NDOT Research Report

Report No. 643-15-803

Development of Mix Design and Structural Design Procedures for Cold In-Place Recycling

June 2018

Nevada Department of Transportation
1263 South Stewart Street
Carson City, NV 89712

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<tr><td colspan="4">16. Abstract
This research effort conducted extensive evaluations of CIR mixtures in support of the development of a mix design method for CIR mixtures and a structural design method for flexible pavements with CIR layers. CIR mixtures with two gradations, two lime slurries, and four asphalt emulsions were designed using the Hveem and Superpave methods and their engineering properties and performance characteristics were evaluated. The data generated in this research showed that CIR mixtures can be effectively designed using the NDOT Hveem mix design method with some minor modifications in the number of tamps and the leveling stress. The optimum air voids content has been identified as 13±1. The moisture sensitivity evaluation of the CIR mixtures showed that CIR mixtures can be designed to deliver good levels of dry tensile strength property and tensile strength ratio. The evaluation of the dynamic modulus master curve data for the CIR mixtures indicated that the majority of CIR mixtures develop E* properties that are very comparable to AC mixtures at all levels of temperatures and frequencies. It was found that, for the NDOT standard CIR mixtures manufactured with non-graded RAP and 6.0% lime slurry, an average rutting model can be recommended with 95% confidence to estimate the rutting performance of CIR mixtures manufactured with different asphalt emulsions. The fatigue data generated up to this point showed the CIR mix with the rubber-modified emulsion has the best resistance at 70ºF followed by the CIR mix with the Latex-modified emulsion. However, this observation may not hold true at the other testing temperatures of 55 and 85ºF. The data generated from the overlay tester showed that the resistance of the CIR mixture to reflective cracking is sensitive to the type of asphalt emulsion. The analysis of the reflective cracking data indicated that some CIR mixtures are less resistant to crack initiation but more resistant to crack propagation than others.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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Chapter 1. INTRODUCTION

Cold in-place recycling (CIR) is an on-site 100 percent pavement recycling process to a typical treatment depth of 2 – 5 inch. An additive or combination of additives (asphalt emulsions, rejuvenating agents, foamed asphalt, lime, fly ash, or cement) may be used. The CIR construction process can be summarized by the following steps:

1. Milling and crushing of the existing pavement
2. Mixing and addition of a recycling agent
3. Lay down
4. In-place compaction
5. Placement of the wearing course

Figure 1.1 shows the CIR process using a train of equipment (tankers, trucks, milling machines, crushing and screening units, and mixer). The water tanker supplies the optimum water content to achieve the maximum density of the compacted CIR mixture. The optimum water content and maximum density are determined on the reclaimed asphalt pavement (RAP) material in the laboratory through the modified proctor compaction method as specified in AASHTO T180.

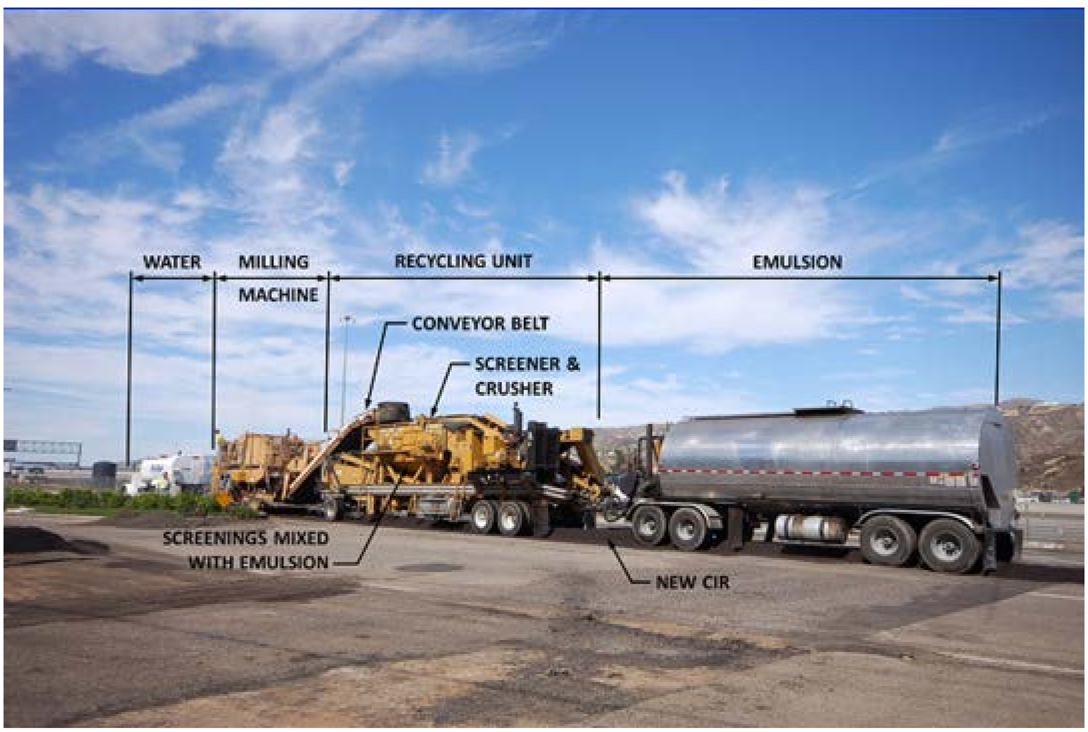

Figure 1.1. Cold in-place recycling train components.

The milling machine pulverizes the existing asphalt concrete (AC) layer to the specified depth of the CIR process. The milled material is referred to as RAP. It should be noted that some water is added (i.e., 1.0 – 1.5% by weight of RAP) to cool the milling heads which should be accounted for in the calculation of the amount of additional water needed to achieve the optimum water content. The recycling unit crushes the RAP material to meet the gradation specification of the project and mixes the RAP material with the asphalt emulsion. Some projects apply full gradation specification while other projects may only apply a maximum size specification. The emulsion tank is connected to the recycling unit and delivers the amount of asphalt emulsion specified per the job mix formula (JMF). The final CIR mix is laid-down in a windrow behind the recycling unit.

Figure 1.2 shows the final two steps of the construction process where the CIR mix is picked up by the paver, laid-down to the specified thickness, and compacted by the rollers. The degree of compaction achieved in the CIR layer plays a major role in its long-term performance as a structural layer in the AC pavement.

Figure 1.2. The CIR mix is picked up by the paver and roller compacted.

Typically, in-place compaction is controlled through the measurement of density of the compacted mat and the calculation of in-place air voids. In the case of AC mixtures, a combination of cores and nuclear density gauge is used to determine the in-place density of the compacted mat following well-established AASHTO and Agency's procedures. The implementation of the same procedures for CIR faces serious limitations due to: (1) the inability of cutting cores from the CIR mat until full curing of the CIR mix has occurred which requires 7-14 days; and (2) the ineffectiveness of the nuclear density gauge during the compaction process because of the high moisture content of the CIR mix. A recent research project by the research team of the Pavement Engineering and Science (PES) Program at the University of Nevada, Reno (UNR) has developed an in-place density measuring procedure based on the sand cone technique as per ASTM D1556 to be used on the freshly compacted CIR layer (1). Knowing the in-place bulk density of the compacted CIR layer and measuring the maximum theoretical density of the CIR mix, leads to the determination of the in-place air voids of the compacted CIR layer. This new research makes the CIR technology ready for full implementation by road agencies in Nevada and throughout the US.

NDOT uses CIR to rehabilitate a significant portion of the state road network due to its desirable economical and environmental benefits. Economically, a well-designed and constructed CIR has proven to be highly effective in reducing reflective cracking from the old cracked-up asphalt pavement, therefore, eliminating the need of costly re-construction of the road section. Environmentally, CIR makes full use of the existing highly distressed AC layer whereby eliminating the need for its removal and the wasting of its valuable natural products; aggregates and asphalt binder.

Recent research efforts of the PES-UNR research team in cooperation with NDOT Maintenance and Materials Divisions completed an extensive study that evaluated the long-term performance of CIR pavements throughout the state of Nevada (2). The evaluation program covered over 100 CIR projects constructed with three types of emulsions; CMS-2S, PASS, and Reflex, and two different structures: CIR with AC overlay and surface treatment and CIR with only surface treatment. The following represents the major recommendations of this study:

- Transverse and longitudinal cracking were the major type of distresses in CIR pavements.
- The thickness of the AC overlay was found crucial for the long-term performance of CIR pavements, therefore, a rigorous structural design should be conducted to establish the appropriate thickness of the overlay over the CIR on high and medium traffic volume roads.
- A life cycle cost analysis should be conducted on the two major categories of CIR with the three types of emulsions being used in Nevada.
- Even-though the overall performance of CIR pavements in Nevada has been good, the data showed that some CIR projects did not perform well or as expected. Figure 1.3 shows the performance of the CMS-2S emulsion on two evaluated projects from the south (CMS-16 and CMS-21) with similar traffic and climatic conditions. It is very clear that significant variations exist in the long-term performance of CIR pavements on Nevada's roads.

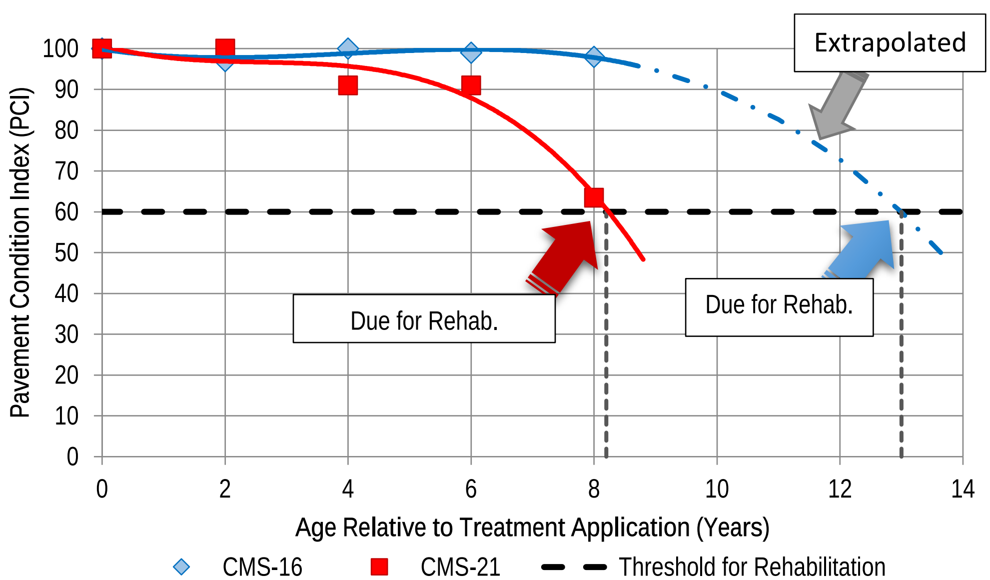

Figure 1.3. Performance of CMS-16 and CMS-21 projects.

1.1. Objective and Scope

Over the past decade, NDOT has made great progress towards the implementation of the CIR technology in various parts of the state, however, the current methods for mix and structural designs of CIR need to be updated to incorporate the latest technologies in pavements and materials engineering. Hence, the overall objective of this research study is to develop mix design and structural design procedures for CIR materials for implementation by the Nevada DOT. In order to achieve the overall objective, the following activities were completed:

- Conduct benefit-cost analysis for CIR projects that have been constructed throughout Nevada within the past 20 years.
- Develop mix design procedures for CIR materials based on the Nevada DOT Hveem method and the Superpave method.
- Evaluate the engineering properties and performance characteristics of CIR mixtures.
- Incorporate the properties and characteristics of the CIR mixtures into a structural design procedure for asphalt concrete overlay over a CIR layer.

Chapter 2. LIFE CYCLE COST ANALYSIS

NDOT has constructed over 1500 centerline miles of CIR pavements in the past 20 years. In most cases a CMS-2s asphalt emulsion was used, however, solvent free asphalt emulsion and polymer modified asphalt emulsion have been introduced in some CIR projects.

Depending on the traffic volume of the road NDOT has been constructing two types of CIR projects. For high volume roads, typically a 2.0 – 3.0 inch CIR layer has been constructed, followed by the required structural overlay (1.5 – 4.0 inch) and an 0.75 – 1.0 inch open grade friction course (OGFC) or a surface treatment as the wearing surface. For low volume roads, a 2.0 – 3.0 inch CIR layer has been constructed, followed by a surface treatment such as chip seal, double chip seal, or microsurfacing as the wearing course. This part of the research assessed the long-term performance and conducted benefit-cost analysis of CIR pavements throughout Nevada constructed over the period of 2000 – 2015.

2.1. Long-Term Performance of CIR Pavements in Nevada

Long-term performance of CIR pavements throughout Nevada was evaluated based on condition surveys obtained from NDOT's Pavement Management System (PMS) conducted on 2-years cycle. As mentioned earlier, CIR projects were divided into two categories; projects with CIR layer and AC overlay, and projects with CIR layer and surface treatment. The study identified a total of 94 CIR pavements in Nevada from NDOT database constructed during the period of 2000 – 2015; 63 CIR pavements with AC overlays, and 31 CIR pavements with surface treatments.

Table 2.1 and Table 2.2 summarize the CIR pavements with AC overlay and surface treatment selected for the long-term performance and benefit-cost analysis, respectively. Projects with less than 10 years of condition survey information, and projects with insufficient cost information were excluded from the analysis.

Maintenance treatments were applied over the service life of most CIR pavements. Table 2.3 summarizes the identified maintenance treatments for the selected CIR pavements. On average, the first maintenance treatment for CIR pavements with AC overlay was applied close to the 8^{th} year after construction, and the second maintenance treatment was applied around the 11^{th} year after construction. For CIR pavements with surface treatment, on average, the first maintenance treatment was applied close to the 4^{th} year after construction and the second maintenance treatment was applied around the 8^{th} year after construction. The most used maintenance treatments were chip seal and flush seal.

Table 2.1. CIR Pavements with AC Overlay constructed by NDOT: 2000-2015.

Contract ID	Route	Award Year	Layer Thickness (in)		CIR Emulsion	AADT
			CIR	HMA		
3013	US095	2001	3	3	CMS-2s	3,343
3025A	US093	2000	2	2	CMS-2s	656
3025B	US093	2000	2	2.25	CMS-2s	400
3025C	US093	2000	2	2	CMS-2s	400
3097	US050	2002	2.5	2.5	CMS-2s	1,123
3099	US095	2002	3	3	CMS-2s	2,600
3116	SR225	2002	3	2.5	CMS-2s	800
3138	SR429	2002	3	2	CMS-2s	1,250
3139	US093	2002	3	2.5	CMS-2s	2,600
3143A	US095	2002	3	3	CMS-2s	2,663
3143B	US095	2002	3	3	CMS-2s	2,700
3143C	US095	2002	2	3	CMS-2s	2,765
3151A	SR487	2003	3	1.5	CMS-2s	233
3151B	SR488	2003	3	1.5	CMS-2s	350
3165	SR207	2003	3	2.5	CMS-2s	5,600
3191	US050	2003	3	3	CMS-2s	15,875
3198	SR225	2004	3	2	CMS-2s	520
3201	SR163	2004	3	3	CMS-2s	4,300
3220A	FRWA48	2004	2.75	2	CMS-2s	N/A
3220B	SR425	2004	2.75	3	CMS-2s	2,480
3239A	SR208	2005	3	2	CMS-2s	3,100
3239B	SR209	2005	3	2	CMS-2s	1,334
3250	SR227	2005	3	3	CMS-2s	8,000
3256	US006	2005	3	1.5	CMS-2s	486
3259	SR206	2005	2	2	CMS-2s	1,564
3261	US093	2005	3	3	CMS-2s	2,600
3262	SR318	2005	3	3	CMS-2s	1,413
3278A	US093	2005	3	3	CMS-2s	1,968
3278B	US093	2005	3	1.5	CMS-2s	500

Table 2.2. CIR Pavements with Surface Treatment constructed by NDOT: 2000-2015.

Contract ID	Route	Award Year	Layer Thickness (in)		CIR Emulsion	AADT
			CIR	Surface Treatment		
3151C	SR487	2003	3	Chip seal	CMS-2s	150
D0-124-08A	SR757	2008	3	Double chip seal	Reflex	1,600
D0-124-08B	SR447	2008	3	Chip seal	Reflex	350
D0-124-08D	US050	2008	3	Double chip seal	Reflex	550
D2-004-09A	SR828	2009	3	N/A	CMS-2s	4,880
D2-004-09B	SR447	2009	3	N/A	CMS-2s	350
D2-004-11R	SR447	2011	3	Double chip seal	CMS-2s	350
D2-047-10A	SR726	2010	2.5	Double chip seal	CMS-2s	350
D2-047-10B	SR339	2010	2.5	Double chip seal	CMS-2s	1,757
D2-047-10C	SR447	2011	3	Double chip seal	CMS-2s	447
D3-010-05A	SR892	2005	1.5	Double chip seal	Pass-R	100
D3-010-05B	SR892	2005	1.5	Double chip seal	Reflex	100
D3-041-10	SR278	2010	3	Double chip seal	CMS-2s	439
P197-60-050A	SR445	2006	2	Double chip seal	Reflex	550
P197-60-050C	SR772	2006	2	Double chip seal	Reflex	40
P264-03-050A	US006	2003	2	Double chip seal	CMS-2s	250
P264-03-050B	US006	2003	2	Double chip seal	CMS-2s	250
P264-03-050C	US006	2003	2	Double chip seal	Reflex	250
P264-03-050D	US006	2003	2	Double chip seal	Reflex	250
P264-03-050F	US006	2003	2	Double chip seal	Reflex	250
P264-03-050H	US006	2003	2	Double chip seal	CMS-2s	250
P264-03-050I	US006	2003	2	Double chip seal	CMS-2s	250
P319-05-101	SR168	2005	3	Chip seal	CMS-2s	250
P463-07-301A	US0006	2007	3	N/A	Reflex	250
P463-07-301B	SR140	2007	3	Double chip seal	Reflex	250

Table 2.3. Maintenance Treatments Applied on the Identified CIR Pavements.

Contract ID	Year of Treatment 1	Treatment 1	Year of Treatment 2	Treatment 2
3013	2009	Flush seal	2012	Flush seal
3025A	2006	Chip seal & flush seal	2011	Chip seal
3025B	2007	Chip seal & flush seal		
3025C	2007	Chip seal & flush seal	2014	Chip seal & flush seal
3097	2008	Flush seal		
3099	2010	Flush seal	2014	Chip seal
3116	2010	Chip seal & flush seal		
3138	2010	Flush seal		
3139	2011	Chip seal & flush seal		
3143A	2011	Chip seal		
3143B	2011	Chip seal		
3143C	2011	Chip seal		
3151A	2011	Chip seal & flush seal		
3151B	2011	Chip seal & flush seal		
3165	2013	Fog/flush seal		
3191	2013	Fog/flush seal		
3198	2011	Chip seal	2012	Chip seal
3201	2010	Flush seal		
3220A	2011	Flush seal		
3220B	2012	Flush seal		
3239A	2010	Flush seal		
3239B	2010	Flush seal		
3250				
3256	2013	Chip seal & flush seal		
3259	2013	Fog/flush seal		
3261	2014	Chip seal		
3262	2014	Chip seal		
3278A	2010	Flush seal		
3278B				
3151C	2011	Chip seal & flush seal		
D0-124-08A	2013	Flush seal		
D0-124-08B	2008	Double chip seal & flush seal		
D0-124-08D				
D2-004-09A	2014	Chip seal		
D2-004-09B	2009	Double chip seal		
D2-004-11R				
D2-047-10A				

Contract ID	Year of Treatment 1	Treatment 1	Year of Treatment 2	Treatment 2
D2-047-10B				
D2-047-10C				
D3-010-05A	2005	Chip seal & flush seal		
D3-010-05B	2006	Chip seal & flush seal		
D3-041-10	2014	Chip seal		
P197-60-050A	2010	Flush seal	2014	Double chip seal
P197-60-050C	2012	Flush seal		
P264-03-050A				
P264-03-050B				
P264-03-050C				
P264-03-050D				
P264-03-050F				
P264-03-050H				
P264-03-050I				
P319-05-101	2013	Chip seal & flush seal		
P463-07-301A	2007	Double chip seal	2012	Microsurfacing
P463-07-301B	2007	Double chip seal & flush seal		

NDOT uses the Pavement Rating Index (PRI) as the overall performance indicator for monitoring the condition of the road network. PRI has a scale of 0 to 700, and is calculated based on the severity and extent of the identified distresses from the condition surveys.

In this study, the Pavement Condition Index (PCI) was selected as the indicator of the overall pavement condition. PCI ranges from 0 to 100, with 100 representing the best possible condition of the pavement and 0 the worst. The overall condition of the pavement is identified according to PCI range as defined below:

- PCI values greater than 85 represent pavements in excellent condition
- PCI values ranging between 85-70 represent pavements in very good condition
- PCI values ranging between 69-55 represent pavements in good condition
- PCI values ranging between 54-40 represent pavements in fair condition
- PCI values lower than 40 represent pavements in poor condition

PCI calculation also include severity and extent of each pavement distress, but since the distress formats used by NDOT and PCI are different (i.e., level of severity and extent), the distress format from the NDOT condition survey database was converted into PCI distress format in order to calculate PCI values according to ASTM D6433. Table 2.4 summarizes the overall conversion process from the NDOT-PRI distress format to ASTM-PCI distress format that was developed in a previous NDOT study and is used in this current study (2).

Table 2.4. Conversion of NDOT-PRI Distress Format to ASTM-PCI Distress Format.

Distress Type	NDOT PRI System			ASTM PCI System				Conversion for NDOT distress parameters (level of severity and extent) into PCI format			
	Type	Severity	Extent	Severity level			Extent	Severity level: Low	Medium	High	Extent
Fatigue cracking	A	crack width	crack length	low	med	high	crack length	crack width < 0.375"	0.375" ≤ crack width ≤ 3"	crack width > 3"	crack length
	B	crack width	crack area	low	med	high	crack area				crack area
Block cracking	A	crack width	crack length	low	med	high	crack area	crack width < 0.375"	0.375" < crack width < 3"	crack width > 3"	(extent/ 510)x 1000
	B	crack width	crack area	low	med	high	crack area				crack area
	C	crack width	crack area	low	med	high	crack area				crack area
Long / Trans cracking	N/A	crack width	crack length	low	med	high	crack length	crack width < 0.375"	0.375" < crack width < 3"	crack width > 3"	crack length
Rutting	N/A	rut depth	N/A	low	med	high	rutting area	0.25" ≤ rut depth ≤ 0.5"	0.5" < rut depth ≤ 1.0"	rut depth > 1.0"	rutting area
Raveling	N/A	low, med, high	N/A	N/A	med	high	area	N/A	low and moderate severity	high severity	raveling area
Bleeding	N/A	low, med, high	N/A	low	med	high	area	low severity	medium severity	high severity	bleeding area
Patching	N/A	N/A	Area	low	med	high	area	low severity			patching area

*N/A denotes there is no extent or severity or type for distresses.

Table 2.5 and Table 2.6 summarize the determined PCI values of the selected CIR pavements with AC overlay and with surface treatment used for the long-term performance and benefit cost analysis, respectively.

The PCI data calculated from NDOT condition surveys were used to develop performance prediction models using polynomial regression, as shown in Figure 2.1 and Figure 2.2 for CIR pavements with AC overlay and CIR pavements with surface treatment, respectively. Table 2.7 summarizes the performance models along with the applicable ranges of models parameters. It is highly recommended not to use the models to predict the performance of CIR pavements with parameters outside the ranges specified for each model (Table 2.7).

PCI data shown in Figure 2.1 and Figure 2.2 indicate that most of the projects are in excellent or very good condition, until the age of 15 years for CIR pavements with AC overlay and 12 years for and CIR pavements with surface treatment. Using the performance prediction models, the PCI was estimated up to the 15th year for the CIR pavements with AC overlay having less than 15 years and until the 12th year for the CIR pavements with surface treatment having less than 12 years. The estimated PCI values are shown in red and underlined in Table 2.5 and Table 2.6. The predicted values were adjusted using a correction factor for each project, calculated as the difference between the last measured PCI value and the respective predicted PCI value at the same year (3).

Table 2.5. PCI Values for CIR Pavements with Overlay.

No.	Contract ID	Award Year	Existing Condition	Initial PCI	Pavement Condition Index (PCI)														
					1 year	2 years	3 years	4 years	5 years	6 years	7 years	8 years	9 years	10 years	11 years	12 years	13 years	14 years	15 years
13	3013	2001	94	100		100		100		95		94		94			94	93	98
14	3025A	2000	92	100		100		95		96		87						81	86
15	3025B	2000	89	100		97		97		100		86						83	85
16	3025C	2000	81	100		96		88		100		80			81			80	92
18	3097	2002	91	100		100		100		100		99				99	100	94	99
19	3099	2002	92	100		100		100		100		96				96	100	94	99
20	3116	2002	85	100		100		98		96		90				97	95	89	94
21	3138	2002	72	100		100		98		97		100				100	100	94	99
22	3139	2002	96	100		100		100		100		100				100	90	84	89
23	3143A	2002	85	100		100		100		100		100				100	85	79	84
24	3143B	2002	89	100		100		100		99		98				100	71	65	70
25	3143C	2002	83	100		100		100		100		100				100	72	66	71
26	3151A	2003	95	100		97		100		99		98			100	97	91	85	90
27	3151B	2003	97	100		86		100		100		100			100	100	94	88	93
28	3165	2003	85	100		100		100		91		89			98	95	89	83	88
29	3191	2003	48	100		100		100		100		92			100	92	86	80	85
30	3198	2004	81	100		100		91		99		63		73	99	96	90	84	89
31	3201	2004	61	100		100		99		99				100	99	96	90	84	89
32	3220A	2004	44	100		100		100		89				100	100	97	91	85	90
33	3220B	2004	44	100		100		100		89				89	100	97	91	85	90
34	3239A	2005	51	100		100		100		99			99	100	100	98	92	86	91
35	3239B	2005	62	100		100		100		99			100	98	99	96	90	84	89
36	3250	2005	73	100		100		99		100			100	97	98	95	89	83	88
37	3256	2005	90	100		98		95		91			91	99	100	97	91	85	90
38	3259	2005	87	100		100		100		100			100	100	100	98	92	86	91
39	3261	2005	66	100		100		100		100			100	98	99	96	90	84	89
40	3262	2005	93	100		100		100		90			90	99	100	97	91	85	90
41	3278A	2005	88	100		100		100		100			100	98	99	96	90	84	89
42	3278B	2005	85	100		100		98		95			95	90	91	88	82	76	81

Table 2.6. PCI Values for CIR Pavements with Surface Treatment.

No.	Contract ID	Award Year	Existing Condition	Initial PCI	Pavement Condition Index (PCI)											
					1 year	2 years	3 years	4 years	5 years	6 years	7 years	8 years	9 years	10 years	11 years	12 years
65	3151C	2003	95	100		100		95		95		95			100	91
68	D0-124-08A	2008	91	100		64				64	99	97	96	96	97	84
69	D0-124-08B	2008	84	100		98				98	92	90	89	89	90	77
70	D0-124-08D	2008	81	100		91				90	91	89	88	88	89	76
71	D2-004-09A	2009	100	100		92			92	86	87	85	84	84	85	72
72	D2-004-09B	2009	84	100		91			91	90	91	89	88	88	89	76
73	D2-004-11R	2011	84	100			84	97	99	100	100	100	100	100	100	88
74	D2-047-10A	2010		100	100			100	92	95	96	94	93	93	94	81
75	D2-047-10B	2010	72	100	100			100	76	79	80	78	77	77	78	65
76	D2-047-10C	2010	91	100	81			81	84	87	88	86	85	85	86	73
77	D3-010-05A	2005	80	100		100		98		94			88	91	92	79
78	D3-010-05B	2005	95	100		94		90		87			95	93	94	81
79	D3-041-10	2010	74	100	85			85	74	77	78	76	75	75	76	63
82	P197-60-050A	2006	66	100		100		94		95		96	100	100	100	88
84	P197-60-050C	2006	92	100		100		93		80		80	84	84	85	72
85	P264-03-050A	2003	92	100		89		92		73		89			91	73
86	P264-03-050B	2003	93	100		95		92		92		97			97	74
87	P264-03-050C	2003	89	100		100		91							99	74
88	P264-03-050D	2003	86	100		93		95		98		99			94	74
89	P264-03-050F	2003	92	100		100		100		98		89			83	75
90	P264-03-050H	2003	98	100		91		93		81		91			91	69
91	P264-03-050I	2003	98	100		95		96		88		91			88	73
92	P319-05-101	2005	79	100		99		92		90			90	93	94	81
93	P463-07-301A	2007	82	100		98		93			94	90	89	89	90	77
94	P463-07-301C	2007	55	100		99		89			88	86	85	85	86	73

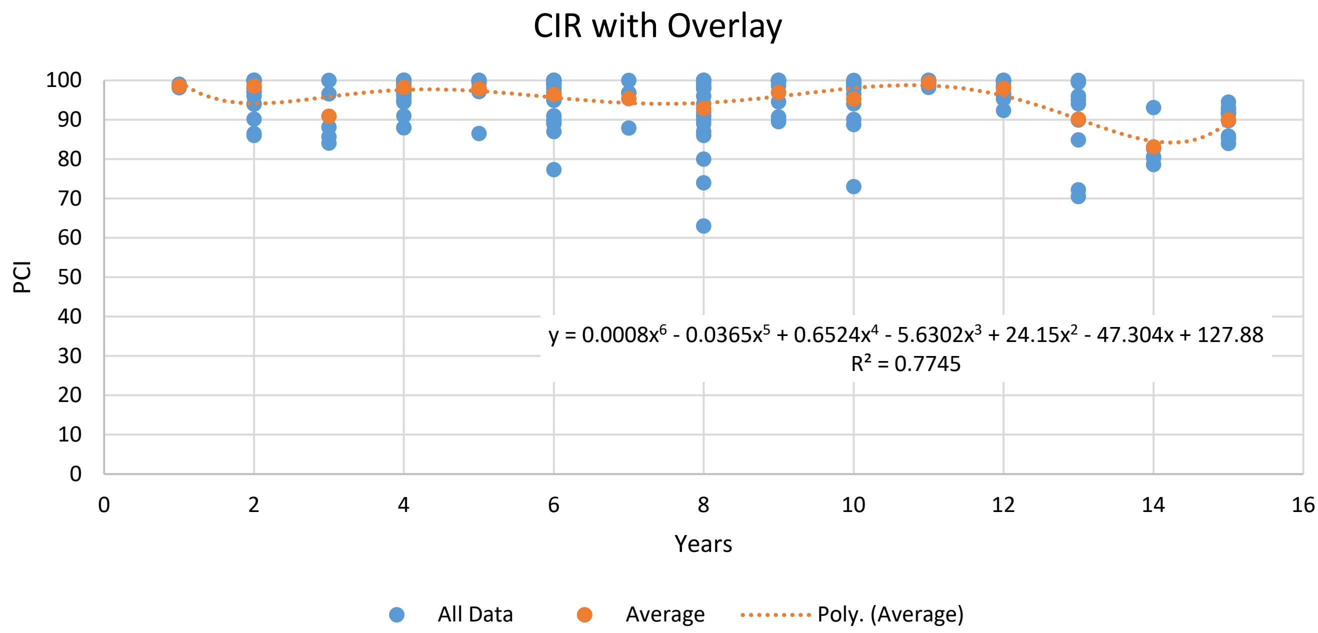

Figure 2.1. Performance model for CIR pavements with overlay.

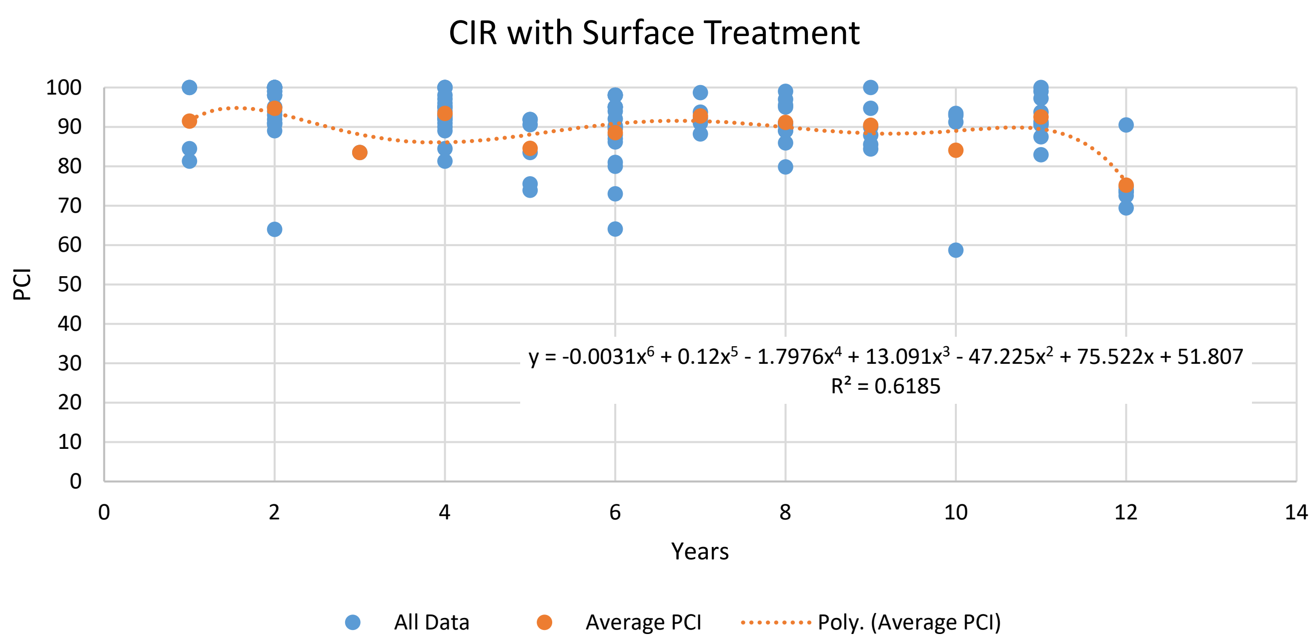

Figure 2.2. Performance model for CIR pavements with surface treatment.

Table 2.7. CIR Performance Models Parameters and Ranges.

CIR with AC Overlay						
Model	**Range of CIR Thickness (in)**	**Range of AC Overlay Thickness (in)**	**Range of AADT (veh./day)**	**AADT (%)**		
				AADT < 1,000	**1,000-5,000**	**AADT > 5,000**
$PCI = 0.0008 * Age^6 - 0.0365 * Age^5 + 0.6524 * Age^4 - 5.6302 * Age^3 + 24.15 * Age^2 - 47.304 * Age + 127.88$	2.0 - 3.0	1.5 - 3.0	233 -15,875	32	57	11
CIR with Surface Treatment						
Model	**Range CIR Thickness (in)**	**Range AC Overlay Thickness (in)**	**Range AADT (veh./day)**	**AADT (%)**		
				AADT < 1,000	**1,000-2,000**	**AADT > 2,000**
$PCI = -0.0031 * Age^6 + 0.12 * Age^5 - 1.7976 * Age^4 + 13.091 * Age^3 - 47.225 * Age^2 + 75.522 * Age + 51.807$	1.5 - 3.0	-	40 - 4,880	88	8	4

2.2. Benefit-Cost Analysis

A benefit-cost analysis was used to determine the relative cost-effectiveness of the different CIR projects throughout Nevada and identify key factors that led to more effective treatments. The benefit-cost ratio is defined as the ratio of the benefit offered by the CIR divided by the cost of the project. In this study, the cost of the project was defined as the initial construction cost of the CIR application, the cost of overlay or surface treatment application, and the cost of any maintenance treatment applied during the analysis period. The Present Worth (PW) of the initial and future costs was calculated and used for the benefit-cost analysis.

The costs of the CIR, overlay, and surface treatment were determined using bid information of various projects obtained from NDOT. As an example, Table 2.8 summarizes the cost of the CIR application and the cost of the AC overlay application for contract 3013. These costs were divided by the number of lanes and the number of miles of each project to determine cost per lane mile. In this example, project 3013 had two lanes and 19.602 miles, therefore, the CIR cost per lane mile was calculated as follows:

$$CIR\ [\$/lane\ mile] = \frac{\$938{,}250}{2\ lanes * 19.602\ mi} = \$23{,}933/lane\ mile$$

And

$$AC\ Overlay\ [\$/lane\ mile] = \frac{\$1{,}814{,}735}{2\ lanes * 19.602\ mi} = \$46{,}290/lane\ mile$$

Table 2.8. Costs for a CIR Pavement with Overlay on Contract 3013 at Year of Construction.

Layer	Item	Unit	Unit Price ($)	Amount	Cost ($)
CIR	Cold Milling	sqm	4	5700	22,800
	Lime	mton	125	814	101,750
	Recycled Bituminous Surface (75mm depth)	sqm	2	305100	610,200
	Emulsified Asphalt, Type CMS-2s	mton	250	814	203,500
	Total				**938,250**
Overlay	Plantmix Bituminous Surface Aggregate (Type 2)	mton	22	59050	1,299,100
	Milled Rumble Strips	km	225	63	14,175
	Emulsified Asphalt, Type CMS-2s (Diluted)	mton	250	138	34,500
	Emulsified Asphalt, Type SS-1H	mton	240	317	76,080
	Plantmix Bituminous Open-Graded Surface Aggregate (9.5mm)	mton	28	13960	390,880
	Total				**1,814,735**

Since the available bid information of each project included only the initial construction costs, the cost of maintenance treatments applied during the service life of the pavement were calculated as the average cost of the treatment based on several projects using that used the same treatment. Once the cost per lane mile of the CIR, AC overlay, surface treatment, and maintenance treatments were determined, the PW at the year of construction was calculated for each project, as summarized in Table 2.9 and Table 2.10 for CIR with overlay and CIR with surface treatment, respectively. Average costs of CIR and surface treatment were assumed for projects without bid information as shown in red and underlined in Table 2.10.

The benefit is defined as the area under the performance curve of the pavement during the analysis period. Analysis period of 15 years was selected for CIR pavements with AC overlay and 12 years for CIR pavements with surface treatment. The benefit was calculated using areas of triangles and rectangles under the PCI curves. Figure 2.3 shows a sample of the PCI curve for contract 3013 over an analysis period of 15 years. The total area under the PCI was subdivided into triangles and rectangles and the overall benefit was calculated as follows:

$$Benefit_{3013} = [100 * 4] + \left[\frac{(100-95)*2}{2} + 95*2\right] + \left[\frac{(95-94)*2}{2} + 94*2\right] + [94*5] + \left[\frac{(94-93)*1}{2} + 93*1\right] + \left[\frac{(98-93)*1}{2} + 93*1\right]$$

$$Benefit_{3013} = 400 + 195 + 189 + 470 + 93.5 + 95.5 = 1443$$

Table 2.11 summarizes the benefit cost ratios of the CIR pavements with AC overlay selected for this study over analysis period of 15 years. Some factors that may influence the benefit cost ratio were identified as; CIR thickness, AC overlay thickness, asphalt emulsion type, and average annual daily traffic (AADT).

Table 2.9. Cost Per Lane Mile of CIR Pavements with Overlay and Present Worth at Year of Construction.

Contract ID	CIR Cost ($/lane mile)	Overlay Cost ($/lane mile)	Maintenance 1 Cost ($/lane mile)	Maintenance 2 Cost ($/lane mile)	Present Worth at Construction Year ($/lane mile)
3013	23,933	46,290	1,360	1,486	72,369
3025A	17,041	28,016	11,435	11,813	63,168
3025B			11,778		54,634
3025C			11,778	14,485	64,210
3097	22,070	67,042	1,321		90,218
3099	26,788	73,222	1,401	12,909	110,169
3116	24,587	63,190	12,870		97,937
3138	27,783	75,816	1,401		104,705
3139	15,787	41,892	13,256		67,839
3143A	27,056	75,881	11,813		111,991
3143B			11,813		111,991
3143C			11,813		111,991
3151A	20,139	31,308	13,256		61,912
3151B			13,256		61,912
3165	25,333	101,627	1,531		128,099
3191	63,548	86,451	1,531		151,138
3198	14,415	31,677	11,813	12,168	65,302
3201	36,441	112,545	1,401		150,159
3220A	37,862	66,730	1,443		105,765
3220B			1,486		105,765
3239A	45,568	280,105	1,401		326,882
3239B			1,401		326,882
3250	33,875	128,815			162,690
3256	19,395	29,233	14,063		59,730
3259	46,503	77,806	1,531		125,517
3261	19,879	69,120	12,533		98,604
3262	22,579	95,945	12,533		128,128
3278A	32,911	106,220	1,401		140,340
3278B					139,131

Table 2.10. Cost Per Lane Mile of CIR Pavements with Surface Treatment and Present Worth at Year of Construction.

Contract ID	CIR Cost ($/lane mile)	Surf. Treatment Cost ($/lane mile)	Maintenance 1 Cost ($/lane mile)	Maintenance 2 Cost ($/lane mile)	Present Worth at Construction Year ($/lane mile)
3151C	157,815	1,424	13,256		169,704
D0-124-08A	116,107	8,632	1,530		60,448
D0-124-08B			22,126		60,448
D0-124-08D					126,060
D2-004-09A	86,155	8,970	12,908		146,867
D2-004-09B			21,430		124,740
D2-004-11R	33,222*	22,735*			55,957
D2-047-10A	36,151	35,354			71,505
D2-047-10B					71,505
D2-047-10C					71,505
D3-010-05A	16,611*	19,040*	11,101		46,753
D3-010-05B			11,434		46,753
D3-041-10	37,316	35,710	12,908		84,496
P197-60-050A	22,148*	19,612*	1,400	24,843	62,616
P197-60-050C			1,486		43,004
P264-03-050A	22,148*	17,947*			40,095
P264-03-050B					40,095
P264-03-050C					40,095
P264-03-050D					40,095
P264-03-050F					40,095
P264-03-050H					40,095
P264-03-050I					40,095
P319-05-101	33,222*	9,893*	14,063		54,217
P463-07-301A	33,222*	20,200*	20,200	25,451	95,577
P463-07-301B			21,482		74,904

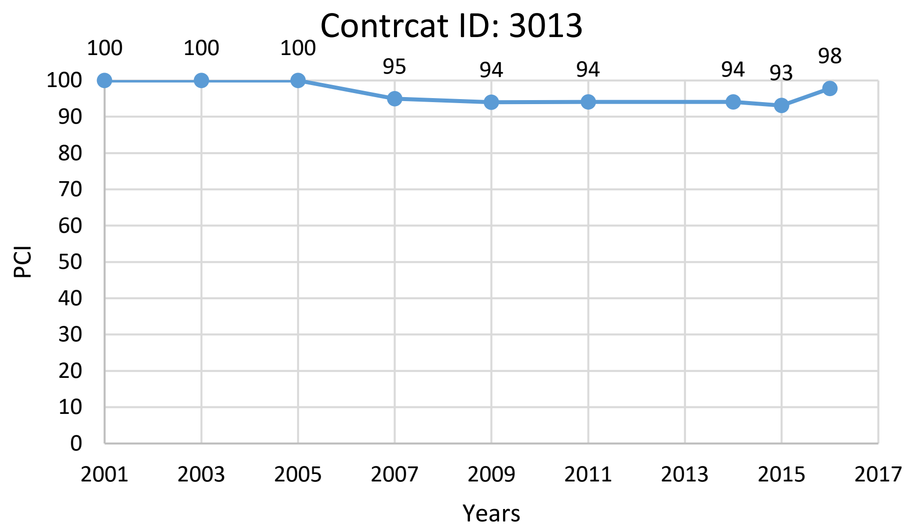

Figure 2.3. Performance of CIR pavement on contract 3013.

Table 2.11. Benefit-Cost Analysis for CIR Pavements with AC Overlay Projects over 15-years Analysis Period.

Contract ID	PW at Construction Year ($/lane mile)	Predicted Benefit over 15 years	Predicted Benefit/Cost (B/C x 100) over 15 years (%)	CIR Thickness (in)	Overlay Thickness (in)	Emulsion Type	AADT
3013	72,369	1443	1.99	3	3	CMS-2s	3,343
3025A	63,167	1357	2.15	2	2	CMS-2s	656
3025B	54,633	1365	2.50	2	2.25	CMS-2s	400
3025C	64,210	1317	2.05	2	2	CMS-2s	400
3097	90,218	1488	1.65	2.5	2.5	CMS-2s	1,123
3099	110,168	1472	1.34	3	3	CMS-2s	2,600
3116	97,936	1432	1.46	3	2.5	CMS-2s	800
3138	104,705	1484	1.42	3	2	CMS-2s	1,250
3139	67,838	1469	2.17	3	2.5	CMS-2s	2,600
3143A	111,991	1456	1.30	3	3	CMS-2s	2,663
3143B	111,991	1413	1.26	3	3	CMS-2s	2,700
3143C	111,991	1424	1.27	2	3	CMS-2s	2,765
3151A	61,911	1455	2.35	3	1.5	CMS-2s	233
3151B	61,911	1451	2.34	3	1.5	CMS-2s	350
3165	128,098	1412	1.10	3	2.5	CMS-2s	5,600
3191	151,138	1431	0.95	3	3	CMS-2s	15,875
3198	65,302	1329	2.04	3	2	CMS-2s	520
3201	150,159	1459	0.97	3	3	CMS-2s	4,300
3220A	105,764	1435	1.36	2.75	2	CMS-2s	

Contract ID	PW at Construction Year ($/lane mile)	Predicted Benefit over 15 years	Predicted Benefit/Cost (B/C x 100) over 15 years (%)	CIR Thickness (in)	Overlay Thickness (in)	Emulsion Type	AADT
3220B	105,764	1408	1.33	2.75	3	CMS-2s	2,480
3239A	326,881	1418	0.43	3	2	CMS-2s	3,100
3239B	326,881	1459	0.45	3	2	CMS-2s	1,334
3250	162,690	1454	0.89	3	3	CMS-2s	8,000
3256	59,730	1413	2.37	3	1.5	CMS-2s	486
3259	125,517	1472	1.17	2	2	CMS-2s	1,564
3261	98,603	1462	1.48	3	3	CMS-2s	2,600
3262	128,128	1422	1.11	3	3	CMS-2s	1,413
3278A	140,339	1462	1.04	3	3	CMS-2s	1,968
3278B	139,131	1391	1.00	3	1.5	CMS-2s	500

Figure 2.4 shows the benefit-cost comparison of CIR pavements with AC overlay over analysis period of 15 years. Benefit-costs were divided into three levels; low for benefit-cost ratio less than 1%, medium for benefit-cost ratio between 1 and 2%, and high for benefit-cost ratio higher than 2%. The boundaries between the three levels of benefit-cost ratios were selected in order to obtain reasonable distribution of CIR pavements within each category. From the estimated benefit-cost data, 28% of the projects had a high benefit-cost ratio, 52% of the projects had medium benefit-cost ratio, and 21% of the projects had low benefit-cost ratio.

Projects with lower AADT tend to have higher benefit-cost ratio. The average AADT of CIR with overlay projects with high benefit-cost ratio was 706 vehicles, while for projects with medium benefit-cost ratio the average AADT was 2348 vehicles, and for projects with low-benefit cost ratio the average AADT was 5518 vehicles. On average, the CIR thickness of projects with high benefit-cost ratio was 2.6 inch, while for medium benefit-cost ratio the average CIR thickness was 2.8 inch, and for low benefit-cost ratio the average CIR thickness was 3.0 inch.

The observed inverse relationship between benefit-cost ratio and thickness of CIR and AC overlay is caused by the inter-dependency between traffic level and layers thickness. The data indicate that the influence of traffic on the benefit-cost is highly significant and could not be balanced by the recommended thickness of the CIR and AC overlay. This may indicate that the structural design method used for CIR pavements does not properly take into consideration the traffic level. Since the asphalt emulsion used for all the CIR pavements with AC overlay was CMS-2s, the impact of asphalt emulsion type on the benefit cost could not be investigated.

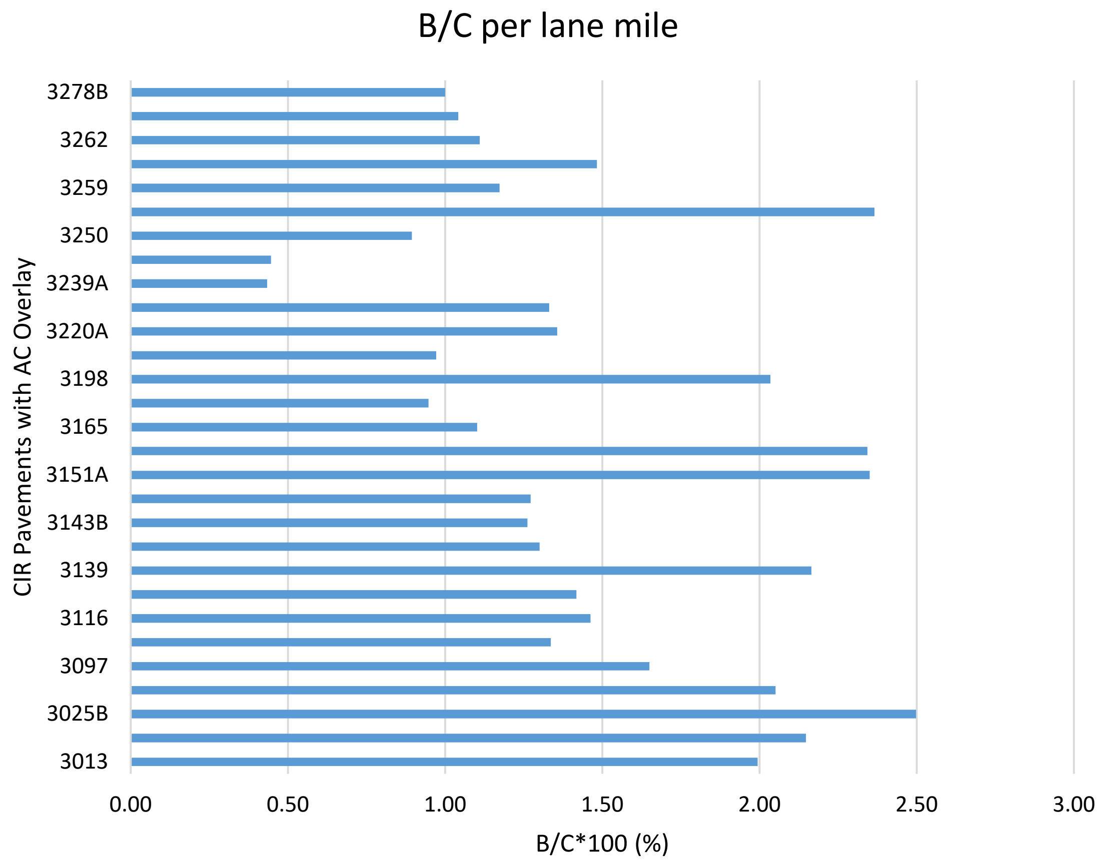

Figure 2.4. Benefit-cost analysis for CIR pavements with AC overlay over 15-years analysis period.

The same analysis was conducted for the CIR pavements with surface treatment. Table 2.12 summarizes the benefit-cost ratios of the CIR pavements with surface treatment over analysis period of 8 years. Some factors that may influence the benefit-cost ratio were identified as; CIR thickness, asphalt emulsion type, and average annual daily traffic (AADT).

Figure 2.5 shows the benefit-cost comparison of the selected CIR pavements with surface treatment over analysis period of 8 years. Benefit-cost ratios were divided into three levels; low for benefit-cost ratio less than 0.75%, medium for benefit-cost ratio between 0.75 and 1.5%, and high for benefit-cost ratio higher than 1.5%. The boundaries between the three levels of benefit-cost ratios were selected in order to obtain reasonable distribution of CIR pavements within each category. From the estimated benefit-cost data, 40% of the projects had a high benefit-cost ratio, 36% of the projects had medium benefit-cost ratio, and 24% of the projects had low benefit-cost ratio.

As in the case of CIR pavements with AC overlay, CIR pavements with surface treatment with lower AADT tend to have higher benefit-cost ratio. The average AADT of CIR pavements with surface treatment with high benefit-cost ratio was 199 vehicles, while for projects with medium benefit-cost ratio the average AADT was 516 vehicles, and for projects with low benefit-cost ratio the average AADT was 1313 vehicles. On average, the CIR thickness of projects with high benefit-cost ratio was 2.0 inch, while for medium and low benefit-cost ratio the average CIR thickness was 3.0 inch. The type of asphalt emulsion used did not have a considerable impact on the benefit-cost ratio. The data indicate that the influence of traffic on the benefit-cost is highly significant and could not be balanced by the recommended thickness of the CIR.

Table 2.12. Benefit-Cost Analysis for CIR with Surface Treatment Projects over 8-years Analysis Period.

Contract ID	PW at Construction Year ($/lane mile)	Predicted Benefit over 8 years	Predicted Benefit/Cost (B/C x 100) over 8 years (%)	CIR Thickness (in)	Emulsion Type	AADT
3151C	169,704	775	0.46	3	CMS-2s	150
D0-124-08A	126,061	600	0.48	3	Reflex	1,600
D0-124-08B	146,867	776	0.53	3	Reflex	350
D0-124-08D	124,740	734	0.59	3	Reflex	550
D2-004-09A	106,261	730	0.69	3	CMS-2s	4,880
D2-004-09B	116,556	735	0.63	3	CMS-2s	350
D2-004-11R	55,958	764	1.37	3	CMS-2s	350
D2-047-10A	71,505	780	1.09	2.5	CMS-2s	350
D2-047-10B	71,505	724	1.01	2.5	CMS-2s	1,757
D2-047-10C	71,505	676	0.95	3	CMS-2s	447
D3-010-05A	46,754	774	1.66	1.5	Pass-R	100
D3-010-05B	46,754	734	1.57	1.5	Reflex	100
D3-041-10	84,496	657	0.78	3	CMS-2s	439
P197-60-050A	62,617	774	1.24	2	Reflex	550
P197-60-050C	43,005	726	1.69	2	Reflex	40
P264-03-050A	40,096	697	1.74	2	CMS-2s	250
P264-03-050B	40,096	755	1.88	2	CMS-2s	250
P264-03-050C	40,096	764	1.91	2	Reflex	250
P264-03-050D	40,096	771	1.92	2	Reflex	250
P264-03-050F	40,096	785	1.96	2	Reflex	250
P264-03-050H	40,096	721	1.80	2	CMS-2s	250
P264-03-050I	40,096	749	1.87	2	CMS-2s	250
P319-05-101	54,217	752	1.39	3	CMS-2s	250
P463-07-301A	95,578	762	0.80	3	Reflex	250
P463-07-301B	74,905	740	0.99	3	Reflex	250

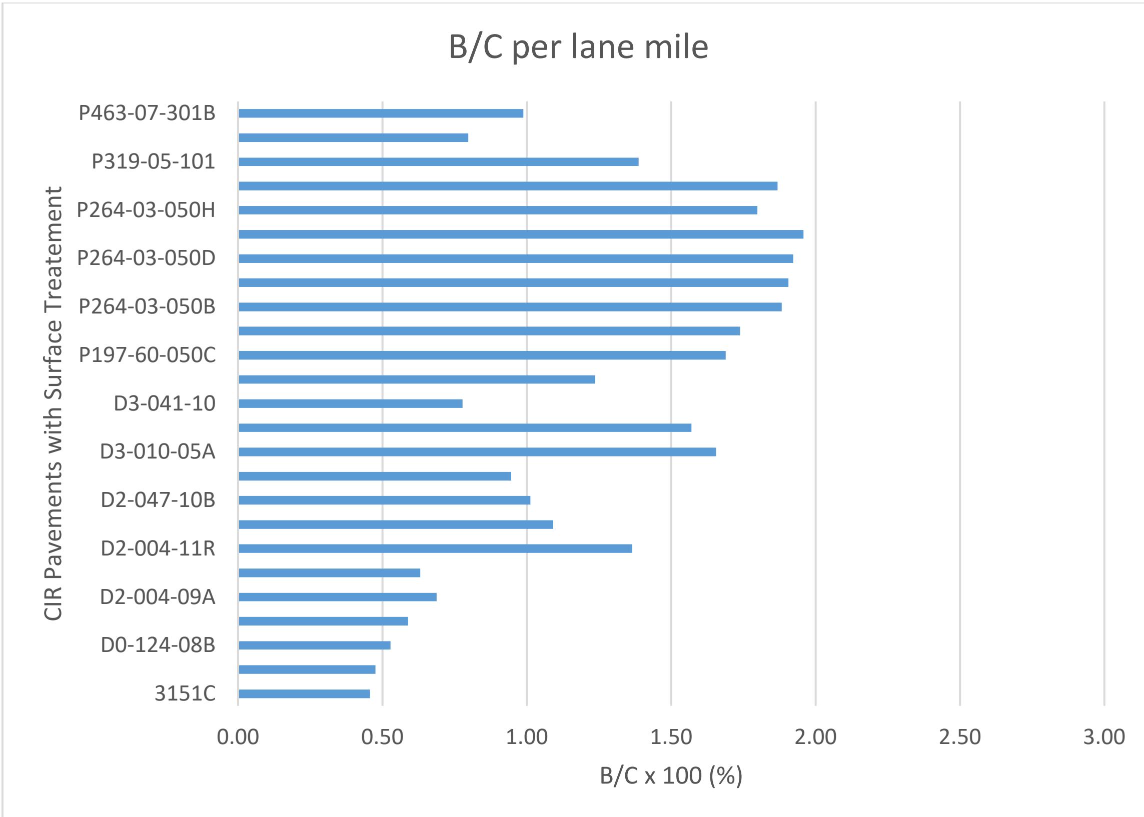

Figure 2.5. Benefit-cost analysis for CIR pavements with surface treatment over 8- years Analysis Period.

2.3. Findings and Recommendations

In summary, the benefit-cost ratio for CIR pavements with AC overlay and surface treatment exhibited inverse relationship between traffic (AADT) and the thicknesses of the CIR layer and AC overlay. This observations leads to the conclusion that the current methods of mix design and structural design do not properly represent the engineering properties of the CIR layer. Therefore, new methods for mix design and structural design are needed for the CIR layer as presented in Chapters 3, 4, and 5 of this report.

Chapter 3. MIX DESIGN PROCEDURE

The objective of this effort was to develop a mix deign method for CIR mixtures to be used by the Nevada DOT to design mixtures for CIR pavements with AC overlay and surface treatment as the wearing course. Since the Nevada DOT uses the Hveem mix design method to design asphalt mixtures, the first goal was to develop a mix design method for CIR mixtures based on the Hveem method. The second goal was to recommend a mix design method for CIR mixtures based on the Superpave method in order to accommodate any future plans for NDOT to adopt the Superpave mix design method.

3.1. Experimental Plan

An extensive laboratory-based experimental plan was develop in order to develop a robust mix design method that is applicable over a wide range of parameters that considered critical to the performance of CIR pavements. Table 3.1 summarizes the selected parameters and their levels that were incorporated into the experimental plan.

Table 3.1. Parameters Incorporated into the Mix Design Experiment.

Parameter	Levels	Type
Asphalt Emulsion	4	A: Standard CMS-2s B: Latex-Modified C: Polymer-Modified D: Rubber-Modified
RAP Gradation	2	Graded Non-graded
Lime Slurry	2	6.0%: 2% Lime + 4% water 4.5%: 1.5% Lime + 3% water

The RAP material was obtained from the Granite Construction Inc. Lockwood plant. All RAP materials were crushed to a maximum size of 1.0 inch. The non-graded RAP was used as is after crushing while the graded RAP were combined to meet the PCCAS specification for medium CIR gradation as shown in Figure 3.1. All RAP materials were oven-dried at 140^{o}F until constant mass prior to the batching and mixing process.

The asphalt emulsions were obtained from the four sources in quantities sufficient for 3-month worth of research to avoid separation due to long-term storage. The lime slurry were prepared immediately prior to the mixing process. In addition to the water from the lime slurry, a 1.5% water was added to all CIR mixtures to represent the amount of water added in the field during the milling operation.

All components of the CIR mixture were determined as percent by dry weight of the RAP material in the mix. For example, a CIR mix with an asphalt emulsion content of 3.0% indicates that the weight of asphalt emulsion added is 3.0% of the dry weight of RAP material present in the mix.

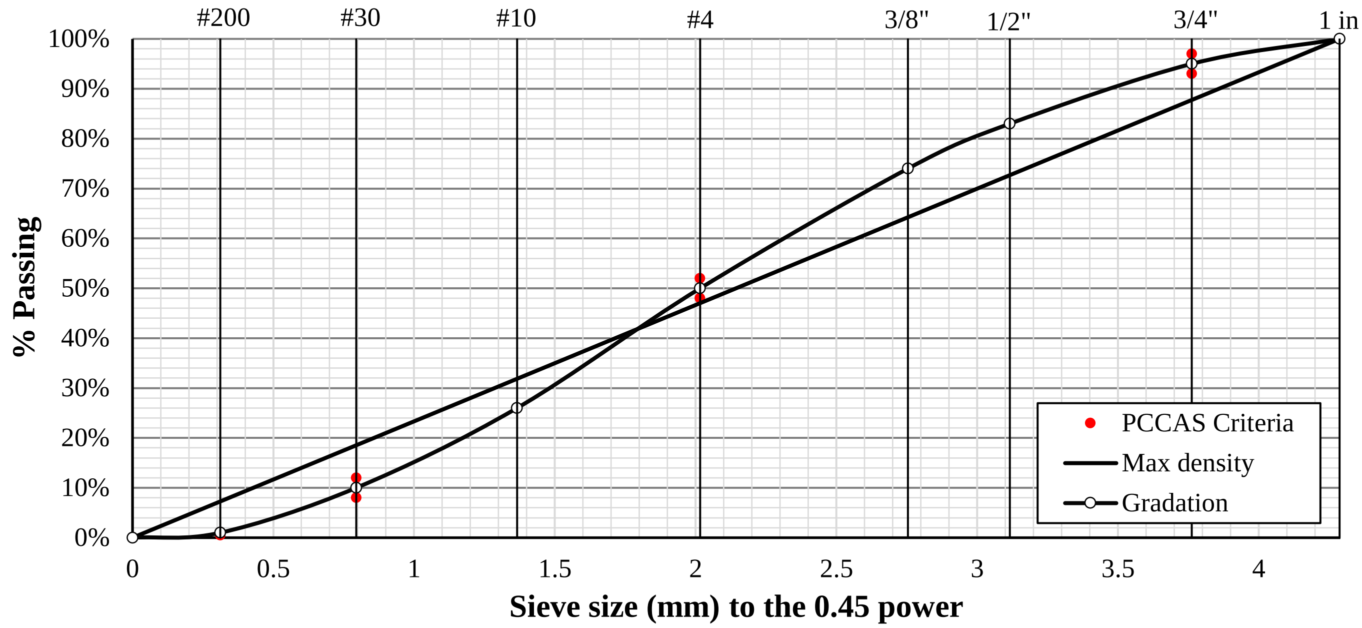

Figure 3.1. Gradations of the graded RAP materials.

3.2. Preparation of CIR Mixtures

This section presents the various steps involved in the preparation of the CIR mixtures. During the preparation of the CIR mixtures; RAP materials, asphalt emulsions, water, and lime slurry were all used at ambient temperature around 77^{o}F. The steps presented in this section are common to both the Hveem and Superpave mix design methods.

3.2.1. Mixing Time

Mixing times for CIR mixtures were determined through previous studies performed at the Western Regional Superpave Center (WRSC) (4). The following sequence and mixing times are used in the preparation of the CIR mixture:

- Dry the RAP to a constant weight; 24 hours at 140^{o}F.
- Mix the RAP with 1.5% water for 1-minute
- Mix he RAP+1.5% water with the lime slurry for 2-minutes
- Mix the RAP+1.5% water + lime slurry with the asphalt emulsion for 1-minute

A satisfactory coating of the RAP materials must be observed after the completion of the last mixing process. Figure 3.2 shows the four stages of the preparation of the CIR mixture.

3.2.2. Determination of Maximum Theoretical Specific Gravity

The theoretical maximum specific gravity of the CIR mix (G_{mm}) was determined as per AASHTO T209 with a sample weight of 2500g. Two replicate samples are used to measure G_{mm}. The measured values should meet the AASHTO T209 specifications for (for single-operator precision, less than 0.014) and for standard deviation (for single-operator precision, less than 0.0051).

The G_{mm} is measured at a single asphalt emulsion content of 3.0% and back-calculated at other contents, assuming a constant effective specific gravity of the aggregates (G_{se}) determined using the equation below. Earlier research at UNR indicated that the G_{se} of the RAP materials remains constant up to an asphalt emulsion content of 4.0%.

a) Dry RAP

b) RAP+1.5% water

c) RAP+1.5%water+Slurry

d) RAP+1.5%water+Slurry+Emuslion

Figure 3.2. Four stages of the CIR mix preparation.

$$G_{se} = \frac{P_s}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}}$$

Where; P_s is the percent of RAP in the CIR mix, G_b is the specific gravity of asphalt binder (i.e., residue), and P_b represents the percent of asphalt binder from the emulsion; for example, emulsion content 3.0%, emulsion residue 65% ---- P_b = 3.0 x 0.65 = 1.95%.

Once the Gse is determined, the Gmm at the other asphalt emulsion contents can be calculated from the relationship below.

$$G_{mm} = \frac{100}{\frac{Ps}{G_{se}} + \frac{P_b}{G_b}}$$

3.3. Hveem Mix Design Method

The NDOT Hveem method uses the California Kneading compactor to compact the loose mixtures as shown in Figure 3.3. For AC mixtures, the NDOT process applies 25 tamps at 250 psi followed by 150 tamps at 500 psi using. The compaction step is followed by the application of a uniform leveling stress of 1,000 psi.

Figure 3.3. Hveem kneading compaction set-up.

In the case of CIR mixtures, a target design air voids of 13±1% was established through earlier research work (4). For this study, multiple compaction efforts were used on trial CIR mixtures to determine the appropriate number of tamps and the magnitude of the leveling stress to achieve the target air voids at asphalt emulsion contents in the range of 2 – 4%. The final kneading compaction procedure for CIR mixtures consisted of:

- 25 tamps at 250 psi
- 100 tamps at 500 psi
- leveling stress:
    - 300 psi for graded RAP
    - 500 psi for non-graded RAP

Following the compaction of the Hveem samples, the compacted samples are cured in an oven at 140°F for 24 hours prior to the determination of the bulk specific gravity (G_{mb}). The G_{mb} of the compacted and cured samples is determined following ASTM D1188 using the parafilm method due to the high air voids content of the compacted CIR mix.

In this research, a total of 16 CIR mixtures were prepared at 4 asphalt emulsion contents using the mixing process described in Section 3.2 and compacted in the kneading compactor following the recommended number of tamps and leveling stress. Two replicates were prepared at each asphalt emulsion content. Table 3.2 summarizes the 16 CIR mixtures that were evaluated.

Table 3.2. Characteristics of the 16 CIR Mixtures.

Asphalt Emulsion	Lime Slurry (%)	RAP	Asphalt Emulsion Content
A: Standard CMS-2s	4.5	Graded	2.5, 3.0. 3.5, and 4.0
		Non-Graded	
	6.0	Graded	
		Non-Graded	
B: Latex-Modified	4.5	Graded	
		Non-Graded	
	6.0	Graded	
		Non-Graded	
C: Polymer-Modified	4.5	Graded	
		Non-Graded	
	6.0	Graded	
		Non-Graded	
D: Rubber-Modified	4.5	Graded	
		Non-Graded	
	6.0	Graded	
		Non-Graded	

The G_{mm} for each of the 16 CIR mixtures were determined at the asphalt emulsion content of 3.0% and calculated at the other contents using the G_{se}. Table 3.3 summarizes typical data from the full Hveem mix design of a CIR mixture.

The next step in the mix design process is to determine the optimum emulsion content (OEC). Figure 3.4 presents the relationship between air voids and asphalt emulsion content for the same CIR mix summarized in Table 3.3. The OEC is determined as the asphalt emulsion content that produces an air voids content of 13±1%. In this case, the OEC was identified as 3.2% by dry weight of RAP materials. This process was repeated for all 16 CIR mixtures to identify and the OEC's summarized in Table 3.4.

Table 3.3. Mix Design Results of CIR Mix; Type B Emulsion, 6% Lime Slurry, and Graded RAP Material.

Sample ID	Emulsion Content (%)	Gmb	Gmm	Air voids (%)	Standard Deviation	Spec[1]	D2S	Spec[2]
1	2.5	2.019	2.345	13.90	0.002	0.028	0.002	0.079
2	2.5	2.017	2.345	14.00				
3	3.0	2.027	2.338	13.30	0.003	0.028	0.005	0.079
4	3.0	2.032	2.338	13.10				
5	3.5	2.030	2.331	12.90	0.005	0.028	0.007	0.079
6	3.5	2.037	2.331	12.60				
7	4.0	2.042	2.323	12.10	0.007	0.028	0.009	0.079
8	4.0	2.033	2.323	12.50				

[1] Standard deviation criteria as per ASTM D1188 for bulk specific gravity
[2] Acceptable range of two test results criteria per ASTM D1188

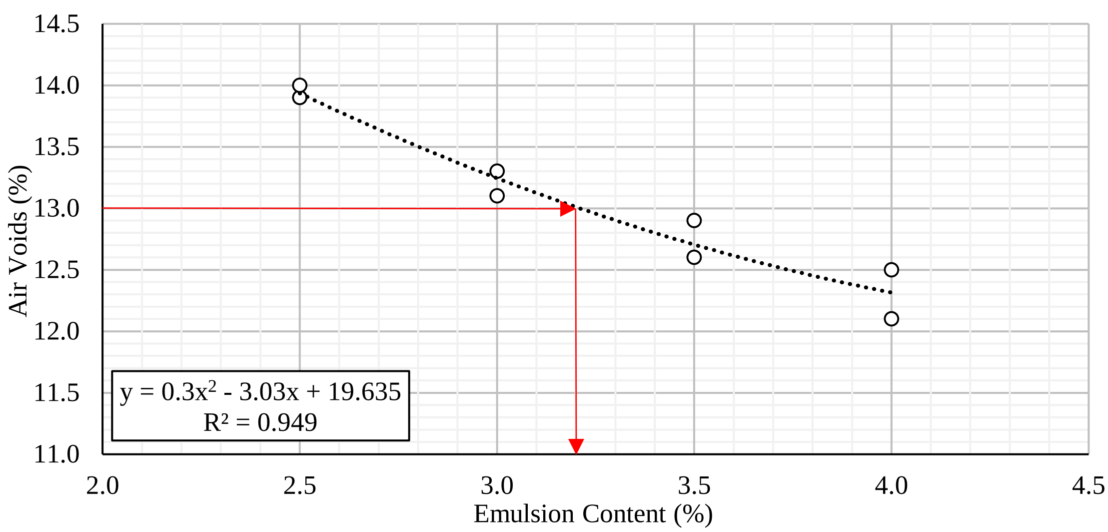

Figure 3.4. Air voids versus emulsion content of CIR mix: Type B emulsion, 6% lime slurry, and graded RAP material.

Table 3.4. Summary of the Hveem Mix Designs for the 16 CIR Mixtures.

Asphalt Emulsion	Lime Slurry (%)	RAP	Optimum Emulsion Content, OEC (%)
A: Standard CMS-2s	4.5	Graded	3.7
		Non-Graded	3.4
	6.0	Graded	3.7
		Non-Graded	4.0
B: Latex-Modified	4.5	Graded	3.5
		Non-Graded	3.8
	6.0	Graded	3.2
		Non-Graded	3.5
C: Polymer-Modified	4.5	Graded	3.0
		Non-Graded	3.1
	6.0	Graded	2.9
		Non-Graded	2.8
D: Rubber-Modified	4.5	Graded	3.5
		Non-Graded	3.6
	6.0	Graded	4.0
		Non-Graded	4.0

Figure 3.5 compares the OEC's of the 16 CIR mixtures determined by the Hveem mix design method. A review data presented in Figure 3.5 leads to the following observations:

- The optimum emulsion contents of the majority of the CIR mixtures evaluated in this study range between 3.0 and 4.0% by dry weight of RAP materials.
- There is no significant difference between the OEC for non-graded and graded RAP materials.
- There is no significant difference between the OEC for 4.5 and 6.0% lime slurry.
- Emulsion type C resulted in the lowest OEC while emulsion type D resulted in the highest OEC.
- All the above observations leads to the conclusion that every combination of RAP material source and asphalt emulsion type/source constitutes a unique CIR mixture that must be individually designed.

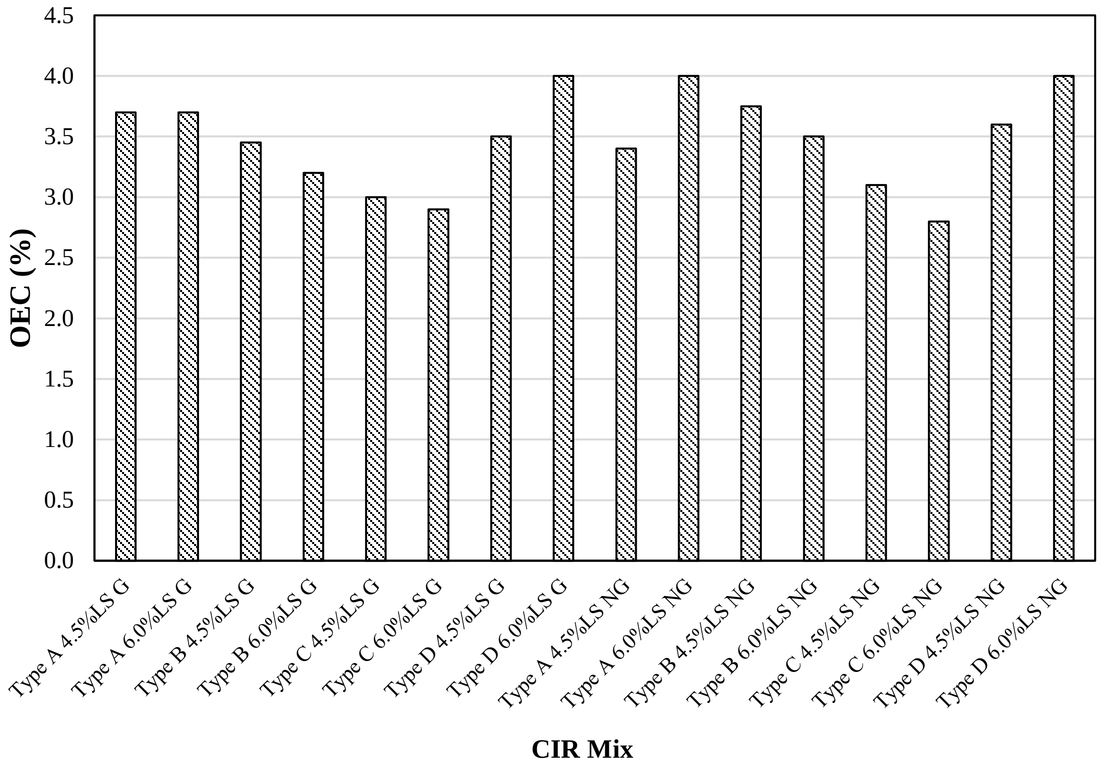

Figure 3.5. Optimum emulsion contents for the CIR mixtures designed with the Hveem method.

The final step of the Hveem mix design method is to evaluate the moisture sensitivity of the CIR mixtures at OEC in accordance with AASHTO T283. The moisture sensitivity was evaluated in terms of the tensile strength ratio (TSR) defined as the ratio of the wet tensile strength (TS) over the dry TS of the CIR mixture measured at 77°F. Six samples (per mix) were mixed at OEC and compacted at 2.5 inches height by 4.0 inches diameter at air voids content of 13±1%.

The TS properties of the moisture-conditioned and unconditioned sets were measured at 77°F. The average TS of the moisture-conditioned set will be referred to as the "Wet TS" and the average TS of the unconditioned set will be referred to as the "Dry TS". Table 3.5 summarizes the moisture sensitivity properties of the 16 CIR mixtures.

Table 3.5. Moisture Sensitivity Properties of the 16 CIR Mixtures Designed with the Hveem Method.

Asphalt Emulsion	Lime Slurry (%)	RAP Materials	Avg Dry TS (psi) @77°F	Avg Wet TS (psi) @77°F	TSR (%) @77°F
A: Standard CMS-2s	4.5	Graded	96	66	69
		Non-Graded	101	65	64
	6.0	Graded	101	70	69
		Non-Graded	94	69	73
B: Latex-Modified	4.5	Graded	88	66	76
		Non-Graded	102	68	67
	6.0	Graded	77	71	93
		Non-Graded	85	73	85
C: Polymer-Modified	4.5	Graded	93	69	75
		Non-Graded	114	83	73
	6.0	Graded	91	71	78
		Non-Graded	106	89	84
D: Rubber-Modified	4.5	Graded	88	56	64
		Non-Graded	91	67	74
	6.0	Graded	76	67	88
		Non-Graded	91	67	74

Figure 3.6, 3.7, and 3.8 present the dry TS, wet TS, and TSR for all 16 CIR mixtures. The bars represent the average value while the whisker present the 95% confidence interval. An overlap in the 95% confidence interval indicates statistically similar properties. Examination of the data presented in Figure 3.6, 3.7, and 3.8 leads to the following observations:

- The impact of RAP gradation on the dry TS and wet TS properties of the CIR mixtures is insignificant which is shown by the overlapping of the 95% confidence intervals of the graded (G) and non-graded (NG) mixtures.
- The dry TS properties of the CIR mixtures with 6.0% lime slurry are higher than the dry TS properties of the CIR mixtures with 4.5% lime slurry. The wet TS properties of the CIR mixtures with 6.0% lime slurry are similar to the wet TS properties of the CIR mixtures with 4.5% lime slurry which is shown by the overlapping of the 95% confidence intervals of the 6.0% LS and 4.5% LS mixtures
- The impact of RAP gradation on the TSR of the CIR mixtures is insignificant which is shown by the overlapping of the 95% confidence intervals of the graded (G) and non-graded (NG) mixtures.
- The TSR's of the CIR mixtures with 6.0% lime slurry are lower than the TSR's of the CIR mixtures with 4.5% lime slurry. This observation is somewhat misleading due to the fact the fact that CIR mixtures with 6.0% lime slurry exhibited higher dry TS properties and similar wet TS properties to the CIR mixtures with 4.5% lime slurry. When the ratio of the TS properties is determined, the impact of the higher dry TS property is reversed.

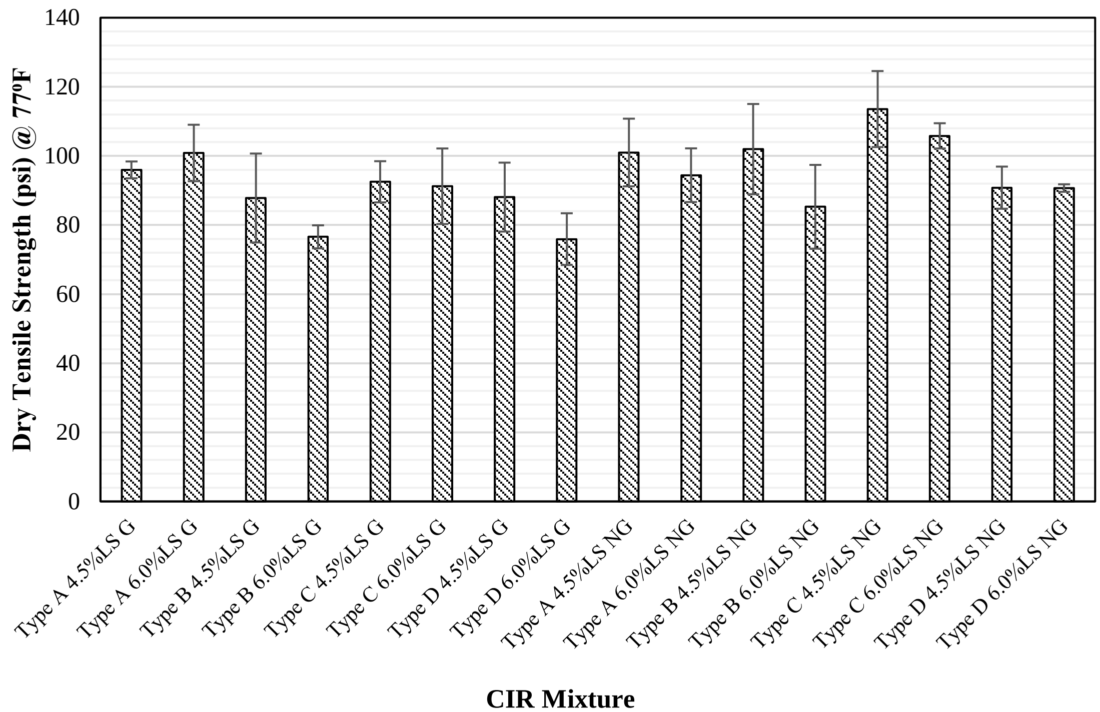

Figure 3.6. Dry TS properties of CIR mixtures designed with the Hveem method.

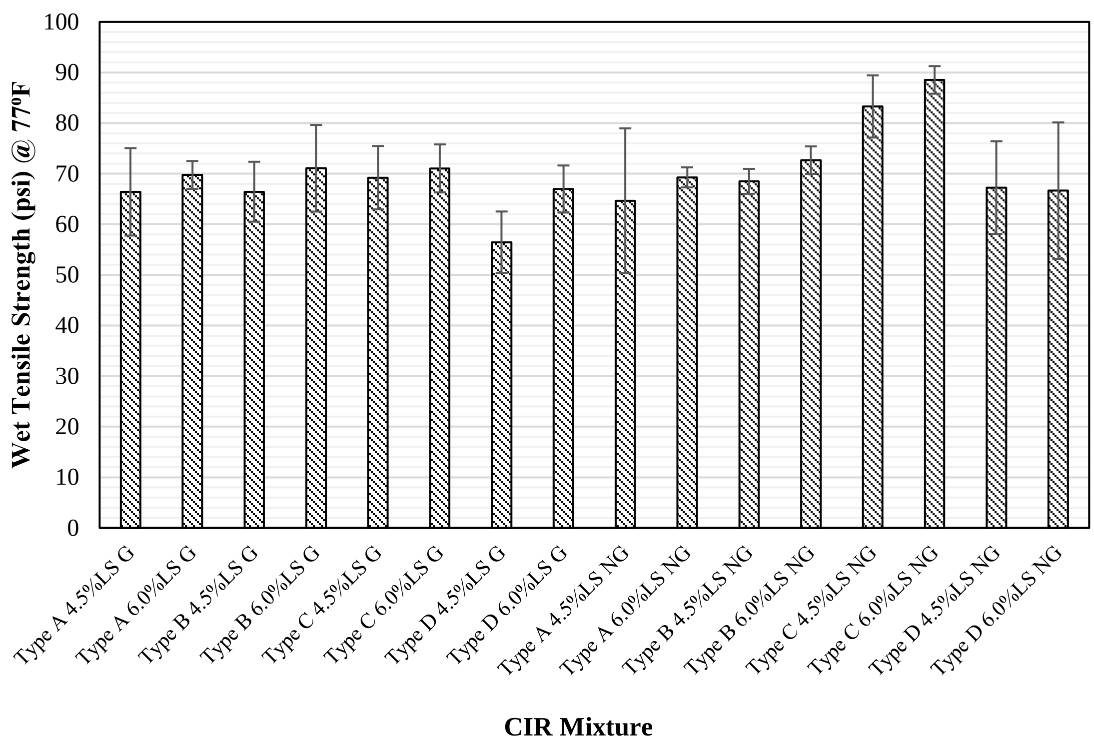

Figure 3.7. Wet TS properties of CIR mixtures designed with the Hveem method.

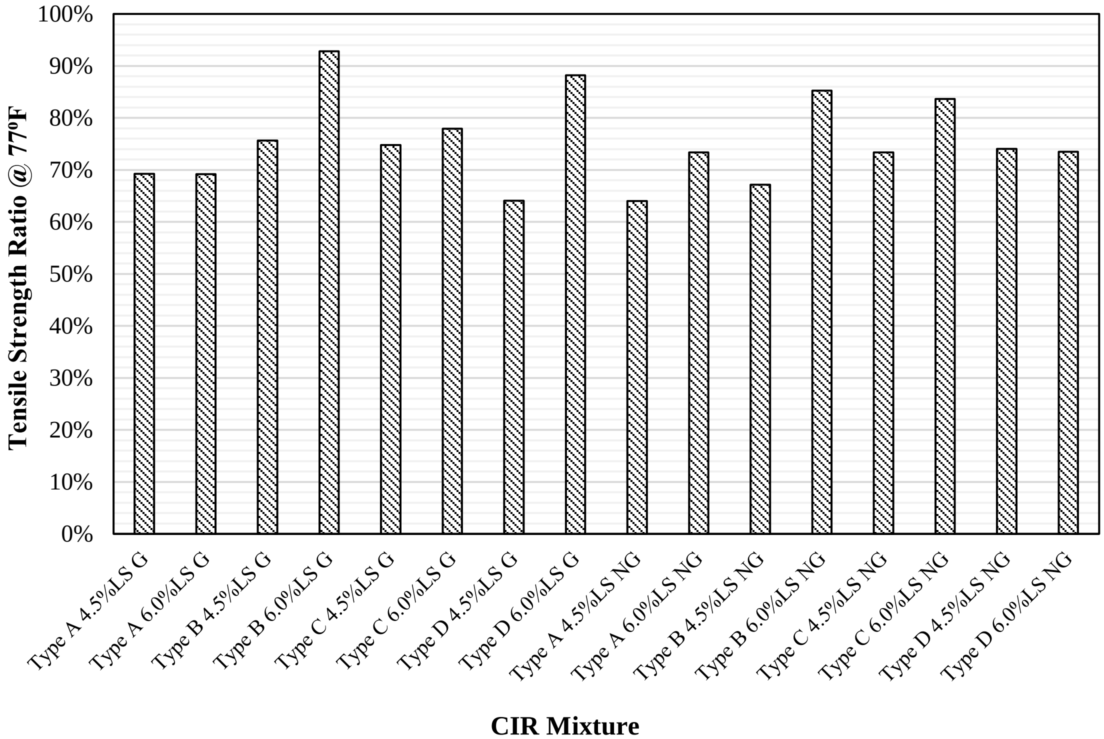

Figure 3.8. Tensile strength ratios of CIR mixtures designed with the Hveem method.

The recommended moisture sensitivity criteria for CIR mixtures is; minimum dry TS at 77°F for 50 psi and a minimum TSR of 70% (4). Implementing the recommended criteria on the CIR mixtures designed with the Hveem method indicate the following:

- All 16 CIR mixtures pass the dry TS criteria
- A total of 13 out of the 16 CIR mixtures pass the TSR criteria
- The 3 CIR mixtures failing the TSR criteria include 4.5% lime slurry

3.4. Superpave Mix Design Method

The same 16 CIR mixtures summarized in Table 3.2 were also designed using the Superpave mix design method. The CIR mixtures were compacted in the Superpave gyratory compactor (SGC) using a perforated mold as shown in Figure 3.9. The compacted CIR samples had 6.0 inch dimeter and a height of 4.5±0.2 inch. The following criteria were determined through a previous research study conducted at WRSC (4).

- Target compacted sample height: 4.5±0.2 inch
- Target design air voids = 13±1 %
- SGC N_{design}:
    - 75 gyrations for graded RAP
    - 100 gyrations for non-graded RAP

The preparation of the CIR mixtures and the determination of G_{mm} followed the procedures presented in Section 3.2.

Following the compaction of the SGC samples, the compacted samples are cured in an oven at 140°F for 24 hours prior to the determination of the bulk specific gravity (G_{mb}). The G_{mb} of the compacted and cured samples is determined following ASTM D1188 using the parafilm method due to the high air voids content of the compacted CIR mix.

Figure 3.9. SGC perforated mold used in the compaction of CIR mixtures.

The next step in the mix design process is to determine the optimum emulsion content (OEC). The OEC is determined as the asphalt emulsion content that produces an air voids content of 13±1%. The OEC's for all 16 CIR mixtures using the Superpave method are summarized in Table 3.6.

Figure 3.10 compares the OEC's of the 16 CIR mixtures determined by the Superpave mix design method. A review data presented in Figure 3.10 leads to the following observations:

- In most of the cases the OEC for the non-graded mixtures is higher than the OEC for the graded mixtures.
- The optimum emulsion contents of the majority of the CIR mixtures evaluated in this study range between 2.5 and 4.0% by dry weight of RAP materials.
- In the majority of the cases the CIR mixtures with 4.5% lime slurry resulted in higher OEC than the CIR mixtures with 6.0% lime slurry.
- Emulsion type C resulted in the lowest OEC.
- All the above observations leads to the conclusion that every combination of RAP material source and asphalt emulsion type/source constitutes a unique CIR mixture that must be individually designed.

Table 3.6. Summary of the Superpave Mix Designs for the 16 CIR Mixtures.

Asphalt Emulsion	Lime Slurry (%)	RAP	Optimum Emulsion Content, OEC (%)
A: Standard CMS-2s	4.5	Graded	3.4
		Non-Graded	3.6
	6.0	Graded	3.0
		Non-Graded	4.0
B: Latex-Modified	4.5	Graded	3.8
		Non-Graded	4.0
	6.0	Graded	3.1
		Non-Graded	3.0
C: Polymer-Modified	4.5	Graded	2.9
		Non-Graded	3.3
	6.0	Graded	2.5
		Non-Graded	2.5
D: Rubber-Modified	4.5	Graded	3.0
		Non-Graded	3.9
	6.0	Graded	3.5
		Non-Graded	4.0

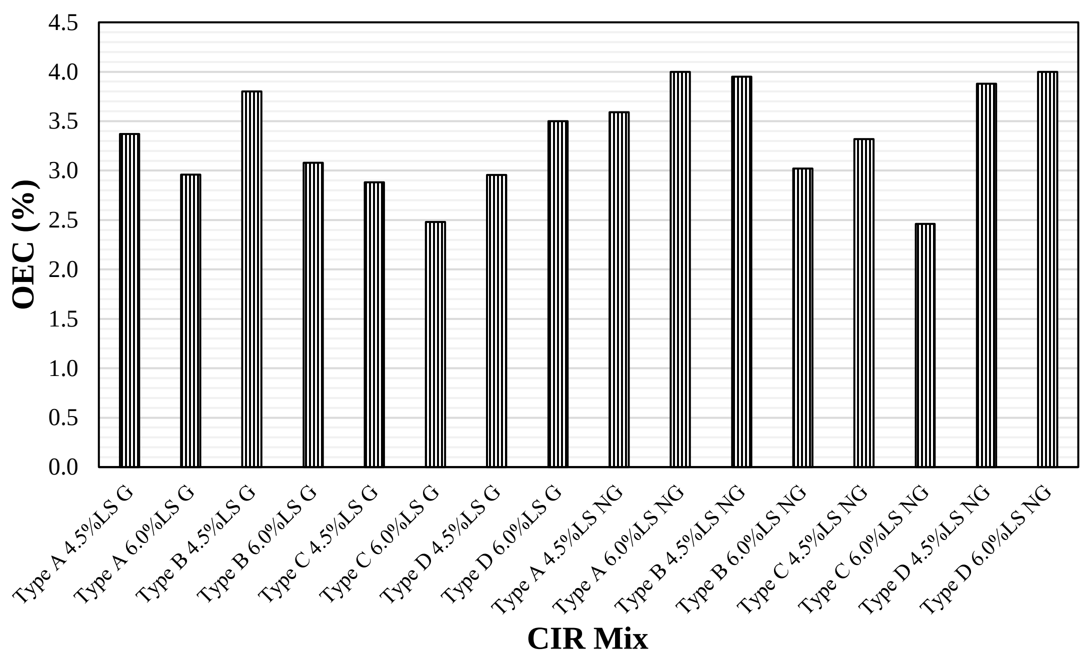

Figure 3.10. Optimum emulsion contents for the CIR mixtures designed with the Superpave method.

The final step of the Superpave mix design method is to evaluate the moisture sensitivity of the CIR mixtures at OEC in accordance with AASHTO T283. The moisture sensitivity was evaluated in terms of the tensile strength ratio (TSR) defined as the ratio of the wet tensile strength (TS) over the dry TS of the CIR mixture measured at 77°F. Six samples (per mix) were mixed at OEC and compacted at 2.5 inches height by 4.0 inches diameter at air voids content of 13±1%.

The TS properties of the moisture-conditioned and unconditioned sets were measured at 77°F. The average TS of the moisture-conditioned set will be referred to as the “Wet TS” and the average TS of the unconditioned set will be referred to as the “Dry TS”. Table 3.7 summarizes the moisture sensitivity properties of the 16 CIR mixtures.

Table 3.7. Moisture Sensitivity Properties of the 16 CIR Mixtures Designed with the Superpave Method.

Asphalt Emulsion	Lime Slurry (%)	RAP Materials	Avg Dry TS (psi) @77°F	Avg Wet TS (psi) @77°F	TSR (%) @77°F
A: Standard CMS-2s	4.5	Graded	70	43	62
		Non-Graded	57	44	78
	6.0	Graded	60	50	84
		Non-Graded	52	40	77
B: Latex-Modified	4.5	Graded	76	66	87
		Non-Graded	58	50	86
	6.0	Graded	70	63	90
		Non-Graded	57	45	79
C: Polymer-Modified	4.5	Graded	82	53	65
		Non-Graded	77	59	76
	6.0	Graded	65	41	63
		Non-Graded	76	60	79
D: Rubber-Modified	4.5	Graded	52	37	71
		Non-Graded	61	43	71
	6.0	Graded	55	42	76
		Non-Graded	56	43	77

Figures 3.11, 3.12, and 3.13 present the dry TS, wet TS, and TSR for all 16 CIR mixtures. The bars represent the average value while the whisker present the 95% confidence interval. An overlap in the 95% confidence interval indicates statistically similar properties. Examination of the data presented in Figures 3.11, 3.12, and 3.13 leads to the following observations:

- The impact of RAP gradation on the dry TS and wet TS properties of the CIR mixtures depends on the types of emulsion. In general, for emulsions A and B, the graded RAP had higher TS properties than the non-graded while for emulsions C and D the impact was insignificant.

- The impact of lime slurry on the dry TS and wet TS properties and TSR of the CIR mixtures is insignificant which is shown by the overlapping of the 95% confidence intervals of the 4.5% and 6.0% lime slurry mixtures.

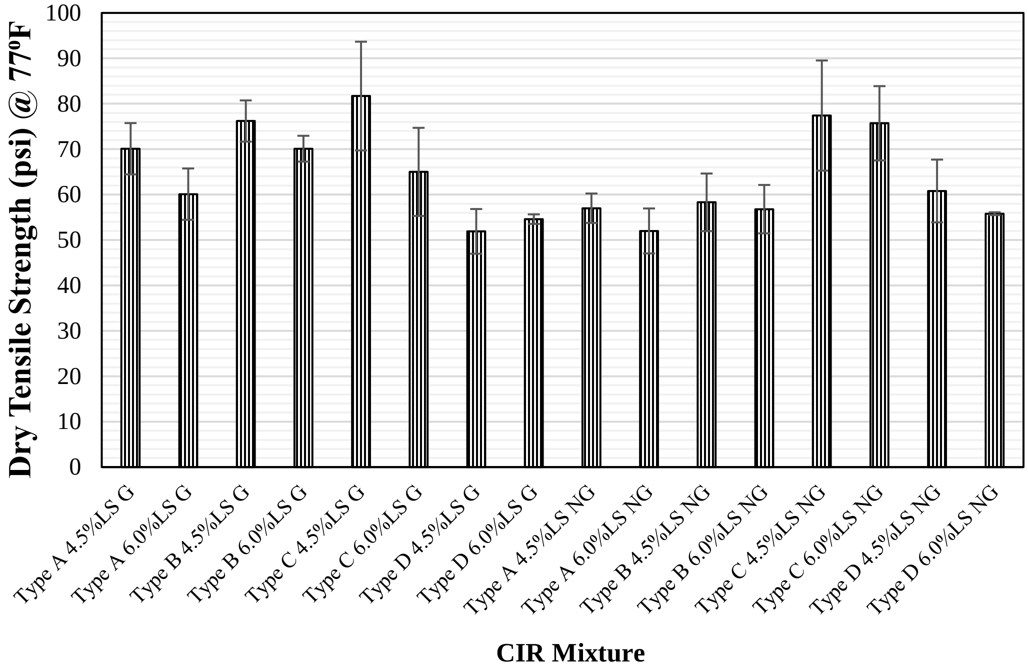

Figure 3.11. Dry TS properties of CIR mixtures designed with the Superpave method.

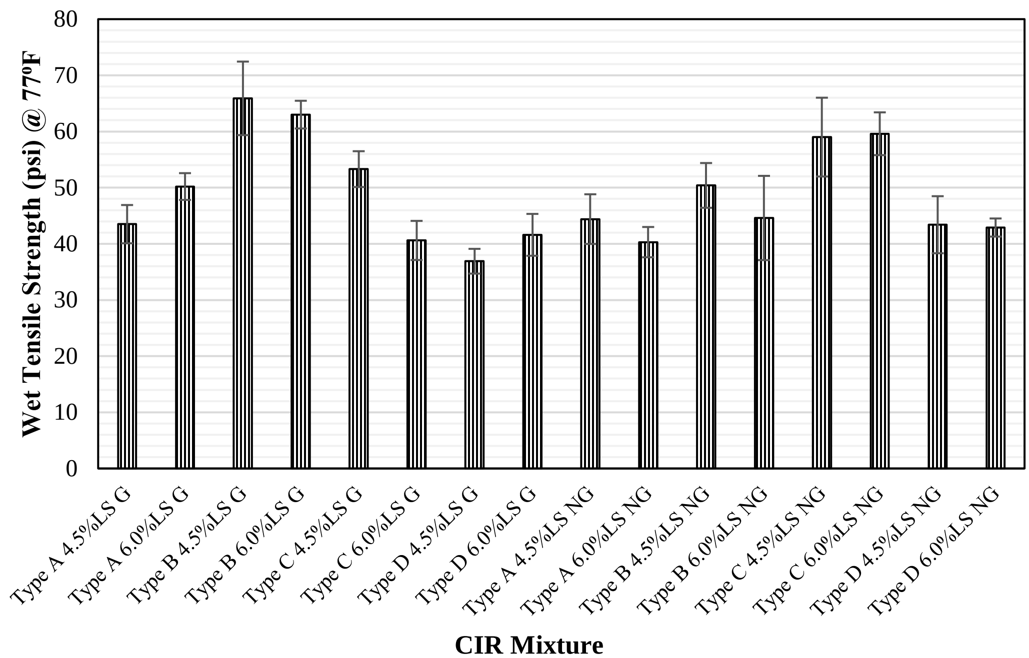

Figure 3.12. Wet TS properties of CIR mixtures designed with the Superpave method.

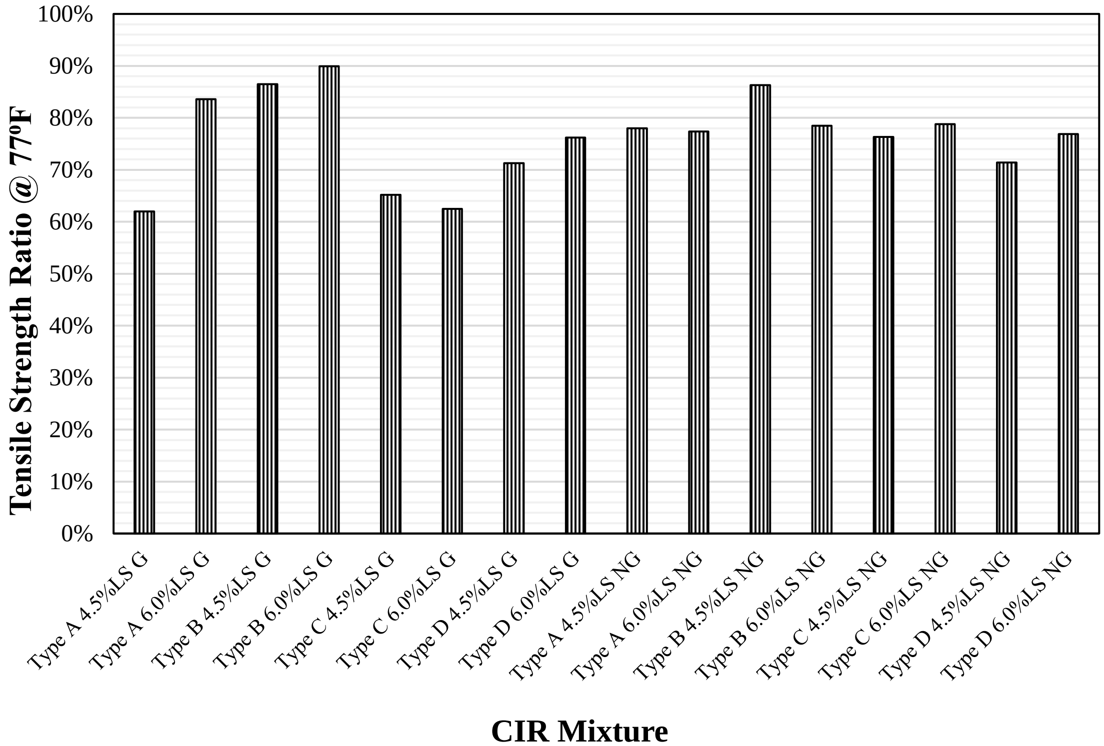

Figure 3.13. Tensile strength ratios of CIR mixtures designed with the Superpave method.

The recommended moisture sensitivity criteria for CIR mixtures is; minimum dry TS at 77ºF of 50 psi and a minimum TSR of 70% (4). Implementing the recommended criteria on the CIR mixtures designed with the Superpave method indicate the following:

- All 16 CIR mixtures pass the dry TS criteria
- A total of 13 out of the 16 CIR mixtures pass the TSR criteria
- The 3 CIR mixtures failing the TSR criteria include 2 mixtures with 4.5% lime slurry and 1 mixture with 6.0% lime slurry

3.5. Comparison of Hveem and Superpave CIR Mixtures

This section compares the OEC's and the moisture sensitivity properties of the CIR mixtures designed with the Hveem and Superpave methods. The following observations can be made:

- Figure 3.14: there is no specific trend between the OEC's from the Hveem and Superpave methods and the OEC's determined from the two methods are within ±0.25% in most cases.
- Figure 3.15 and Figure 3.16: CIR mixtures designed with the Hveem method exhibited higher dry and wet TS values at 77oF than CIR mixtures designed with the Superpave method.
- Figure 3.17: there is no specific trend between the TSR's of the CIR mixtures designed with the Hveem and Superpave methods and the TSR's for the CIR mixtures designed with the two methods are within ±5% in most cases

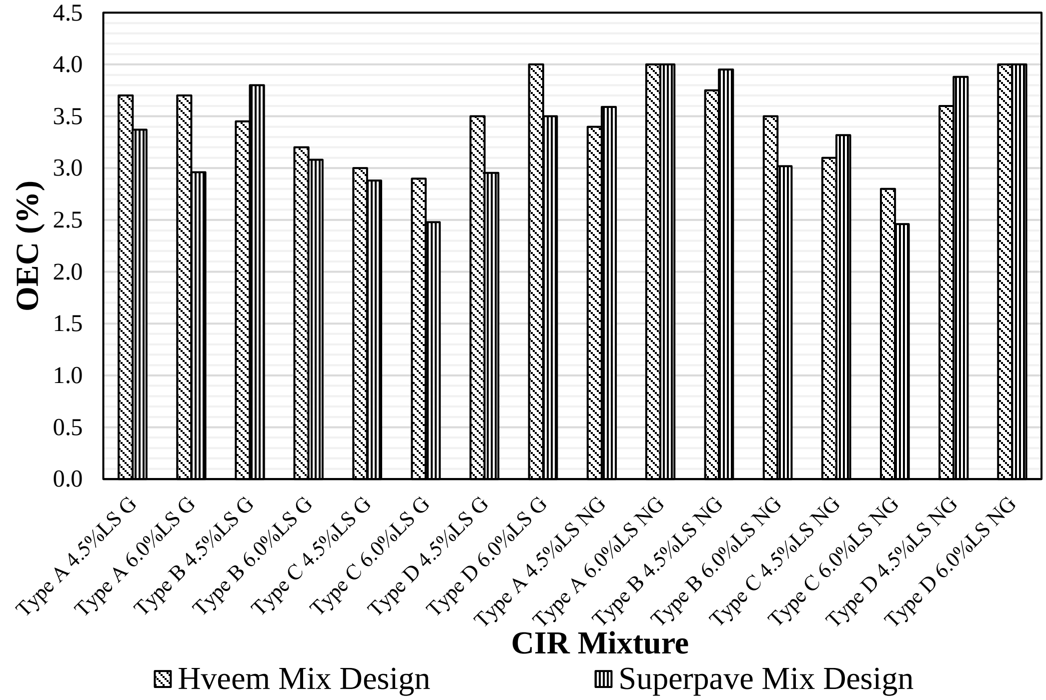

Figure 3.14. Comparison of the OEC's from the Hveem and Superpave methods.

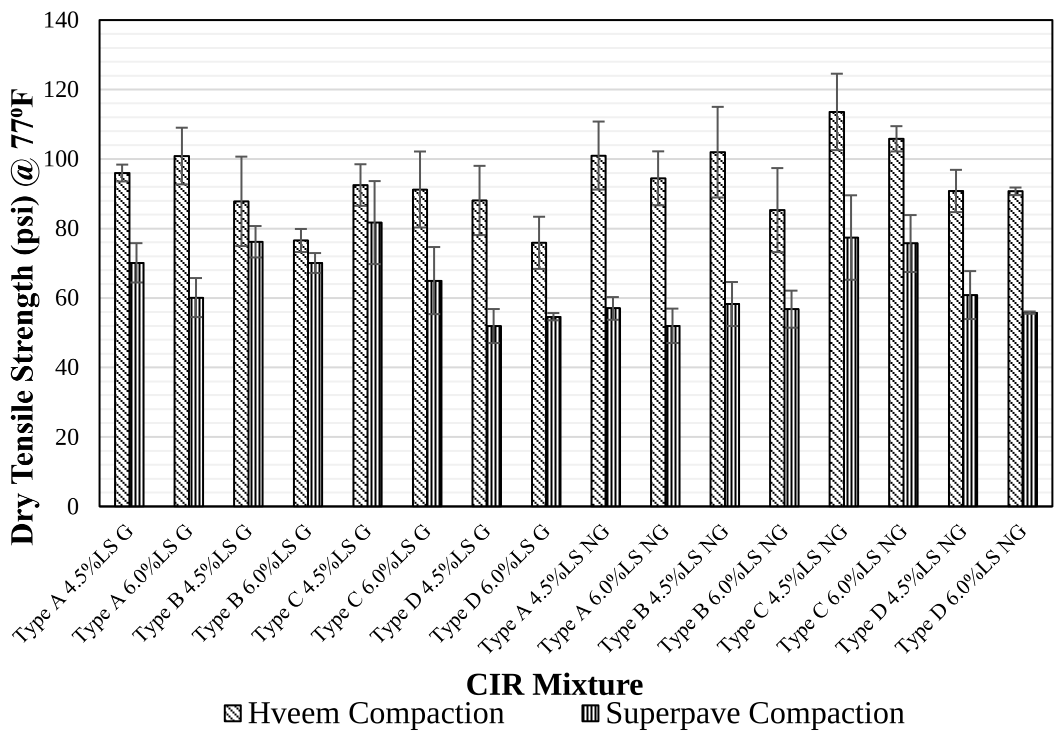

Figure 3.15. Comparison of dry TS from the Hveem and Superpave methods.

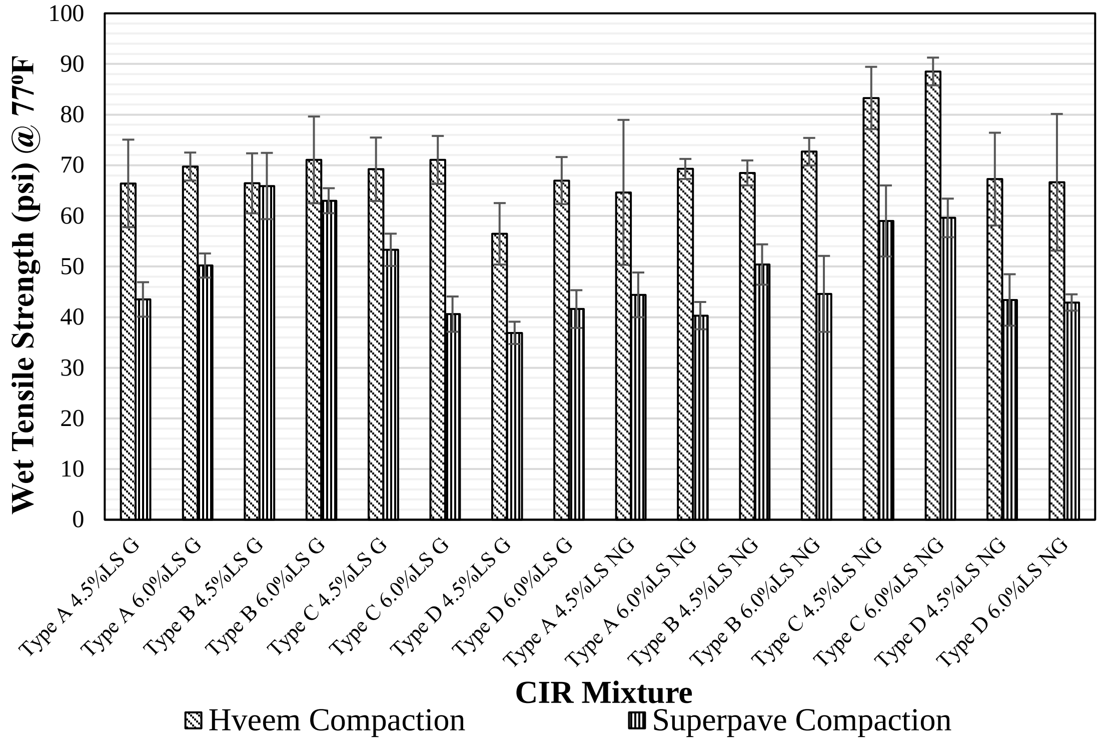

Figure 3.16. Comparison of wet TS from the Hveem and Superpave methods.

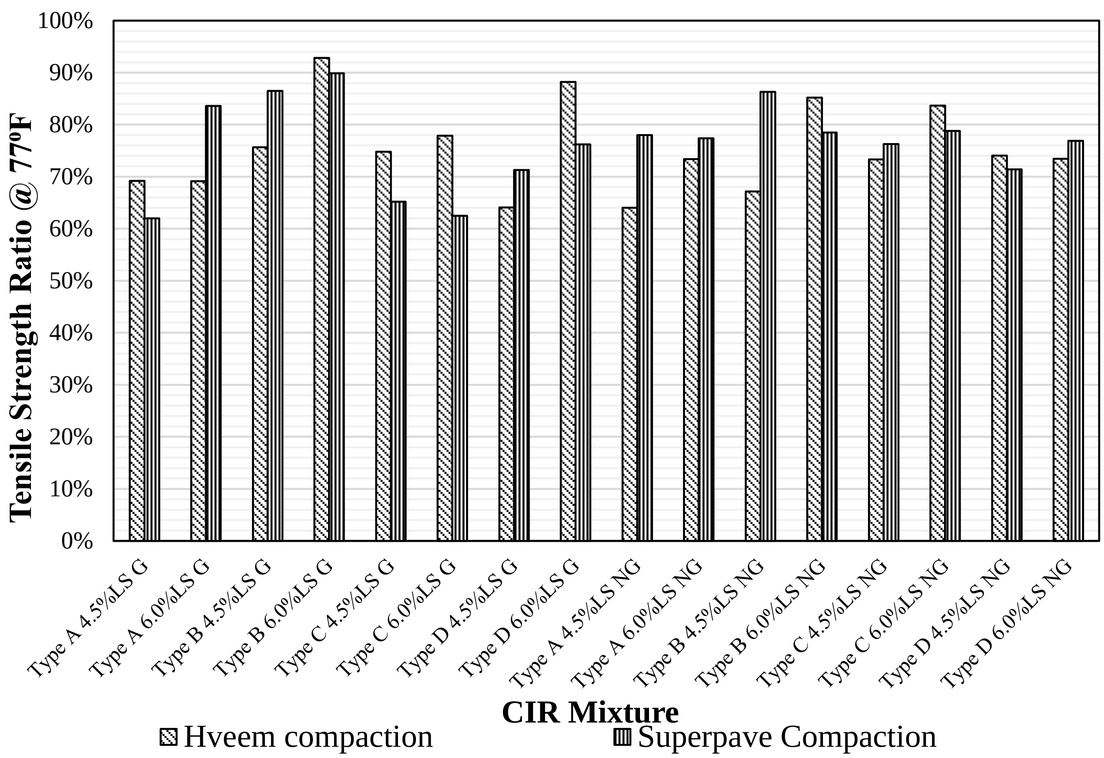

Figure 3.17. Comparison of TSR from the Hveem and Superpave methods.

Chapter 4. EVALUATION OF CIR MIXTURES

This part of the research evaluated the engineering properties and performance characteristics of the CIR mixtures designed with the Hveem method. The engineering property of the CIR mix was evaluated in terms of the dynamic modulus, E*. The performance characteristics of the CIR mix were determined in terms of its resistance to rutting, reflective cracking, and fatigue cracking. This chapter presents the measured engineering properties and performance characteristics of the various CIR mixtures.

4.1. Engineering Property of CIR Mixtures

The Nevada DOT M-E Design Guide for flexible pavements, uses the dynamic modulus (E*) master curve to evaluate the structural response of the asphalt bound layers under various combinations of traffic loads, speed, and environmental conditions. The E* property of the various CIR mixtures was evaluated under various combinations of loading frequency and temperature. The dynamic modulus was measured according to "AASHTO T378: Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)." The E* tests were conducted on 4.0 inch diameter by 6.0 inch cylindrical specimens cored from the center of samples compacted in the SGC as described in Section 3.4. The test is conducted at frequencies of: 10, 1, 0.1, and 0.01 Hz and at temperatures of: 40, 68, and 104^{o}F. Using the visco-elastic behavior of the CIR mixture (i.e. interchangeability of the effect of loading rate and temperature) the master curve can be used to identify the appropriate E* for any combination of pavement temperature and traffic speed per AASHTO R84. Figure 4.1 shows the components dynamic modulus test for the CIR mixtures.

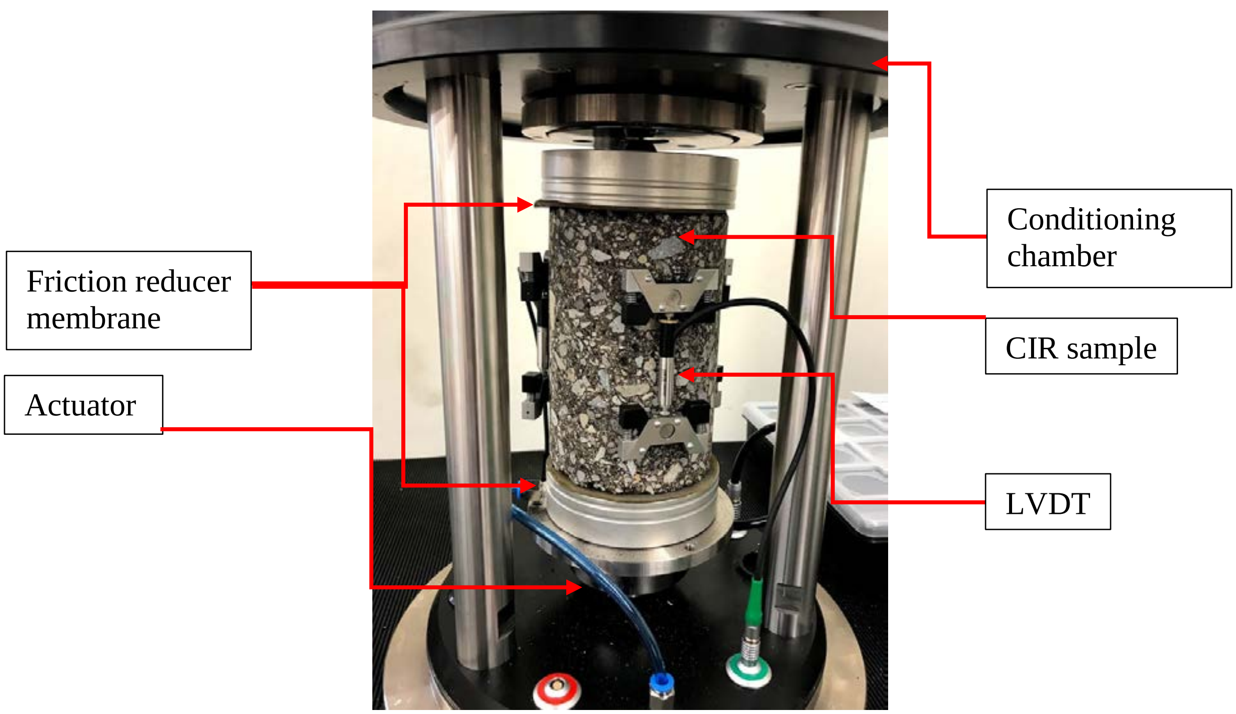

Figure 4.1. Dynamic modulus set-up (AMPT).

The E* master curves were measured for all 16 CIR mixtures designed with the Hveem method. Figure 4.2 to Figure 4.5 present the E* master curves for the four types of asphalt emulsions. The data presented in Figure 4.2 to Figure 4.5 indicate that the gradation of RAP and level of lime slurry do not have a significant impact on the E* master curve of the CIR mixtures manufactured with asphalt emulsions types A, B, and C. In the case of CIR mixtures manufactured with asphalt emulsion type D, the graded CIR mix exhibited significantly higher E* mater curve than the non-graded CIR mix with both the 4.5% and 6.0% lime slurry.

The next analysis evaluated the impact of the various factors on the magnitude of the E* property (|E*|) of the CIR mixtures at temperatures that are critical to fatigue cracking and rutting performance. The loading frequency of 10 Hz was selected as a representative of highway traffic speed and the critical temperatures for fatigue cracking and rutting performance were selected as 68^{o}F and 104^{o}F, respectively. Figure 4.6 and Figure 4.7 compare the |E*| properties of the various CIR mixtures at the selected loading frequency and critical temperatures. The whiskers over the bars represent the 95% confidence interval for each CIR mix. An overlap in the confidence intervals of any two CIR mixtures indicates that the represented properties are statistically similar.

The |E*| values of the CIR mixtures at 68°F and 10 Hz range from 500 to 800 ksi, while the |E*| of the CIR mixtures at 104°F and 10 Hz range from 200 to 400 ksi. The measured |E*| values indicate that the CIR mixtures are developing a stiffness that is similar to AC mixtures at the critical temperatures for rutting and fatigue cracking. This should lead to a better benefit-cost ratio for CIR pavements as compared to full AC pavements.

Overall, based on the |E*| property, the CIR mixtures with the polymer-modified asphalt emulsion is expected to deliver the best resistance to rutting and fatigue followed by the CIR mixtures with the latex and rubber modified asphalt emulsions. However, it should be recognized that this analysis is based solely on the |E*| property of the CIR mixtures and its anticipated impact on the measured responses of the CIR layer under traffic loads. The next sections will present the evaluated performance characteristics of the CIR mixtures which will provide a direct assessment of the resistance of the CIR mixtures to rutting and fatigue cracking.

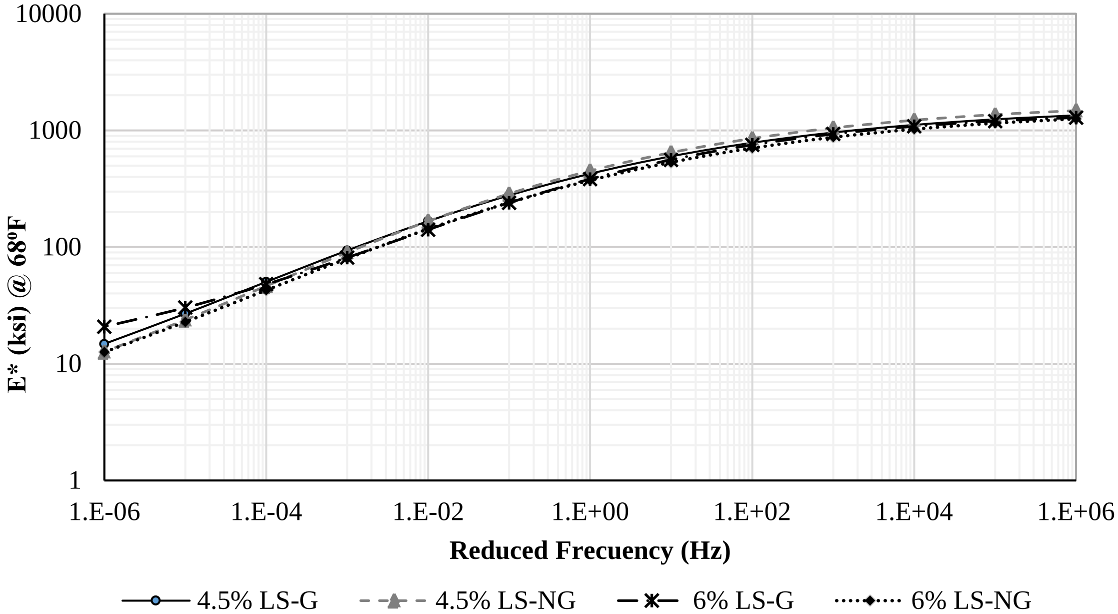

Figure 4.2. Dynamic modulus master curves for CIR mixtures with asphalt emulsion A.

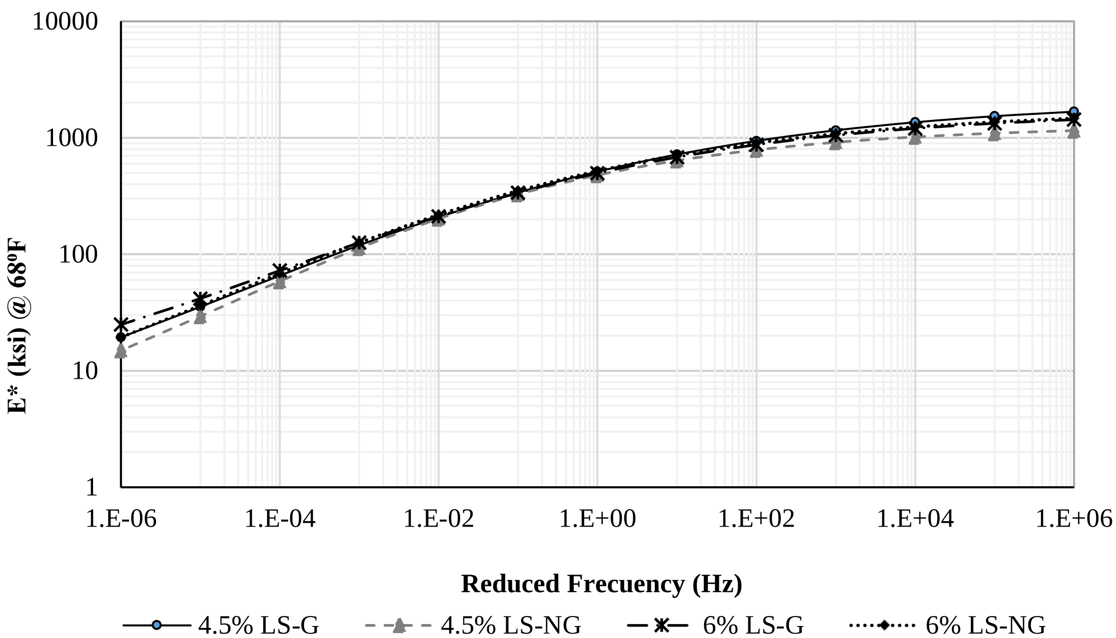

Figure 4.3. Dynamic modulus master curves for CIR mixtures with asphalt emulsion B.

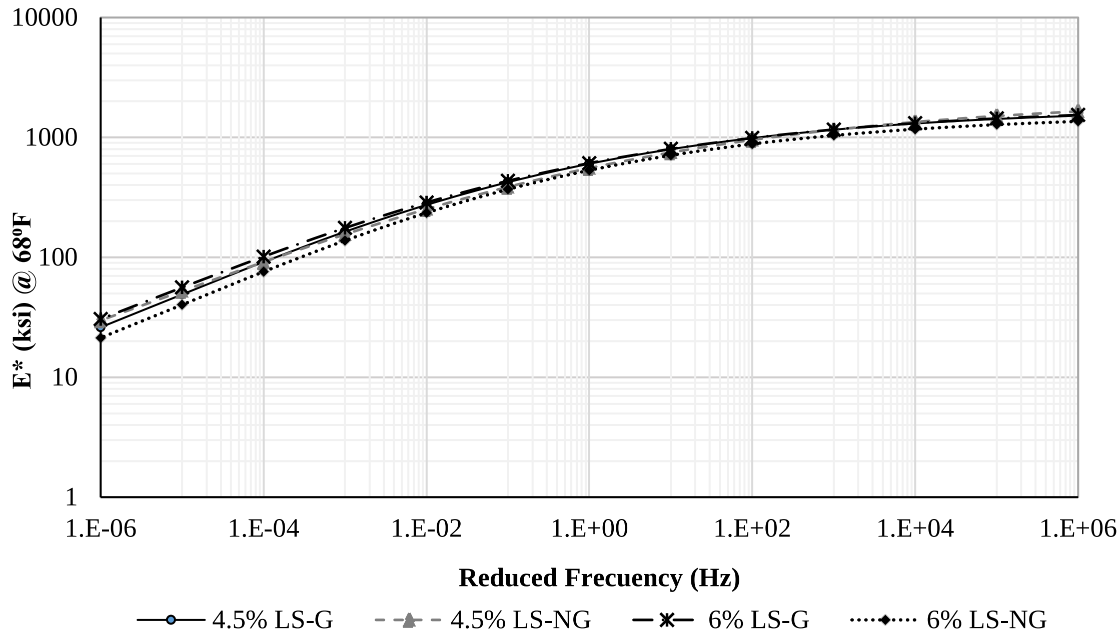

Figure 4.4. Dynamic modulus master curves for CIR mixtures with asphalt emulsion C.

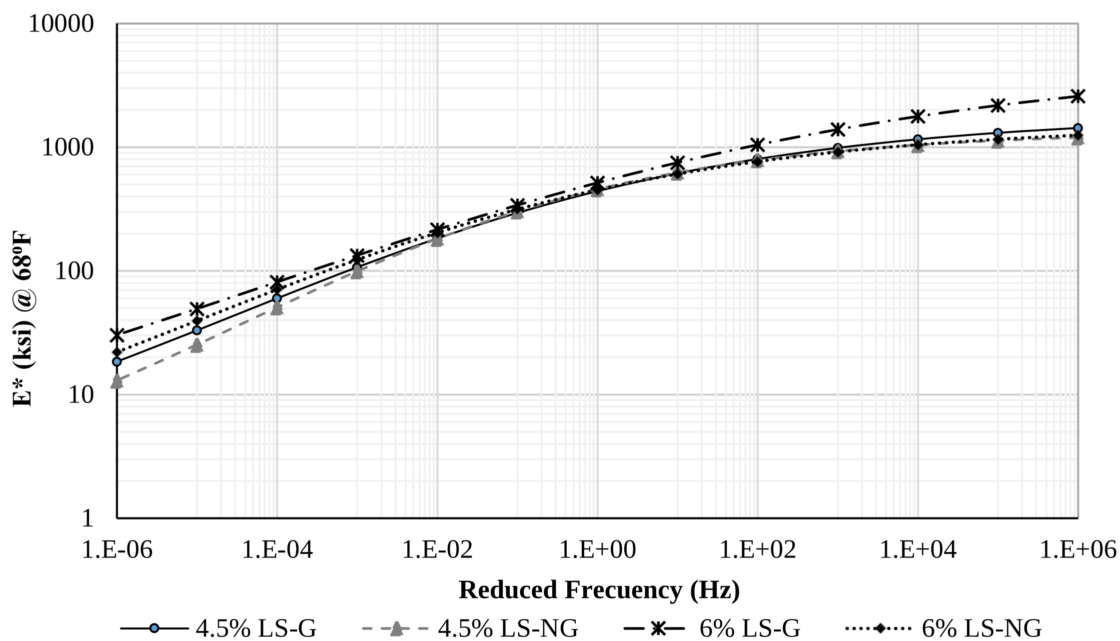

Figure 4.5. Dynamic modulus master curves for CIR mixtures with asphalt emulsion D.

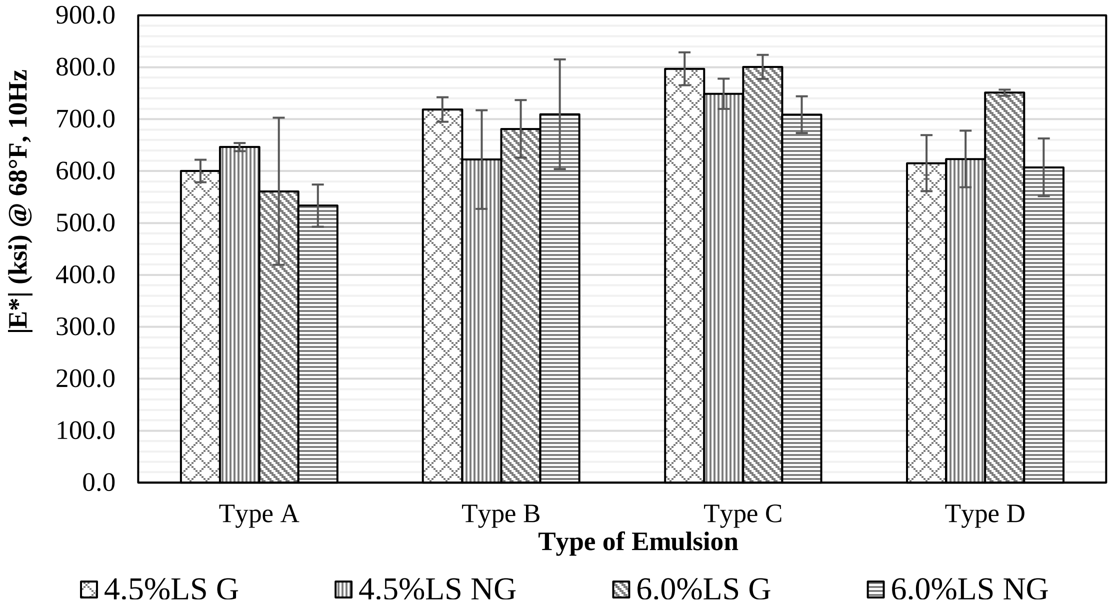

Figure 4.6. Dynamic modulus magnitude for CIR mixtures at 68ºF and 10Hz.

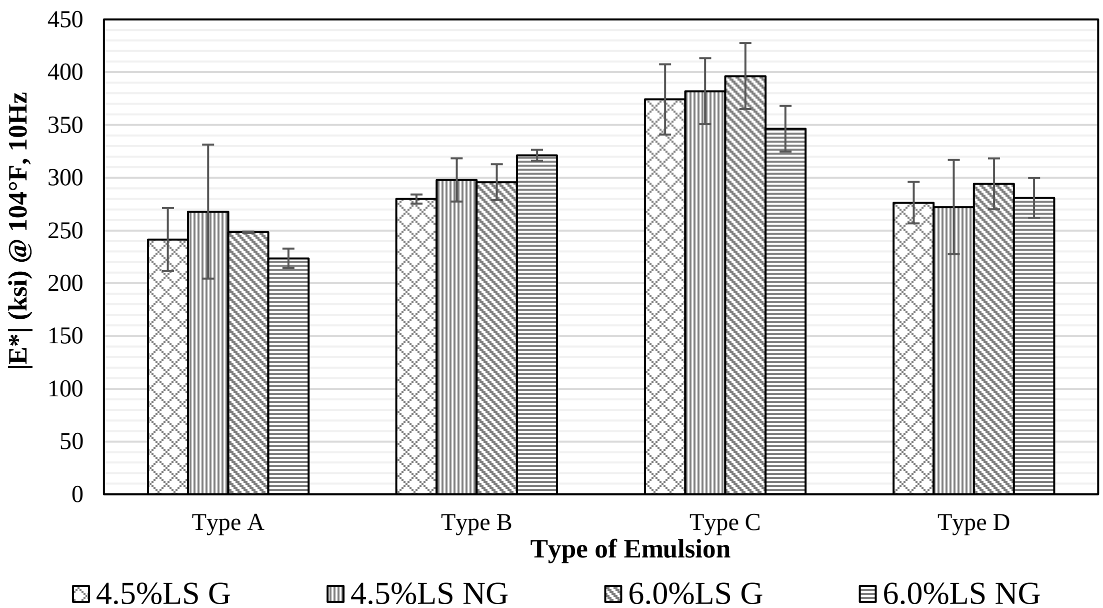

Figure 4.7. Dynamic modulus magnitude for CIR mixtures at 104ºF and 10Hz.

4.2. Performance Characteristics of CIR Mixtures

The performance characteristics of the CIR mixtures designed with the Hveem method were measured in terms of their resistance to rutting, fatigue cracking, and reflective cracking. Due to the extensive efforts involved in the testing for the three performance characteristics, only the 4 CIR mixtures currently used by NDOT were evaluated, namely; CIR mixtures with the four asphalt emulsions (A, B, C, and D), the 6.0% lime slurry, and non-graded RAP material.

4.2.1. Resistance of CIR mixtures to Rutting

The resistance of the CIR mixtures to rutting was evaluated using the repeated load triaxial (RLT) test. The RLT tests were conducted on 4.0 in diameter by 6.0 in cylindrical specimens cored from the center of samples compacted in the SGC. The samples were subjected to a dynamic deviator stress of 40 psi and a static confining stress of 25 psi representing the stress conditions within the CIR layer under an AC overlay. The deviator stress was applied as a pulse load with a loading period of 0.1 sec and a rest period of 0.9 sec. Figure 4.8 shows the setup of the RLT test and Figure 4.9 shows a typical relationship between the permanent axial strain and the number of load repetitions.

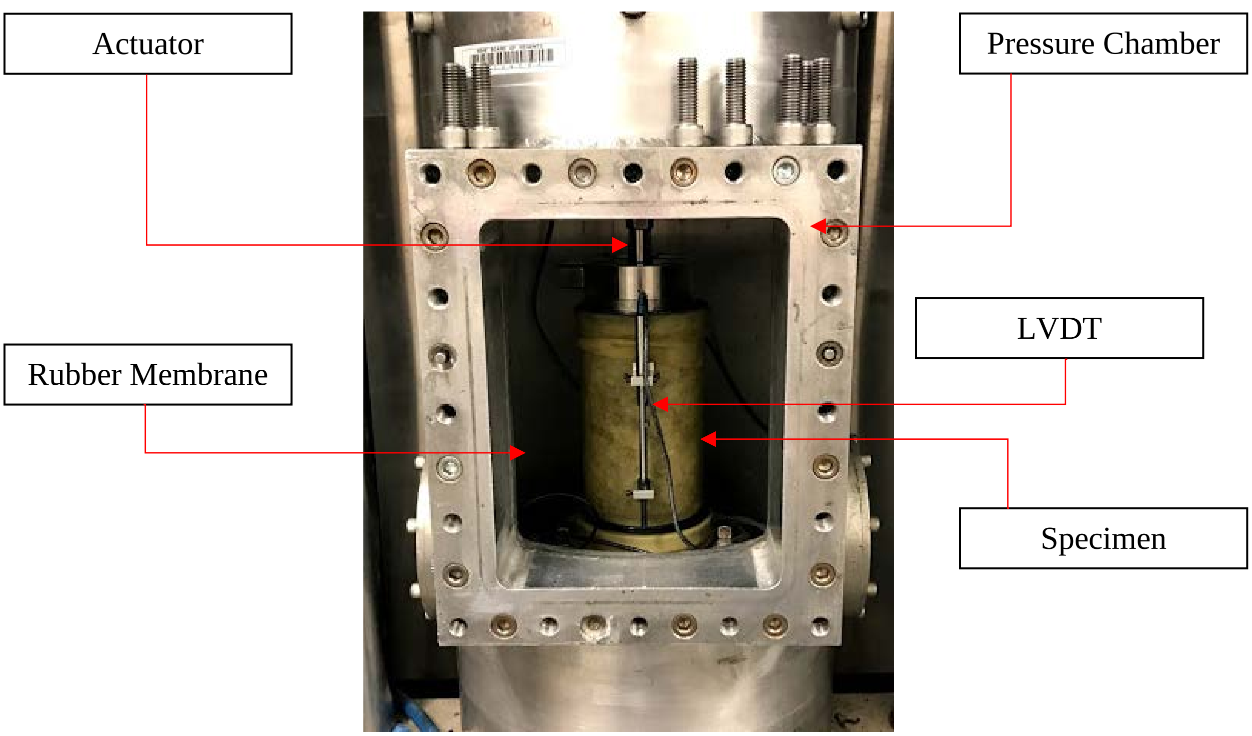

Figure 4.8. Repeated load triaxial test setup.

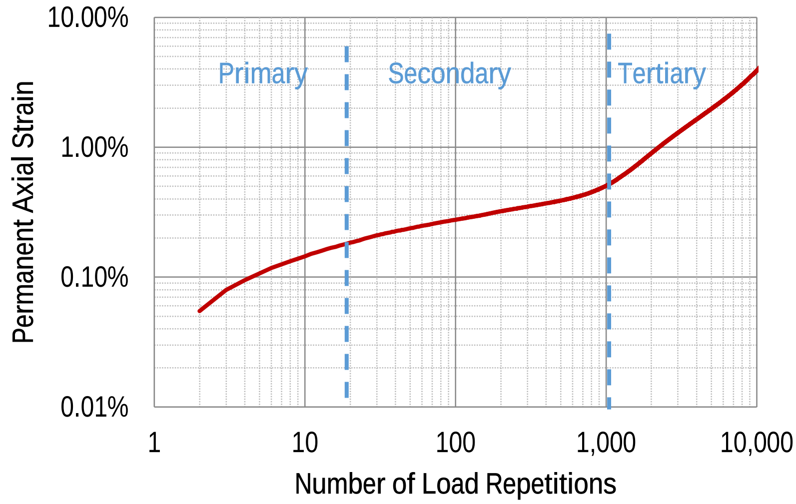

Figure 4.9. Typical performance of CIR mixtures in the RLT test.

All tested samples were mixed at the Hveem optimum emulsion content and compacted in the SGC to air voids of 13±1%. The RLT tests were conducted on each of the 4 CIR mixtures at three temperatures of 68°F, 98°F, and 127°F. The secondary stage in the relationship between permanent strain and number of load cycles was modeled to obtain the rutting model for each CIR mix as follows:

$$\frac{\varepsilon_p}{\varepsilon_r} = 10^{k_{r1}} (T)^{k_{r2}} (N)^{k_{r3}}$$

Where; ε_p is the permanent axial strain (in/in), ε_r is the resilient axial strain (in/in), *N* is the number of load repetitions, *T* is the temperature of the CIR mixture in (°F), k_{r1}-k_{r2}-k_{r3} are experimentally determined coefficients.

Table 4.1 summarizes the rutting models for the 4 CIR mixtures with non-graded RAP and 6.0 lime slurry designed with the Hveem method. The rutting models are used in a mechanistic-empirical pavement design to estimate the permanent strain, ε_p, within the CIR layer at any temperature and number of load cycles from the calculated resilient strain, ε_r.

Table 4.1. Rutting Performance Models for CIR mixtures with Non-Graded RAP and 6.0% Lime slurry.

Asphalt Emulsion	Rutting Model
A: Standard CMS-2s	$\frac{\varepsilon_P}{\varepsilon_r} = 10^{-10.93031} (N)^{0.32408} (T)^{5.30878}$
B: Latex-Modified	$\frac{\varepsilon_P}{\varepsilon_r} = 10^{-8.10753} (N)^{0.24871} (T)^{4.08190}$
C: Polymer-Modified	$\frac{\varepsilon_P}{\varepsilon_r} = 10^{-1.75152} (N)^{0.20540} (T)^{0.79574}$
D: Rubber-Modified	$\frac{\varepsilon_P}{\varepsilon_r} = 10^{-10.16571} (N)^{0.34739} (T)^{4.76969}$

Figure 4.10 compares the rutting models of the 4 CIR mixtures at the rutting critical temperature of 104°F. The lower the rutting curve, the higher the resistance of the CIR mixture to rutting. In addition, a flatter rutting curve is preferred since it represents a slower rate of rutting as a function of load cycles. The rutting models indicate that the CIR mixture with asphalt emulsion C will offer the best resistance to rutting followed by the CIR mixture with asphalt emulsion D. CIR mixtures with asphalt emulsions A and B are expected to offer lower rutting resistance. This is observation is consistent with the findings based on the E* property, except for CIR with asphalt emulsion B.

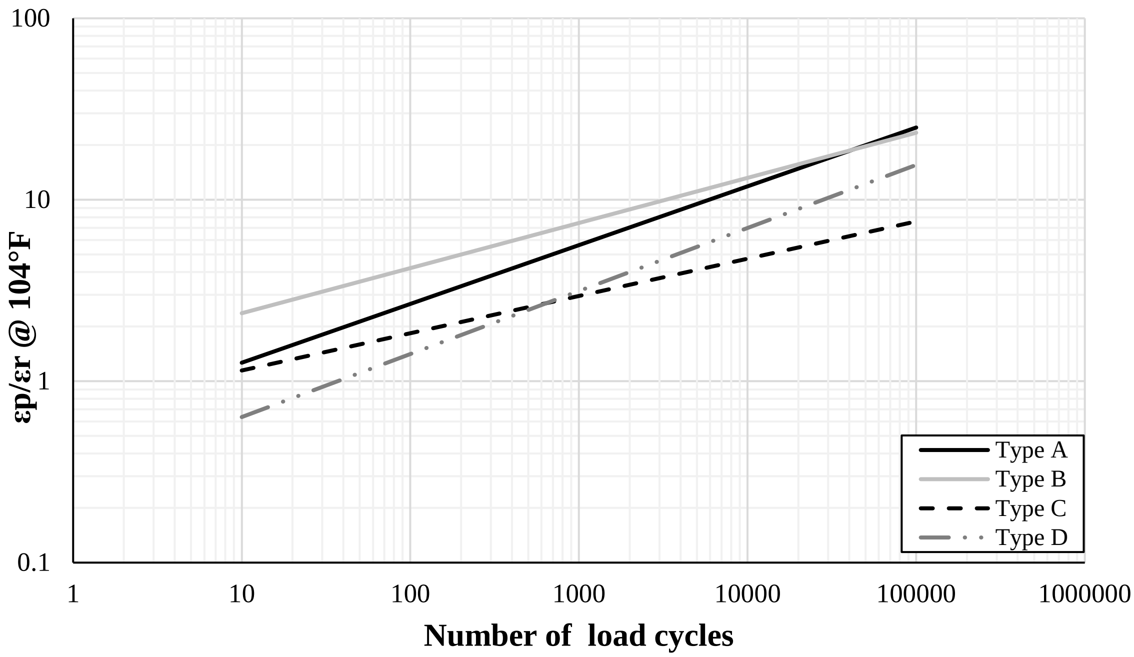

Figure 4.10. Rutting models for CIR mixtures with non-grade RAP and 6.0% lime slurry.

4.2.2. Resistance of CIR Mixtures to Fatigue Cracking

The resistance of the CIR mixtures to fatigue cracking was evaluated using the flexural beam fatigue test per ASTM D7460: Standard Test Method for Determining Fatigue Failure of Compacted Asphalt Concrete Subjected to Repeated Flexural Bending. The beam specimen is subjected to a 4-point bending with free rotation and horizontal translation at all load and reaction points. This produces a constant bending moment over the center portion of the specimen. In this research, constant strain tests were conducted at multiple strain levels between 350 and 800 micro-strain using a repeated haversine load at a frequency of 10 Hz, and three test temperatures of 55, 70, and 85°F. All the flexural beam fatigue tests were conducted in the pneumatic testing system. Figure 4.11 shows the testing set-up of the flexural beam fatigue test.

All tested samples were mixed at the Hveem optimum emulsion content and compacted in the kneading compactor to air voids of 13±1%. The test beams of 2.5x2.0x15.0 inch were cut from the original compacted beams of 3.0x3.0x15.0 inch as shown in Figure 4.12.

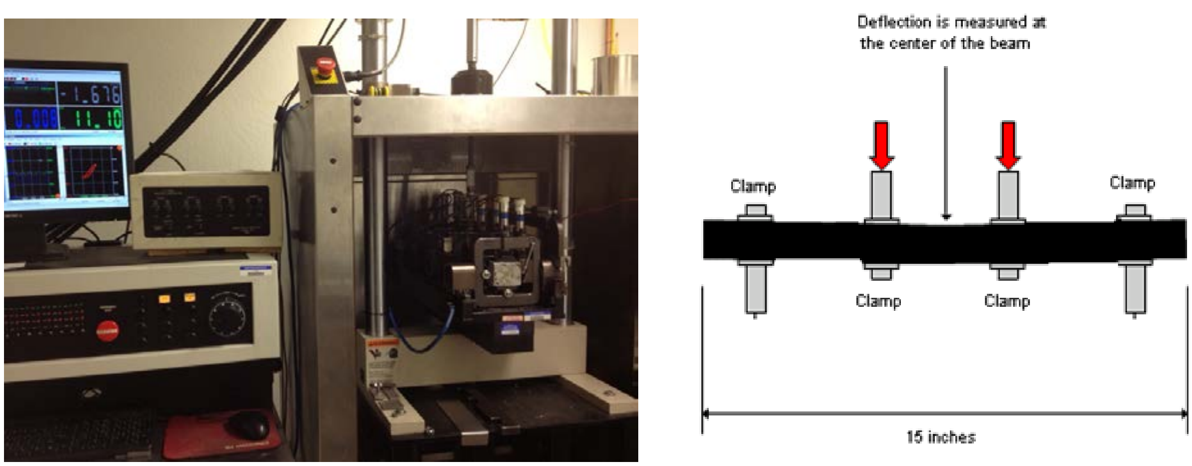

Figure 4.11. Components of the flexural beam fatigue test.

Figure 4.12. Original CIR beams and cut test beams.

The number of cycles to fatigue failure was determined in accordance to ASTM D7460. In ASTM D7460 the failure point is defined as the number of cycles at which the stiffness ratio is equal to 0.50. The stiffness ratio is defined as the ratio of the stiffness at any number of cycles over the initial stiffness measured at 50 cycles.

Table 4.2 summarizes the fatigue data for the NDOT standard CIR mixtures with the four types of asphalt emulsions at 70°F. Figure 4.13 compares the fatigue curves for the CIR mixtures at 70°F. It can be seen that the fatigue behavior at 70°F of the CIR mix with the rubber-modified emulsion (D) is the best followed by the CIR mix made with the Latex-modified emulsion (B). However, this observation may not hold true for the other two testing temperatures. The evaluations of the fatigue properties at the other two testing temperatures of 55 and 85°F are still in-progress and will be incorporated in the Final Report. Once the fatigue characteristics of the CIR mixtures are determined at all three testing temperatures, a fatigue model will be developed for each asphalt binder type in the form below:

$$\mathbf{N_f} = \mathbf{k_{f1}} \left(\frac{\mathbf{1}}{\boldsymbol{\varepsilon_t}}\right)^{\mathbf{k_{f2}}} \left(\frac{\mathbf{1}}{E}\right)^{\mathbf{k_{f3}}}$$

Where; N_f is the number of cycles to fatigue failure, $\boldsymbol{\varepsilon_t}$ is the flexural strain, and E is the stiffness of the CIR mix.

Table 4.2. Fatigue Properties of CIR mixtures at 70ºF; Non-Graded RAP and 6.0% Lime Slurry.

Asphalt Emulsion	Air Voids (%)	Flexural Strain, ε_t (micro-strain)	Number of Cycles to Failure N_f
A: Standard CMS-2s	13.3	415	25,909
	13.1	642	3,353
	13.8	753	2,054
	13.0	800	1,214
B: Latex-Modified	13.2	410	47,618
	13.6	610	5,228
	13.3	760	2,414
	13.2	803	1,218
C: Polymer-Modified	13.4	400	31,411
	13.1	603	3,618
	13.6	618	4,069
	13.1	801	1,711
D: Rubber-Modified	14.0	423	59,069
	13.8	601	6,721
	13.9	723	3,127
	13.7	824	4,528

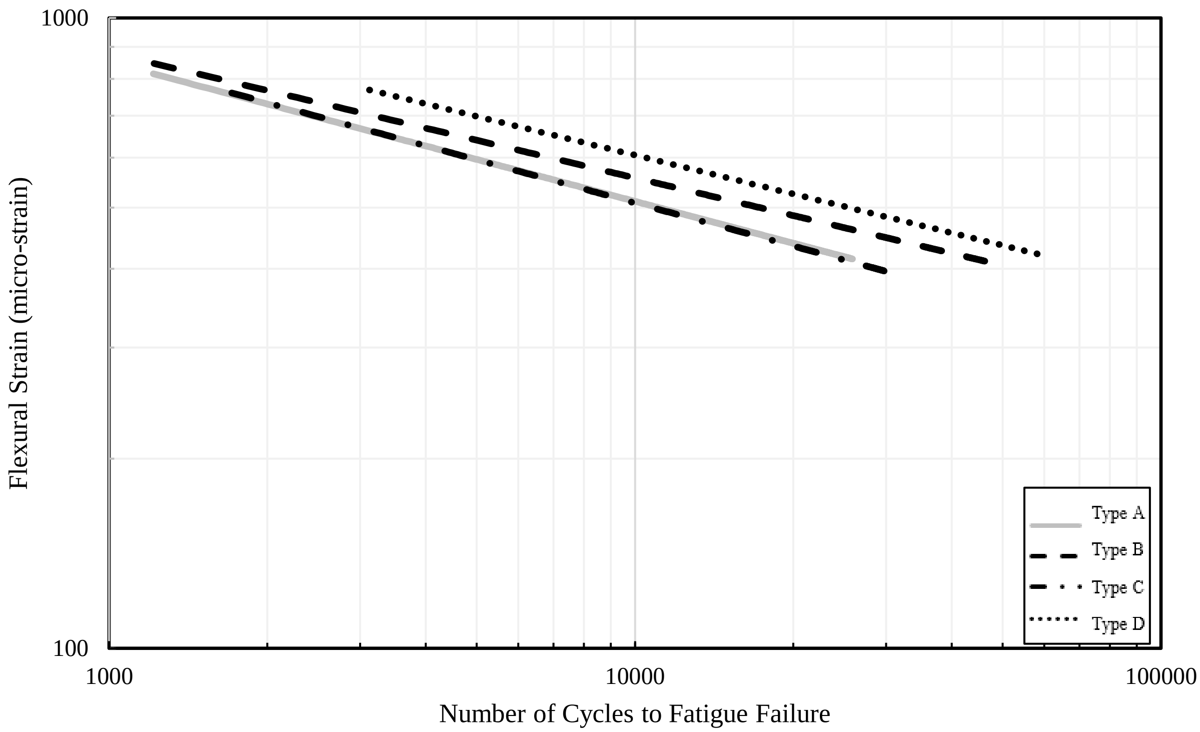

Figure 4.13. Fatigue curves for CIR mixtures at 70ºF; non-graded RAP and 6.0 lime slurry.

4.2.3. Resistance of CIR Mixtures to Reflective Cracking

The resistance of the 4 CIR mixtures to reflective cracking were evaluated using the Texas Overlay Tester (OT) by subjecting the compacted samples to repeated opening and closing horizontal movements. The OT simulates the horizontal opening and closing of joints and/or cracks that may exist underneath the CIR layer. The OT test specimen consists of a 6.0 inch long by 3.0 inch wide and 1.5 inch thick sample that is trimmed from a 6.0 inch diameter by 7.0 inch height SGC sample. A total of three samples are obtained from the SGC compacted sample. Figure 4.14 shows the schematic and actual machine of the Texas OT. The test is conducted in a controlled displacement mode until the failure occurs at a loading rate of one cycle per 10 seconds. Each cycle consists of triangular load profile with 5 seconds of loading and 5 seconds of unloading. As the CIR mixture is subjected to the repeated openings and closings, its internal strength is reduced which is represented by a drop in the applied load needed to maintain the constant opening.

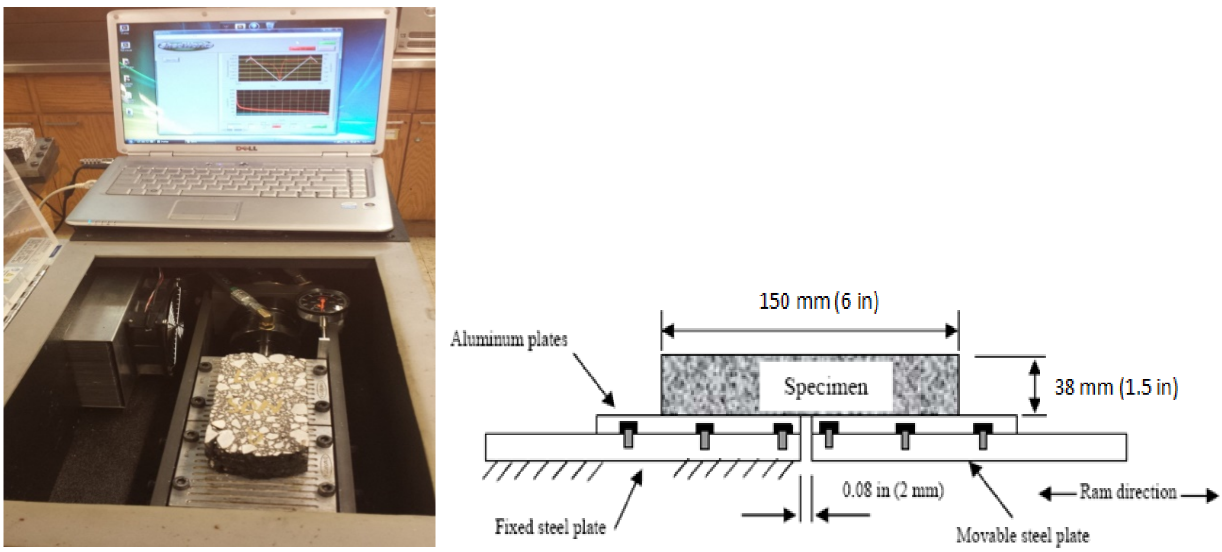

Figure 4.14. Texas overlay tester; actual machine and schematics.

All tested samples were mixed at the Hveem optimum emulsion content and compacted in the SGC to air voids of 13±1%. The OT tests were conducted at a temperature of 77°F. When testing AC mixtures, the OT applies a displacement of 0.018 inch. Taking into consideration that CIR projects mill the top 2 – 3 inches of the old AC and apply an AC overlay of 2 – 3 inches as a wearing course, a displacement of 0.010 inches was assumed to simulate field conditions at the bottom of the CIR layer.

The analysis of the OT data followed the latest procedures recommended in TxDOT test standard Tex-248-F, where the resistance of the mixture to reflective cracking is determined in terms of three parameters: number of cycles to failure, crack initiation, and crack propagation.

The number of cycles to failure is defined by a drop of 93% of the maximum load measured on the first cycle. If the critical drop in the applied load is not reached, the test runs to 4,000 cycles.

The resistance of the mixture to crack initiation is defined as the dissipated energy required to initiate a crack. The area under the hysteresis loop of the first cycle obtained from the OT test is used to determine the critical fracture energy given by the expression:

$$G = W/A$$

Where;

G: Energy (lbs-in./in^2)
W: Facture area (portion of the hysteresis loop)
A: Area of the cracked section
(thickness times width of the specimen:1.5 in. x 3.0. in.)

Figure 4.15 shows an example of the hysteresis loop of one CIR specimen, mixed and compacted with asphalt emulsion A, non-graded RAP, and 6% of lime slurry. Calculations of the fracture energy is conducted as follows:

- Maximum load: 398 lbs
- Displacement at maximum load: 0.0047 inches.
- 4th grade polynomial fitted to the hysteresis curve:

  $y = -2 * 10^{11}x^4 + 5 * 10^9x^3 - 5 * 10^7x^2 + 223379x - 10.427.$
- Fracture Area (W):

$$W = \int_0^{0.004748} -8 * 10^{10}x^4 + 2 * 10^9x^3 - 3 * 10^7x^2 + 165575x + 75.961\, dx = 1.37\ lb \cdot in$$

- Critical Fracture Energy:

$$G = \frac{W}{A} = \frac{1.37}{1.5 * 3.0} = 0.30\ lb \cdot in/in^2$$

The crack propagation rate provides an indication on the ability of the mix to attenuate the crack after it has been initiated. This property is quantified by fitting a power equation to the load reduction curve from the OT test. The crack propagation rate is defined as the coefficient in the power model $y = x^{-b}$ (i.e., b-coefficient). Figure 4.16 shows the power model for a CIR sample with emulsion A, non-graded RAP, and 6% of lime slurry. In this case, the fitted power equation is; $y = x^{-0.439}$, and therefore the crack progression rate is defined as 0.44.

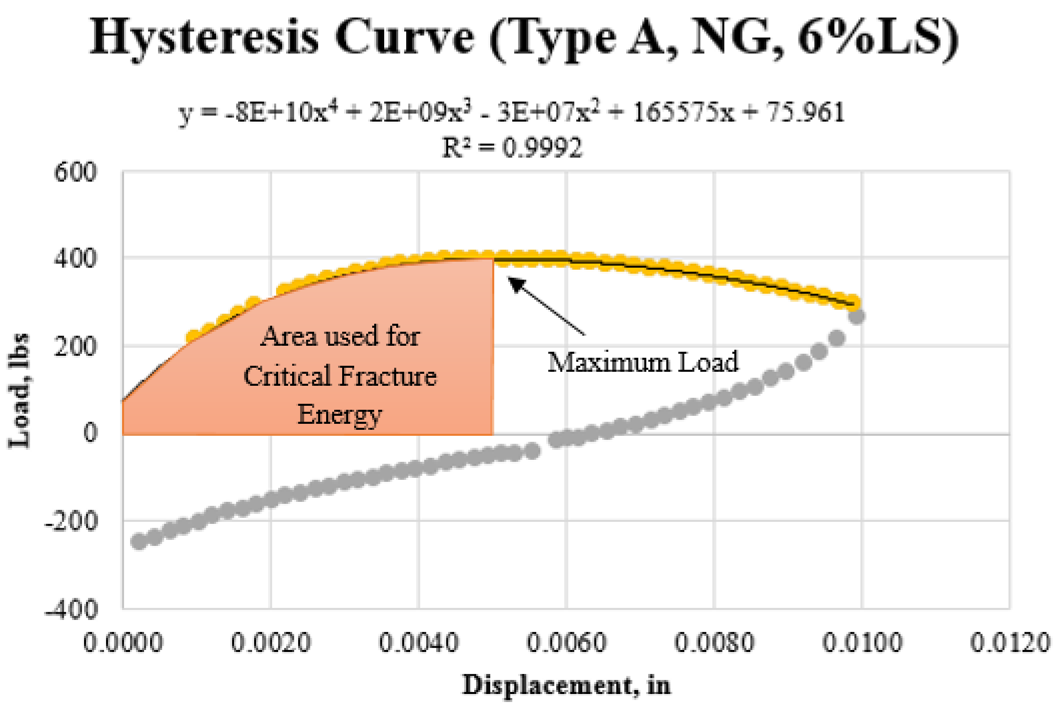

Figure 4.15. Hysteresis loop for CIR mixture under the first OT cycle.

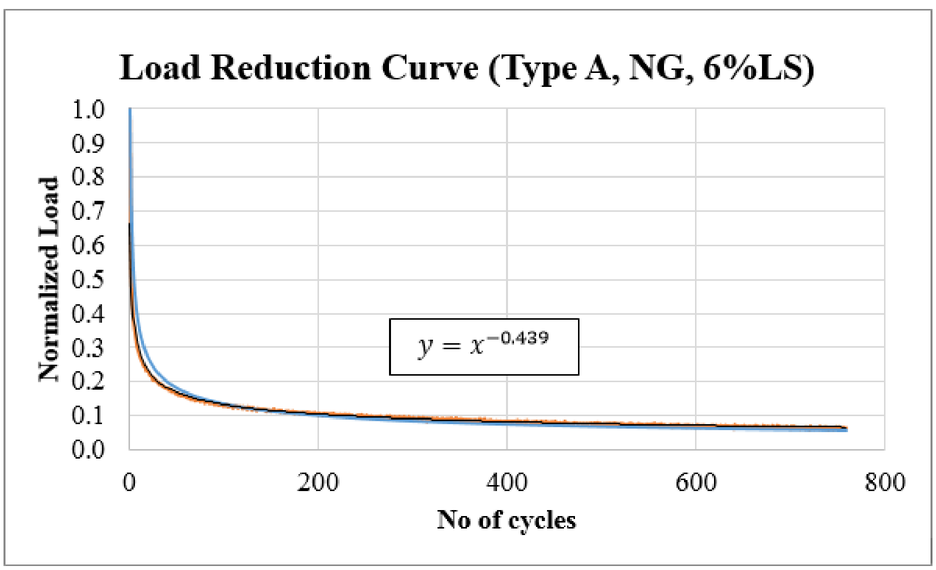

Figure 4.16. Power model fitting for CIR mixture in the OT.

A CIR mixture having high number of cycles to failure with high resistance to crack initiation and low rate of crack propagation is expected to exhibit excellent resistance to reflective cracking. Table 4.2 summarizes the reflective cracking properties of the 4 CIR mixtures with non-graded RAP and 6.0% lime slurry designed with the Hveem method. The data show that the number of load cycles to failure has the highest variability while the crack initiation and crack propagation rate have low variability, except for emulsion C.

Table 4.3. Summary of Reflective Cracking Characteristics of CIR Mixtures.

		No of Cycles to Failure			**Critical Fracture Energy**			**Crack Propagation Rate**		
Asphalt Emulsion	**Air Voids**	**Average**	**Std. Dev.**	**COV (%)**	**Average**	**Std. Dev.**	**COV (%)**	**Average**	**Std. Dev.**	**COV (%)**
A	13.6	496	32	6%	0.33	0.0007	1%	0.44	0.0007	1%
B	13.8	132	26	20%	0.36	0.0163	4%	0.51	0.0198	4%
C	13.1	280	51	18%	0.20	0.0035	2%	0.41	0.0955	23%
D	13.6	1254	226	18%	0.24	0.0120	5%	0.35	0.0049	1%

Figure 4.17 to Figure 4.19 compare the reflective cracking properties of the 4 CIR mixtures. The whiskers over the bars represent the 95% confidence interval for each CIR mix. An overlap in the confidence intervals of any two CIR mixtures indicates that the represented properties are statistically similar.

The high variability of the number of the number of cycles to failure makes it an inefficient indicator of the resistance to reflective cracking. The OT data show some interesting trends where the standard CMS-2s and the latex-modified emulsions (i.e., A and B) seems to be able to resist the initiation of the reflective crack (i.e. higher fracture energy) but they are not able to slow down its propagation as good as the polymer and rubber modified emulsions (C and D).

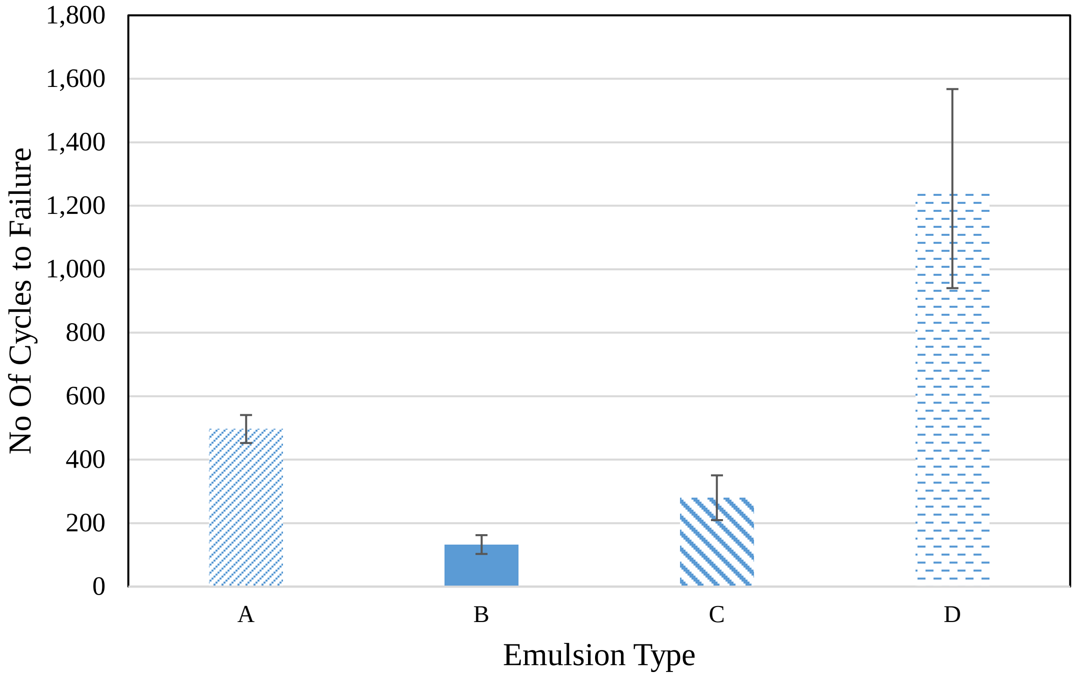

Figure 4.17. Cycles to failure of CIR mixtures; non-graded RAP and 6.0% lime slurry.

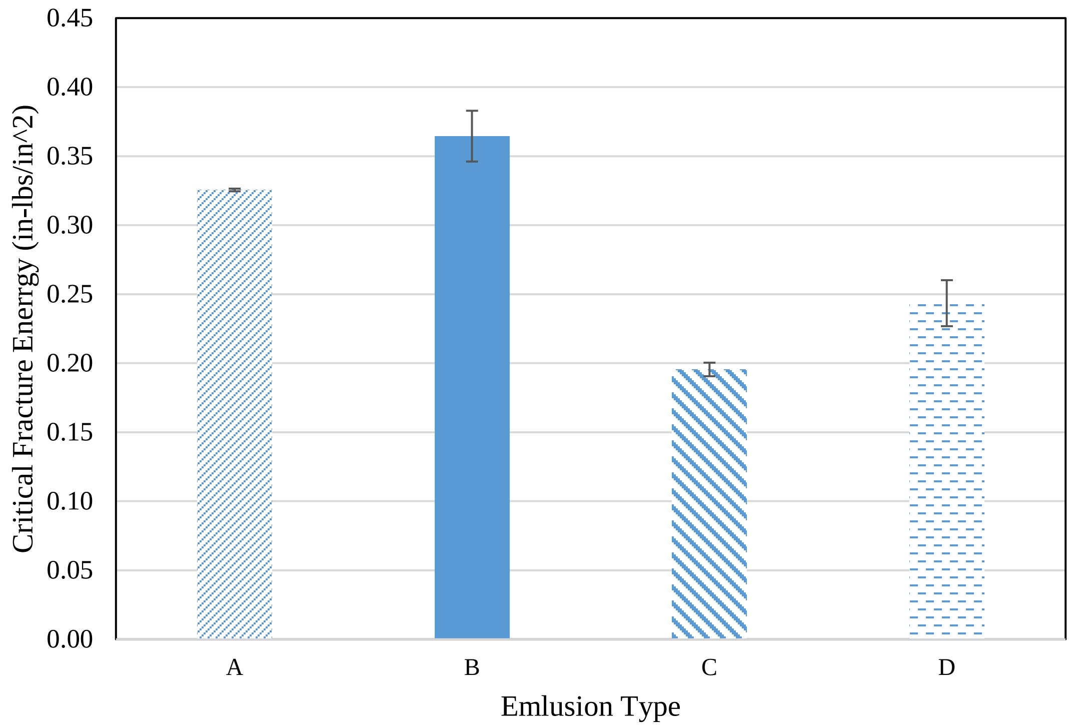

Figure 4.18. Crack initiation of CIR mixtures; non-graded RAP and 6.0% lime slurry.

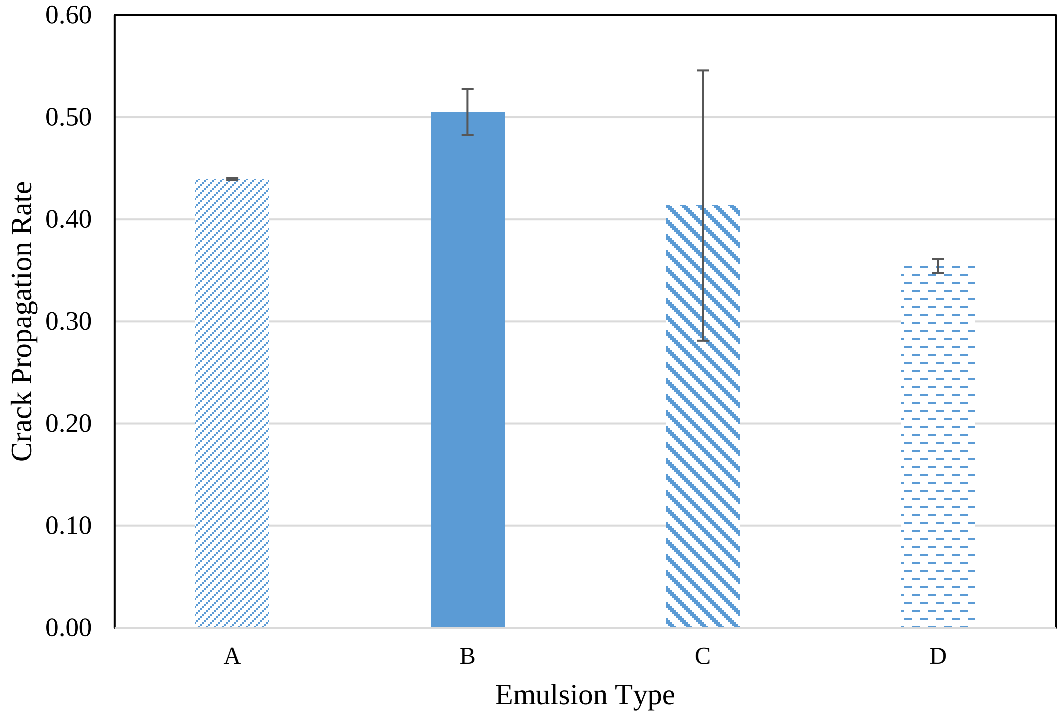

Figure 4.19. Crack propagation rate of CIR mixtures; non-graded RAP and 6.0% lime slurry.

Chapter 5. STRUCTURAL DESIGN PROCEDURE

The Nevada DOT is currently implementing the AASHTO M-E Design for flexible pavements per the; "Manual for Designing Flexible Pavements in Nevada Using AASHTOWare Pavement-ME Design." The objective of this task was to develop the necessary data to incorporate the CIR layer as a structural layer within the flexible pavement. Figure 5.1 shows a typical flexible pavement structure consisting of a 3.0 in CIR layer under a 2.0 in AC overlay.

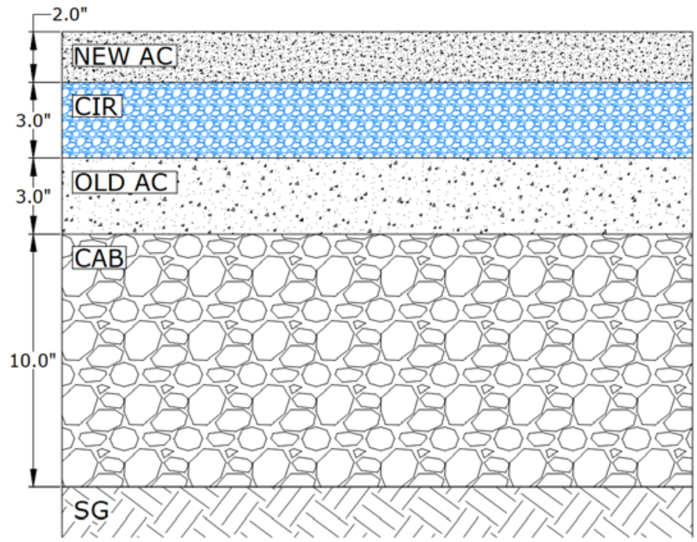

Figure 5.1. Typical CIR pavement in Nevada.

5.1. Characterization of the CIR Layer

In order to conduct a full M-E design for the flexible pavement structure shown in Figure 5.1, the CIR layer must be fully characterized as an asphalt bound layer. The Hveem mix design information presented in Chapter 3 and the E* master curves data presented in Chapter 4 can be used to characterize the CIR layer for the M-E Design per the Nevada Manual. Since the standard NDOT CIR mix uses non-graded RAP with 6.0% lime slurry, only the properties of these mixtures are included in the M-E Design. Table 5.1 summarizes the recommended input values for the CIR layer when used as an asphalt-bound layer under the new AC overlay with any of the four asphalt emulsions evaluated in this research.

Table 5.1. Design Inputs for New CIR Layer, Mixture Volumetrics, and Mechanical Properties (New Flexible Pavement Design).

Parameter	Design Input	Remarks
CIR Layer		
Thickness (in)	Define thickness of the Cold In-Place Recycling layer.	
Mixture Volumetrics		
Unit weight (pcf)	• District I: 137 • District II and III: 132	Weight of the selected material in pounds per cubic foot.
Effective binder content (%)	A typical value of 5.2 can be used for CIR mixtures in all Nevada districts.	Effective asphalt content by volume for the as-constructed CIR layer.
Air voids (%)	13	Percent volume of air voids in the as-constructed CIR layer.
Poisson's ratio	Select *True*. Use default values for the Poisson's ratio model: • *Poisson's ratio Parameter A* = -1.63 • *Poisson's ratio Parameter B* = 3.84E-06	Calculate Poisson's ratio as a function of dynamic modulus.
Mechanical Properties		

Dynamic Modulus	• Select dynamic modulus input level: 1.
	• Select temperature levels: 5
	• Select frequency levels: 6
	• Define dynamic modulus values in psi:
	  • Emulsion A: Table 5.2
	  • Emulsion B: Table 5.3
	  • Emulsion C: Table 5.4
	  • Emulsion D: Table 5.5
		Input directly the dynamic modulus properties of the CIR and the asphalt binder properties from the Tables.

Select CIR Estar predictive model	Select *False* for simple conversion of asphalt binder G* values to viscosity values without frequency adjustments.	Use Viscosity based model (nationally calibrated).
Reference temperature (deg F)	70	Baseline temperature for use in deriving the dynamic modulus master curve.

Asphalt Binder	• Select *Superpave Performance Grade*.
	• Define dynamic shear modulus (G*) in Pa and phase angle in degrees:
	  • Emulsion A: Table 5.6
	  • Emulsion B: Table 5.7
	  • Emulsion C: Table 5.8
	  • Emulsion D: Table 5.9
		Once the dynamic modulus input level 1 is selected, the program automatically defines the same input level (i.e., Level 1) for asphalt binder properties.

Table 5.2. Dynamic Modulus Input Values in psi for CIR with Non-graded RAP, Emulsion A, and 6.0% Lime Slurry.

	Frequency (Hz) →					
Temperature (deg F)	**0.1**	**0.5**	**1**	**5**	**10**	**25**
14	847868	958212	1002682	1097758	1135000	1180751
40	514702	634151	686275	805699	855524	919145
70	226396	312721	354924	462541	512114	579578
100	83492	126059	149226	215418	249406	299278
130	30382	47227	57066	87769	105011	132109

Table 5.3. Dynamic Modulus Input Values in psi for CIR with Non-graded RAP, Emulsion B, and 6.0% Lime Slurry.

	Frequency (Hz) →					
Temperature (deg F)	**0.1**	**0.5**	**1**	**5**	**10**	**25**
14	1070724	1184229	1229130	1323663	1360185	1404688
40	696336	832090	889685	1018421	1070941	1137085
70	331824	443455	496174	626170	684217	761621
100	128027	189364	221752	311217	355676	419407
130	46072	71736	86476	131414	156034	193964

Table 5.4. Dynamic Modulus Input Values in psi for CIR with Non-graded RAP, Emulsion C, and 6.0% Lime Slurry.

	Frequency (Hz) →					
Temperature (deg F)	**0.1**	**0.5**	**1**	**5**	**10**	**25**
14	1015062	1113285	1151737	1231941	1262650	1299856
40	688643	811743	863174	976520	1022141	1079100
70	349899	459356	510012	632429	686045	756619
100	143817	209573	243591	335435	380056	442986
130	53911	83601	100413	150701	177704	218643

Table 5.5. Dynamic Modulus Input Values in psi for CIR with Non-graded RAP, Emulsion D, and 6.0% Lime Slurry.

	Frequency (Hz) →					
Temperature (deg F)	**0.1**	**0.5**	**1**	**5**	**10**	**25**
14	924296	1018236	1055693	1135267	1166319	1204435
40	607184	718032	765187	871141	914664	969797
70	298107	389888	432929	538743	585984	649093
100	120630	172791	199848	273543	309798	361528
130	45708	68670	81534	119831	140406	171734

Table 5.6. Representative Mean Dynamic Shear Modulus and Phase Angle Input Values for Asphalt Emulsion Residue A.

Temperature (deg F)	Binder Gstar (Pa)	Phase angle (deg)
114.8	3510	84.3
125.6	1470	86.1
136.4	690	87.5

Table 5.7. Representative Mean Dynamic Shear Modulus and Phase Angle Input Values for Asphalt Emulsion Residue B.

Temperature (deg F)	Binder Gstar (Pa)	Phase angle (deg)
136.4	3635	84.1
147.2	1680	85.6
158.0	823	86.7

Table 5.8. Representative Mean Dynamic Shear Modulus and Phase Angle Input Values for Asphalt Emulsion Residue C.

Temperature (deg F)	Binder Gstar (Pa)	Phase angle (deg)
136.4	3500	84.0
147.2	1635	85.7
158.0	781	87.0

Table 5.9. Representative Mean Dynamic Shear Modulus and Phase Angle Input Values for Asphalt Emulsion Residue D.

Temperature (deg F)	Binder Gstar (Pa)	Phase angle (deg)
125.6	2765	86.6
136.4	1230	87.5
147.2	582	88.2

5.2. Performance of the CIR Layer

In order to conduct a full M-E design for the flexible pavement structure shown in Figure 5.1, the performance of the CIR layer in terms of its resistance to rutting and fatigue cracking must be fully developed. The performance characteristics data presented in Chapter 4 can be used to describe the performance of the CIR layer.

Figure 5.2 presents the rutting models for the standard NDOT CIR mixtures with the four asphalt emulsions evaluated in this research. The measured rutting performance data for all the 4 CIR mixtures were grouped together to develop an average rutting model. The average rutting model is shown in Figure 5.3 along with its corresponding 95% confidence interval. As can be seen in Figure 5.2, the 95% confidence interval of the average rutting model encompasses the rutting models from all 4 CIR mixtures. This indicates that, statistically, the rutting models of the 4 CIR mixtures can be represented by the average rutting model with 95% confidence. Therefore, the average rutting model shown in Figure 5.3 is recommended to represent performance of the standard NDOT CIR mixtures in the M-E Design for flexible pavements with CIR layer as presented below:

$$\frac{\varepsilon_{\mathbf{p}}}{\varepsilon_{\mathbf{r}}} = \mathbf{10}^{-7.802}(\mathbf{T})^{0.282}(\mathbf{N})^{3.768}$$

A similar analysis will be conducted to develop the representative fatigue performance model after the completion of the fatigue evaluations at the remaining two testing temperatures. This analysis will be included in the Final Report.

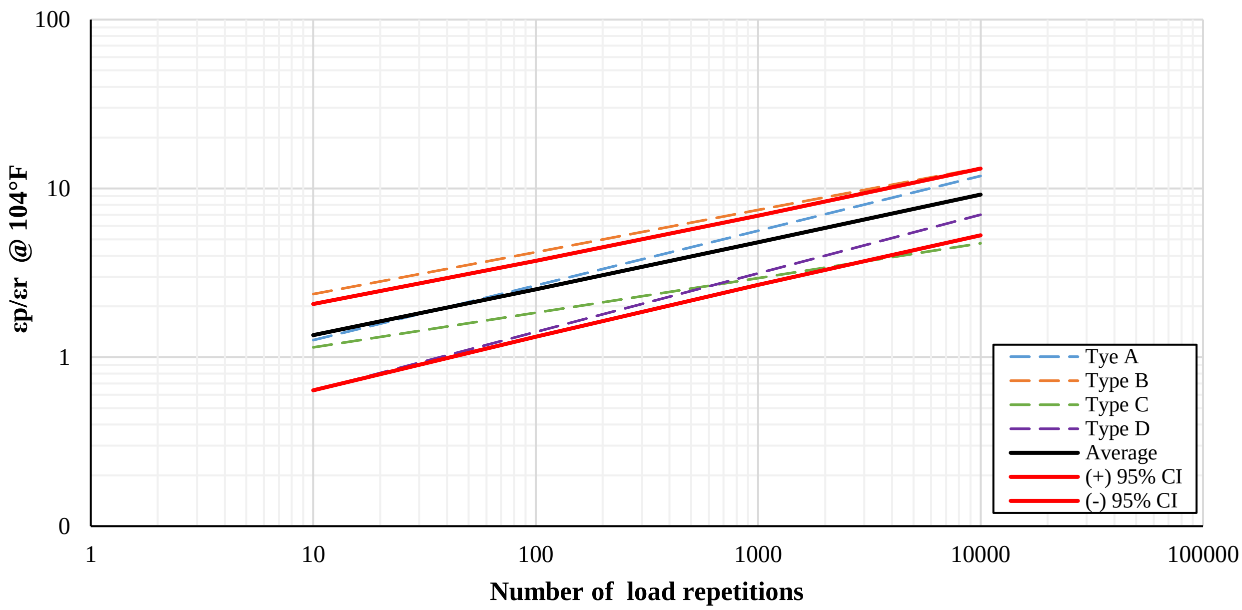

Figure 5.2. Rutting performance models for CIR mixtures with non-grade RAP and 6.0% lime slurry.

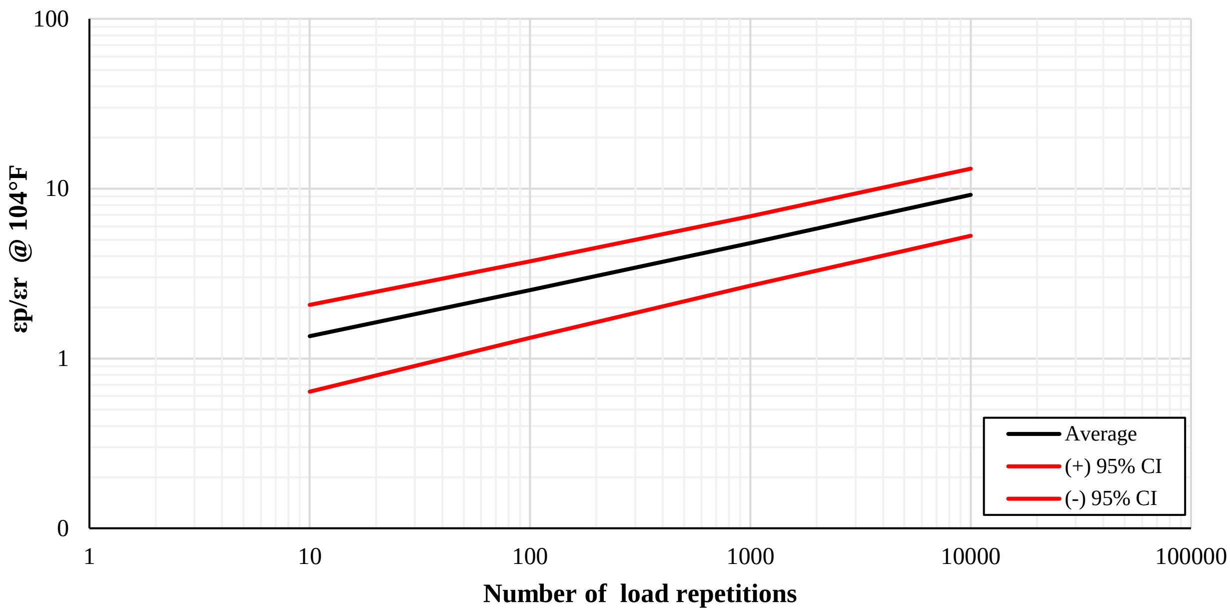

Figure 5.3. Average rutting performance model for NDOT standard CIR mixtures.

Chapter 6. FINDINGS AND RECOMMENDATIONS

This research effort conducted extensive evaluations of CIR mixtures in support of the development of a mix design method for CIR mixtures and a structural design method for flexible pavements with CIR layers. First, the research conducted a benefit-cost analysis of CIR pavements constructed throughout Nevada during the period of 2000 – 2015. Second, two mix design methods were developed based on the Hveem and Superpave techniques. Third, the engineering and performance characteristics of the CIR mixtures were evaluated in preparation to incorporate the CIR layer into the NDOT M-E design as an asphalt-bound structural layer. Based on the analysis of the data generated from this extensive evaluation, the following findings and recommendations can be made:

- Overall, the majority of the CIR pavements constructed by NDOT over the period of 2000 – 2105 are performing well. However, the average design life for CIR pavements with AC overlay seems to be around 15 years while the average design life of CIR pavements with surface treatment seem to be around 8 years. The implementation of a reliable mix design method and an effective structural design method can have a positive impact on the extension of the average design life of the two types of CIR pavements.
- The benefit-cost analysis of the CIR pavements constructed by NDOT over the period of 2000 – 2015 did not identify the highly expected positive correlation between the thicknesses of the CIR and the AC overlay layers. Again, this may have been caused by the lack of a reliable mix design method and an effective structural design method.
- The data generated in this research showed that CIR mixtures can be effectively designed using the NDOT Hveem mix design method with some minor modifications in the number of tamps and the leveling stress. The optimum air voids content has been identified as 13±1%. In addition, a mix design method based on the Superpave technology has also been developed. Step by step procedures have been recommended for the two mix design methods developed in this research.
- The moisture sensitivity evaluation of the CIR mixtures showed that CIR mixtures can be designed to deliver good levels of dry tensile strength property and tensile strength ratio. It has been established that a good criteria for the moisture sensitivity of CIR mixtures would be; minimum dry tensile strength at 77°F of 50psi and a minimum tensile strength ratio of 70%. This criteria is consistent with NDOT's criteria for AC mixtures.
- The evaluation of the dynamic modulus master curve data for the CIR mixtures indicated that the majority of CIR mixtures can develop E* properties that are very comparable to AC mixtures at all levels of temperatures and frequencies.
- The analysis of the tensile strength and dynamic modulus properties of CIR mixtures manufactured with two types of gradations, two levels of lime slurry, and four types of asphalt emulsions indicated that each CIR mix is unique and must be individually designed following either the Hveem or the Superpave method. In addition, as NDOT moves towards using engineered emulsions, the properties of the CIR mixture must be evaluated on a case by case basis.
- The evaluation of the performance characteristics of the CIR mixtures showed that the standard methods of repeated load triaxial and flexural beam fatigue tests can be

effectively used to characterize the resistance of the CIR mixtures to rutting and fatigue cracking, respectively. It was found that, for the NDOT standard CIR mixtures manufactured with non-graded RAP and 6.0% lime slurry, an average rutting model can be recommended with 95% confidence to estimate the rutting performance of CIR mixtures manufactured with different asphalt emulsions.

- *The data generated from the fatigue evaluation indicate that the fatigue behavior at 70°F of the CIR mix with the rubber-modified emulsion (D) is the best followed by the CIR mix made with the Latex-modified emulsion (B). However, this observation may not hold true for the other two testing temperatures. The evaluations of the fatigue properties at the other two testing temperatures of 55 and 85°F are still in-progress and will be incorporated in the Final Report.*
- The data generated from the overlay tester showed that the resistance of the CIR mixture to reflective cracking is sensitive to the type of asphalt emulsion. As previous studies in Nevada showed, CIR mixtures offer good resistance to reflective cracking, this study employed a new approach to assess resistance to reflective cracking in terms of crack initiation and propagation. The analysis of the reflective cracking data indicated that some CIR mixtures are less resistant to crack initiation but more resistant to crack propagation than others.

REFERENCES

1. P. E. Sebaaly, J.A. Castro, E.Y. Hajj, and P.S. Sebaaly; “Development of In-Place Density Method for Cold In-Place Recycling,” Research Report, SOLARIS University Transportation Center, University of Nevada, Reno, 2018.
2. M. Piratheepan, P.E. Sebaaly, E.Y. Hajj, and S. Selvaratnam, "Evaluation of Long-term Performance of Cold In-Place Recycling Pavements in Nevada," Research Report, University of Nevada, Reno, 2014.
3. J.A. Castro; “Cold In-Place Recycling Mix Design, In-Place Density, and Long-Term Performance in Nevada,” Master Thesis in Pavement Engineering and Science, Department of Civil & Environmental Engineering, University of Nevada, Reno, December 2017.
4. P. E. Sebaaly, M. Piratheepan, and E. Y. Hajj; “Designing Cold-In-Place Recycling (CIR) Using SUPERPAVE Gyratory Compactor,” Research Report, Asphalt Research Consortium, FHWA, May 2015.

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