for HMA, however, for CIR mixes several assumptions must be made. With HMA, the properties of the asphalt and aggregate are easily determined. With CIR the aggregate is coated with old, aged asphalt. New asphalt is added and partial blending occurs, making determination of aggregate and asphalt properties problematic.

Most researchers model CIR mixtures as a black rock where aggregate properties are properties of RAP and asphalt properties are of new asphalt. This was our approach; therefore, all gradation parameters were of the RAP and asphalt properties were of the new asphalt in the emulsion. Effective specific gravity (G_{se}) of RAP was obtained by AASHTO T-209 using the new asphalt in the emulsion. Specific gravity of base binder (G_b) in the emulsion is difficult to obtain due to the blending. Therefore G_b of 1.020 was assumed. Bulk specific gravity (G_{sb}) of RAP, which is problematic to determine, was obtained by assuming RAP has no absorption, so G_{sb} is equal to G_{se} of RAP. The specific gravity of the RAP and binder were required to determine the volumetric properties of the samples, which were used in the Witczak's equation to determine the predicted dynamic modulus.

TABLE 4-6 Volumetric and Mix Design Properties

Emulsion	Reflex		CSS-1h		CSS-1h+Lime		HFE-150P	
Sample ID	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Pb (%)	1.95	1.95	1.95	1.95	1.95	1.95	1.95	1.95
P200 (%)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
G_{mm}	2.406	2.406	2.406	2.406	2.406	2.406	2.406	2.406
G_{sb}	2.473	2.473	2.473	2.473	2.473	2.473	2.473	2.473
G_b	1.020	1.020	1.020	1.020	1.020	1.020	1.020	1.020
G_{mb}	2.114	2.134	2.114	2.117	2.142	2.146	2.130	2.134
V_{beff} (%)	4.05	4.09	4.05	4.05	4.10	4.11	4.08	4.09
VTM (%)	12.1	11.3	12.1	12.0	11.0	10.8	11.5	11.3

CHAPTER 5

ANALYSIS OF EXPERIMENTAL AND PREDICTED RESULTS

This chapter provides the analysis of the experimental data. The analysis was performed to determine the effect of emulsion type on dynamic modulus of the mixture. Experimentally determined dynamic modulus values were compared to values determined using Witczak's predictive equation used in the M-EPDG. Lastly, the impact on the pavement thickness of any statistical difference found in dynamic modulus was evaluated using the M-EPDG.

ANALYSIS OF VARIANCE (ANOVA)

Temperature and frequency have a significant effect on dynamic modulus of bituminous mixtures. AASHTO TP-62 requires testing at different frequencies and temperatures. A review of the test data indicated that frequency had a consistent effect on dynamic modulus showing an increase in dynamic modulus with an increase in frequency. Therefore, an ANOVA was performed to determine if there is a statistical difference in dynamic modulus between EAC and temperature by using a single frequency. The middle frequency (5Hz) was selected since all the frequencies showed a similar trend.

The results, shown in table 5-1 indicate that dynamic modulus values for CIR between EAC and temperature were significantly different. The interaction of EAC*Temp was not significant at a confidence limit of 95% ($\alpha = 0.05$) but was significant at 93% ($\alpha = 0.07$). Because there was a slight interaction, the effect of EAC on dynamic modulus was evaluated by temperature. Table 5-2 shows results from

Duncan's multiple range test at 4.4° C (40°F) test temperature. Means with the same letter not significantly different at a confidence limit of 95% (alpha = 0.05). No statistical difference exists between CSS-1h + Lime and HFE-150P, and HFE-150P, CSS-1h and Reflex for dynamic modulus at 4.4°C (40°F) test temperature. A statistical difference exists between CSS-1h + Lime and CSS-1h, Reflex.

TABLE 5-1 ANOVA for CIR Dynamic Modulus

Source	Degrees Freedom	Sum Squares	Mean Square	F Ratio	Prob. > F
EAC	3	386324703952	128774901317	24.97	<.0001
Temp	2	2.6255345E12	1.3127673E12	254.52	<.0001
EAC * Temp	6	81527140720	13587856787	2.63	0.0723
Error	12	61894527698	5157877308.1		
Total	23	3.1552809E12			

TABLE 5-2 Results of Duncan's Multiple Range Test for CIR Dynamic Modulus at 4.4°C (40°F) Test Temperature

Grouping *	Mean Dynamic Modulus	N	EAC
A	1247547	2	CSS-1h + Lime
A & B	1032807	2	HFE-150P
B	859775	2	CSS-1h
B	755356	2	Reflex

* Means with the same letter not significantly different

Table 5-3 shows results from Duncan's multiple range test at 21.1° C (70°F) test temperature. No statistical difference exists between CSS-1h, HFE-150P and Reflex for dynamic modulus at 21.1°C (70°F) test temperature. A statistical difference exists between CSS-1h + Lime and the other 3 emulsions.

TABLE 5-3 Results of Duncan's Multiple Range Test for CIR Dynamic Modulus at 21.1°C (70°F) Test Temperature

Grouping *	Mean Dynamic Modulus	N	EAC
A	705630	2	CSS-1h + Lime
B	441812	2	HFE-150P
B	407482	2	CSS-1h
B	331652	2	Reflex

* Means with the same letter not significantly different

Table 5-4 shows results from Duncan's multiple range test at 37.8° C (100°F). A statistical difference exists between all the EAC tested at 37.8°C (100°F) test temperature.

TABLE 5-4 Results of Duncan's Multiple Range Test for CIR Dynamic Modulus at 37.8°C (100°F) Test Temperature

Grouping *	Mean Dynamic Modulus	N	EAC
A	275244	2	CSS-1h + Lime
B	164347	2	HFE-150P
C	135164	2	CSS-1h
D	114046	2	Reflex

* Means with the same letter not significantly different

The ANOVA indicates the emulsion type has a significant effect on dynamic modulus. Therefore, when using the M-EPDG emulsion type could result in different pavement performance.

MASTER CURVES

According to the user manual of the new M-E PDG [1], the stiffness of HMA at all levels of temperature and time rate of load, is determined from a master curve constructed at a reference temperature (generally taken as 70°F). Master curves are constructed using the principle of time-temperature superposition. The data at various temperatures are shifted with respect to time until the curves merge into a single smooth function. The master curve of the modulus, as a function of time, formed in this manner describes the time dependency of the material. The amount of shifting at each temperature required to form the master curve describes the temperature dependency of the material. In general, the master modulus curve can be mathematically modeled by a sigmoidal function described as:

$$Log\left|E^*\right| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log t_r)}} \tag{1}$$

Where,

t_r = reduced time of loading at reference temperature

δ = minimum value of E*

$\delta + \alpha$ = maximum value of E*

β, γ = parameters describing the shape of the sigmoidal function

The shift factor can be shown in the following form:

$$a(T) = \frac{t}{t_r} \tag{2}$$

Where,

a (T) = shift factor as a function of temperature

t = time of loading at desired temperature

t_r = reduced time of loading at reference temperature

T = temperature of interest

For precision, a second order polynomial relationship between the logarithm of the shift factor i.e. log a (Ti) and the temperature in degrees Fahrenheit is used. The relationship can be expressed as follows:

$$Loga(T_i) = aT_i2 + bT_i + c \qquad (3)$$

Where,

a (Ti) = shift factor as a function of temperature Ti
Ti = temperature of interest, °F
a, b and c = coefficients of the second order polynomial

Extrapolated results for E* at 54.4°C (130°F)

The data which was available at various temperatures were shifted with respect to time until the curves merged into a single sigmoidal function representing the master curve using a second order polynomial relationship between the logarithm of the shift factors, log a (T_i) and the temperature. The time-temperature superposition was done by simultaneously solving for the four coefficients of the sigmoidal function (δ, α, β, and γ) as described in equation (1) and the three coefficients of the second order polynomial (a, b, and c) as described in equation (3). The “Solver” function of Microsoft™ Excel was used to conduct the nonlinear optimization for simultaneously solving these seven parameters. Nam Tran at the University of Arkansas [18] developed the program used to produce the master curves.

The dynamic modulus of the CIR samples at 54.4°C (130°F) test temperature could not be tested due to the unavailability of the smaller load cell. However, to perform a level 1 analysis, the M-EPDG needs the dynamic modulus of the samples at 54.4° C

(130°F). The dynamic modulus data for 54.4° C (130°F) was obtained by extrapolating the master curve using the coefficients delta, alpha, beta and gamma, determined from the master curves developed for the three available test temperatures. Tables 5-5 – 5-8 show the extrapolated dynamic modulus values for 54.4°C (130°F) test temperature and figures 5-1 – 5-4 show the complete master curves.

TABLE 5-5 Dynamic Modulus for Samples Prepared with Reflex Emulsion

Temperature (°C)	Frequency (Hz)	Dynamic Modulus (psi)		
		Sample 1	Sample 2	Average
4.4	25	863,500	907,981	885,741
	10	793,072	868,540	830,806
	5	719,848	790,864	755,356
	1	549,311	611,389	580,350
	0.5	494,693	550,399	522,546
	0.1	378,596	418,034	398,315
21.1	25	468,193	467,638	467,915
	10	404,601	392,505	398,553
	5	335,638	327,665	331,651
	1	222,871	212,830	217,850
	0.5	187,392	177,024	182,208
	0.1	129,229	124,899	127,064
37.8	25	209,876	240,229	225,052
	10	147,115	148,995	148,055
	5	116,352	111,739	114,046
	1	70,777	78,173	74,475
	0.5	45,131	59,926	52,528
	0.1			27,456*
54.4	25			56,499*
	10			38,492*
	5			30,845*
	1			15,344*
	0.5			10,343*
	0.1			5,783*

* Extrapolated data from fitting the master curve due to unavailability of smaller load cell

TABLE 5-6 Dynamic Modulus for Samples Prepared with CSS – 1h

Temperature (°C)	Frequency (Hz)	Dynamic Modulus (psi)		
		Sample 1	Sample 2	Average
4.4	25	957,585	1,065,514	1,011,549
	10	877,498	1,023,436	950,467
	5	801,942	917,607	859,774
	1	627,014	715,094	671,054
	0.5	563,247	641,563	602,405
	0.1	436,626	494,033	465,329
21.1	25	547,109	766,988	657,049
	10	458,460	611,676	535,068
	5	386,915	496,709	441,812
	1	250,693	318,907	284,800
	0.5	203,647	253,565	228,606
	0.1	133,546	167,652	150,599
37.8	25	308,067	256,034	282,050
	10	185,093	168,303	176,698
	5	140,080	130,248	135,164
	1	84,859	81,665	83,262
	0.5	66,527	66,517	66,522
	0.1			42,343*
54.4	25			71,000*
	10			53,078*
	5			44,000*
	1			29,087*
	0.5			25,867*
	0.1			19,878*

* Extrapolated data from fitting the master curve due to unavailability of smaller load cell

TABLE 5-7 Dynamic Modulus for Samples Prepared with CSS – 1h + Lime

Temperature (°C)	Frequency (Hz)	Dynamic Modulus (psi)		
		Sample 1	Sample 2	Average
4.4	25	1,341,448	1,462,943	1,402,196
	10	1,298,784	1,363,747	1,331,266
	5	1,216,269	1,278,824	1,247,547
	1	1,016,050	1,076,058	1,046,054
	0.5	940,586	1,002,879	971,732
	0.1	761,391	816,113	788,752
21.1	25	788,497	954,739	871,618
	10	742,074	871,825	806,949
	5	648,761	762,499	705,630
	1	457,786	554,572	506,179
	0.5	400,590	476,392	438,491
	0.1	296,027	332,223	314,125
37.8	25	657,462	473,953	565,708
	10	364,400	328,642	346,521
	5	274,119	276,368	275,243
	1	170,400	178,529	174,464
	0.5	143,043	146,876	144,960
	0.1	96,228	96,163	96,195
54.4	25			157,897*
	10			123,876*
	5			97,865*
	1			60,864*
	0.5			54,765*
	0.1			35,876*

* Extrapolated data from fitting the master curve due to unavailability of smaller load cell

TABLE 5-8 Dynamic Modulus for Samples Prepared with HFE – 150P

Temperature (°C)	Frequency (Hz)	Dynamic Modulus (psi)		
		Sample 1	Sample 2	Average
4.4	25	1,373,061	1,029,089	1201075
	10	1,298,416	965,219	1131817
	5	1,169,526	896,088	1032807
	1	919,560	717,806	818683
	0.5	833,857	652,000	742929
	0.1	648,841	513,803	581322
21.1	25	595,883	557,936	576910
	10	492,334	466,930	479632
	5	424,817	390,146	407481
	1	284,121	255,358	269739
	0.5	243,267	218,099	230683
	0.1	176,855	163,468	170161
37.8	25	251,286	224,751	238018
	10	206,213	188,768	197490
	5	173,096	155,597	164346
	1	117,213	99,409	108311
	0.5	98,498	84,583	91540
	0.1	66,157	60,055	63106
54.4	25	110,558	84,378	97468
	10	100,189	69,632	84910
	5	73,385	56,095	64740
	1	39,864	34,734	37299
	0.5	36,090	30,443	33267
	0.1	25,413	22,609	24011

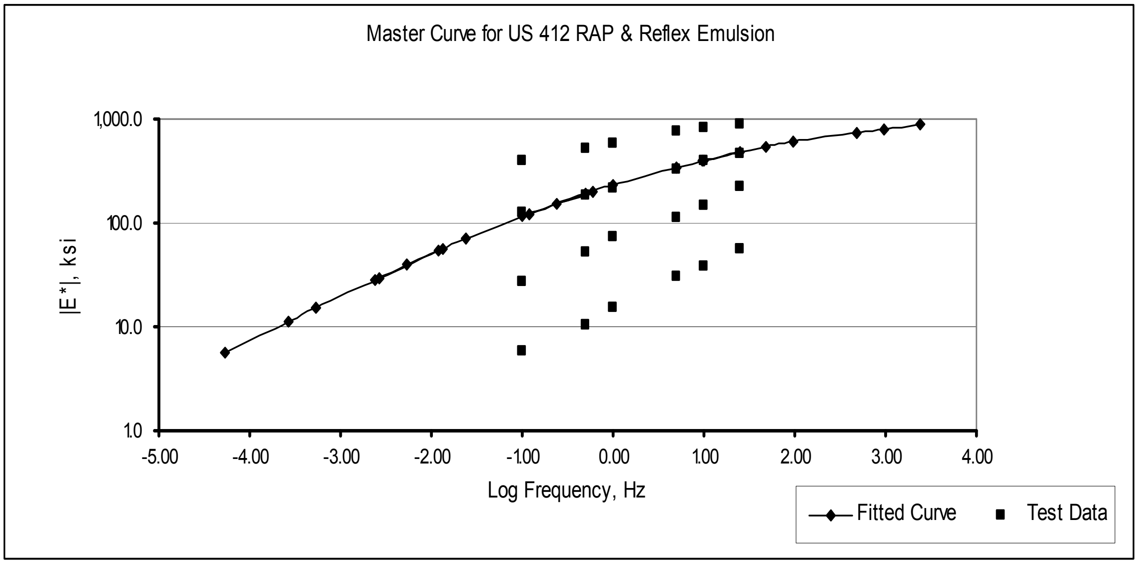

FIGURE 5-1 Master Curve for US-412 and Reflex.

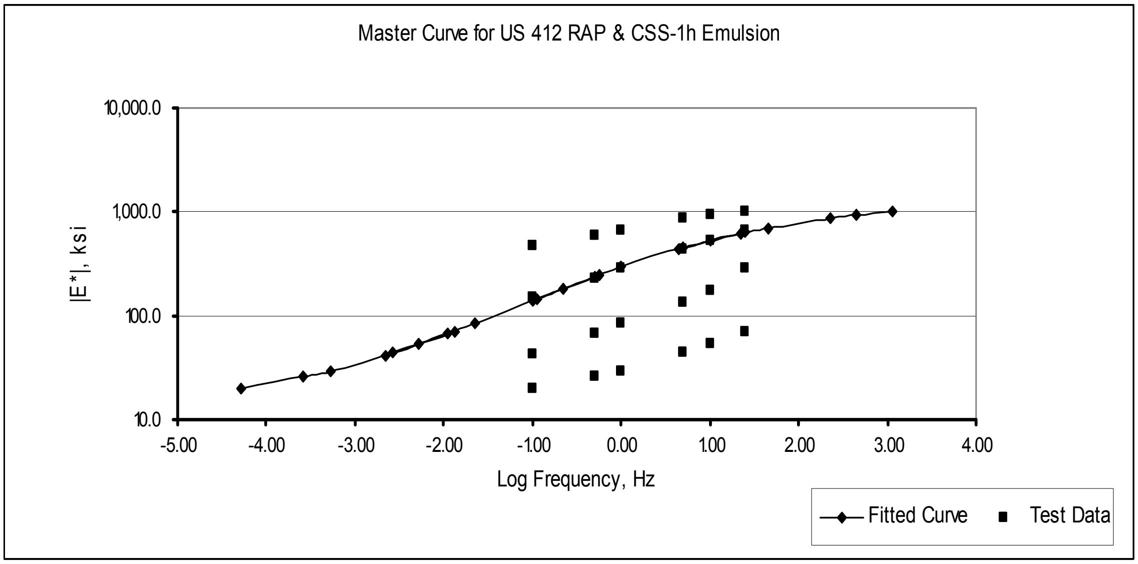

FIGURE 5-2 Master Curve for US-412 RAP and CSS-1h Emulsion.

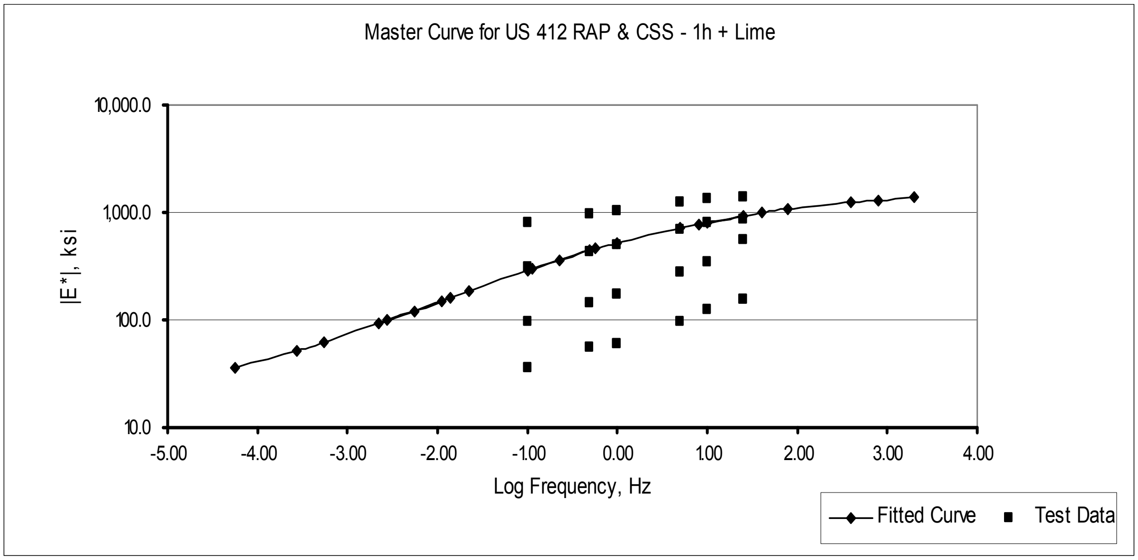

FIGURE 5-3 Master Curve for US-412 RAP and CSS-1h+Lime Emulsion.

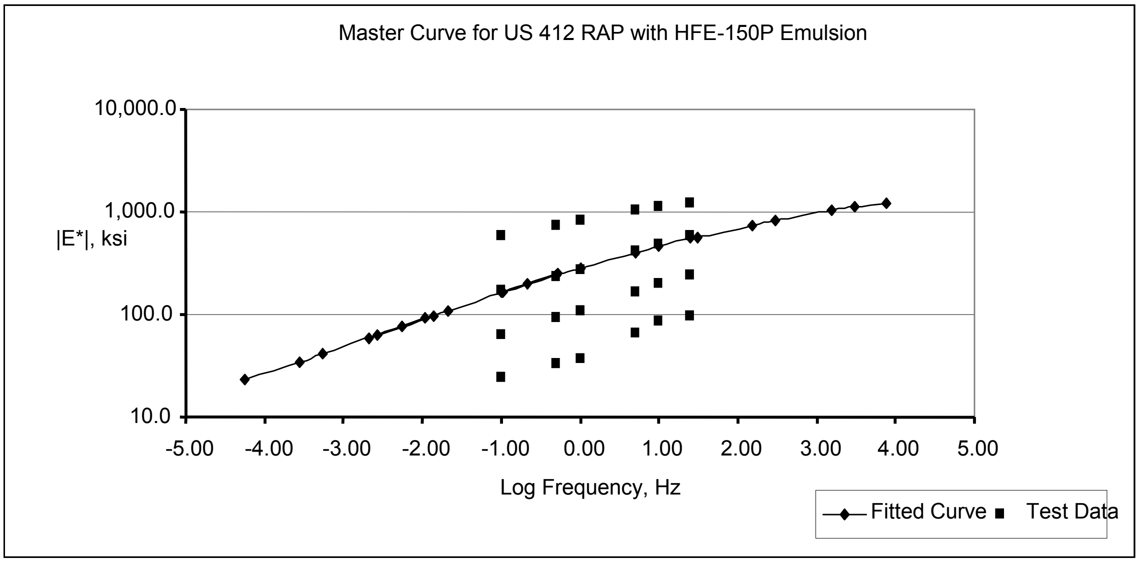

FIGURE 5-4 Master Curve for US-412 RAP and HFE-150P Emulsion.

E* PREDICTIVE EQUATION

One of the objectives of this study was to compare the experimental dynamic modulus data to the predicted values using Witczak's equation. The new M-EPDG uses the laboratory E* data for input Level 1, while it uses E* values from Witczak's E* predictive equation for input Levels 2 and 3. The Witczak's E* predictive model was based upon 2750 test points and 205 different HMA mixtures (34 of which are modified). Most of the 205 HMA mixtures were dense-graded using unmodified asphalts. The current version of the E* predictive equation, updated in 1999, is [1]:

$$\log E^* = -3.750063 + 0.02932\rho_{200} - 0.001767(\rho_{200})^2$$

$$-0.002841\rho_4 - 0.058097V_a - 0.82202\frac{V_{beff}}{V_{beff}+V_a} +$$

$$\frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.00547\rho_{34}}{1+e^{(-0.603313-0.313351\log(f)-0.393532\log(\eta))}}$$

(4)

Where,

E* = dynamic modulus, 10^5 psi

η = asphalt viscosity at the age and temperature of interest, 106 Poise (use of RTFO aged viscosity is recommended for short-term oven aged lab blend mix)

f = loading frequency, Hz

Va = air void content, %

Vbeff = effective asphalt content, % by volume

ρ34 = cumulative % retained on 3/4 in (19 mm) sieve

ρ38 = cumulative % retained on 3/8 in (9.5 mm) sieve

$\rho4$ = cumulative % retained on #4 (4.76 mm) sieve

$\rho200$ = % passing #200 (0.075 mm) sieve

The asphalt viscosity (η) required in equation (4) is calculated using equation (5) shown below. Default values for A and VTS , measures of an asphalt's temperature susceptibility, were obtained only from a report by SemMaterials for Reflex emulsion [19].

$$\log \log \eta = A + VTS \log T_R \qquad (5)$$

Where,

η = asphalt viscosity, cP

A, VTS = regression parameters

T_R = temperature, ° Rankine

The Witczak's equation, equation 4, was used to determine the predicted dynamic modulus for each of the samples tested. The predicted dynamic modulus data for all the samples tested is given in tables 5-9 – 5-12. The volumetric properties used to determine the predicted dynamic modulus for each of the samples were listed in table 4-6 of chapter 4. The master curves constructed for the predicted data are shown in figures 5-5 – 5-8.

TABLE 5-9 Predicted Dynamic Modulus for US-412 RAP and Reflex Emulsion

Temperature (°C)	Frequency (Hz)	Dynamic Modulus (psi)		
		Sample 1	Sample 2	Average
-10	25	2,359,068	2,553,931	2456499
	10	2,229,960	2,414,158	2322059
	5	2,127,763	2,303,519	2215641
	1	1,877,736	2,032,840	1955288
	0.5	1,765,796	1,911,653	1838725
	0.1	1,500,726	1,624,689	1562707
4.4	25	1,317,491	1,426,318	1371904
	10	1,169,271	1,265,855	1217563
	5	1,060,191	1,147,765	1103978
	1	822,120	890,028	856074
	0.5	727,965	788,097	758031
	0.1	533,099	577,134	555116
21.1	25	490,610	531,135	510872
	10	401,095	434,226	417661
	5	341,430	369,633	355532
	1	228,562	247,442	238002
	0.5	190,191	205,901	198046
	0.1	121,461	131,494	126477
37.8	25	160,649	173,919	167284
	10	124,109	134,361	129235
	5	101,562	109,951	105757
	1	62,945	68,144	65545
	0.5	51,046	55,263	53154
	0.1	31,335	33,923	32629
54.4	25	57,842	62,619	60231
	10	43,817	47,436	45626
	5	35,506	38,439	36972
	1	21,891	23,699	22795
	0.5	17,849	19,323	18586
	0.1	11,287	12,219	11753

TABLE 5-10 Predicted Dynamic Modulus for US-412 and CSS-1h Emulsion

Temperature (°C)	Frequency (Hz)	Dynamic Modulus (psi)		
		Sample 1	Sample 2	Average
-10	25	2,359,068	2,381,904	2,370,486
	10	2,229,960	2,251,546	2,240,753
	5	2,127,763	2,148,360	2,138,061
	1	1,877,736	1,895,913	1,886,824
	0.5	1,765,796	1,782,889	1,774,342
	0.1	1,500,726	1,515,254	1,507,990
4.4	25	1,317,491	1,330,245	1,323,868
	10	1,169,271	1,180,590	1,174,931
	5	1,060,191	1,070,454	1,065,323
	1	822,120	830,078	826,099
	0.5	727,965	735,012	731,489
	0.1	533,099	538,259	535,679
21.1	25	490,610	495,359	492,984
	10	401,095	404,978	403,037
	5	341,430	344,736	343,083
	1	228,562	230,775	229,668
	0.5	190,191	192,032	191,111
	0.1	121,461	122,637	122,049
37.8	25	160,649	162,204	161,426
	10	124,109	125,311	124,710
	5	101,562	102,545	102,054
	1	62,945	63,554	63,250
	0.5	51,046	51,540	51,293
	0.1	31,335	31,638	31,487
54.4	25	57,842	58,402	58,122
	10	43,817	44,241	44,029
	5	35,506	35,850	35,678
	1	21,891	22,103	21,997
	0.5	17,849	18,022	17,935
	0.1	11,287	11,396	11,342

TABLE 5-11 Predicted Dynamic Modulus for US-412 and CSS-1h+Lime

Temperature (°C)	Frequency (Hz)	Dynamic Modulus (psi)		
		Sample 1	Sample 2	Average
-10	25	2,630,370	2,681,176	2,655,773
	10	2,486,414	2,534,439	2,510,426
	5	2,372,464	2,418,288	2,395,376
	1	2,093,683	2,134,122	2,113,902
	0.5	1,968,869	2,006,898	1,987,884
	0.1	1,673,316	1,705,636	1,689,476
4.4	25	1,469,008	1,497,381	1,483,194
	10	1,303,742	1,328,924	1,316,333
	5	1,182,117	1,204,950	1,193,534
	1	916,667	934,372	925,520
	0.5	811,684	827,362	819,523
	0.1	594,407	605,888	600,148
21.1	25	547,032	557,598	552,315
	10	447,223	455,861	451,542
	5	380,696	388,049	384,373
	1	254,847	259,770	257,309
	0.5	212,063	216,159	214,111
	0.1	135,429	138,045	136,737
37.8	25	179,124	182,584	180,854
	10	138,382	141,055	139,719
	5	113,242	115,429	114,336
	1	70,184	71,540	70,862
	0.5	56,917	58,016	57,466
	0.1	34,939	35,614	35,276
54.4	25	64,494	65,739	65,116
	10	48,856	49,800	49,328
	5	39,589	40,354	39,972
	1	24,408	24,880	24,644
	0.5	19,902	20,286	20,094
	0.1	12,585	12,828	12,707

TABLE 5-12 Predicted Dynamic Modulus for US-412 and HFE-150P

Temperature (°C)	Frequency (Hz)	Dynamic Modulus (psi)		
		Sample 1	Sample 2	Average
-10	25	2,504,390	2,553,931	2,529,160
	10	2,367,328	2,414,158	2,390,743
	5	2,258,836	2,303,519	2,281,177
	1	1,993,407	2,032,840	2,013,123
	0.5	1,874,571	1,911,653	1,893,112
	0.1	1,593,173	1,624,689	1,608,931
4.4	25	1,398,650	1,426,318	1,412,484
	10	1,241,300	1,265,855	1,253,577
	5	1,125,500	1,147,765	1,136,632
	1	872,763	890,028	881,396
	0.5	772,809	788,097	780,453
	0.1	565,938	577,134	571,536
21.1	25	520,832	531,135	525,984
	10	425,803	434,226	430,015
	5	362,463	369,633	366,048
	1	242,642	247,442	245,042
	0.5	201,907	205,901	203,904
	0.1	128,943	131,494	130,218
37.8	25	170,545	173,919	172,232
	10	131,755	134,361	133,058
	5	107,818	109,951	108,885
	1	66,823	68,144	67,484
	0.5	54,191	55,263	54,727
	0.1	33,265	33,923	33,594
54.4	25	61,405	62,619	62,012
	10	46,516	47,436	46,976
	5	37,693	38,439	38,066
	1	23,239	23,699	23,469
	0.5	18,949	19,323	19,136
	0.1	11,982	12,219	12,101

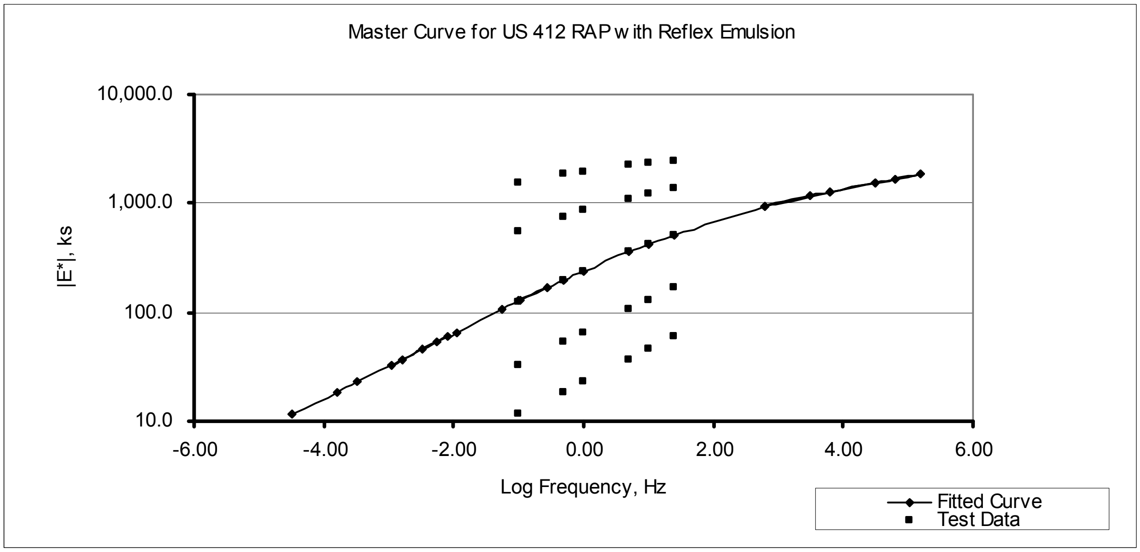

FIGURE 5-5 Master Curve of Predicted Dynamic Modulus for US-412 RAP and Reflex Emulsion.

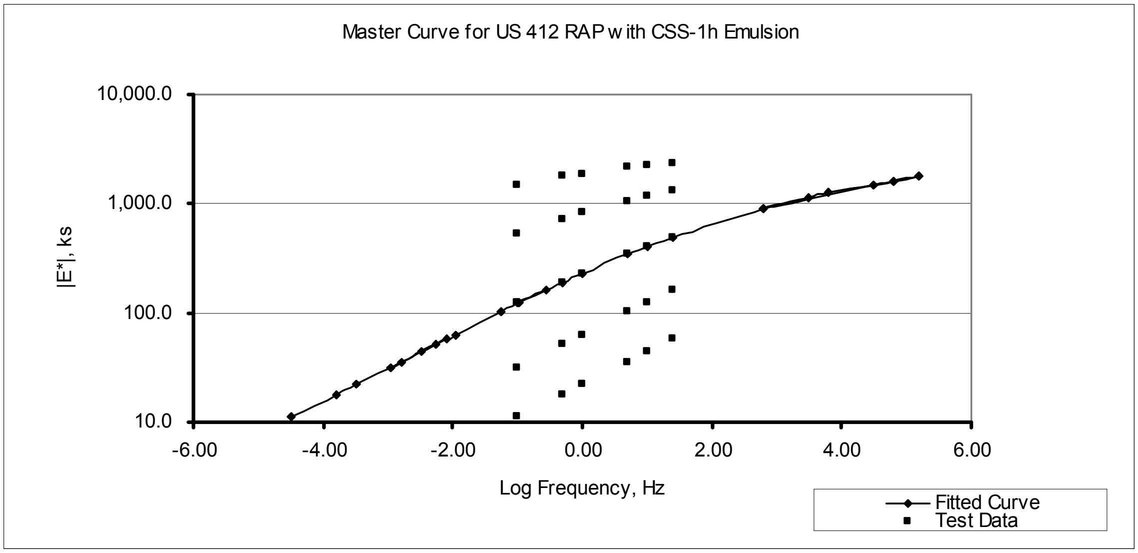

FIGURE 5-6 Master Curve of Predicted Dynamic Modulus for US-412 RAP and CSS-1h Emulsion.

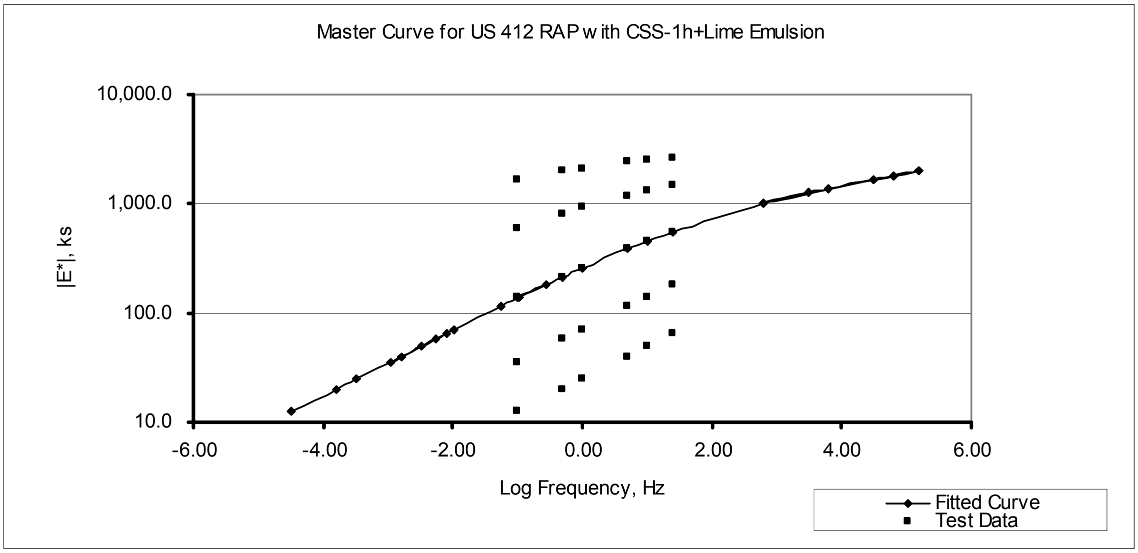

FIGURE 5-7 Master Curve of Predicted Dynamic Modulus for US-412 RAP and CSS-1h+ Lime Emulsion.

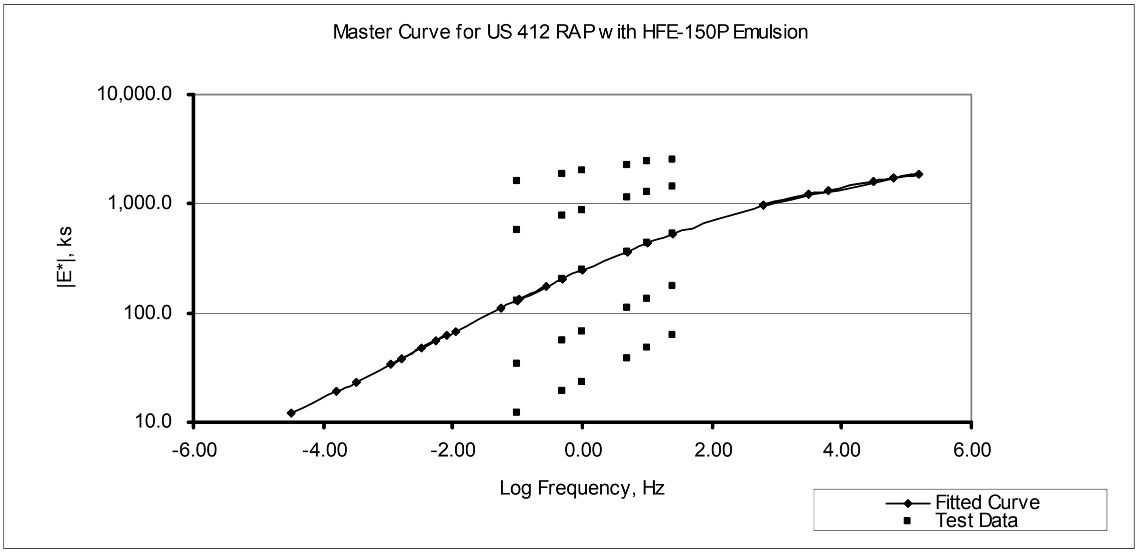

FIGURE 5-8 Master Curve of Predicted Dynamic Modulus for US-412 and HFE-150P Emulsion.

Comparison of Experimental and Predicted Master Curves

Figures 5-9 – 5-12 show the experimental and predicted master curves for the CIR mix with different emulsions. Numerous assumptions were required to determine the predicted dynamic modulus for CIR mix. Master curves in figure 5-12 for HFE-150P emulsion samples shows that the predicted numbers are close to the experimental. Dynamic modulus values for the 54.4° C (130°F) test temperature were the measured rather than the extrapolated as compared to the other emulsion samples. A detailed study needs to be performed to determine the input parameters of CIR for Witczak's equation.

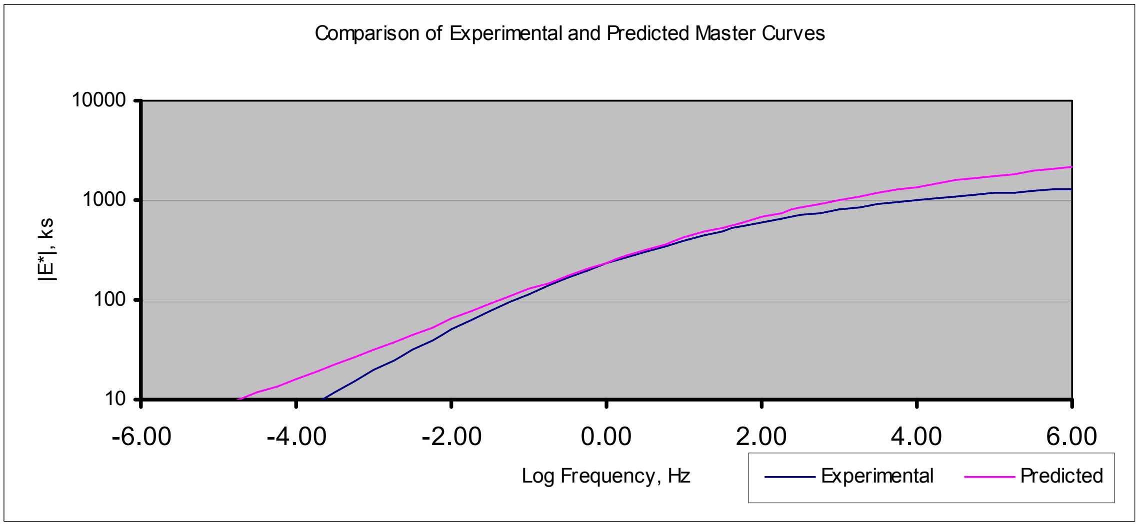

FIGURE 5-9 Master Curves of Experimental and Predicted Dynamic Modulus for US-412 and Reflex Emulsion.

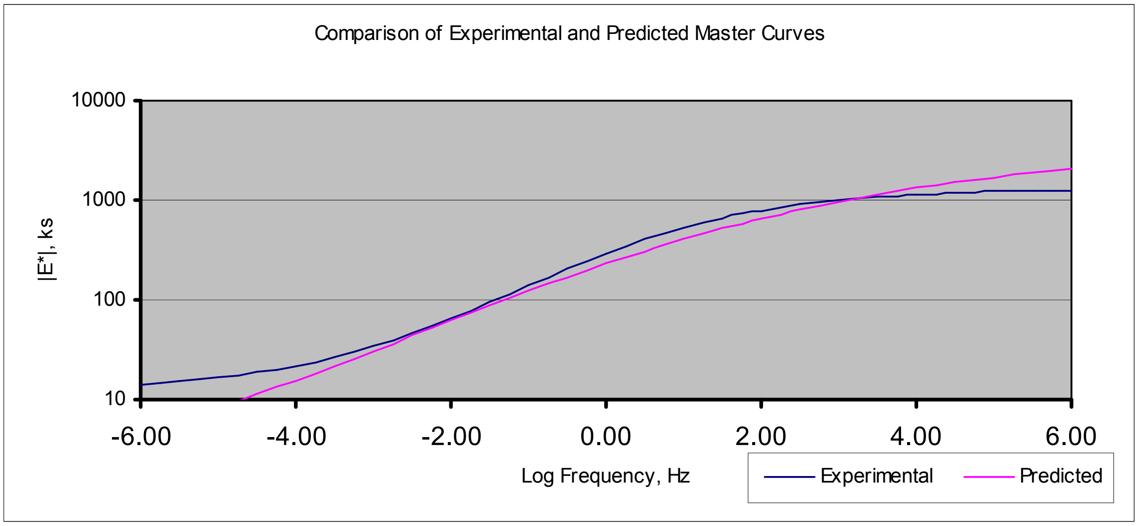

FIGURE 5-10 Master Curves of Experimental and Predicted Dynamic Modulus for US-412 and CSS-1h Emulsion.

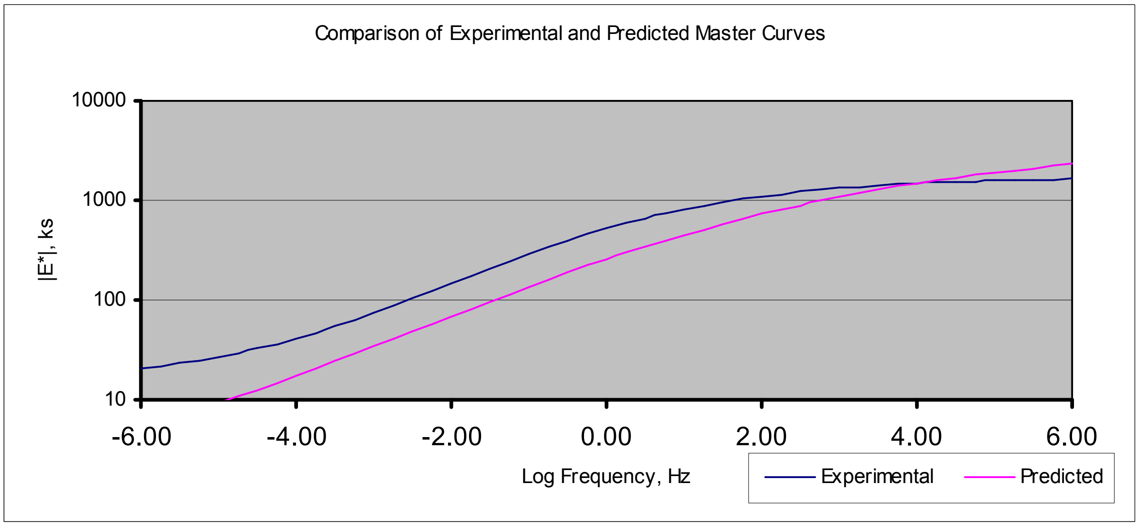

FIGURE 5-11 Master Curves of Experimental and Predicted Dynamic Modulus for US-412 and CSS-1h + Lime Emulsion.

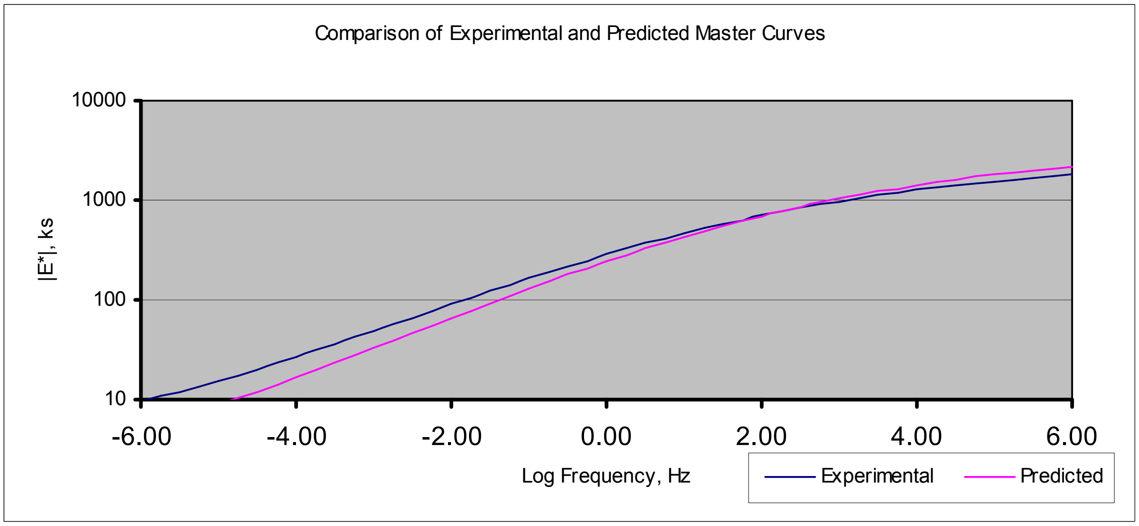

FIGURE 5-12 Master Curves of Experimental and Predicted Dynamic Modulus for US-412 and HFE-150P Emulsion.

M-EPDG

M-EPDG is a analysis tool that gives levels of distress for Terminal IRI, Longitudinal Cracking, Alligator Cracking, Thermal Cracking and Permanent Deformation (rutting). The user selects failure criteria for each distress or selects default values. For this study defaults values were used. The default initial IRI (in/mi) was 63 and the other analysis parameters are shown table 5-13.

TABLE 5-13 Default Performance Criteria

Distress	Limit	Reliability
Terminal IRI (in/mile)	172	90
Longitudinal Cracking (ft/mile)	2000	90
Alligator Cracking (%)	25	90
Thermal Cracking (ft/mile)	1000	90
Permanent Deformation - Total Pavement (in)	0.75	90

The ANOVA showed a significant effect of EAC on dynamic modulus. To determine if the differences in the dynamic modulus by emulsions would have an effect on pavement performance, the M-EPDG was used. The M-EPDG requires traffic, climatic and soil information as well as material properties. The traffic and climatic data for the evaluation were obtained from the CIR project on US-412 in Beaver Co. Default values for a CL type of soil for the subgrade was selected as typical for the project location.

Input Parameters

1. Design Life : 20 years
2. Traffic:
    - 1800 AADT
    - 45 % heavy trucks
    - 0.5 % growth rate
3. Climate: Western portion of US-412 in Beaver Co., OK.

4. Structure:

The CIR project on US-412 in Beaver Co. consisted of 4 inches of CIR using Reflex emulsion and a 2 inch HMA overlay using a PG 76-28 asphalt. CIR goes back down slightly thicker than the milling depth so a 4.5 inches thick layer was used. The remaining thickness of the old HMA was unknown.

The thickness of the old HMA layer was calculated using the M-EPDG to result in a failure in 20-30 of one or more performance parameters. The mix properties are shown below. Figure 5-13 shows the trial section used for analysis.

- Layer 1: For the HMA overlay, level 3 default input parameters were used with a PG 76-28 asphalt.
- Layer 2: For the CIR layer, level 1 input parameters were used. The dynamic modulus for each type of emulsions obtained in lab were used. The binder properties required were G* and delta (δ) values which were obtained from NCAT lab. The default inputs for thermal properties were used.
- Layer 3: For existing HMA section level 1 input parameters were used. For a existing HMA section the software only needs the gradation of the mix and the binder properties.
- Layer 4: For the subgrade, a level 3 input was used with an assumed CL soil for the subgrade.

The default parameters for thermal cracking were used because the measure equipment is not available at Oklahoma State University and default values considered sufficient for HMA.

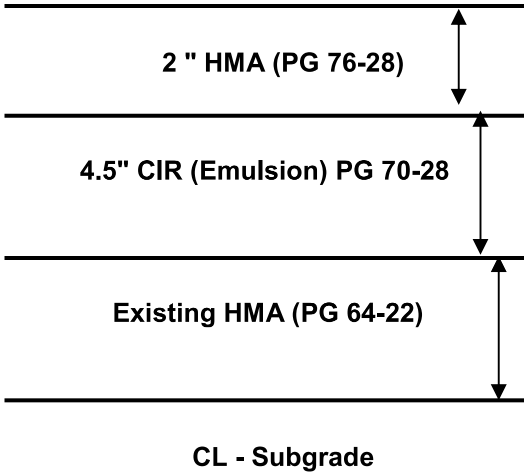

FIGURE 5-13 M-EPDG Trial Section.

Design Trials and Results

The trial section shown in figure 5-13 was considered as the benchmark. The dynamic modulus values for the other three emulsions were substituted for the Reflex emulsion data and the remaining parameters held constant. The thickness of the HMA overlay was varied until the pavement structure failed within a 20-30 year time frame or the minimum overlay thickness was reached. The summary of the results are provided in the Table 5-13. Figure 5-14 shows a typical performance plot for AC bottom up cracking (Alligator Cracking) for Reflex emulsion and an HMA overlay thickness of 1.5 inches.

The required minimum thickness of the HMA overlay with each of the emulsions is given in table 5-14.

A trial was performed with a PG 58-28 base binder in the emulsion keeping all the other input parameters the same to determine if this had any effect on performance parameters. No major change in the performance was indicated. The base binder input parameters (G*, δ) of the emulsion did not appear to have a major effect on the predicted performance.

TABLE 5-13 Trials Run in the M-EPDG to Arrive at a Economical Thickness for HMA Overlay

Trial No.	Emulsions	HMA Overlay Thickness	Pavement Distresses				
			IRI	LC	AC	TC	R
1	Reflex	2.00"	√	√	√	√	√
2	Reflex	1.75"	√	√	√	√	√
3	Reflex	1.50"	√	√	**X**	√	√
4	CSS - 1h	2.00"	√	√	√	√	√
5	CSS - 1h	1.75"	√	√	√	√	√
6	CSS - 1h	1.50"	√	√	√	√	√
7	CSS - 1h	1.25"	√	√	√	√	√
8	CSS - 1h	1.00"	√	√	**X**	√	√
9	CSS-1h+Lime	2.00"	√	√	√	√	√
10	CSS-1h+Lime	1.75"	√	√	√	√	√
11	CSS-1h+Lime	1.50"	√	√	√	√	√
12	CSS-1h+Lime	1.25"	√	√	√	√	√
13	CSS-1h+Lime	1.00"	√	√	√	√	√
14	HFE-150P	2.00"	√	√	√	√	√
15	HFE-150P	1.75"	√	√	√	√	√
16	HFE-150P	1.50"	√	√	√	√	√
17	HFE-150P	1.25"	√	√	√	√	√
18	HFE-150P	1.00"	√	√	√	√	√

IRI = Terminal IRI (in/mi), LC = AC Surface Down Cracking (Long. Cracking) (ft/mile), AC = AC Bottom Up Cracking (Alligator Cracking) (%), TC = AC Thermal Fracture (Transverse Cracking) (ft/mi), R = Permanent Deformation (Total Pavement) (in)
√ = Pass, **X** = fail

TABLE 5-14 Minimum HMA Overlay Thickness

Emulsions	Overlay Thickness
Reflex	1.75”
CSS-1h	1.25”
CSS-1h+Lime*	1.00”
HFE-150P*	1.00”

* Both CSS-1h+Lime and HFE-150P pass with 1.00 inch thickness of HMA overlay but further trials cannot be run, because M-EPDG software does not accept thickness below 1.00 inch

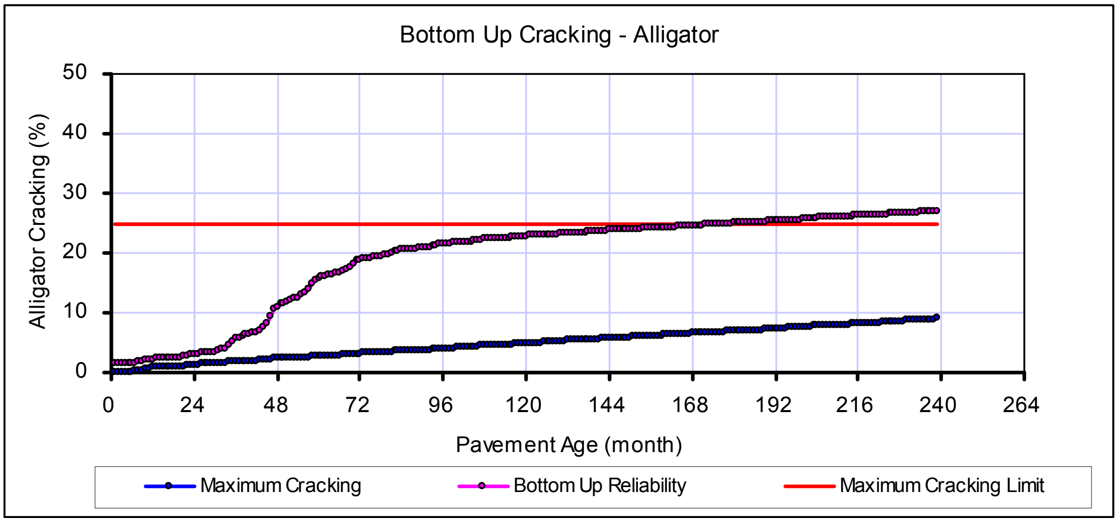

FIGURE 5-14 Typical Performance Plot.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Based on the test results obtained and analysis performed, the following conclusions are made concerning the evaluation of dynamic modulus data for CIR mixture to be used as an input parameter in M-EPDG. There is a limitation in the data presented in this study, only one source of RAP material was used.

1. EAC had a significant effect on dynamic modulus, the CSS-1h + Lime resulted in the stiffest mix and the Reflex was the softest mix among the four emulsions used in the project.
2. Temperature and the frequency of loading had a major effect on the dynamic modulus values, which was as expected. The data followed the expected trends and matched reported data found in the literature [19].
3. Comparison of the experimental and predicted dynamic modulus data showed that the experimental data was lower than the predicted. Numerous assumptions were required to obtain the predicted dynamic modulus and the experimental data was extrapolated for the missing temperatures. Further study needs to be performed in this area to determine whether the predicted data matches CIR mixtures.

4. Witczak's equation can be used for CIR. By assuming that RAP is a "Black Rock" with negligible absorption, meaning G_{se} of the RAP can be used for G_{sb} to determine the volumetric properties of the mixture. The as received gradation of the RAP is used as aggregate gradation in the predictive equation.
5. Emulsion type had an effect on the thickness of the HMA overlay

RECOMMENDATIONS

1. Numerous assumptions were required to use CIR in the M-EPDG. These assumptions need to be evaluated before the design guide can be used with confidence. More research needs to be performed with different sources of RAP to determine the effect of RAP, and the aggregate type in the RAP, on the dynamic modulus.
2. Numerous binder input parameters are required to use the M-EPDG. These are difficult to obtain because the binder in the RAP is already blended and oxidized and cannot be easily recovered to determine the required input parameters. The effect of the asphalt properties on the pavement performance from M-EPDG needs to be evaluated.
3. There were occasionally problems with the software crashing and providing inconsistent results with the same scenario. It is recommended that each scenario or trial be run at least twice to verify the output for use.

The following recommendations are made for preparation and testing of CIR samples for dynamic modulus testing

1. During CIR dynamic modulus sample preparation, mix water contents need to be carefully measured as it influences mixing and workability of the mixture.

Another important point to remember during sample preparation is to stir the emulsion completely to mix the settled asphalt or polymer.

2. Extra care should be taken when coring and sawing the CIR samples since they are softer than HMA samples and can be easily damaged.
3. For the dynamic modulus testing, test chamber temperature and test specimen temperature needs to be maintained and monitored within the tolerance limits as temperature has a major effect on dynamic modulus.

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The objectives of this thesis were to evaluate the dynamic modulus of Cold Inplace Recycling (CIR) mixture made with one reclaimed asphalt pavement (RAP) and four different emulsions and to compare the results with the default values in the Mechanistic-Empirical Pavement Design Guide (M-EPDG). The dynamic modulus (|E*|) of hot-mix asphalt (HMA) is one of the fundamental inputs in the M-EPDG developed in NCHRP Project 1-37A. The M-EPDG provides three levels for |E*| input, which are related nominally to the reliability of pavement performance estimates generated by the Guide. Level 1 |E*| inputs require laboratory measured |E*| values while level 2 and 3 |E*| inputs are estimated using a predictive equation. The study included the determination of input parameters of CIR mixture to be used in the M-EPDG and comparison of the effect of different emulsion types on the dynamic modulus of the mixture.

Emulsion type, test temperature and frequency of loading had a significant effect on the dynamic modulus of the mixture. Comparison of the experimental and predicted dynamic modulus data showed that the experimental data was lower than the predicted. Numerous assumptions were required to obtain the predicted dynamic modulus and the experimental data was extrapolated for the missing temperatures. Further study needs to be performed in this area to determine whether the predicted data matches CIR mixtures. Witczak's equation can be used for CIR by assuming that RAP is a "Black Rock" with negligible absorption.

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