EXAMINATION OF CURING CRITERIA FOR COLD IN-PLACE RECYCLING

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16. Abstract

Cold In-Place Recycling (CIR) has been used widely in rehabilitating the rural highways because it improves a long-term pavement performance. A CIR layer is normally covered by a hot mix asphalt (HMA) overlay in order to protect it from water ingress and traffic abrasion and obtain the required pavement structure and texture. Curing is the term currently used for the period of time that a CIR layer should remain exposed to drying conditions before an HMA overlay is placed. The industry standard for curing time is 10 days to 14 days or a maximum moisture content of 1.5 percent, which appear to be very conservative. When the exposed CIR layer is required to carry traffic for many weeks before the wearing surface is placed, it increases the risk of a premature failure in both CIR layer and overlay.

This study was performed to explore technically sound ways to identify minimum in-place CIR properties necessary to permit placement of the HMA overlay. To represent the curing process of CIR pavement in the field construction, three different laboratory curing procedures were examined: 1) uncovered, 2) semi-covered and 3) covered specimens. The indirect tensile strength of specimens in all three curing conditions did not increase during an early stage of curing but increased during a later stage of curing usually when the moisture content falls below 1.5%. Dynamic modulus and flow number increased as curing time increased and moisture contents decreased. For the same curing time, CIR-foam specimens exhibited the higher tensile strength and less moisture content than CIR-emulsion. The laboratory test results concluded that the method of curing temperature and length of the curing period significantly affect the properties of the CIR mixtures. The moisture loss index was developed to predict the moisture condition in the field and, in the future, this index be calibrated with the measurements of temperature and moisture of a CIR layer in the field.

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1. INTRODUCTION

The Cold In-Place Recycling (CIR) has become one of the popular methods in rehabilitating the existing asphalt pavements due to its cost-effectiveness, the conservation of paving materials, and its environmental friendliness. Particularly, in Iowa, the CIR has been widely used in rehabilitating the rural highways because it improves a long-term pavement performance.

A CIR layer is normally covered by a hot mix asphalt (HMA) overlay or chip seal in order to protect it from water ingress and traffic abrasion and obtain the required pavement structure and texture. Curing is the term currently used for a time period that a CIR layer must remain exposed in the air for drying before an HMA overlay or chip seal is placed. The curing period depends on several factors, which include day and night-time temperatures, humidity levels and rainfall activity, wind, layer thickness, type of asphalt used, moisture content of CIR mix before and after recycling, the level of compaction, in-place voids, and the drainage characteristics of the material below the CIR layer and the shoulders. Overlaying the CIR surface prior to adequate moisture loss through a proper curing may result in a premature failure of the CIR and/or HMA overlay (ARRA 2001). The Asphalt Institute (1998) reported that the inadequate curing can produce high retained moisture contents that increase the possibility of asphalt stripping and slow the rate of strength development after HMA overlay is placed.

All laboratory and field test results indicate that the method of curing temperature and length of the curing period significantly affect the properties of the CIR mixtures. The current practice in Iowa simply controls the maximum moisture content in the CIR of 1.5 percent, whereas numerous projects with CIR, struggling with unfavorable climate, have been overlaid successfully with higher levels of moisture. Questions about the curing criteria generally fall into two categories: 1) When, since construction, the CIR layer can handle the placement of the wearing surface and 2) If and how much of the moisture in the CIR layer is detrimental to a HMA overlay.

To further Iowa's development of asphalt recycling technology, this study explored technically sound and more effective ways to identify minimum in-place CIR properties necessary to permit placement of the HMA overlay or chip seal. The research effort focused on developing a procedure that would optimize the CIR exposure time to traffic before an HMA overlay. The main of this research is to develop a better analysis tool that the industry and the owner agency can apply to monitor the CIR layer in preparation for a timely placement of the wearing surface.

Chapter 1 introduces study objective and scope and Chapter 2 summarizes the past research efforts on curing criteria for both CIR-emulsion and CIR-foam. Chapter 3 presents the results of preliminary tests on influences of curing temperature and time for CIR-foam mixtures. Chapter 4 discusses the impacts of laboratory curing procedures on indirect tensile strength. Chapter 5 summarizes the fundamental characteristics of RAP materials from two sources and Chapter 6 presents an analysis result of various curing processes using these RAP materials. Chapter 7 investigates the effects of moisture contents on the indirect tensile strength change and Chapter 8 evaluates the dynamic modulus and flow number of the CIR specimens with various curing conditions. Chapter 9 presents an effort to develop a moisture loss index and Chapter 10 presents findings from the study with further research.

2. LITERATURE REVIEW ON CIR CURING PROCEDURES

This chapter presents the past research efforts on curing criteria for both CIR-emulsion and CIR-foam in the field and laboratory. Based on the literature review, most agencies adopted a curing requirement of 1.5% moisture condition in the field. However, many researchers proposed various laboratory curing procedures, which would represent both short and long-term curing process in the field. The field curing procedure of CIR is presented first followed by the laboratory curing procedures of CIR-emulsion and CIR-foam.

2.1 Field Curing Procedure of Cold In-place Recycling

AIPCR and PIARC (2002) recommended that the application of the HMA overlay should be delayed until the residual water has largely evaporated. This duration should not only depend on the climatic conditions following CIR construction, but also on the traffic level that the CIR layer could support after completion of the pavement construction. In most European countries, the residual moisture content are used to determine the timing of placing the HMA overlay in the ranges between 1.0% and 1.5%. Particularly, in Spain, it is recommended to place an HMA overlay only after the moisture content in a CIR layer has become less than 1.0% for at least 7 days or when the materials can be extracted from the CIR pavement by coring.

South Dakota DOT (2004) recommended that the HMA overlay shall not be placed until the moisture content of the CIR layer is less than 1.5 percent. Minnesota DOT (2005) recommended, before placing the HMA overlay or other applicable surface treatment, the CIR layer shall be allowed to cure until the moisture of the mixes is reduced to 2.0% or less. FHWA (2007) issued a guideline that a CIR layer should be cured for two weeks during favorable weather conditions, preferably at temperatures higher than 16°C.

Although most agencies did not specify a different curing requirement of CIR-foam versus CIR-emulsion, AIPCR and PIARC (2002) allows a higher moisture content for CIR-foam than CIR-emulsion. They recommend between 1.0% and 1.5% moisture for CIR-emulsion layer before an HMA overlay whereas at least 2.0% below the optimum moisture content (OMC) for the CIR-foam layer. Assuming a typical OMC value of RAP materials between 4.0% and 4.5%, it seems to allow the moisture content between 2.0% and 2.5% for CIR-foam, which is 2.0% below OMC. Particularly, in the United Kingdom, the minimum curing period of CIR-foam before the HMA layer is specified as just 36 hours.

2.2 Laboratory Curing Procedure of CIR-emulsion

The Asphalt Institute (AI) recommends using the heaviest asphalt that can be worked, while advocating the use of low-viscosity asphalt for fine aggregates and high-viscosity asphalt for coarse aggregates (TAI 1979). Oregon DOT used CMS-2s (now called CMS-2RA) but, in 1988, they switched to HFE-150. The province of Ontario, Canada also uses HFE-150 (Murphy and Emery 1996). The Pennsylvania DOT uses CMS-2 emulsion with an asphalt residue of 100~120 penetration. When the penetration of the recovered asphalt is in the range of 15~20, CSS-1h emulsion with an asphalt residue of 40~90 penetration is used to achieve softer recovered asphalt (Epps 1990). To address the problem of rutting, reflective cracking and moisture damage, the New Mexico DOT has elected to use high-float polymer-modified emulsion instead of SS-1 and CMS-2S (McKeen et al. 1997). Lee et al. (2002) reported that most states use high-float type emulsion; a few exceptions prefer slow- or medium-setting cationic emulsions. Several states include lime, fly ash and Portland cement as an additive. Iowa DOT (2006) states, "CSS-1 emulsion may be used in place of HFMS-2s when the traffic permitted on the CIR layer is less than 500 ADT."

Cationic slow-setting (CSS) emulsion typically contains about 65% asphalt and 35% water although some emulsions can hold up to 75% asphalt. Salomon and Newcomb (2000) evaluated three emulsions, CSS-1 (cationic slow-setting emulsion), HFMS-2S (high-float medium-setting emulsion with a residue of relatively low viscosity), and HFMS-2P (high-float medium-setting emulsion modified with a polymer). They found that the HFMS-2P emulsion gave the lowest overall air voids, and recommended that the Minnesota DOT should use it until more precise PG binder information could be collected on the aged asphalt from RAP.

Sebaaly et al. (2001) recommended that the design process should evaluate the early stability of the designed CIR-emulsion mixture using Hveem stability and resilient modulus. They evaluated the CIR-emulsion mixtures at three different curing stages: (1) initial curing, (2) final curing, and (3) long term curing as follows:

1) Initial curing: compacted CIR-emulsion samples are cured in the mold at 25°C for fifteen hours. After curing, the samples are extruded from the mold and cured at room temperature for three hours prior to conducting any tests.
2) Final curing: compacted CIR-emulsion samples are extruded out of the mold and cured in an oven at 60°C for three days. After the oven curing, the samples are cured at room temperature for three hours prior to conducting any tests.
3) Long term curing: compacted CIR-emulsion samples are extruded out of the mold and cured in an oven at 60°C for thirty days

They reported that the resilient modulus property could be used to assess the stability and strength of CIR mixtures at various stages. They also reported that the resilient modulus property was highly sensitivity to CIR mixture parameters and could be used to evaluate the effectiveness of different binders.

Lee et al. (2002) reported that there are considerable variations in the curing temperature and time adopted for CIR-emulsion mix design process in the laboratory. Lee et al. (2003) recommended the curing periods of six hours and twenty-four hours to simulate short-term and long-term curing in the field at 60˚C, a typical hot summer day's pavement temperature, and at 25˚C, a typical summer night's pavement temperature.

Because only the CIR pavement surface is directly exposed to air in the field condition, Batista and Antunes (2003) covered some of CIR-emulsion specimens with a plastic film except the top in order to allow the water to evaporate through the top surface only. They reported that water content evolution in the field would be between laboratory specimens with and without plastic films. They obtained the cores from the site after one year of traffic and tested them for the resilient modulus. The resilient modulus of CIR-emulsion samples cured at room temperature for four months (two months with lateral film strip and two months without it) exhibited the resilient modulus between 2,000 and 2,500 MPa, which were similar to those of cores. The specimens cured in the oven at 60°C for three days, however, did not achieve the resilient modulus of the cores. As a result, they concluded that CIR-emulsion mixtures subjected to the accelerated curing process, which was the one used in the mix design method, did not represent the mixtures that had undergone one year of traffic in the field.

2.3 Laboratory Curing Procedure of CIR-foam

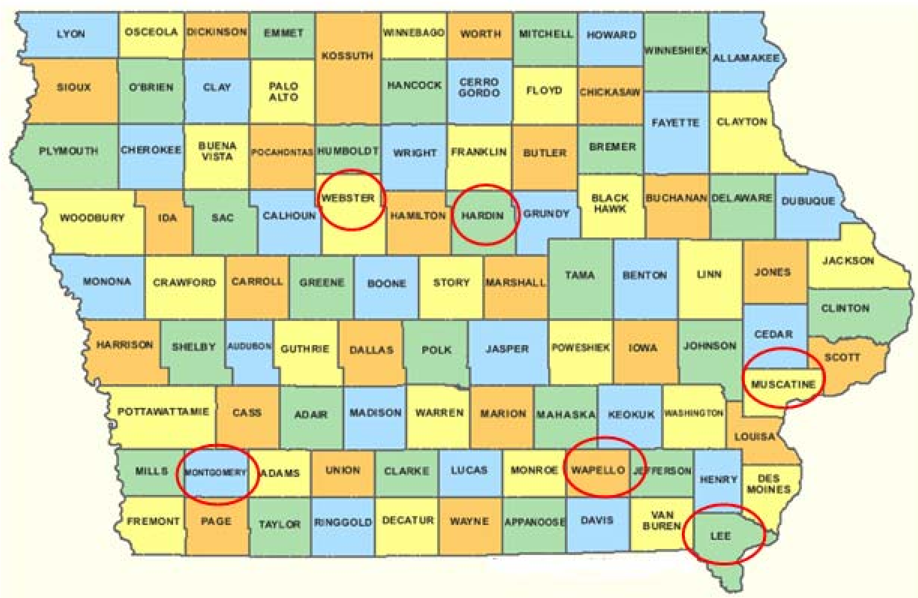
Since most research efforts were made on the development of the mix design procedure of full-depth reclamation using foamed asphalt (FDR-foam), there exists very limited literature available in the area of the laboratory curing procedure of CIR-foam. Although the laboratory curing procedure of FDR-foam mixtures may not be directly applicable for the curing of CIR-foam, they are provided here as a relevant laboratory curing procedure, which can be modified to simulate the curing process of CIR-foam in the field.

To simulate the initial loss of mixing water while reaching the strength of the mixture during construction and the early service life of FDR-foam, many researchers adopted the laboratory curing procedure proposed by Bowering (1970) and Bowering and Martin (1976) that is curing in the oven at 60˚C for three days. Lee (1981) suggested that the effect of curing on the strength of FDR-foam could be best established on the basis of laboratory-field correlation. Ruckle et al. (1983) recommended the laboratory curing procedure for FDR-foam in the oven at 40˚C for one day for a short-term and for three days for a long-term curing, which was later adopted by CSIR Transportek (1999). Maccarrone et al. (1995) reported that three-day curing at 60˚C appeared to be equivalent to thirteen-month field curing of FDR-foam because the oven-cured FDR-foam samples showed similar resilient modulus values as the field core taken at twelve months after construction.

Jenkins and Ven (1999) recommended that the FDR-foam should be cured in the oven at 46˚C for three days to simulate a 150-mm thick FDR-foam base layer with thin surfacing in a region with a mean monthly air temperature of 30˚C. This curing condition in the oven at 46˚C for three days would represent the medium or long-term curing of FDR-foam base layer in the field. To predict short-term performance, i.e., seven to fourteen days after construction, they recommended the oven curing at 40˚C for one day. Marquis et al. (2002) adopted curing procedure of the FDR-foam in the oven at 40˚C for three days. Lane and Kazmierowski (2003) adopted a curing procedure of the FDR-foam in the oven at 60±2°C for 72±4 hours. Lee and Kim (2007) confirmed that the curing temperature and length of the curing period significantly affect the engineering properties of the CIR-foam mixtures and reported that CIR-foam mixtures cured in the oven at 60°C for two days exhibited significantly higher indirect tensile strength than those cured in the oven at 40°C for three days.

3. INFLUENCES OF CURING TEMPERATURE AND TIME ON CIR-FOAM

During the summer of 2004, RAP materials were collected from six different Cold In-Place Recycling (CIR) project sites: three CIR-Foam and three CIR-ReFlex® sites. As shown in Figure 3-1, CIR project sites were selected across the state of the Iowa, which include Muscatine County, Webster County, Hardin County, Montgomery County, Lee County, and Wapello County.



County	Road Name	Rehabilitation Method
Muscatine	State Highway 22	CIR-Foam
Webster	County Road P 33	CIR-ReFlex®
Hardin	County Road 175	CIR-Foam
Montgomery	State Highway 48	CIR-ReFlex®
Lee	County Road W 62	CIR-ReFlex®
Wapello	County Road V 37	CIR-Foam

Figure 3-1. Locations of CIR project sites where RAP materials were collected

3.1 RAP Gradation Analysis

First, dried RAP materials were divided into six stockpiles that were retained on the following sieves: 25mm, 19mm, 9.5mm, 4.75mm, 1.18mm and below 1.18mm. The sorted RAP materials were then weighed and their relative proportions were computed. Gradations used for sample preparations of preliminary tests are plotted on a 0.45 power chart in Figure 3-2. To allow the comparison among six RAP material sources side by side, their relative proportions are graphed in Figure 3-3. Although they are quite similar in gradation, overall, RAP materials from Muscatine County are the most coarse, those from Montgomery, and Wapello Counties are coarse, and those from Hardin, Lee Counties can be considered as densely graded.

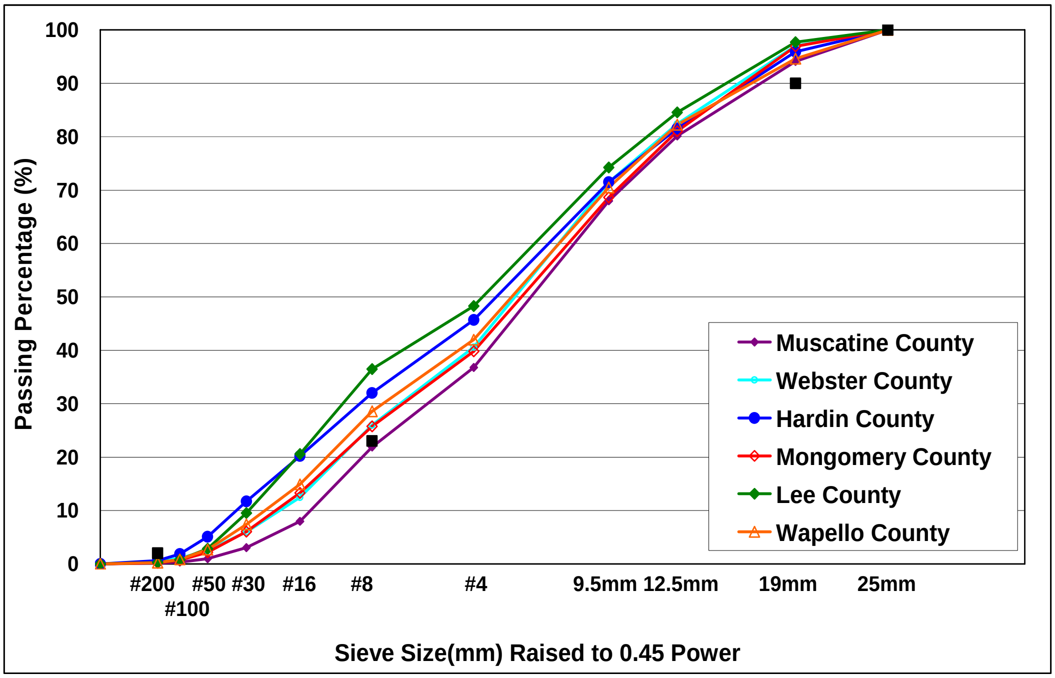


Figure 3-2. Gradation plots from six different RAP sources passing 25mm sieve

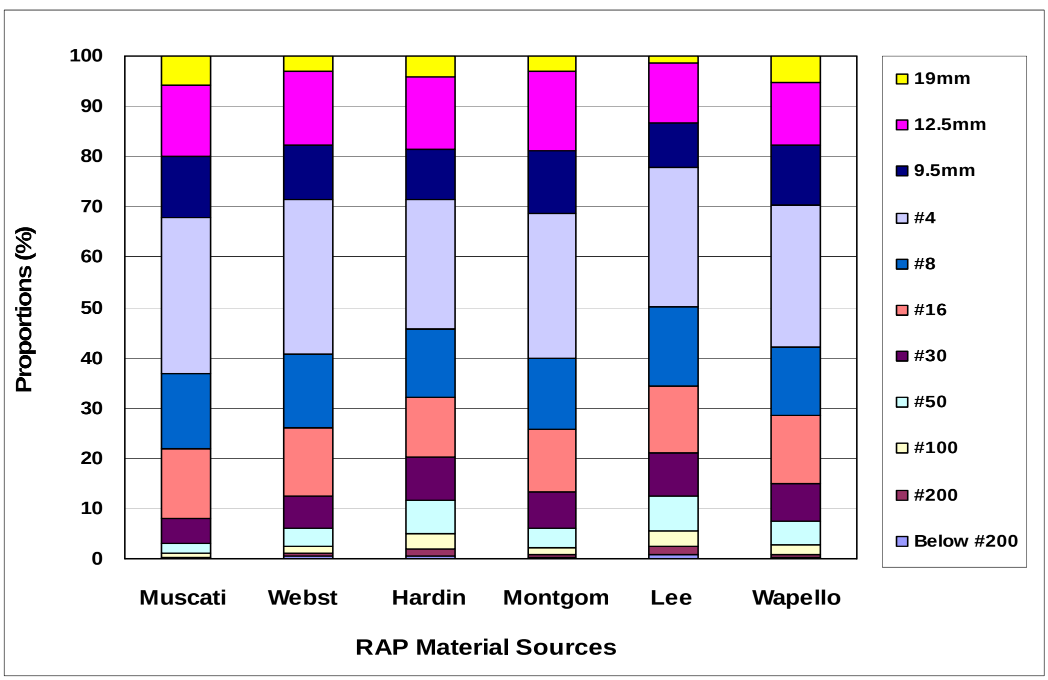


Figure 3-3. Gradation bar chart of six different RAP materials passing 25mm sieve

3.2 Influences of Curing Temperature and Time on CIR-foam Mixtures

CIR mixtures do not gain a required strength for traffic until a significant amount of the mixing moisture is evaporated over time. The curing temperature and length of the curing period significantly affect the engineering properties of the CIR mixtures. Recently, Lee and Kim (2007) presented that the CIR-foam mixtures cured in the oven at 60°C for two days showed the much higher indirect tensile strengths than those cured in the oven at 40°C for three days.

The influences of curing temperature and time on the CIR-foam mixtures were evaluated using indirect tensile strength on the vacuum-saturated CIR-foam specimens from three different RAP sources of Muscatine, Hardin, and Wapello Counties. As shown in Table 3-1, two specimens were prepared using gyratory compactor at 25 gyrations, all at 2.5% foamed asphalt content (FAC) and 4.0 % moisture content (MC). Table 3-2 summarizes the number of test specimens prepared for a combination of three levels of curing temperature (25°C, 40°C and 60°C) and six levels of curing period (1^{st}, 2^{nd}, 3^{rd}, 5^{th}, 7^{th}, and 28^{th} day).

Table 3-1. Design parameters used for CIR-foam specimens

Asphalt Binder	PG 52 - 34
Foaming Temperature (°C)	170°C
Foaming Water Content (%)	1.3 %
Moisture Content of RAP (%)	4.0 %
Foamed Asphalt Content (%)	2.5 %
Compaction Method	Gyratory compactor at 25 gyrations

Table 3-2. Number of specimens prepared for indirect tensile strength test

Curing Period / Oven Curing Temperature	1^{st} day	2^{nd} day	3^{rd} day	5^{th} day	7^{th} day	28^{th} day
25°C	2	2	2	2	2	2
40°C	2	2	2	2	2	2
60°C	2	2	2	2	2	2

As shown in Table 3-3, moisture contents were measured from each specimen prepared at each combination of three levels of curing temperature and six levels of curing period. It is interesting to note that the moisture level dropped quickly to the lowest level after one day curing at 60°C.

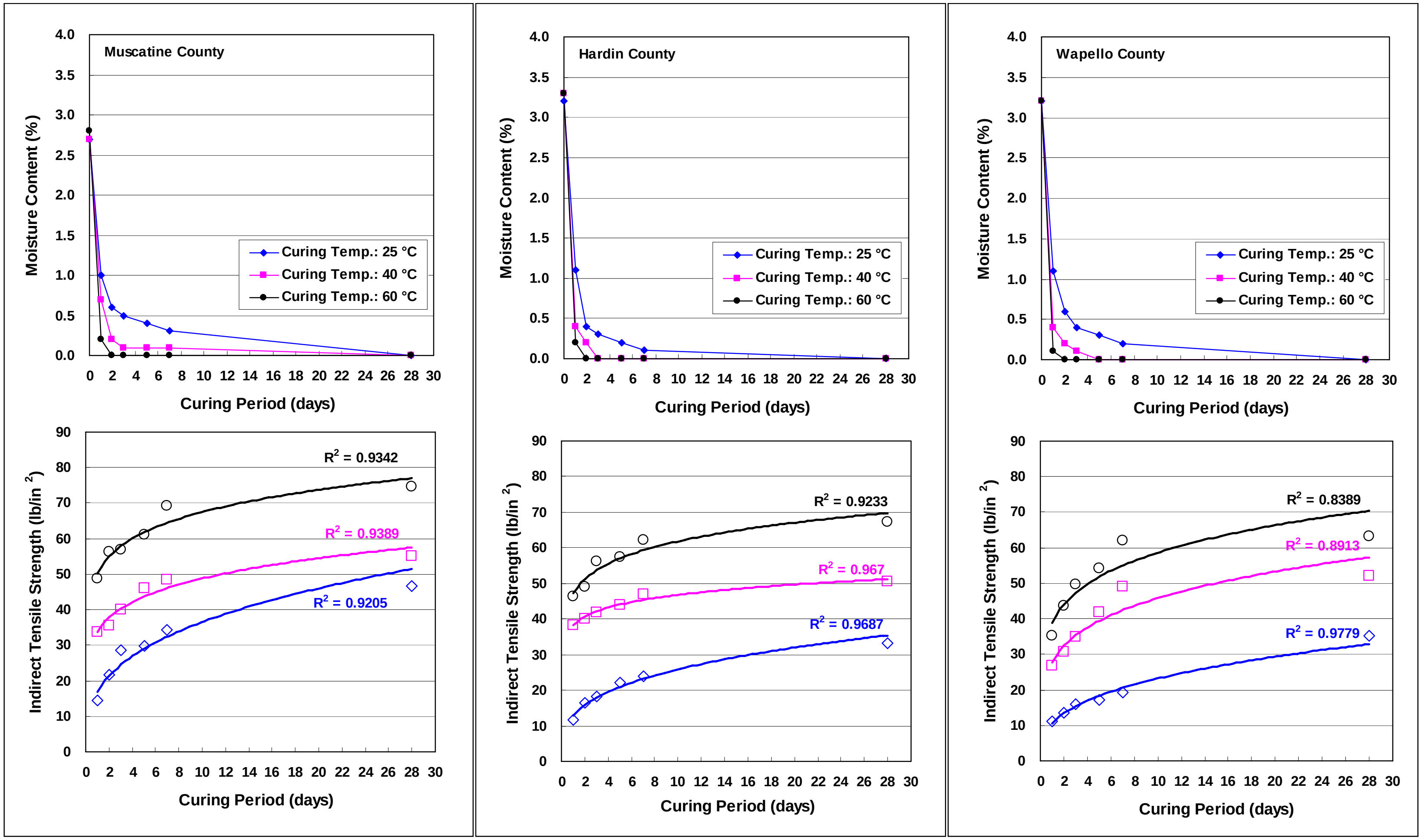
Table 3-3. Moisture contents after various curing times and temperatures for three different RAP sources

Oven Curing Period \ Curing Temp.	RAP Source								
	Muscatine County (%)			Hardin County (%)			Wapello County (%)		
	25°C	40°C	60°C	25°C	40°C	60°C	25°C	40°C	60°C
after compaction	3.2	3.3	3.3	2.7	2.7	2.8	3.2	3.2	3.2
1st day	1.1	0.4	0.2	1.0	0.7	0.2	1.1	0.4	0.1
2nd day	0.4	0.2	0.0	0.6	0.2	0.0	0.6	0.2	0.0
3rd day	0.3	0.0	0.0	0.5	0.1	0.0	0.4	0.1	0.0
5th day	0.2	0.0	0.0	0.4	0.1	0.0	0.3	0.0	0.0
7th day	0.1	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0
28th day	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The CIR-foam specimens cured at 40°C and 60°C oven were allowed to cool to room temperature. This normally took about 2 hours, but it was reduced to 15 minutes to 30 minutes if a fan was used. The CIR-foam specimens were placed in 25°C water for 30 minutes, submerged under 25°C water for 30 minutes under a 20 mmHg vacuum to achieve a 100% saturation level, and remained under the water for additional 30 minutes. The saturated specimens were tested to determine the wet indirect tensile strength at a room temperature. Table 3-4 summarizes the test results of indirect tensile strength at three levels of curing temperatures and six levels of curing period for three different RAP sources. Figure 3-4 shows the plots of moisture content and indirect tensile strength against curing periods for three different curing temperatures of RAP materials from three different sources. As expected, the indirect tensile strength increased as the curing temperature and time increased. The indirect tensile strength gained more rapidly when the specimens were cured at 40˚C and 60˚C compared to 25˚C. The higher curing temperature produced the higher indirect tensile strength at all six levels of curing periods. It can be concluded that the indirect tensile strength of saturated specimens are significantly affected by both curing temperature and curing period. It should be noted that the specimens continued to gain the indirect tensile strength up to 28 days although the moisture level did not change after one or two days.

Table 3-4. Indirect tensile strength at three levels of curing temperature and six levels of curing period for three different RAP sources

Oven Curing Period \ Curing Temp.	RAP Source								
	Muscatine County (psi)			Hardin County (psi)			Wapello County (psi)		
	25°C	40°C	60°C	25°C	40°C	60°C	25°C	40°C	60°C
1st day	14.5	33.8	48.9	11.6	38.3	46.3	11.1	26.7	35.1
2nd day	21.7	35.6	56.2	16.5	40.1	49.1	13.5	30.6	43.5
3rd day	28.7	40.0	56.8	18.4	41.8	56.1	15.9	34.9	49.8
5th day	29.7	46.1	61.0	22.1	44.0	57.3	17.0	41.7	54.2
7th day	34.2	48.5	69.1	23.9	47.0	62.2	19.2	49.0	61.9
28th day	46.6	55.1	74.5	33.3	50.4	67.3	35.1	52.0	63.3



(a) Muscatine County (b) Hardin County (c) Wapello County

Figure 3-4. Plots of moisture content and indirect tensile strength against curing period at three different curing temperatures for three different RAP sources

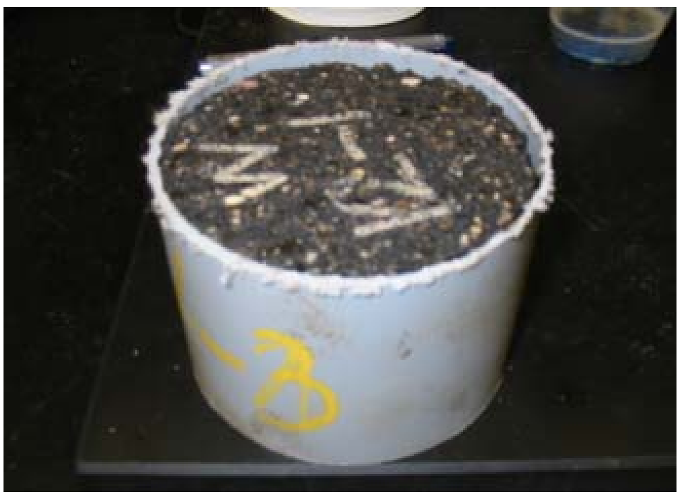
4. IMPACTS OF LABORATORY CURING PROCEDURES ON INDIRECT TENSILE STRENGTH

As discussed in the literature review section, many researchers proposed various laboratory curing procedures, which would represent short- or long-term curing process in the field. This chapter explores the most effective way to identify minimum in-place CIR properties necessary to permit placement of the HMA overlay through various laboratory curing procedures. The following three types of laboratory curing process of CIR mixtures were adopted for this study: 1) curing process of uncovered specimen, 2) curing process of semi-covered specimen and 3) curing process of covered specimen. The moisture conditions of the test specimens were continuously monitored and the indirect tensile strength was measured from the cured specimens at various moisture contents.

4.1 Laboratory Curing Procedures

To represent the curing process of CIR pavement in the field construction, three different laboratory curing procedures were adopted: 1) curing process of uncovered specimen, 2) curing process of semi-covered specimen and 3) curing process of covered specimen. As shown in Figure 4-1 (a), (b) and (c), the uncovered specimen is placed on two wooden sticks to allow ventilation for effective curing in the air, the semi-covered specimen is covered with the plastic mold to allow water to evaporate through its top surface, and the covered specimen is totally covered with the plastic mold, respectively. To obtain different initial moisture contents, the uncovered specimens were cured for 0, 1, 3, 5 and 10 hours at a room temperature. In order maintain a constant moisture content, these specimens were fully enclosed in the plastic mold and cured in the oven at 40˚C.

(a) Uncovered specimen



(b) Semi-covered specimen

(c) Covered specimen

Figure 4-1. Pictures of three curing conditions for CIR specimens

4.2 Mix Design Parameters

Table 4-1 summarizes the mix design parameters used in the curing experiments of CIR-foam and CIR-emulsion. As can be seen in Table 4-1, CIR-foam mixtures were produced at 2.0% foamed asphalt content (FAC) and 4.0% moisture content (MC) and CIR-emulsion mixtures were produced at 3.0% emulsified asphalt content (EAC) and 3.0% MC. Uncovered and semi-covered specimens were compacted using gyratory compactor at 25 gyrations and covered specimens were compacted at 30 gyrations.

Table 4-1. Design parameters selected for curing experiments

CIR-foam Mixture under three curing conditions	
Asphalt Binder	PG 52-34
Foaming Temperature (ºC)	170ºC
Foaming Water Content (%)	1.3%
Foamed Asphalt Content (%)	2.0%
Moisture Contents of RAP (%)	4.0%
Compaction Method	■ Gyratory compactor at 25 gyrations (uncovered and semi-covered specimens) ■ Gyratory compactor at 30 gyrations (covered specimens)
Testing Method	Indirect tensile strength test
Number of Specimen	3 specimens
CIR-emulsion Mixture under semi-covered curing condition	
Emulsion Type	CSS-1
Emulsion Content (%)	3.0% (mix of asphalt and water in 2:1 ratio)
Moisture Content (%)	3.0%
Compaction Method	Gyratory compactor at 25 gyrations
Testing Method	Indirect tensile strength test
Number of Specimen	3 specimens

4.3 Indirect Tensile Strength Gain of Uncovered CIR-foam Specimen over Time

Uncovered CIR-foam specimens were cured in the air at 25˚C to allow water to evaporate. Twelve uncovered CIR-foam specimens were prepared to measure indirect tensile strength and moisture content at four target moisture contents for each of six different RAP sources. Three specimens were prepared for each batch of four target moisture contents of 2.0%, 1.5%, 1.0% and 0.5%. A moisture content was measured every hour until uncovered specimens would achieve the target moisture content assuming the initial moisture content of 3.0% and the indirect tensile strength was measured at each of four target moisture contents. After indirect tensile strength was measured from twelve specimens at four target moisture contents, all specimens were dried in the oven at 40ºC for three days (assumed to reach zero moisture content) to calculate the actual initial moisture content.

Table 4-2 summarizes the indirect tensile strength results and moisture contents of uncovered CIR-foam specimens from six different RAP sources, where the measurements were made at four target moisture contents. As expected, a different curing time was needed to achieve the target moisture depending on its RAP source. It is interesting to note that RAP materials from Lee County, which lost moisture the fastest reaching the moisture content from 2.24% (in 2 hours) to 0.83% (in 22 hours), exhibited a slight increase in the indirect tensile strength from 15.4 psi to 19.5 psi. However, when RAP materials from Wapello County, which lost moisture slowly from 2.23% (in 2 hours) to 0.73% (in 50 hours), exhibited a significant increase in the indirect tensile strength from 17.8 psi to 32.2 psi. A similar trend was observed from the RAP materials from Webster County such that, when the moisture decreased from 2.23% (in 2.5 hours) to 0.72% (in 50 hours), the indirect tensile strength increased by a similar amount from 17.7 psi to 32.3 psi. This result indicates that, for given moisture contents between 0.7% and 0.8%, the specimen with more curing time (50 hours vs. 22 hours) will produce the higher tensile strength.

The RAP materials from Montgomery, Muscatine and Hardin Counties, which were cured fast in the early stage at 1.64% (in 2 hours), 1.65% (2.5 hours) and 1.62% (in 3.5 hours), exhibited the relatively high initial tensile strengths of 28.0 psi, 30.6 psi and 21.5 psi, and when cured for 50 hours their indirect tensile strengths continued to increase to 32.6 psi, 42.4 psi and 34.9 psi, respectively. This result indicates that, for a given curing time between 2 and 3.5 hours, the specimen with lower moisture content (1.6% vs. 2.2%) will produce the higher tensile strength. It should be noted that the coarser RAP materials exhibited the higher tensile strengths.

As can be seen in Figure 4-2, most RAP materials lost moisture very quickly and reached the moisture content of about 1.0% in 6 hours. Figure 4-3 shows a relationship between indirect tensile strength and curing time for six different RAP sources. It should be noted that there is a significant variation in moisture contents among specimens with the same curing time. Up to 10 hours of curing, the indirect tensile strength did not increase but it increased when curing time increased from 10 to 50 hours. Figure 4-4 shows plots of indirect tensile strengths against the moisture contents for six different RAP sources. Among three specimens within a batch with the same curing time, there is no clear relationship between indirect tensile strength and moisture content. There was no good correlation between indirect tensile strength and moisture content when moisture changed from 1.5% to 1.0% in early curing stage up to 10 hours. With RAP materials from Hardin, Wapello and Webster Counties, the indirect tensile strength increased significantly when the moisture content changed from 1.0% to 0.5%, which coincides with the curing time from 10 hours to 50 hours.

Table 4-2. Summary of ITS and moisture contents for uncovered CIR-foam specimens from six RAP sources

Target Moisture Content	RAP Source																				
	Lee County							Hardin County							Wapello County						
	Time (hr)	Initial Moisture (%)	Moisture after Curing (%)		Gmb	ITS(psi)		Time (hr)	Initial Moisture (%)	Moisture after Curing (%)		Gmb	ITS(psi)		Time (hr)	Initial Moisture (%)	Moisture after Curing (%)		Gmb	ITS(psi)	
		3.34	2.26		2.169	15.7			2.55	1.54		2.597	29.9			3.37	2.26		2.232	17.8	
2.0%	2.0	3.23	2.19	2.24	2.155	16.1	15.4	3.5	2.68	1.68	1.62	2.581	17.4	21.5	2	3.34	2.18	2.23	2.215	18.1	17.8
		3.38	2.27		2.148	14.3			2.70	1.64		2.561	17.3			3.44	2.26		2.210	17.4	
		3.46	1.91		2.168	16.0			2.56	1.06		2.616	30.1			3.24	1.54		2.209	18.2	
1.5%	3.5	3.36	1.87	1.84	2.159	14.9	14.2	6.5	2.58	1.15	1.10	2.573	21.8	24.6	4	3.39	1.68	1.60	2.197	15.4	16.1
		3.30	1.74		2.152	11.8			2.57	1.10		2.592	21.8			3.36	1.57		2.184	14.6	
		3.42	1.40		2.161	17.5			2.91	0.88		2.169	26.5			3.49	1.32		2.207	20.8	
1.0%	6.0	3.27	1.29	1.33	2.148	16.5	16.6	10	3.15	1.05	0.94	2.148	18.3	20.9	10	3.30	1.13	1.19	2.192	18.1	17.1
		3.14	1.31		2.139	15.7			2.69	0.88		2.556	17.9			3.29	1.11		2.190	12.5	
		3.22	0.80		2.160	23.0			2.52	0.42		2.573	40.1			3.34	0.70		2.203	32.8	
0.5%	22	3.38	0.84	0.83	2.125	17.4	19.5	50	2.72	0.47	0.43	2.553	33.2	34.9	50	3.28	0.69	0.73	2.183	34.7	32.2
		3.38	0.84		2.131	18.0			2.71	0.41		2.554	31.3			3.36	0.81		2.177	29.1	

Target Moisture Content	Webster County							Montgomery County							Muscatine County						
	Time (hr)	Initial Moisture (%)	Moisture after Curing (%)		Gmb	ITS(psi)		Time (hr)	Initial Moisture (%)	Moisture after Curing (%)		Gmb	ITS(psi)		Time (hr)	Initial Moisture (%)	Moisture after Curing (%)		Gmb	ITS(psi)	
		3.20	2.21		2.202	19.7			2.46	1.41		2.215	32.7			3.03	2.04		2.689	37.8	
2.0%	2.5	3.23	2.27	2.23	2.192	19.2	17.7	2	2.67	1.63	1.64	2.186	28	28.0	3	2.16	1.15	1.65	2.612	28.8	30.6
		3.11	2.12		2.163	14.1			3.06	1.90		2.180	23.3			2.71	1.75		2.622	25.2	
		3.03	1.55		2.207	24.7			2.27	1.01		2.223	32.9			2.10	0.66		2.220	30.7	
1.5%	5.0	3.08	1.63	1.62	2.182	20.1	21.4	4	2.79	1.30	1.21	2.180	28.8	28.8	6	2.28	0.73	0.76	2.183	26.2	27.4
		3.07	1.67		2.171	19.3			2.89	1.32		2.182	24.7			2.39	0.87		2.595	25.2	
		3.07	0.98		2.202	19.7			2.71	1.21		2.194	27			1.94	0.47		2.231	34.9	
1.0%	10	3.11	1.15	1.07	2.182	23.2	21.2	10	2.27	0.39	0.83	2.161	24.1	25.1	10	2.49	0.51	0.53	2.162	28.1	30.0
		3.11	1.09		2.175	20.7			2.91	0.90		2.164	24.1			2.57	0.60		2.177	26.9	
		3.08	0.68		2.185	35.3			2.57	0.53		2.202	36.6			2.32	0.81		2.665	48.1	
0.5%	50	3.27	0.72	0.72	2.170	30.4	32.3	50	2.93	0.55	0.57	2.165	32.4	32.6	50	2.21	0.38	0.57	2.607	42.2	42.4
		3.28	0.76		2.159	31.1			3.01	0.64		2.155	28.8			2.40	0.53		2.595	36.8	

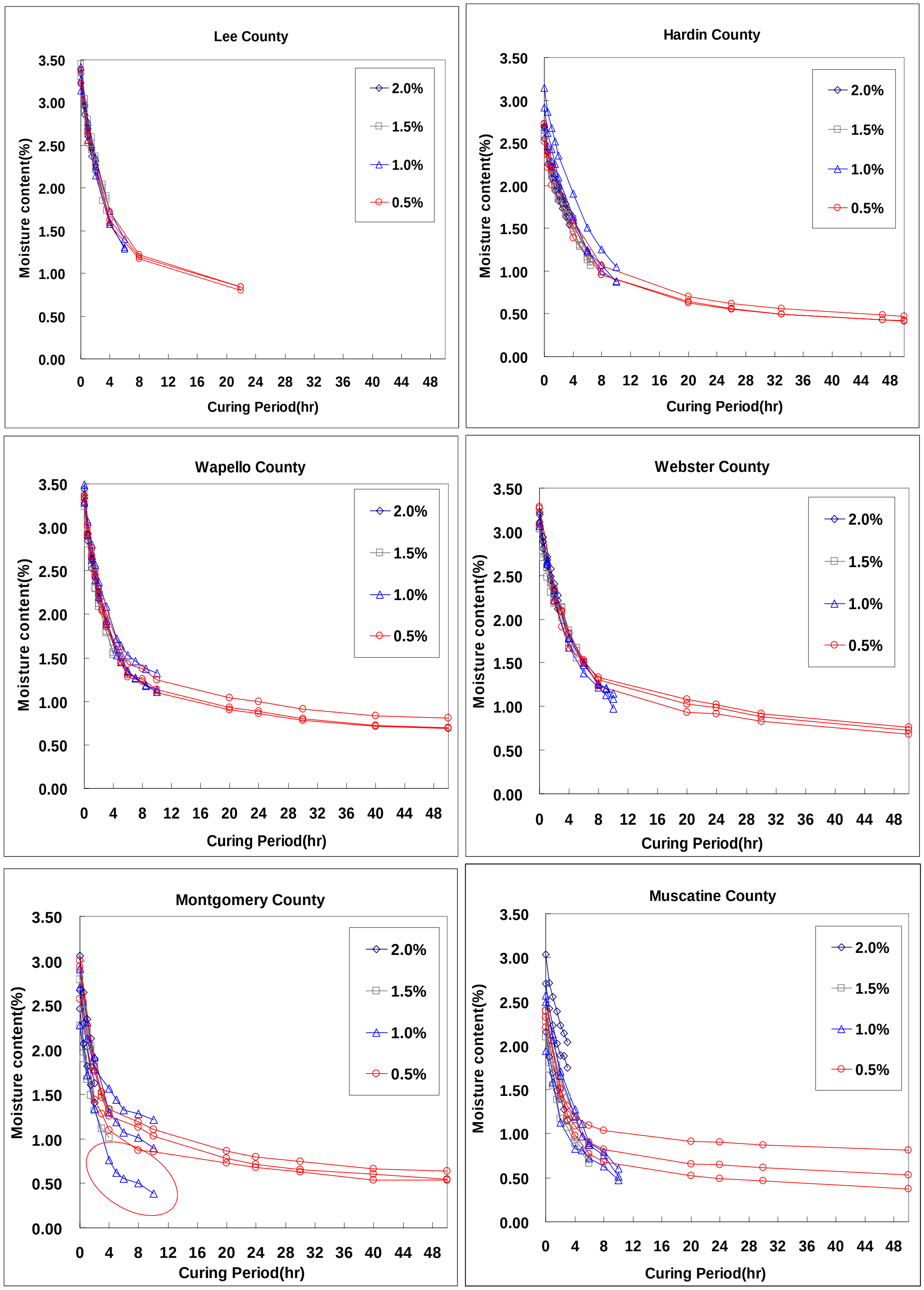


Figure 4-2. Plots of moisture contents of uncovered CIR-foam specimens against curing periods for six different RAP sources

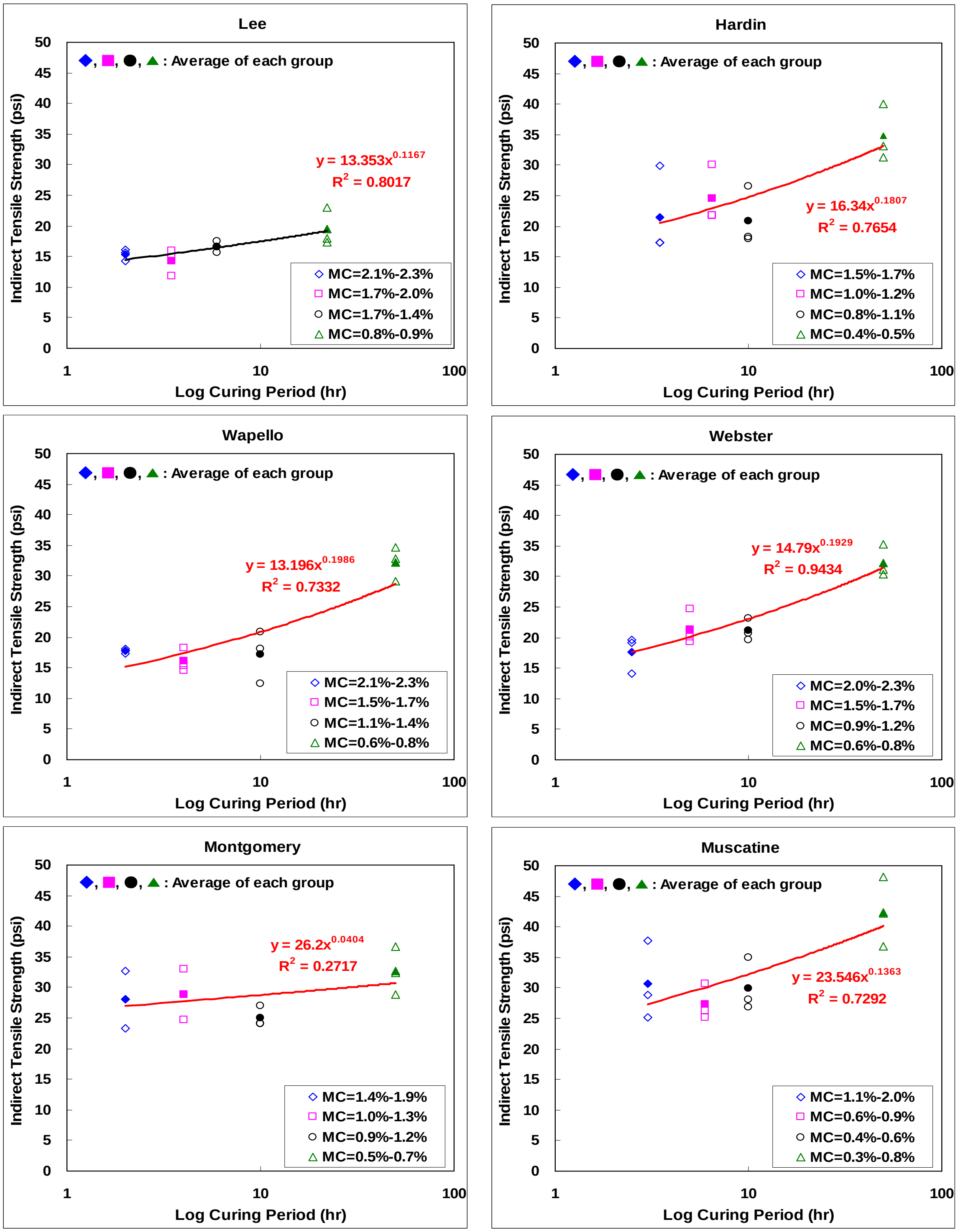


Figure 4-3. Relationships between indirect tensile strength and curing period for uncovered CIR-foam specimens from six different RAP sources

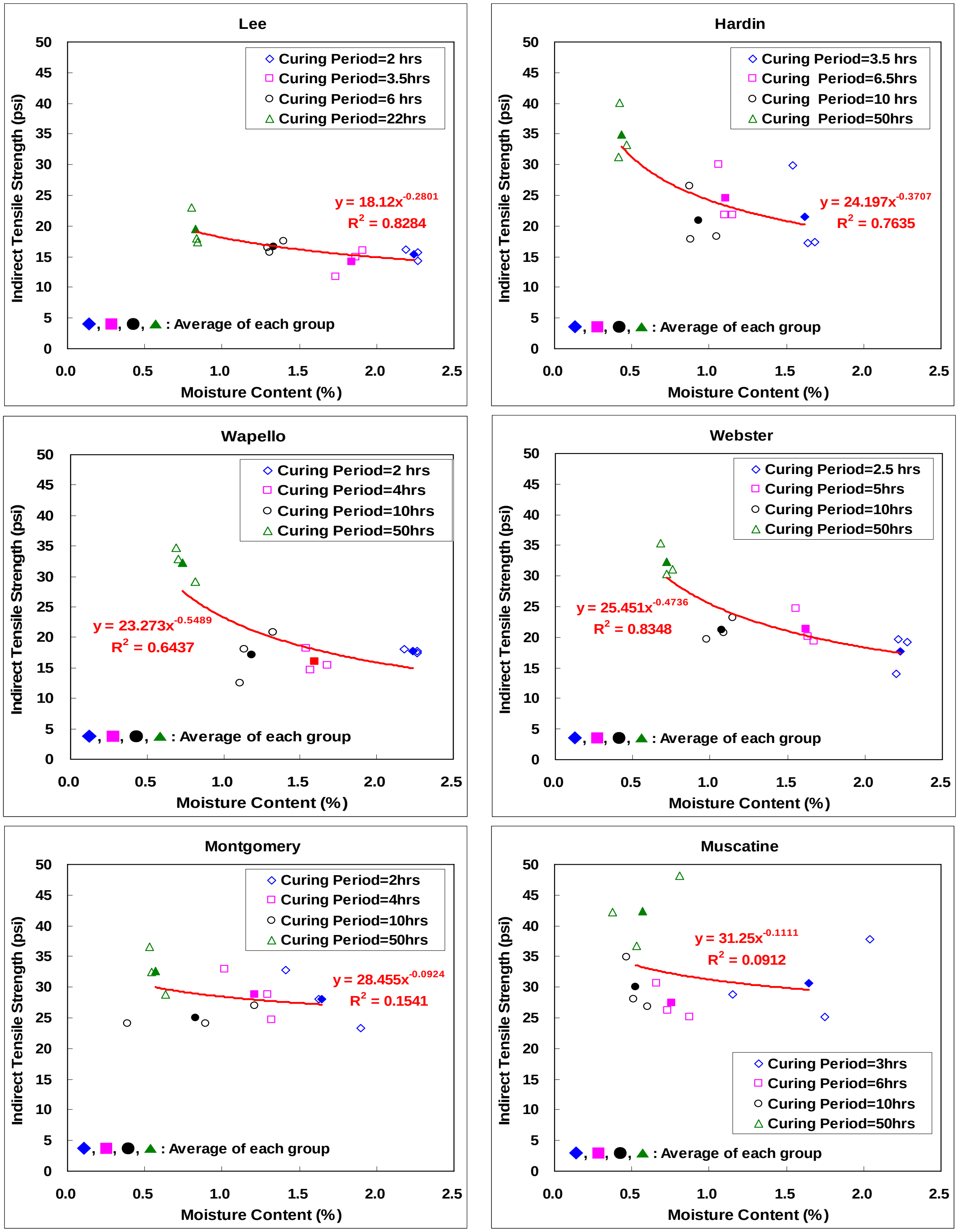


Figure 4-4. Plots of ITS of uncovered CIR-foam specimens against moisture contents for six different RAP sources

4.4 Indirect Tensile Strength Gain of Semi-covered CIR-foam and CIR-emulsion Specimens over Time

To simulate the curing condition of the CIR pavement in the field, semi-covered CIR-foam and CIR-emulsion specimens were prepared by allowing water to evaporate through their top surfaces while being cured. Gyratory compacted CIR-foam and CIR-emulsion specimens were placed into the plastic mold and cured in the oven at 25˚C while only top of the specimen was exposed to the air.

For each of three RAP sources, twenty-one CIR-foam and CIR-emulsion specimens were prepared using foamed asphalt and emulsified asphalt, respectively, to measure indirect tensile strengths and moisture contents after seven curing periods; 3hrs, 6hrs, 12hrs, 24hrs, 48hrs, 168hrs (7 days) and 336hrs (14 days), using RAP materials from Hardin, Webster and Muscatine Counties.

First, due to the slower moisture loss, the indirect tensile strength gain of semi-covered CIR specimens should be slower than that of uncovered CIR specimens. For all RAP materials from three sources, it should be noted that moisture contents of semi-covered CIR-foam specimens were much less than those of semi-covered CIR-emulsion specimens. Due to the higher moisture contents present in CIR-emulsion specimens, their indirect tensile strengths were very low during the first 48 hours. For the given curing period, indirect tensile strengths of semi-covered CIR-foam specimens were higher than those of semi-covered CIR-emulsion specimens.

Table 4-3 and Table 4-4 summarize indirect tensile strength and moisture content for semi-covered CIR-foam specimens and CIR-emulsion specimens from three RAP sources for each of three RAP sources. Figure 4-5 shows relationships between indirect tensile strength and curing period for semi-covered CIR-foam specimens from three different RAP sources. It should be noted that there is a significant variation in moisture contents among CIR specimens with the same curing period. Similar to the uncovered specimens, Up to 12 hours of curing, the indirect tensile strength did not increase but it increased when curing time increased from 12 hours to 14 days.

Figure 4-6 shows plots of indirect tensile strengths of semi-covered CIR-foam and CIR-emulsion specimens against the moisture contents. There was no good correlation between indirect tensile strength and moisture content when moisture changed from 3.0% to 2.0% in early curing stage up to 12 hours. However, the indirect tensile strength increased significantly when the moisture content changed from 2.0% to 0.5%, which coincides with the curing time from 12 hours to 14 days. Given the similar moisture content, the indirect tensile strength of some specimens cured for 14-day was higher than those cured for 7-day. This result indicates, given the similar moisture level, the longer curing time would produce the higher tensile strength.

Figure 4-7 (a) (b) (c) shows plots of indirect tensile strengths of all specimens against moisture contents for uncovered CIR-foam, semi-covered CIR-foam and semi-covered CIR-emulsion specimens, respectively. The uncovered and semi-covered CIR-foam specimens exhibited similar relationships between the indirect tensile strength and moisture content such that indirect tensile strength increased as moisture content decreased. For the given moisture content, semi-covered CIR-foam specimens exhibited the slightly higher indirect tensile strength than semi-covered CIR-emulsion specimens.

Table 4-4. Summary of ITS and moisture content for semi-covered CIR-emulsion specimens cured at 25˚C

Curing Period	RAP Source, cured at 25°C																				
	Hardin County							Webster County							Muscatine County						
	Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)	
	3.65	3.25		2.010		5.8		N/A	N/A		2.019		4.8		4.14	3.62		1.990		3	
3 (hrs)	3.58	3.18	3.17	2.022	2.013	5.5	6.1	4.09	3.00	3.01	2.015	2.021	6.8	5.6	4.01	3.37	3.56	1.991	2.000	3.9	3.5
	3.52	3.08		2.006		7.0		3.79	3.02		2.029		5.1		4.16	3.70		2.020		3.5	
	3.54	2.93		2.026		8.0		3.92	2.57		2.015		4.5		4.21	3.61		1.988		4	
6 (hrs)	3.65	3.08	2.97	2.029	2.026	7.5	7.7	3.95	2.78	2.70	2.005	2.010	4.9	4.5	N/A	N/A	3.71	1.986	1.989	N/A	4.2
	3.43	2.89		2.025		7.7		3.91	2.74		2.008		4		4.29	3.81		1.995		4.3	
	3.69	3.01		2.013		6.8		4.06	2.48		1.997		6.3		3.94	3.13		1.984		4.3	
12 (hrs)	3.58	2.89	2.93	2.014	2.011	7.8	7.6	3.90	2.22	2.39	2.004	2.000	7.3	5.8	4.41	3.56	3.36	1.990	1.985	4	4.2
	3.57	2.90		2.007		8.2		4.06	2.46		2.000		3.9		4.09	3.39		1.981		4.4	
	3.62	2.76		2.021		9.2		3.79	1.61		1.984		9.2		4.48	2.96		1.969		5	
24 (hrs)	3.71	2.50	2.59	2.015	2.021	9.7	9.4	3.94	1.95	1.90	1.986	1.988	6.9	7.7	4.94	3.46	3.12	1.971	1.968	4.3	4.8
	3.43	2.51		2.026		9.3		3.94	2.15		1.994		7.1		4.13	2.93		1.963		5.2	
	3.91	2.29		2.018		10.1		4.07	1.21		1.984		14.8		3.54	1.53		1.941		6.9	
48 (hrs)	3.59	2.14	2.11	1.998	2.011	10.1	11.1	3.92	1.48	1.47	1.972	1.981	12.5	13.0	3.67	2.11	2.00	1.963	1.958	7.1	6.6
	3.57	1.89		2.017		13.0		3.88	1.71		1.986		11.7		3.84	2.35		1.969		5.7	
	3.81	1.32		1.983		20.5		4.67	0.49		1.967		31.0		3.67	0.30		1.939		22.6	
7 days	3.62	1.30	1.27	1.977	1.982	20.9	19.5	4.55	0.90	0.82	1.981	1.979	26.5	26.0	4.54	1.48	0.82	1.951	1.948	15.1	18.3
	3.76	1.18		1.987		17.0		4.51	1.08		1.989		20.5		3.60	0.69		1.955		17.1	
	3.64	0.12		1.960		32.1		4.12	0.18		1.954		35.4		3.73	0.12		1.935		31.5	
14 days	3.79	0.68	0.37	1.971	1.965	26.2	30.1	3.99	0.21	0.20	1.964	1.962	39.3	37.7	3.85	0.38	0.34	1.961	1.950	26.6	27.3
	3.56	0.32		1.963		32.1		4.12	0.21		1.969		38.3		3.80	0.52		1.953		23.9	

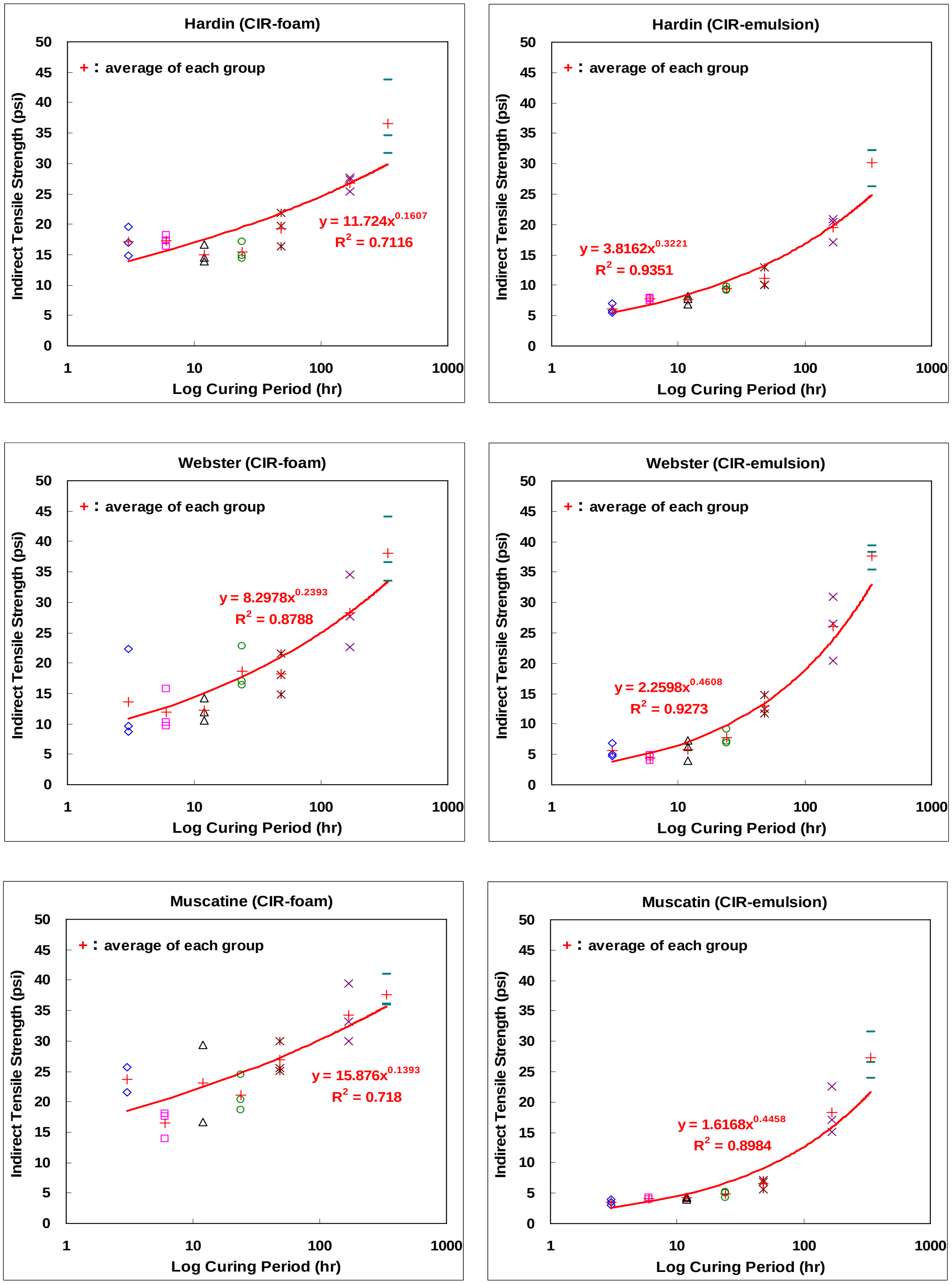


Figure 4-5. Plots of ITS against curing period for three different RAP sources

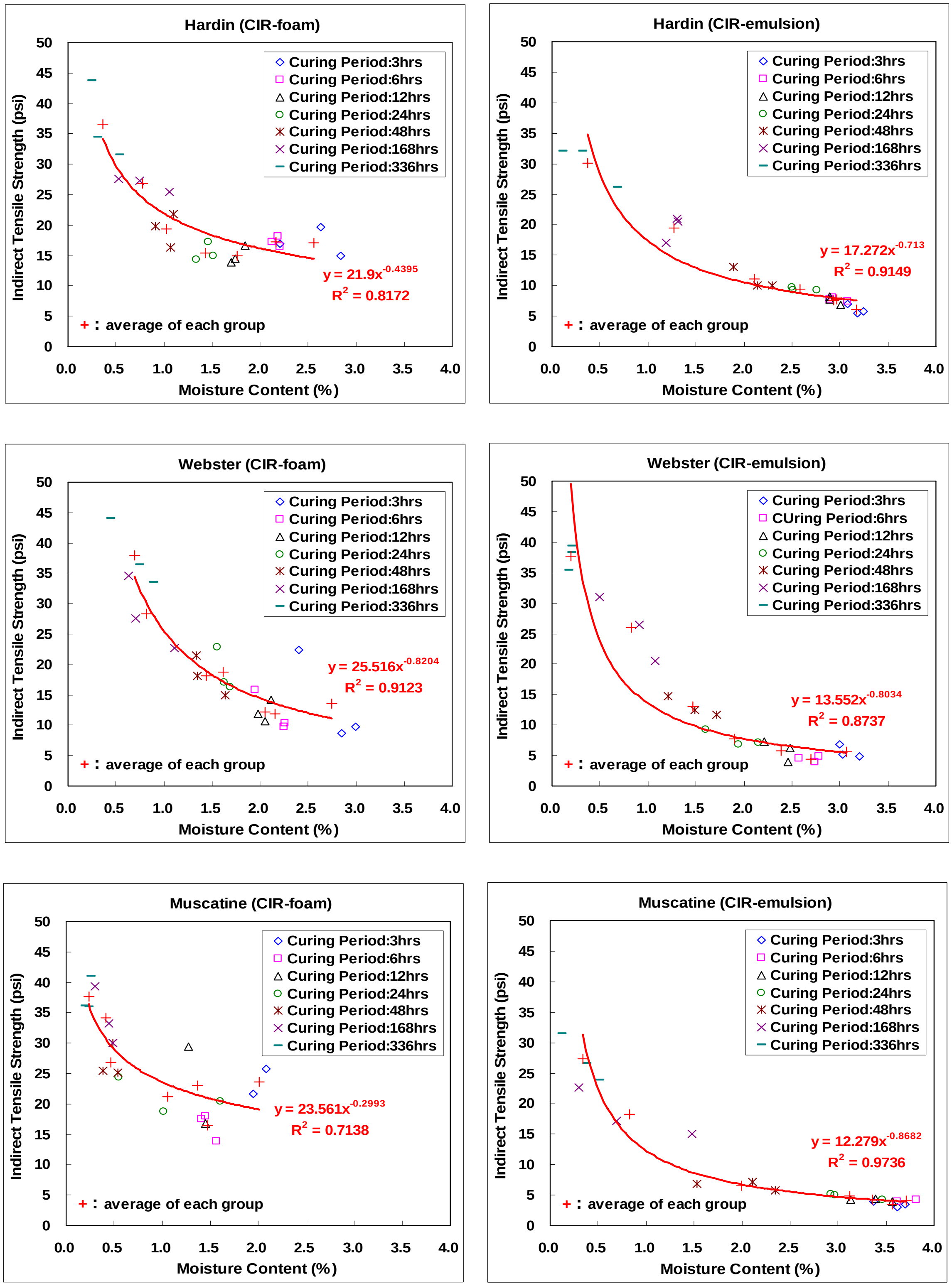
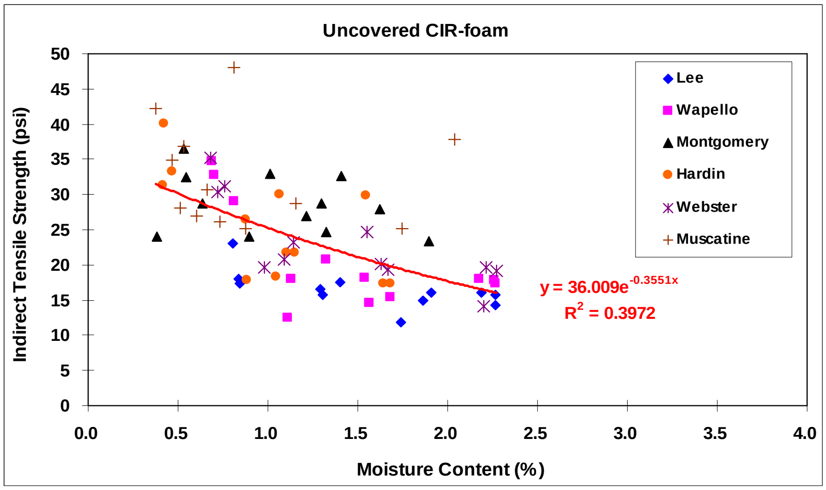
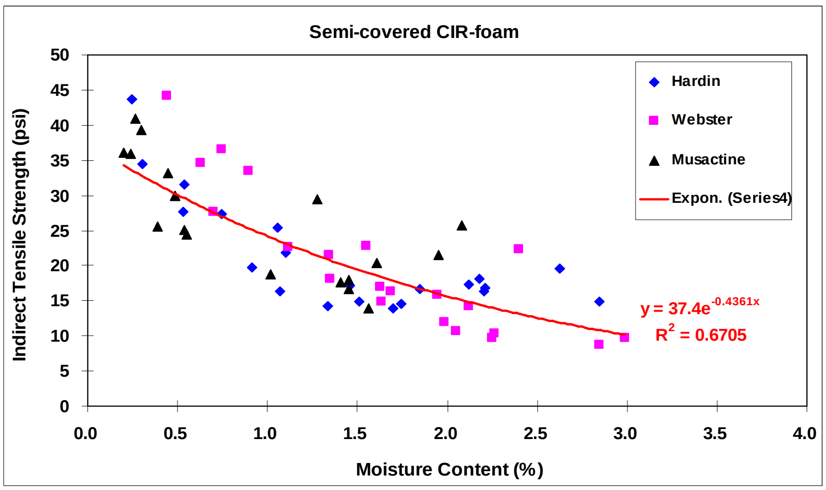


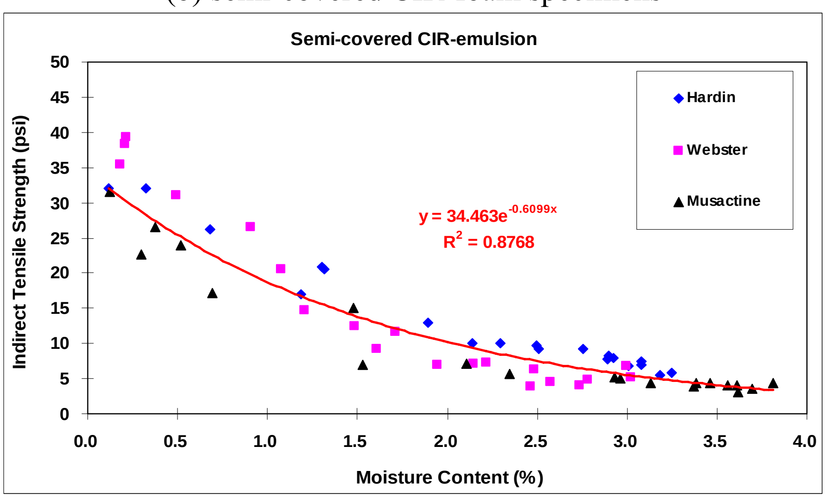
Figure 4-6. Plots of ITS against moisture content for three different RAP sources



(a) uncovered CIR-foam specimens



(b) semi-covered CIR-foam specimens



(c) semi-covered CIR-emulsion specimens

Figure 4-7. Plots of ITS against moisture content for uncovered and semi-covered specimens

4.5 Indirect Tensile Strength Gain of Covered CIR-foam Specimen over Time

To determine the effect of the curing time on indirect tensile strength without influence of moisture, covered CIR-foam specimens were prepared using RAP materials from Webster County. To obtain different initial moisture contents, the uncovered gyratory compacted specimens were cured in the air for 0, 1, 3, 5 and 10 hours. These short-term cured CIR-foam specimens were then fully enclosed in the plastic mold and cured in the oven at 40˚C. The specimens were then cured for one and two weeks before measuring their indirect tensile strengths.

As shown in Figure 4-8, a total of forty-five CIR-foam specimens was prepared and fifteen specimens, which were initially cured for 0, 1, 3, 5 or 10 hours at a room temperature, were tested for their indirect tensile strength and moisture after zero, one-week and two-week curing in the oven at 40˚C. Table 4-5 summarizes the indirect tensile strengths and moisture contents of the covered CIR-foam specimens cured for zero, one and two weeks after initially cured in the air for 0, 1, 3, 5 or 10 hours.

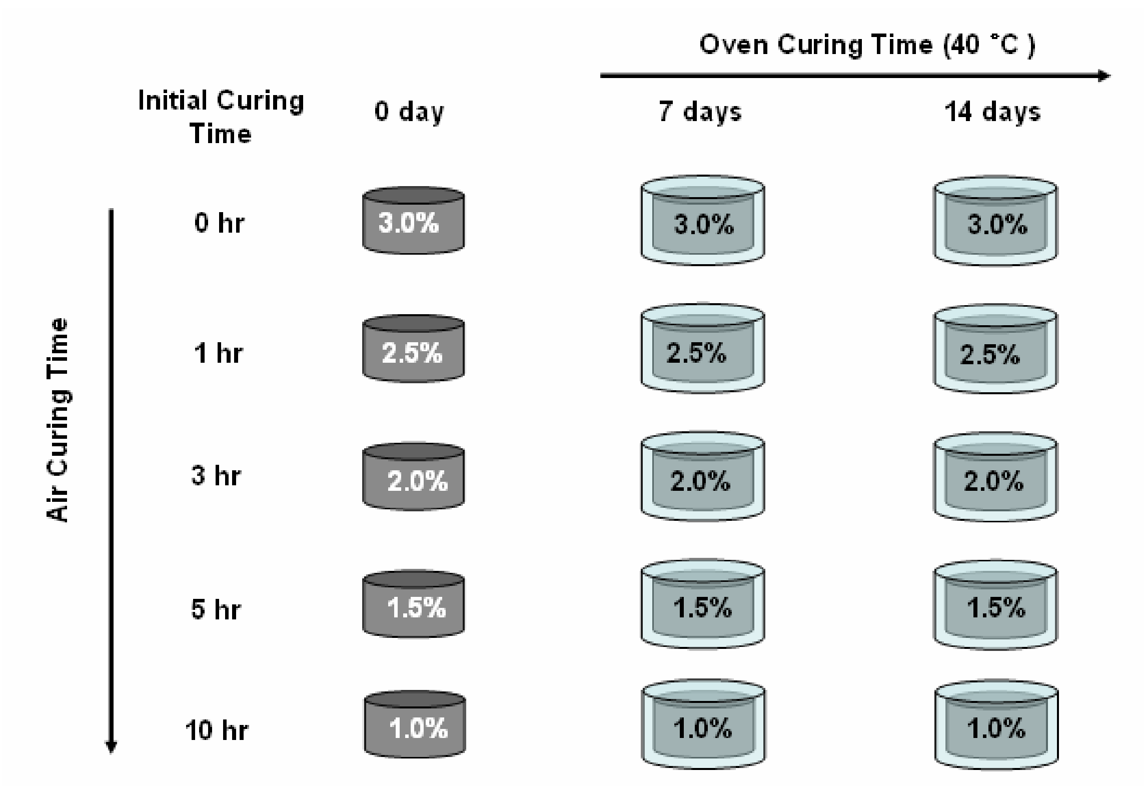


Figure 4-8. Curing process of covered CIR-foam specimens

Table 4-3. Summary of ITS and moisture content for semi-covered CIR-foam specimens cured at 25˚C

Curing Period	RAP Source, cured at 25°C																				
	Hardin County							Webster County							Muscatine County						
	Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture %)		Gmb		ITS (psi)		Initial Moisture	Moisture %)		Gmb		ITS (psi)	
3 (hrs)	3.46	2.63		2.110		19.6		3.12	2.40		2.161		22.4		3.04	2.08		2.139		25.7	
	3.00	2.21	2.56	2.070	2.084	16.9	17.1	3.54	2.99	2.75	2.117	2.125	9.7	13.6	N/A	N/A	2.01	2.116	2.121	N/A	23.7
	3.45	2.84		2.073		14.9		3.28	2.85		2.098		8.7		2.64	1.95		2.108		21.6	
6 (hrs)	3.39	2.12		2.088		17.3		3.30	1.95		2.132		15.8		2.62	1.45		2.101		18.0	
	3.53	2.20	2.17	2.081	2.085	16.4	17.3	3.52	2.26	2.15	2.114	2.121	10.3	11.9	2.53	1.41	1.43	2.085	2.084	17.6	16.5
	3.22	2.18		2.086		18.2		3.42	2.25		2.117		9.7		N/A	N/A		2.065		13.9	
12 (hrs)	3.61	1.85		2.071		16.6		3.74	1.98		2.112		11.9		2.48	1.28		2.154		29.4	
	3.19	1.70	1.76	2.059	2.065	13.9	15.0	3.90	2.12	2.05	2.091	2.095	14.2	12.2	N/A	N/A	1.36	2.120	2.126	N/A	23.1
	2.96	1.74		2.064		14.5		3.73	2.05		2.083		10.6		2.81	1.45		2.104		16.7	
24 (hrs)	3.48	1.46		2.083		17.2		3.06	1.55		2.145		22.8		2.44	0.55		2.106		24.4	
	3.55	1.51	1.43	2.061	2.065	14.9	15.5	3.49	1.63	1.62	2.096	2.113	17.0	18.7	3.18	1.61	1.06	2.091	2.086	20.4	21.2
	3.28	1.33		2.050		14.3		3.44	1.68		2.098		16.3		2.61	1.02		2.060		18.7	
48 (hrs)	3.17	1.10		2.090		21.8		3.40	1.34		2.117		21.5		2.48	0.49		2.098		30	
	3.26	0.91	1.03	2.053	2.066	19.8	19.3	3.51	1.35	1.44	2.086	2.088	18.1	18.2	2.51	0.54	0.47	2.079	2.076	25.1	26.9
	3.00	1.07		2.056		16.3		3.46	1.63		2.061		14.9		2.30	0.39		2.052		25.5	
7 days	3.62	1.06		2.060		25.4		3.52	0.63		2.099		34.6		2.52	0.30		2.099		39.4	
	3.46	0.75	0.78	2.039	2.044	27.3	26.8	3.38	0.70	0.81	2.076	2.086	27.6	28.3	2.63	0.44	0.41	2.082	2.084	33.2	34.2
	3.42	0.53		2.033		27.6		3.20	1.11		2.083		22.7		2.66	0.49		2.069		30.0	
14 days	3.20	0.25		2.047		43.7		3.12	0.44		2.098		44.1		2.56	0.26		2.094		41.0	
	3.21	0.31	0.36	2.043	2.043	34.5	36.6	3.38	0.74	0.69	2.078	2.087	36.5	38.0	2.60	0.20	0.23	2.053	2.065	36.1	37.7
	3.58	0.54		2.040		31.6		3.55	0.89		2.086		33.5		2.79	0.24		2.047		35.9	

Table 4-5. Summary of ITS and moisture contents of covered CIR-foam specimen cured at 40˚C

Time (hr)/ Target Moisture (%)	Webster County, cured at 40˚C																				
	Curing Period Time (0 day)							Curing Period Time (7 days)							Curing Period Time (14 days)						
	Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)	
	3.35	3.07		2.173		10.5		2.69	2.42		2.177		15.2		2.59	2.24		2.205		21.6	
0(hr)/ 3.0%	3.41	3.24	3.22	2.157	2.159	8.2	8.4	2.89	2.56	2.56	2.184	2.173	12.5	13.4	3.21	2.83	2.58	2.185	2.188	22.4	20.7
	3.46	3.34		2.149		6.5		3.15	2.70		2.159		12.4		3.01	2.68		2.175		18.0	
	3.24	2.68		2.155		16.5		2.82	1.99		2.167		16.1		2.64	1.76		2.187		27.4	
1(hr)/ 2.5%	3.41	2.99	2.88	2.143	2.142	11.9	12.9	3.01	2.20	2.10	2.159	2.162	16.8	16.6	3.05	2.30	2.15	2.171	2.170	20.4	22.7
	3.29	2.95		2.128		10.4		2.91	2.12		2.162		16.9		3.08	2.39		2.150		20.2	
	3.03	1.75		2.153		23.4		2.74	1.43		2.155		20.2		2.89	1.54		2.172		29.6	
3(hrs)/ 2.0%	3.10	2.02	2.00	2.146	2.143	22.3	20.3	2.84	1.58	1.58	2.146	2.149	17.8	18.2	3.19	1.92	1.78	2.154	2.159	20.0	24.9
	3.23	2.22		2.131		15.1		3.07	1.74		2.145		16.7		3.11	1.87		2.150		25.1	
	3.22	1.33		2.154		21.8		2.40	0.76		2.189		35.9		2.89	1.11		2.162		39.7	
5(hrs)/ 1.5%	3.36	1.40	1.34	2.133	2.135	20.4	20.0	2.71	0.91	0.91	2.150	2.168	29.5	31.0	3.10	1.24	1.21	2.151	2.152	33.9	35.9
	3.27	1.29		2.117		17.9		2.81	1.08		2.164		27.7		3.05	1.29		2.145		34.1	
	2.97	0.98		2.153		24.1		2.92	0.82		2.146		34.1		2.72	0.80		2.173		53.3	
10(hr)/ 1.0%	3.04	1.17	1.10	2.132	2.139	18.9	19.9	3.14	0.99	0.92	2.137	2.140	29.2	30.8	3.04	0.93	0.88	2.148	2.153	44.7	47.5
	2.99	1.15		2.130		16.8		3.04	0.93		2.138		29.1		3.05	0.91		2.138		44.4	

Figure 4-9 shows plots of the indirect tensile strengths of CIR-foam specimens against curing periods for five initial curing periods of 0, 1, 3, 5, 10 hours and they are plotted together in Figure 4-10. Although the samples were kept in the mold, the moisture content might have decreased slightly during curing. Overall, the indirect tensile strength of covered CIR-foam specimens increased as the curing time increased. Figure 4-11 shows three measurements for each batch of covered specimens. Table 4-6 summarizes the ratio of the indirect tensile strength gain over the moisture reduction (ΔITS/ΔMC) of each batch of the three covered CIR-foam specimens. There is a consistent trend of increase in indirect tensile strength as the reduction in moisture content, which is plotted in Figure 4-12 by taking two representative data points to define a linear slope. Overall, as shown by their steeper slopes at the lower moisture contents, it can be postulated that the indirect strength gain per a same amount of moisture reduction is higher at a lower moisture content level.

The average indirect tensile strengths for each of eight ranges of moisture contents are summarized in Table 4-7 and plotted in Figure 4-13. The indirect tensile strength gain is faster when the moisture content changes from 1.25% to 0.75% than when the moisture changes from 2.25% to 1.25%.

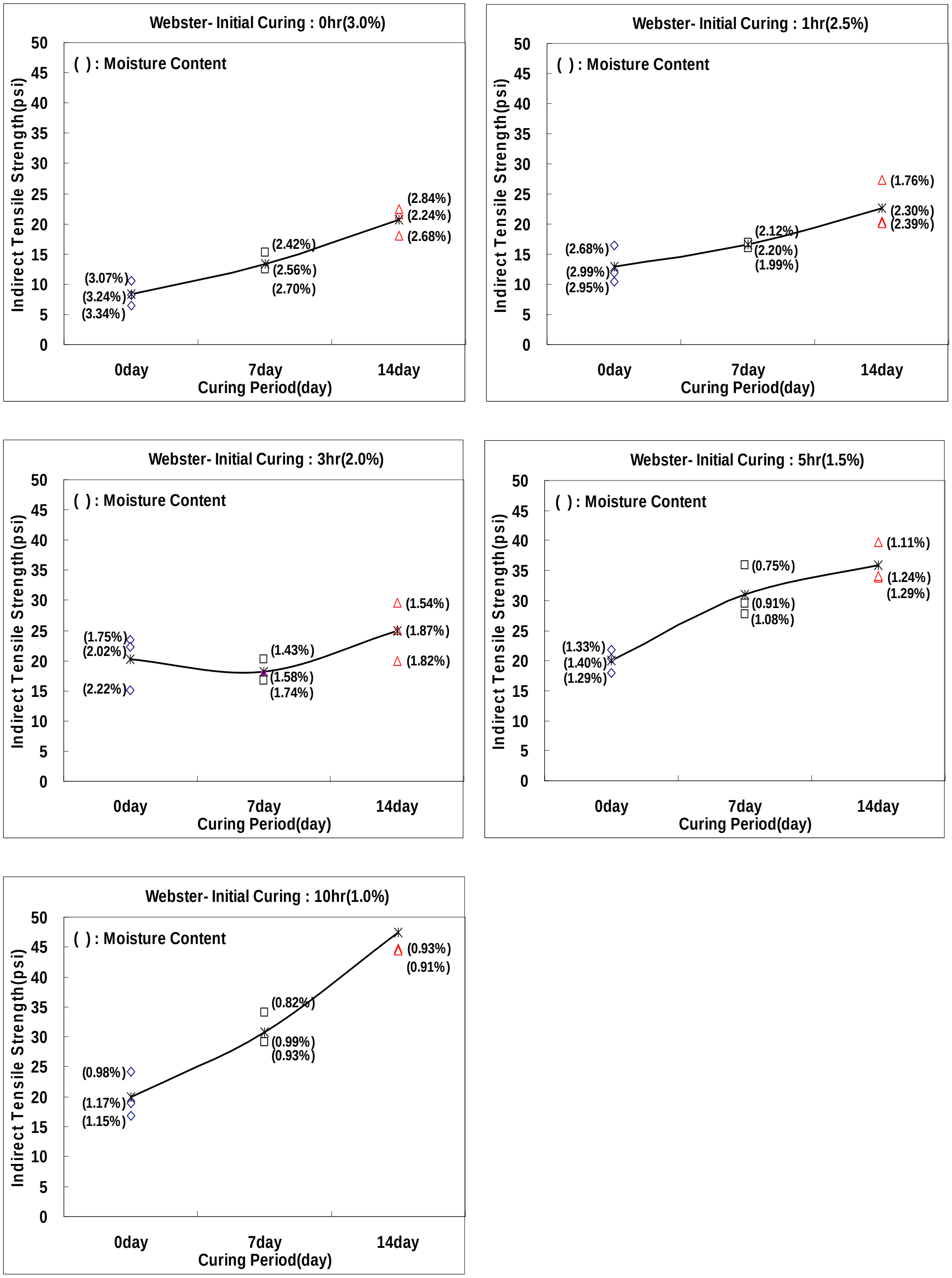


Figure 4-9. Plots of indirect tensile strength of covered CIR-foam specimens versus three curing periods for five initial curing conditions

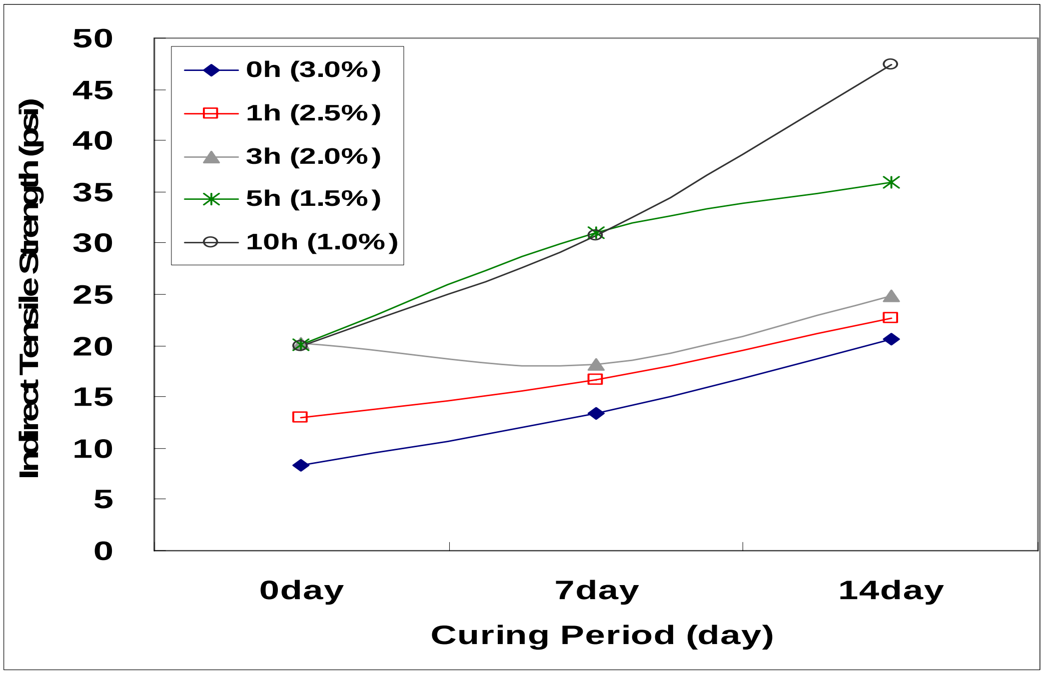


Figure 4-10. Plots of average ITS of covered CIR-foam specimens against curing time for five different initial curing conditions using RAP materials from Webster County

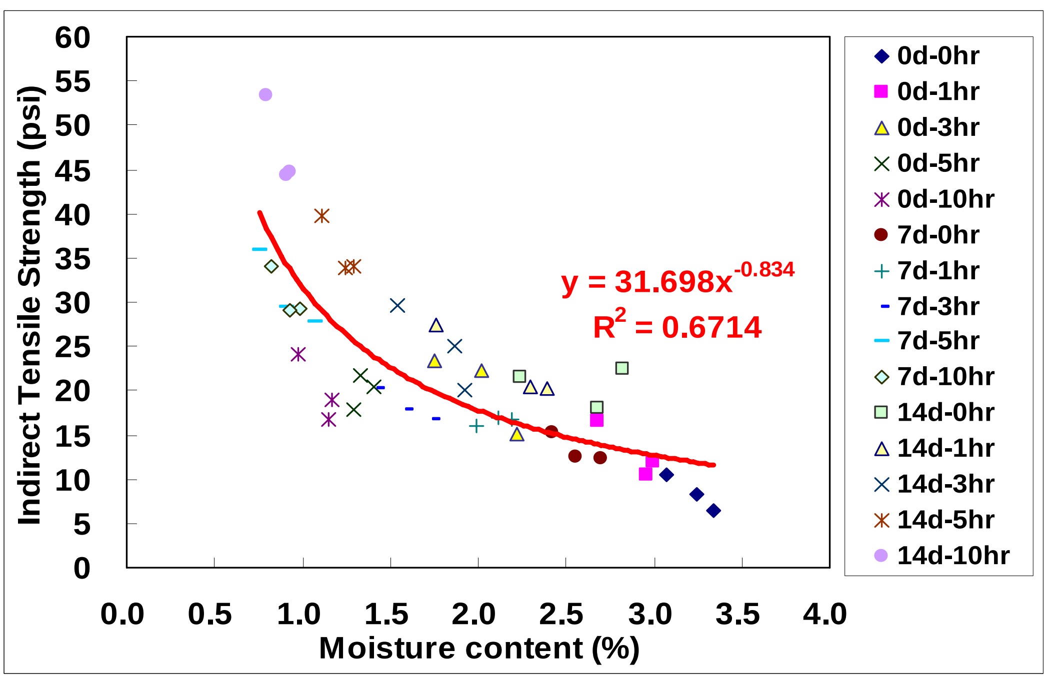


Figure 4-11. ITS of covered CIR-foam specimens against moisture contents for each batch of three specimens using RAP materials from Webster County

Table 4-6. Slope of ΔITS/ΔMC of covered CIR-foam specimens for given curing period

Air Curing Time / Oven Curing Time	0 h	1 h	3 h	5 h	10 h	AVG
0 day	15.36	18.27	17.74	19.69	34.95	21.20
7 days	13.10	1.25	11.36	31.04	36.35	18.62
14 days	8.18	12.10	19.82	35.77	72.62	29.70
AVG	9.16	8.16	12.98	22.88	38.48	-

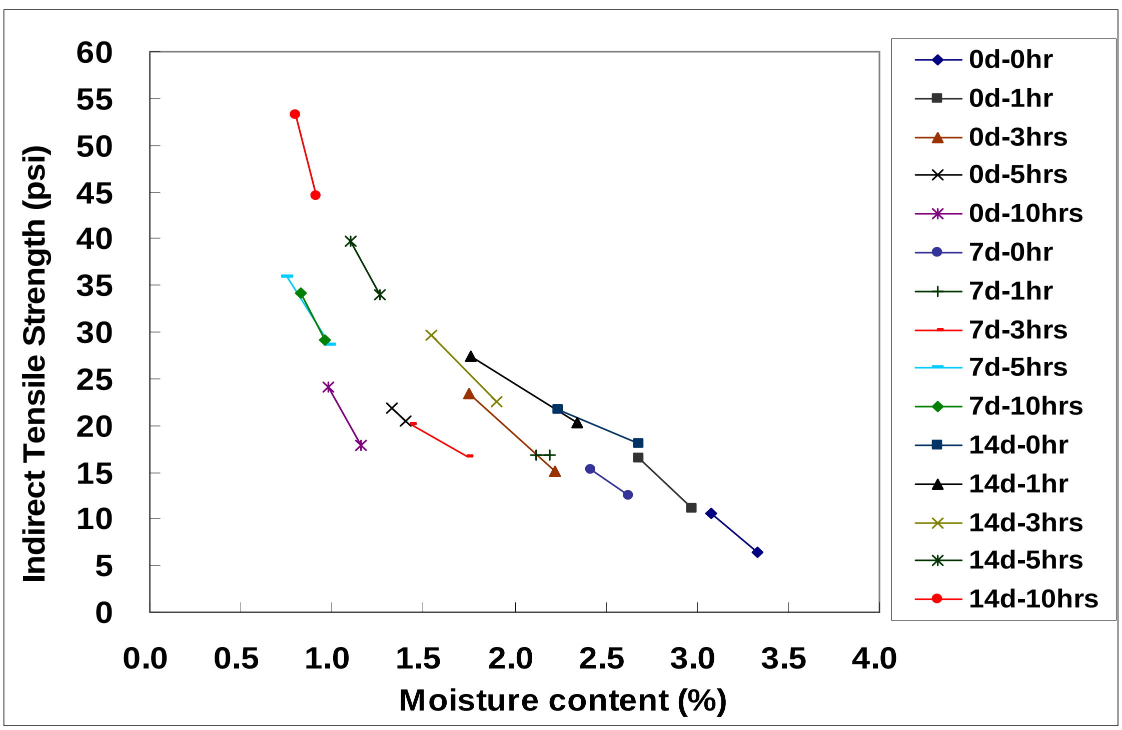


Figure 4-12. Linear slopes of ITS over moisture content for each batch of covered CIR-foam specimens

Table 4-7. Average ITS values of each range of moisture contents

Given Moisture Interval	2.50 ~ 3.50 %	2.25 ~ 2.50 %	2.00~ 2.25%	1.75 ~ 2.00 %	1.50~ 1.75 %	1.25 ~ 1.50 %	1.00~ 1.25%	0.75 ~ 1.00 %
Aveage ITS (psi)	12.9	18.6	18.5	22.4	21.4	22.9	27.4	36.0

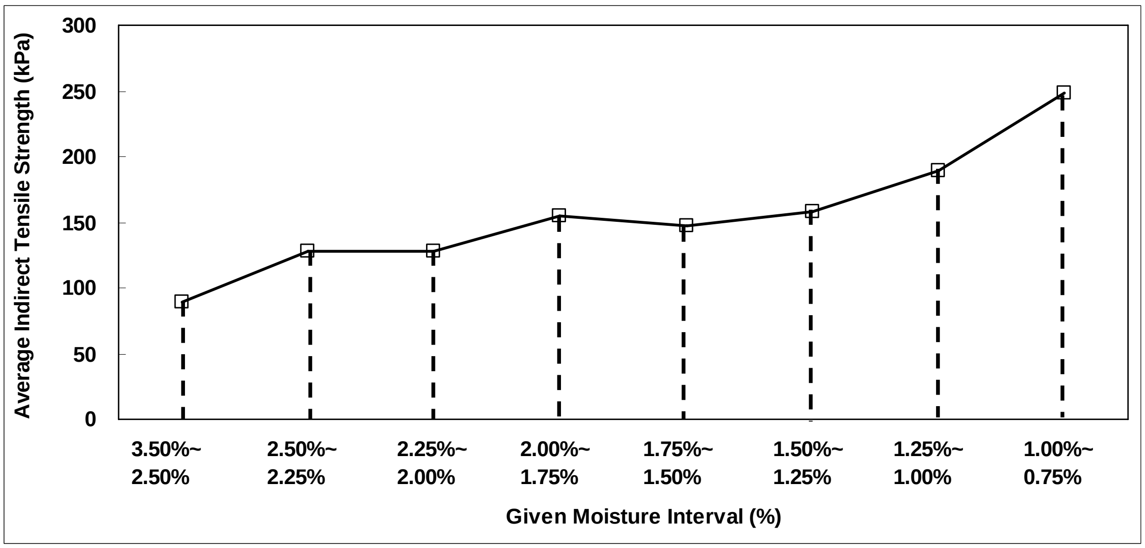


Figure 4-13. Average ITS values against ranges of moisture contents

5. COLLECTION OF RAP MATERIALS TWO ADDITIONAL SOURCES

During the summer of 2008, to study broad range of laboratory curing procedures of CIR-foam and CIR-emulsion mixtures, as shown in Figure 5-1, RAP materials were collected from two additional CIR project sites: 1) CIR-foam in Story County and 2) CIR-CRS-2P in Clayton County.

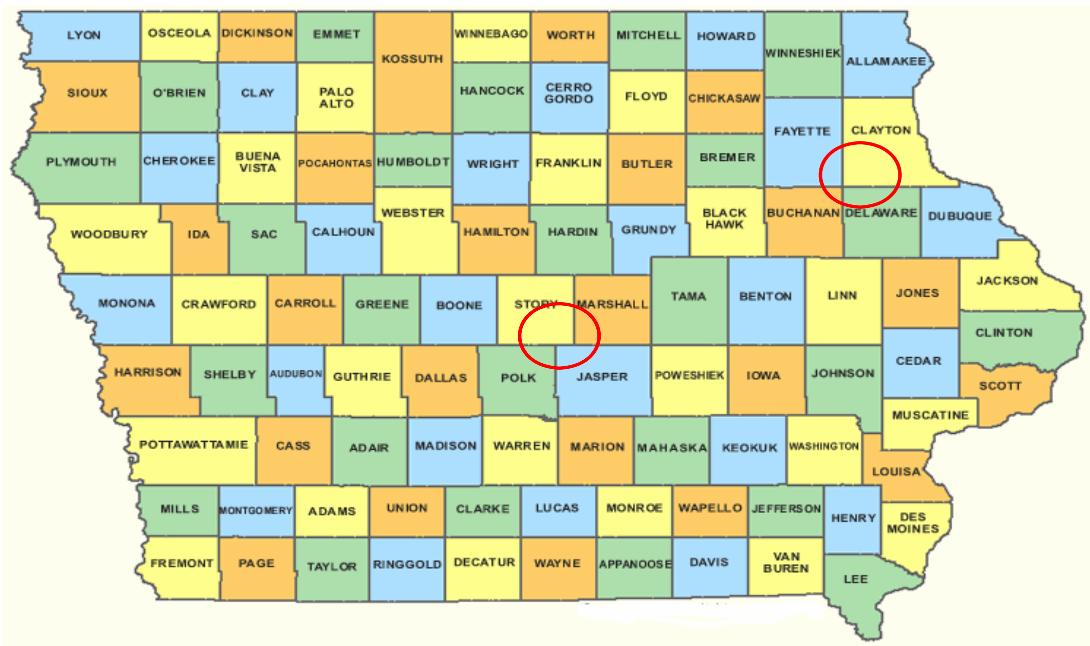


Figure 5-1. Locations of CIR project sites where RAP materials were collected

5.1 Description of Project Sites

The RAP materials were collected from the two different CIR project sites between June 5 and August 21, 2007. The basic information on CIR project sites is summarized in Table 5-1.

Table 5-1. Basic information of two CIR project sites

Items \ Sources	State Highway 210	County Road 13
CIR Project Site	Story County	Clayton County
Collection Date	Jun 5, 2007	Aug 21, 2007
RAP Sampling Time	12:00 p.m.-2:30 p.m.	2:30 p.m.-5:30 p.m.
CIR Method	CIR-foam	CIR-CRS-2P
Quantity	1340 lbs	1992 lbs
Construction Company	WK Construction	Mathy Construction

5.1.1 Story County (State Highway 210) – CIR-foam

The milled RAP materials were collected from the CIR-foam project site in State Highway 210 in Story County. As shown in Figure 5-2, the project site is located on State Highway 210 between I-35 and the city of Slater, Iowa. The RAP materials were collected between 12:00 p.m. and 2:30 p.m. on June 5, 2007. Figure 5-3 shows the CIR-foam construction process and the collection process of RAP materials.

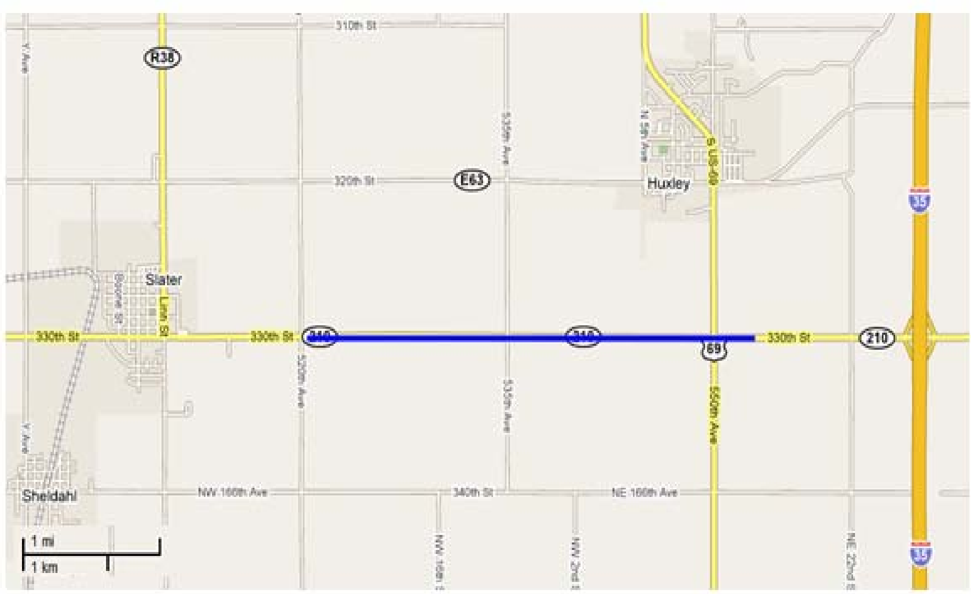


Figure 5-2. Location of CIR-foam project site on State Highway 210 in Story County

(a) CIR-foam process

(b) Collection of RAP materials

Figure 5-3. Pictures of State Highway 210 CIR-foam project site in Story County

5.1.2 Clayton County (County Road 13) – CIR-CRS-2P

The RAP materials collected from CIR-emulsion project in County Road 13 were stockpiled and preserved by Mathy Construction Ltd. in Clayton County. As shown Figure 5-4, the job site is located about 2 miles from the city of Edgewood and the stockpile is located about 1 mile from the job site. The RAP materials were collected from the stockpile between 2:30 p.m. and 5:30 p.m. on August 21, 2007. Figure 5-5 shows the RAP stockpile and the collection process of RAP materials.

Figure 5-4. Locations of CIR-CRS-2P project site and RAP stockpile in Clayton County

(a) RAP stockpile

(b) Collection of RAP materials

Figure 5-5. Pictures of RAP stockpile and RAP collection process in Clayton County

5.2 Evaluation of RAP Materials

RAP materials from Story County were dried in the air (25°C~27°C) for 14 days and RAP materials from Clayton County were dried in the air (25°C~27°C) for 2~3 days. The moisture contents of the dried RAP materials were between 0.2% and 0.3%.

5.2.1 RAP Gradation

First, dried RAP materials were divided into six stockpiles which were retained on the following sieves: 25mm, 19mm, 9.5mm, 4.75 mm, 1.18mm and below 1.18 mm. As shown in Figure 5-6, sorted RAP materials were stored in 5-gallon buckets holding about 40lbs of RAP materials. The sorted RAP materials were then weighed and their relative proportions were computed as shown in Table 5-2. After discarding RAP materials bigger than 25mm, gradation analysis was performed and their results are summarized in Table 5-3 and plotted on a 0.45 power chart in Figure 5-7. To allow a comparison between two RAP material sources for each size, their relative proportions are graphed in Figure 5-8.

Figure 5-6. Sorted RAP materials in 5-gallon buckets

Table 5-2. Stockpile proportions of two RAP materials passing 25mm sieve

RAP Sizes	RAP Sources			
	Story County		Clayton County	
	Weight (lbs)	Proportion (%)	Weight (lbs)	Proportion (%)
25 mm - 19 mm	105,332	7.5	266,105	6.7
19 mm - 9.5 mm	467,726	33.5	1,073,980	27.0
9.5 mm - 4.75 mm	341,523	24.4	1,091,187	27.4
4.75 mm - 1.18 mm	340,548	24.4	1,090,376	27.4
Below 1.18 mm	142,355	10.2	460,506	11.5
Total	1,397,486	100	3,982,182	100

Table 5-3. Gradations of two RAP sources passing 25mm sieve

Sieve Size	RAP source	
	Story County	Clayton County
19mm	7.5	7.5
12.5mm	15.8	14.3
9.5mm	13.6	10.8
4.75 mm	28.5	27.2
2.36 mm	15.8	18.1
1.18 mm	8.3	9.8
0.6 mm	3.9	5.9
0.3 mm	3.2	4.2
0.15 mm	1.9	1.5
0.075 mm	0.7	0.5
passing 0.075 mm	0.8	0.3

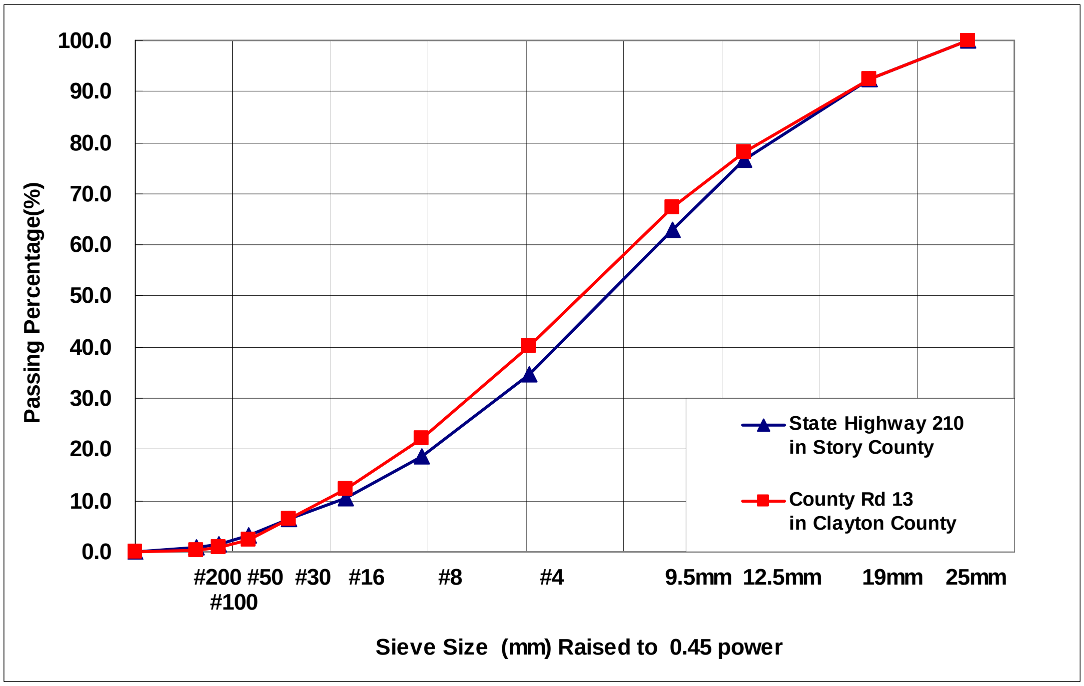


Figure 5-7. Gradation plots of two different RAP materials passing 25mm sieve

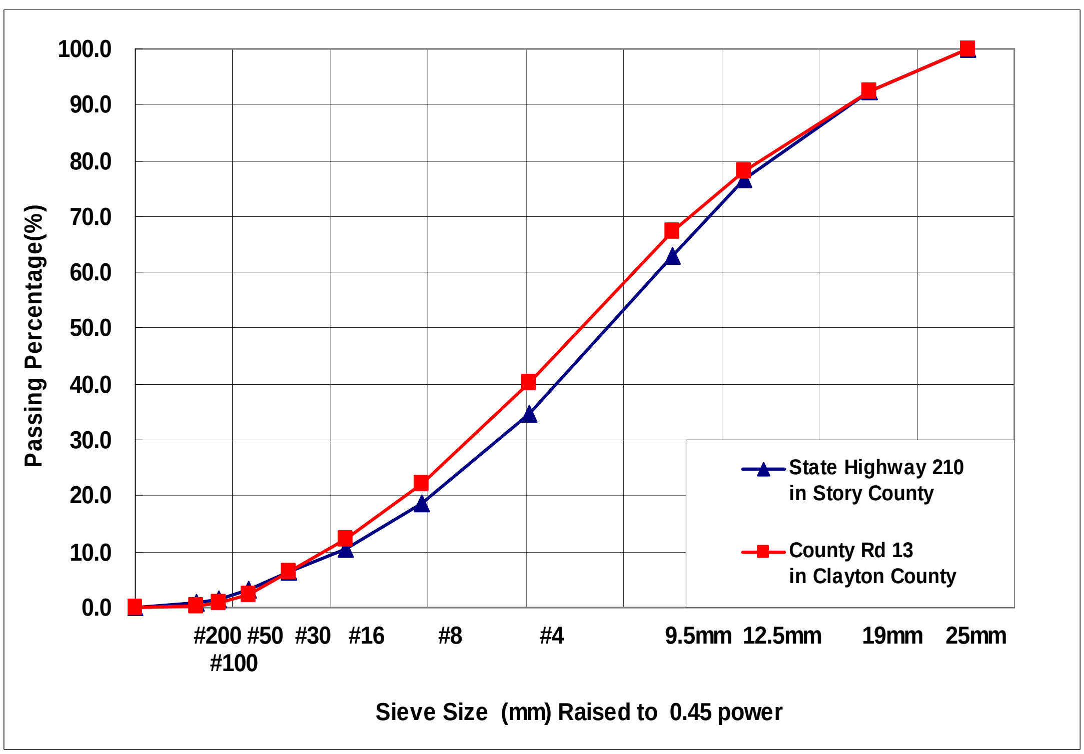


Figure 5-8. Gradation bar charts of RAP materials passing 25mm sieve

5.2.2 Characteristics of Extracted RAP

As summarized in Table 5-4, the extracted asphalt contents were 5.81% for RAP materials from Story County and 5.80% for RAP materials from Clayton County. The dynamic shear rheometer (DSR) test was performed at three different temperatures, 76°C, 82°C, and 88°C. The extracted asphalt of RAP material from Story County exhibited the penetration of 18 and G*/sin δ of 1.48 at 76°C whereas that of Clayton County showed a lower penetration value of 14 and a higher G*/sin δ value of 4.26 at 76°C. As expected, gradations of extracted aggregates were finer than those of RAP materials with a higher amount of fines passing No. 200 sieve.

Table 5-4. Properties of extracted asphalt and extracted aggregates

RAP Source	Residual Asphalt Content (%)	Penetration Index	Performance Grade	Dynamic Shear Rheometer (kPa)		
				76°C	82°C	88°C
Story County	5.81	18	PG 76	1.48	0.73	0.37
Clayton County	5.80	14	PG 88	4.26	2.07	1.04

Gradations of Extracted Aggregates

Sieve Size	Story County	Clayton County
25 mm	100.0	100.0
19.0 mm	99.7	100.0
12.5 mm	96.6	97.3
9.5 mm	90.8	92.9
No. 4	71.6	74.0
No. 8	56.2	59.4
No. 16	44.8	45.5
No. 30	36.0	34.6
No. 50	22.1	23.0
No. 100	10.8	12.5
No. 200	5.7	4.4

5.3. Sample Preparation

As shown in Figure 5-9, 4,500g of RAP materials were stored in a bag to produce a batch for three ITS test specimens. These RAP materials from Story and Clayton Counties were used to prepare covered CIR-foam and CIR-emulsion specimens for indirect tensile strength, dynamic creep and dynamic modulus test.

Figure 5-9. Bagged RAP materials

6. VALIDATION OF COVERED CURING PROCESS

To validate the impacts of the covered curing procedure on indirect tensile strength, more specimens were prepared using two different RAP material sources (Story County and Clayton County) and two different binders (foamed asphalt and HFMS-2S). As shown in Figure 6-1, to obtain different initial moisture contents, uncovered specimens were cured for 0, 1, 3, and 5 hours at a room temperature (please note that curing for 10 hours was dropped to keep the moisture content above 1.5%). These short-term cured specimens were then fully enclosed in the plastic mold to produce covered specimens and cured in the oven at 25˚C and 40˚C. The covered specimens were cured for one- and two-week before measuring their indirect tensile strengths. For each RAP source, thirty-six CIR-foam and CIR-emulsion specimens were prepared to measure indirect tensile strengths and moisture contents after zero, one- and two-week curing in the oven at 25˚C and 45˚C of specimens initially cured for 0, 1, 3, and 5 hours in the air.

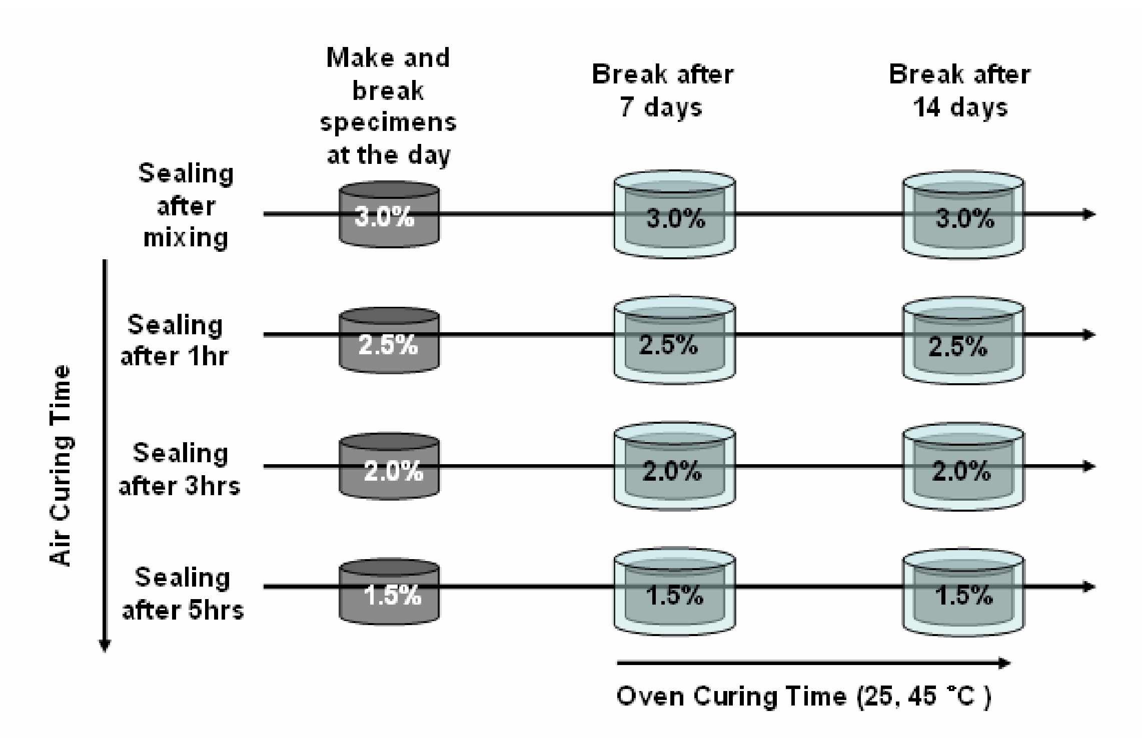


Figure 6-1. Covered curing process of both CIR-foam and CIR-emulsion specimens using RAP materials from Story and Clayton Counties

6.1 Mix Design Parameters

Table 6-1 summarizes the mix design parameters used in covered curing process of CIR mixtures with two types of binder: 1) foamed asphalt (PG 52-34) and 2) HFMS-2S emulsified asphalt (high-float medium-setting emulsion with a residue of relatively low viscosity). The CIR-foam mixtures were produced at 2.0% FAC and 4.0% MC and CIR-emulsion mixtures at 3.0% EAC and 3.0% MC. All specimens were compacted using gyratory compactor at 25 gyrations.

Table 6-1. Design parameters selected for covered CIR-foam and CIR-emulsion mixtures

CIR-foam Mixture	
Asphalt Binder	PG 52-34
Foaming Temperature (C)	170ºC
Foaming Water Content (%)	1.3%
Foamed Asphalt Content (%)	2.0%
Moisture Contents of RAP (%)	4.0%
Compaction Method	Gyratory compactor at 25 gyrations
Testing Method	Indirect tensile strength test
Number of Specimen	3-specimen / batch
CIR-emulsion Mixture	
Emulsion Type	HFMS-2S
Emulsion Content (%)	3.0% (mix of asphalt and water in 2:1 ratio)
Moisture Content (%)	3.0%
Compaction Method	Gyratory compactor at 25 gyrations
Testing Method	Indirect tensile strength test
Number of Specimen	3-specimen/ batch

6.2 Visual Observation

Figure 6-2 shows the pictures of CIR-foam and CIR-emulsion specimens taken right after compacted by gyratory compactor and Figure 6-3 shows the pictures of them taken right after oven dried. Based upon the visual observation, CIR-foam specimens (2.0% FAC) exhibited blown color on the surface and CIR-emulsion specimens (3.0% EC) exhibited black color with a better coating of RAP materials.

Figure 6-2. Visual observation of gyratory compacted CIR-foam and CIR-emulsion specimens

(a) CIR-foam (Story County)

(b) CIR-emulsion (Story County)

(c) CIR-foam (Clayton County)

(d) CIR-emulsion (Clayton County)

Figure 6-3. Visual observation of CIR-foam and CIR-emulsion specimens dried in oven

6.3 Impacts of Moisture Content and Curing Period on ITS

Table 6-2 to Table 6-9 summarize indirect tensile strengths and moisture contents of covered CIR-foam and CIR-emulsion specimens using RAP materials cured in the oven at 25˚C and 45˚C with RAP materials from Story and Clayton Counties, respectively.

Table 6-2. Summary of ITS and moisture contents of covered CIR-foam specimen cured at 25˚C using RAP materials from Story County

Time (hr)/ Target Moisture (%)	Covered CIR-foam specimen cured at 25˚C																				
	Curing Period (0 day)							Curing Period (7 days)							Curing Period (14 days)						
	Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)	
0(hr)/ 3.0%	2.67	2.67		2.264		12.0		3.02	3.02		2.223		16.9		2.62	2.62		2.217		18.9	
	3.01	3.01	2.96	2.212	2.236	8.6	9.2	3.19	3.19	3.03	2.186	2.186	16.3	15.5	2.97	2.97	2.92	2.153	2.178	12.0	14.3
	3.20	3.20		2.233		7.0		2.87	2.87		2.150		13.4		3.17	3.17		2.164		11.8	
1(hr)/ 2.5%	2.42	1.91		2.261		26.1		2.92	2.43		2.221		21.6		2.25	1.70		2.236		22.7	
	3.01	2.58	2.31	2.235	2.240	17.0	18.7	3.08	2.60	2.47	2.200	2.191	18.1	17.9	2.87	2.33	2.13	2.193	2.205	15.2	18.3
	2.95	2.46		2.225		12.9		2.83	2.36		2.153		14.0		2.82	2.35		2.185		17.1	
3(hrs)/ 2.0%	2.36	1.43		2.258		24.4		3.06	2.15		2.205		15.4		2.44	1.55		2.205		22.6	
	2.90	1.93	1.78	2.239	2.240	20.1	21.5	2.86	2.03	2.04	2.197	2.191	16.5	18.9	2.98	2.17	2.02	2.163	2.168	17.8	19.1
	2.93	2.00		2.224		20.1		2.84	1.95		2.170		24.8		3.29	2.33		2.136		16.7	
5(hrs)/ 1.5%	2.77	1.20		2.222		25.3		3.19	1.95		2.200		26.8		2.51	1.26		2.211		32.7	
	2.86	1.49	1.43	2.180	2.204	20.2	20.1	2.99	1.70	1.77	2.149	2.156	18.5	20.6	2.97	1.81	1.63	2.177	2.183	26.1	25.7
	2.85	1.60		2.209		14.8		2.92	1.65		2.118		16.5		2.96	1.82		2.160		18.3	

Table 6-3. Summary of ITS and moisture contents of covered CIR-foam specimen cured at 45˚C using RAP materials from Story County

Time (hr)/ Target Moisture (%)	CIR-foam specimens cured at 45˚C																				
	Curing Period (0 day)							Curing Period (7 days)							Curing Period (14 days)						
	Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)	
0(hr)/ 3.0%	2.67	2.67		2.264		12.0		2.54	2.54		2.227		14.9		3.09	3.09		2.239		8.6	
	3.01	3.01	2.96	2.212	2.236	8.6	9.2	2.93	2.93	2.90	2.193	2.192	14.5	13.4	2.90	2.90	2.91	2.210	2.213	6.4	7.1
	3.20	3.20		2.233		7.0		3.22	3.22		2.154		10.9		2.75	2.75		2.188		6.4	
1(hr)/ 2.5%	2.42	1.91		2.261		26.1		2.57	2.03		2.209		16.3		2.83	2.24		2.189		7.3	
	3.01	2.58	2.31	2.235	2.240	17.0	18.7	2.97	2.55	2.39	2.177	2.182	13.6	14.4	3.34	2.84	2.57	2.169	2.171	5.2	6.2
	2.95	2.46		2.225		12.9		2.95	2.59		2.159		13.3		3.08	2.64		2.155		6.0	
3(hrs)/ 2.0%	2.36	1.43		2.258		24.4		2.40	1.46		2.218		22.7		2.91	1.83		2.207		18.5	
	2.90	1.93	1.78	2.239	2.240	20.1	21.5	2.88	2.05	1.81	2.208	2.197	18.5	19.5	2.74	1.75	1.93	2.179	2.176	13.0	13.2
	2.93	2.00		2.224		20.1		2.72	1.91		2.166		17.5		3.16	2.19		2.140		8.0	
5(hrs)/ 1.5%	2.77	1.20		2.222		25.3		2.72	1.39		2.198		24.8		3.05	1.49		2.187		25.8	
	2.86	1.49	1.43	2.180	2.204	20.2	20.1	2.96	1.71	1.63	2.155	2.169	16.3	19.0	2.85	1.31	1.42	2.171	2.168	19.5	20.3
	2.85	1.60		2.209		14.8		2.99	1.78		2.155		16.1		2.99	1.45		2.146		15.5	

Table 6-4. Summary of ITS and moisture contents of covered CIR-emulsion specimens cured at 25˚C using RAP materials from Story County

Time (hr)/ Target Moisture (%)	CIR-emulsion specimens cured at 25˚C																	
	Curing Period (0 day)						Curing Period (7 days)						Curing Period (14 days)					
	Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)	
0(hr)/ 3.0%	2.45	2.45	2.59	2.188	2.193	10.1	8.6	3.06	3.06	3.03	2.131	2.134	10.4	9.6	2.51	2.51	2.72	2.208	2.182	17.1	14.5
	2.57	2.57		2.206		8.4		3.05	3.05		2.137		8.9		2.87	2.87		2.179		14.4	
	2.76	2.76		2.185		7.3		2.99	2.99		2.134		9.6		2.79	2.79		2.159		12.1	
1(hr)/ 2.5%	2.56	2.16	2.30	2.234	2.202	18.7	16.2	2.46	1.88	2.11	2.176	2.159	16.5	15.5	2.70	2.19	2.41	2.159	2.150	16.4	13.4
	2.63	2.32		2.172		16.7		2.86	2.35		2.163		15.1		2.93	2.49		2.155		12.7	
	2.75	2.42		2.201		13.2		2.66	2.11		2.138		14.8		3.02	2.55		2.135		11.0	
3(hrs)/ 2.0%	3.23	2.34	2.48	2.168	2.146	18.0	15.8	2.71	1.53	1.66	2.144	2.128	17.8	15.3	2.62	1.43	1.64	2.168	2.146	21.5	17.3
	3.17	2.45		2.157		16.1		2.71	1.64		2.111		13.4		2.81	1.73		2.150		17.2	
	3.44	2.66		2.113		13.3		2.92	1.82		2.129		14.8		2.88	1.76		2.121		13.2	
5(hrs)/ 1.5%	2.95	1.70	1.94	2.153	2.130	18.8	14.6	2.69	1.33	1.40	2.182	2.152	28.1	22.9	2.94	1.29	1.47	2.155	2.138	21.4	18.3
	3.16	2.10		2.117		13.5		2.74	1.34		2.151		21.9		3.13	1.56		2.141		15.3	
	3.30	2.03		2.121		11.4		3.12	1.54		2.123		18.6		3.10	1.55		2.118		18.2	

Table 6-5. Summary of ITS and moisture contents of covered CIR-emulsion specimens cured at 45˚C using RAP materials from Story County

Time (hr)/ Target Moisture (%)	CIR-emulsion specimens cured at 45˚C																				
	Curing Period (0 day)							Curing Period (7 days)							Curing Period (14 days)						
	Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)	
0(hr)/ 3.0%	2.45	2.45	2.59	2.188	2.193	10.1	8.6	2.57	2.57	2.81	2.172	2.166	12.1	10.1	3.18	3.18	3.14	2.147	2.152	9.7	11.0
	2.57	2.57		2.206		8.4		2.98	2.98		2.157		7.3		2.99	2.99		2.162		10.6	
	2.76	2.76		2.185		7.3		2.88	2.88		2.169		10.9		3.24	3.24		2.147		12.6	
1(hr)/ 2.5%	2.56	2.16	2.30	2.234	2.202	18.7	16.2	2.45	1.71	1.96	2.168	2.157	11.5	9.9	3.25	2.79	2.62	2.188	2.169	19.0	20.8
	2.63	2.32		2.172		16.7		2.70	1.96		2.170		8.3		2.82	2.47		2.148		17.1	
	2.75	2.42		2.201		13.2		2.85	2.20		2.134		10.1		3.02	2.59		2.171		26.4	
3(hrs)/ 2.0%	3.23	2.34	2.48	2.168	2.146	18.0	15.8	2.37	1.15	1.37	2.189	2.152	19.9	18.6	3.35	2.45	2.15	2.189	2.166	21.6	17.1
	3.17	2.45		2.157		16.1		2.78	1.47		2.159		19.1		2.80	1.97		2.157		15.1	
	3.44	2.66		2.113		13.3		2.72	1.48		2.107		16.7		2.89	2.01		2.151		14.5	
5(hrs)/ 1.5%	2.95	1.70	1.94	2.153	2.130	18.8	14.6	2.64	1.09	1.25	2.165	2.136	20.1	18.7	2.95	1.65	1.73	2.152	2.131	28.6	26.9
	3.16	2.10		2.117		13.5		2.97	1.34		2.132		17.3		3.06	1.84		2.143		28.3	
	3.30	2.03		2.121		11.4		2.96	1.31		2.110		18.7		2.90	1.70		2.098		23.9	

Table 6-6. Summary of ITS and moisture contents of covered CIR-foam specimens cured at 25˚C using RAP materials from Clayton County

Time (hr)/ Target Moisture (%)	CIR-foam specimens cured at 25˚C																				
	Curing Period (0 day)							Curing Period (7 days)							Curing Period (14 days)						
	Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)	
0(hr)/ 3.0%	3.27	3.27	3.45	2.202	2.180	8.1	7.1	3.41	3.41	3.50	2.220	2.204	13.8	11.5	3.29	3.29	3.34	2.220	2.204	14.3	13.1
	3.67	3.67		2.171		7.4		3.51	3.51		2.198		11.6		3.31	3.31		2.198		12.7	
	3.40	3.40		2.166		5.9		3.57	3.57		2.195		9.0		3.41	3.41		2.195		12.4	
1(hr)/ 2.5%	3.28	2.53	2.78	2.151	2.142	12.9	12.7	3.41	2.83	2.83	2.139	2.125	16.3	13.5	3.10	2.44	2.64	2.139	2.125	18.0	14.1
	3.39	2.76		2.138		11.5		3.43	2.94		2.112		13.5		3.47	2.89		2.112		12.0	
	3.73	3.04		2.138		13.6		3.26	2.71		2.122		10.8		3.11	2.59		2.122		12.2	
3(hrs)/ 2.0%	3.51	2.01	2.12	2.136	2.142	12.9	13.0	3.17	1.97	2.11	2.199	2.190	16.8	13.7	3.54	2.27	2.24	2.199	2.190	15.8	15.3
	3.45	2.10		2.151		14.8		3.39	2.27		2.196		13.2		3.35	2.26		2.196		16.1	
	3.53	2.24		2.141		11.3		3.37	2.08		2.175		11.1		3.35	2.19		2.175		13.9	
5(hrs)/ 1.5%	3.52	1.52	1.59	2.152	2.134	21.9	17.1	3.25	1.75	1.65	2.185	2.159	32.2	23.5	3.17	1.51	1.63	2.185	2.159	23.7	17.5
	3.57	1.72		2.136		16.1		3.21	1.55		2.154		21.4		3.18	1.64		2.154		16.0	
	3.54	1.51		2.114		13.3		3.40	1.65		2.137		17.0		3.39	1.74		2.137		13.0	

Table 6-7. Summary of ITS and moisture contents of covered CIR-foam specimens cured at 45˚C using RAP materials from Clayton County

Time (hr)/ Target Moisture (%)	CIR-foam specimens cured at 45˚C																				
	Curing Period (0 day)							Curing Period (7 days)							Curing Period (14 days)						
	Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)	
0(hr)/ 3.0%	3.27	3.27	3.45	2.202	2.180	8.1	7.1	3.65	3.65	3.55	2.173	2.168	16.8	14.2	3.38	3.38	3.40	2.170	2.153	16.7	14.0
	3.67	3.67		2.171		7.4		3.42	3.42		2.182		12.6		3.49	3.49		2.153		13.6	
	3.40	3.40		2.166		5.9		3.59	3.59		2.149		13.2		3.32	3.32		2.136		11.6	
1(hr)/ 2.5%	3.28	2.53	2.78	2.151	2.142	12.9	12.7	2.55	1.90	2.58	2.224	2.197	19.8	17.1	3.18	2.44	2.58	2.203	2.187	20.3	16.7
	3.39	2.76		2.138		11.5		3.53	2.94		2.188		18.9		3.44	2.57		2.180		15.3	
	3.73	3.04		2.138		13.6		3.58	2.91		2.180		12.6		3.47	2.73		2.178		14.6	
3(hrs)/ 2.0%	3.51	2.01	2.12	2.136	2.142	12.9	13.0	3.27	1.91	2.14	2.179	2.152	24.1	18.5	3.07	1.56	1.66	2.183	2.152	25.9	18.3
	3.45	2.10		2.151		14.8		3.62	2.37		2.143		14.6		3.31	1.64		2.138		13.5	
	3.53	2.24		2.141		11.3		3.59	2.14		2.135		16.8		3.33	1.79		2.135		15.6	
5(hrs)/ 1.5%	3.52	1.52	1.59	2.152	2.134	21.9	17.1	3.44	1.55	1.55	2.178	2.156	24.0	20.0	3.28	1.23	1.21	2.150	2.131	23.2	21.1
	3.57	1.72		2.136		16.1		3.54	1.64		2.152		18.7		3.26	1.06		2.127		24.3	
	3.54	1.51		2.114		13.3		3.57	1.46		2.138		17.4		3.45	1.35		2.115		15.7	

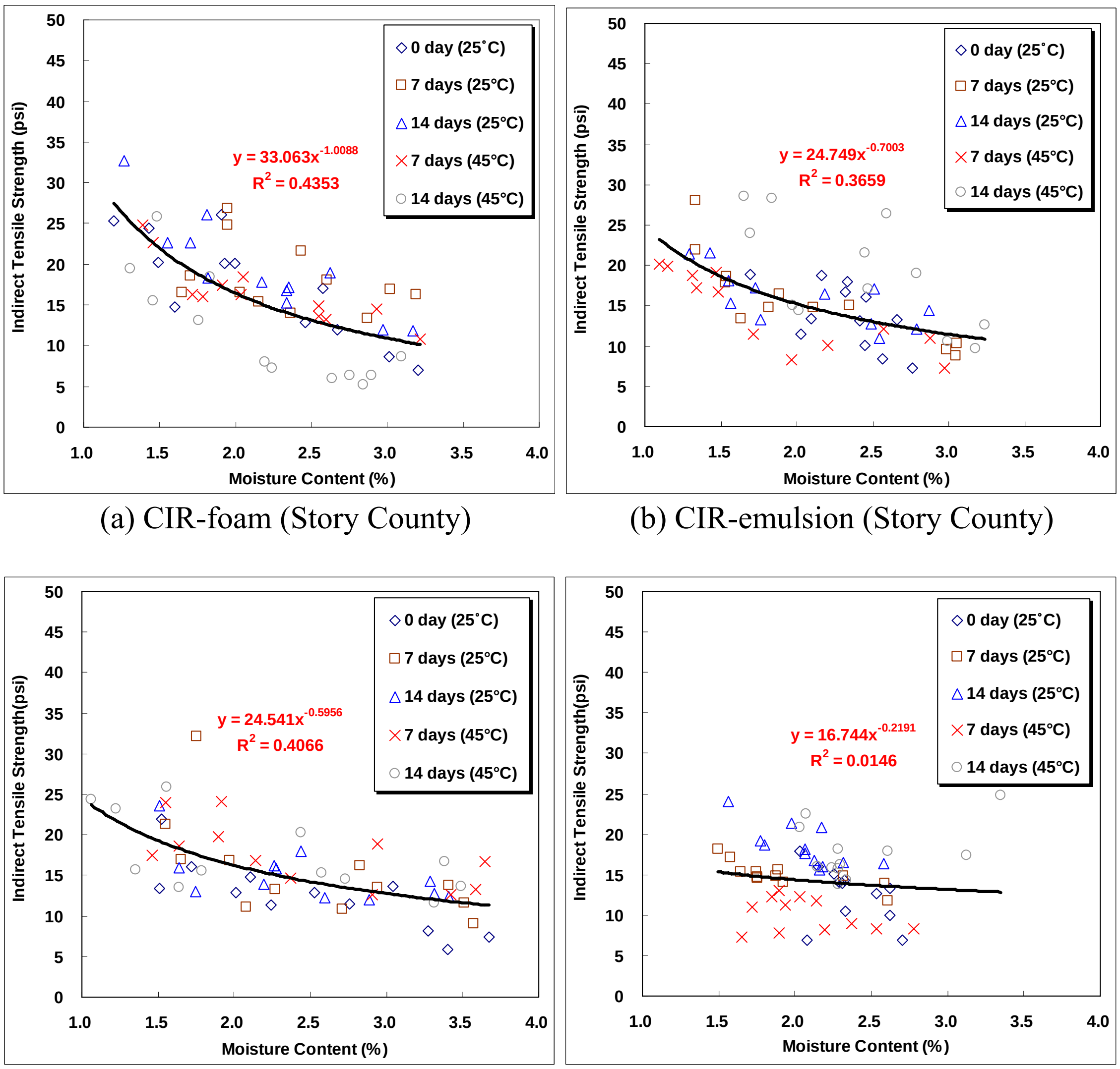
Table 6-8. Summary of ITS and moisture contents of covered CIR-emulsion specimens cured at 25˚C using RAP materials from Clayton County

Time (hr)/ Target Moisture (%)	CIR-emulsion specimens cured at 25˚C																				
	Curing Period (0 day)							Curing Period (7 days)							Curing Period (14 days)						
	Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)	
0(hr)/ 3.0%	2.62	2.62	2.47	2.248	2.240	10.0	8.0	2.32	2.32	2.50	2.249	2.239	14.9	13.5	2.18	2.18	2.36	2.225	2.195	20.9	17.9
	2.71	2.71		2.246		6.9		2.59	2.59		2.242		13.9		2.58	2.58		2.194		16.3	
	2.08	2.09		2.226		6.9		2.61	2.61		2.227		11.7		2.32	2.32		2.165		16.5	
1(hr)/ 2.5%	2.44	2.16	2.44	2.233	2.222	16.0	14.0	2.12	1.75	1.81	2.254	2.248	15.4	14.7	2.40	2.06	2.12	2.182	2.180	18.2	17.0
	2.92	2.62		2.215		13.3		2.11	1.75		2.249		14.6		2.45	2.13		2.171		16.8	
	2.83	2.54		2.219		12.6		2.28	1.92		2.240		14.1		2.47	2.18		2.187		16.0	
3(hrs)/ 2.0%	2.82	2.29	2.31	2.219	2.215	14.0	12.8	2.05	1.50	1.67	2.257	2.243	18.2	16.4	2.56	1.97	2.07	2.198	2.177	21.3	18.2
	2.81	2.31		2.221		13.9		2.25	1.64		2.241		15.3		2.72	2.16		2.177		15.6	
	2.86	2.33		2.206		10.5		2.59	1.89		2.231		15.7		2.58	2.06		2.155		17.6	
5(hrs)/ 1.5%	2.61	2.03	2.20	2.235	2.218	17.9	15.7	2.18	1.58	1.73	2.244	2.225	17.1	15.5	2.10	1.57	1.71	2.223	2.200	24.0	20.6
	2.96	2.26		2.205		15.0		2.43	1.75		2.221		14.7		2.40	1.80		2.186		18.7	
	3.01	2.32		2.214		14.3		2.61	1.87		2.210		14.8		2.38	1.77		2.191		19.2	

Table 6-9. Summary of ITS and moisture contents of covered CIR-emulsion specimens cured at 45˚C using RAP materials from Clayton County

Time (hr)/ Target Moisture (%)	CIR-emulsion specimens cured at 45˚C																				
	Curing Period (0 day)							Curing Period (7 days)							Curing Period (14 days)						
	Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)		Initial Moisture	Moisture (%)		Gmb		ITS (psi)	
0(hr)/ 3.0%	2.62	2.62	2.47	2.248	2.240	10.0	8.0	2.37	2.37	2.56	2.249	2.236	8.9	8.5	3.13	3.13	2.92	2.231	2.206	17.4	19.5
	2.71	2.71		2.246		6.9		2.78	2.78		2.235		8.4		3.35	3.35		2.203		24.8	
	2.08	2.09		2.226		6.9		2.53	2.53		2.223		8.3		2.29	2.29		2.183		16.3	
1(hr)/ 2.5%	2.44	2.16	2.44	2.233	2.222	16.0	14.0	1.97	1.65	2.00	2.245	2.240	7.3	9.1	2.34	2.03	2.14	2.225	2.210	20.8	17.5
	2.92	2.62		2.215		13.3		2.56	2.20		2.236		8.2		2.42	2.15		2.206		16.0	
	2.83	2.54		2.219		12.6		2.56	2.14		2.239		11.8		2.52	2.24		2.199		15.9	
3(hrs)/ 2.0%	2.82	2.29	2.31	2.219	2.215	14.0	12.8	2.29	1.72	1.88	2.238	2.221	11.1	10.4	3.09	2.61	2.41	2.203	2.191	17.9	16.8
	2.81	2.31		2.221		13.9		2.63	1.90		2.212		7.8		2.71	2.28		2.186		18.2	
	2.86	2.33		2.206		10.5		2.76	2.03		2.213		12.3		2.78	2.34		2.183		14.3	
5(hrs)/ 1.5%	2.61	2.03	2.20	2.235	2.218	17.9	15.7	2.61	1.85	1.89	2.229	2.223	12.3	12.2	2.67	2.07	2.21	2.196	2.176	22.5	17.3
	2.96	2.26		2.205		15.0		2.71	1.93		2.216		11.2		2.78	2.28		2.168		13.8	
	3.01	2.32		2.214		14.3		2.64	1.89		2.224		13.0		2.84	2.28		2.163		15.8	

Figure 6-4 shows plots of the indirect tensile strength against moisture content for covered CIR-foam and CIR-emulsion specimens for two RAP sources. Overall, indirect tensile strengths were significantly lower than those of Webster County presented in Chapter 4 because the specimens were cured up to 5 hours instead of 10 hours in the air. The indirect tensile strength increased as the moisture content decreased except the CIR-emulsion specimens with RAP materials from Clayton County.



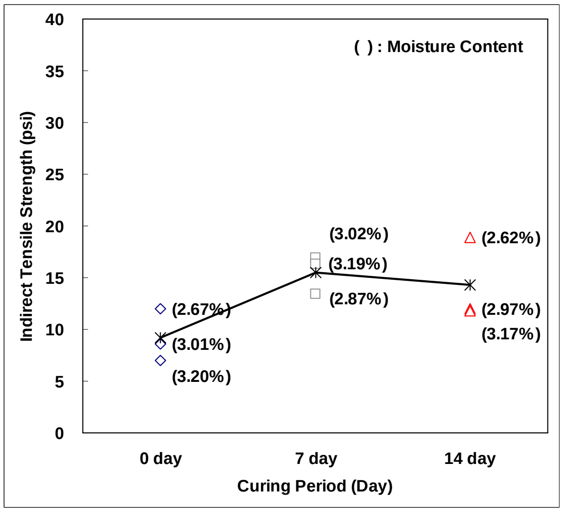
(a) CIR-foam (Story County) (b) CIR-emulsion (Story County)

(c) CIR-foam (Clayton County) (d) CIR-emulsion (Clayton County)

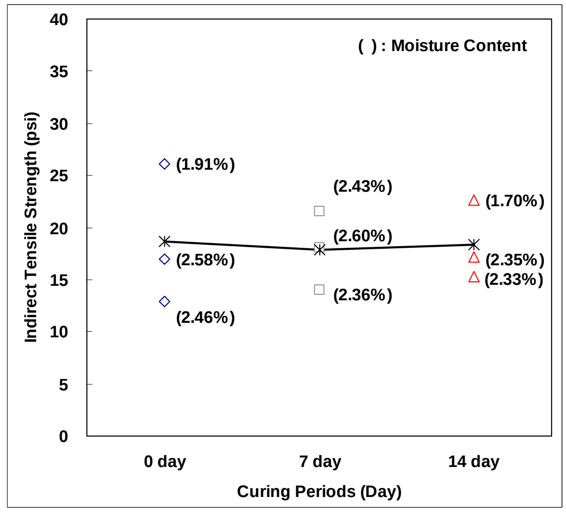
Figure 6-4. Plots of ITS against moisture content for CIR-foam and CIR-emulsion specimens using two RAP sources

Figure 6-5 to Figure 6-12 show plots of the indirect tensile strengths of covered CIR-foam and CIR-emulsion specimens against curing periods cured in the oven at 25˚C and 45˚C with RAP materials from Story and Clayton Counties, respectively. As can be seen in the Figure 6-5 and Figure 6-6, the indirect tensile strength of covered CIR-foam specimen from Story County stayed constant or decreased as curing period increased. As can be seen in the Figure 6-7 and Figure 6-8, the indirect tensile strengths of covered CIR-emulsion specimens from Story County stayed constant or decreased as curing period increased, except for those cured in the air for 5 hours then cured in the oven at 45˚C for 7 days and 14 days. It is interesting to note that the indirect tensile strength of CIR-emulsion specimens with RAP materials from Story County cured for 14 days was higher than those cured for 7 days even if the moisture content of the specimens cured for 14 days was higher than those cured for 7days. As shown in figures from 6-9 to 6-12, the indirect tensile strengths of covered CIR-foam and CIR-emulsion specimens from Clayton County also stayed constant or slightly increased as curing period increased at the similar level of moisture content.

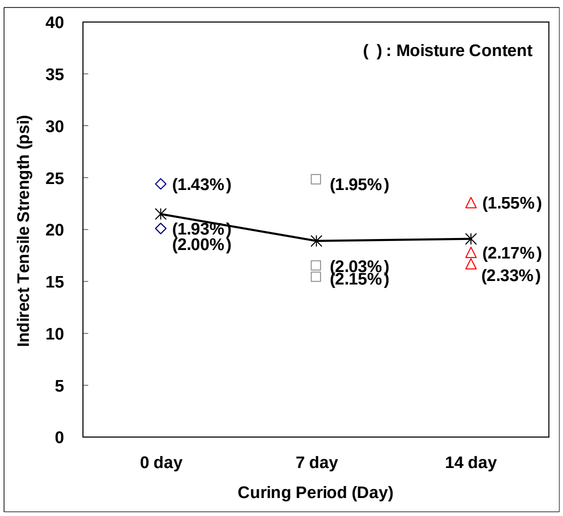
Based on the limited test result using two RAP sources, it can be concluded that indirect tensile strength of covered CIR specimens with the initial moisture content of 1.5% or higher, cured in the oven at 25˚C and 45˚C, did not increase over the curing period from zero to 14 days.



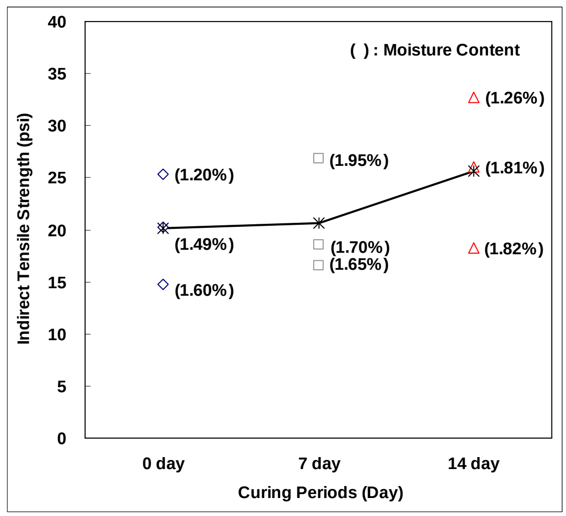
(a) Initial air curing: 0 hr



(b) Initial air curing: 1 hr

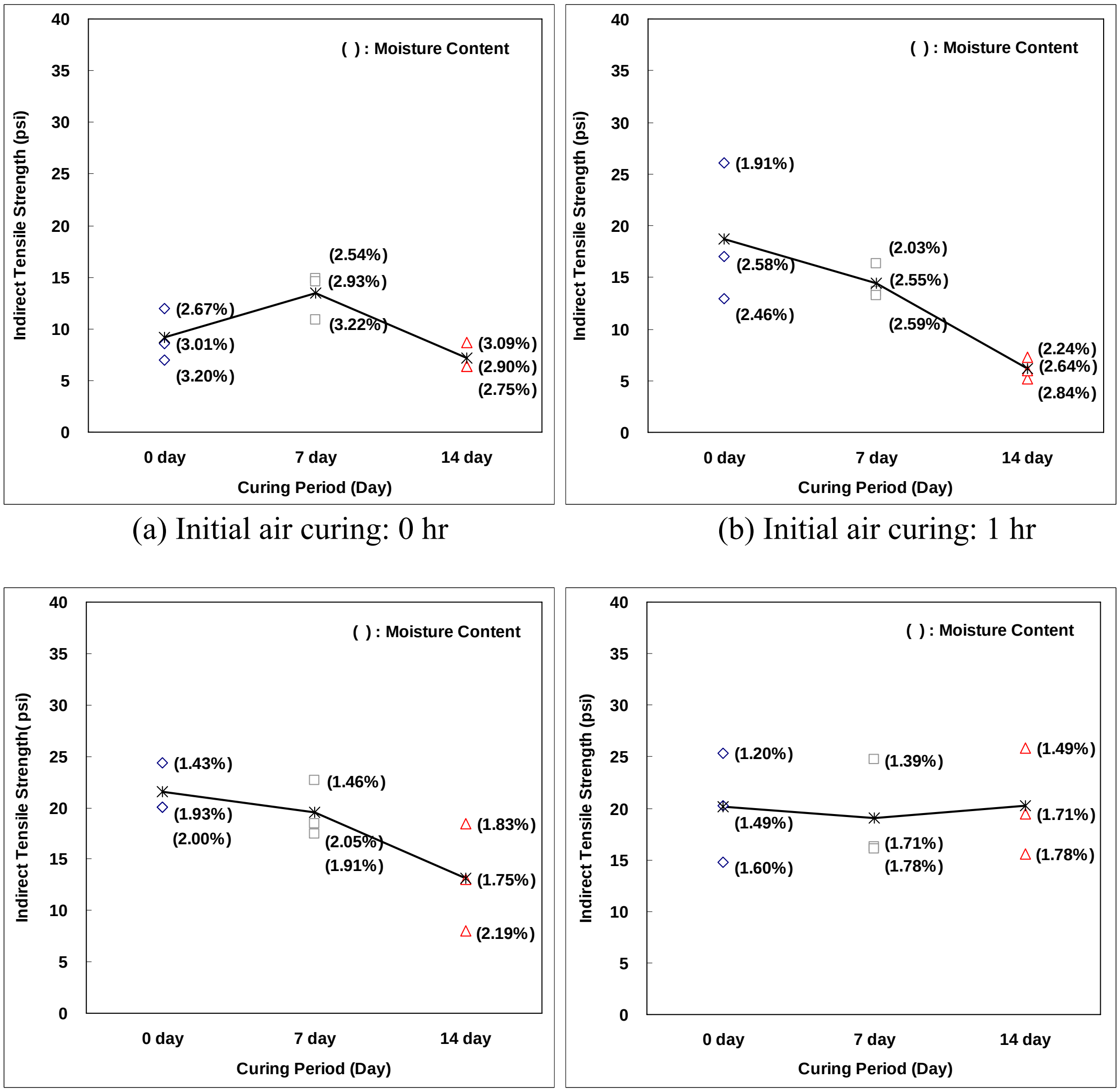


(c) Initial air curing: 3 hrs



(d) Initial air curing: 5 hrs

Figure 6-5. Relationships between ITS and curing period for CIR-foam specimens cured at 25°C using RAP materials from Story County



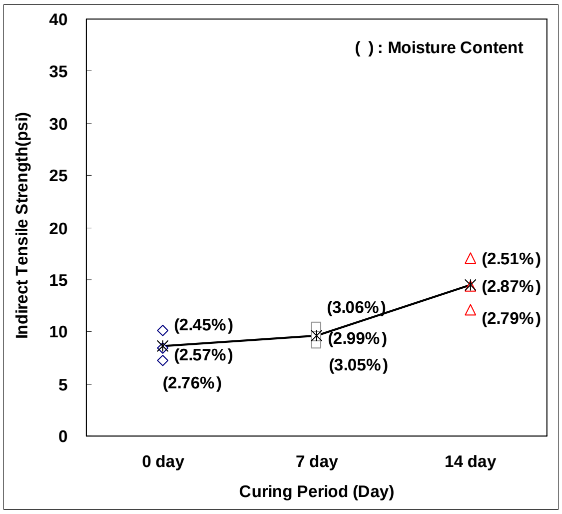
(a) Initial air curing: 0 hr

(b) Initial air curing: 1 hr

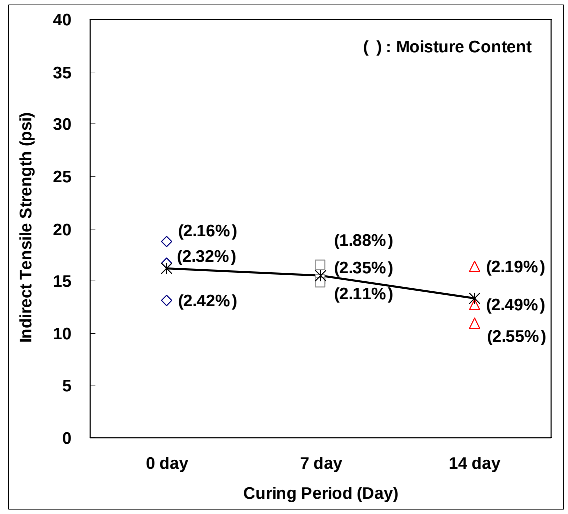
(c) Initial air curing: 3 hrs

(d) Initial air curing: 5 hrs

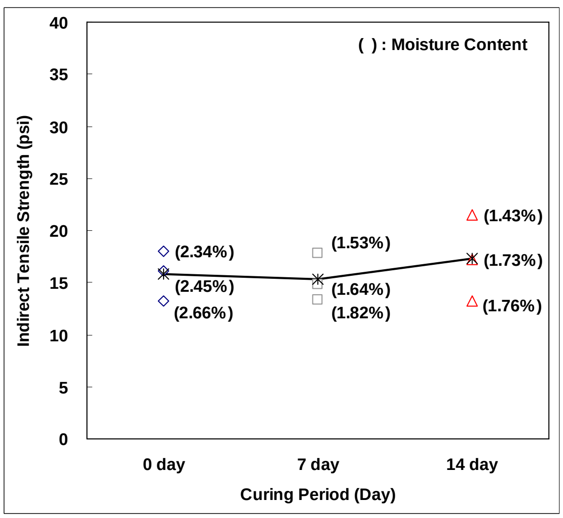
Figure 6-6. Relationships between ITS and curing period for CIR-foam specimens cured at 45°C using RAP materials from Story County



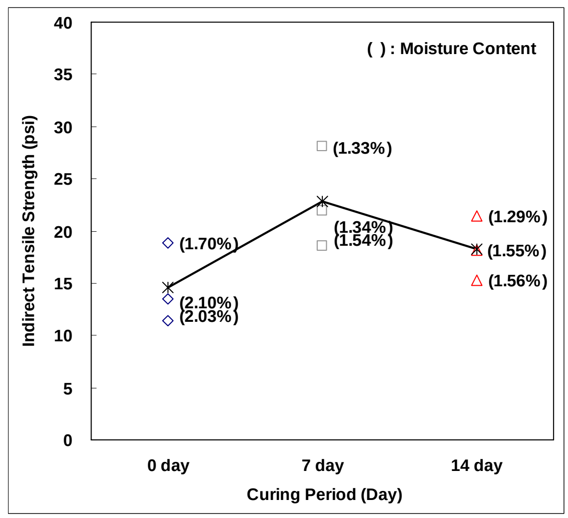
(a) Initial air curing: 0 hr



(b) Initial air curing: 1 hr

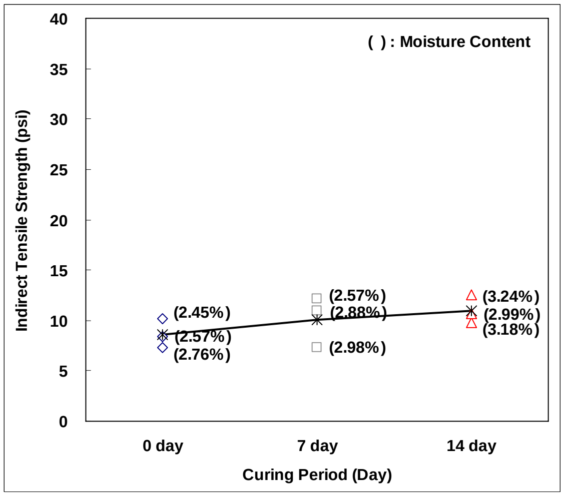


(c) Initial air curing: 3 hrs

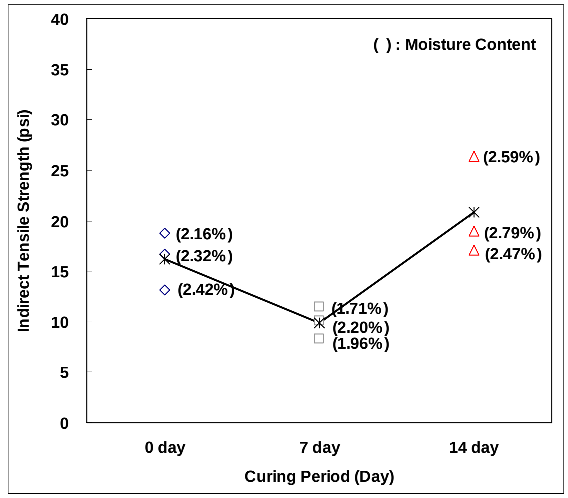


(d) Initial air curing: 5 hrs

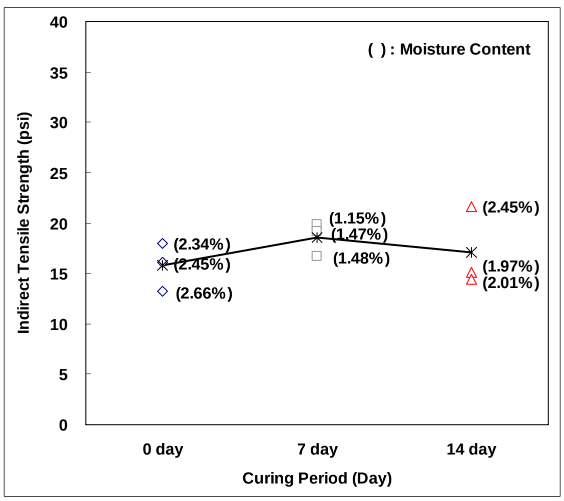
Figure 6-7. Relationships between ITS and curing period for CIR-emulsion specimens cured at 25°C using RAP materials from Story County



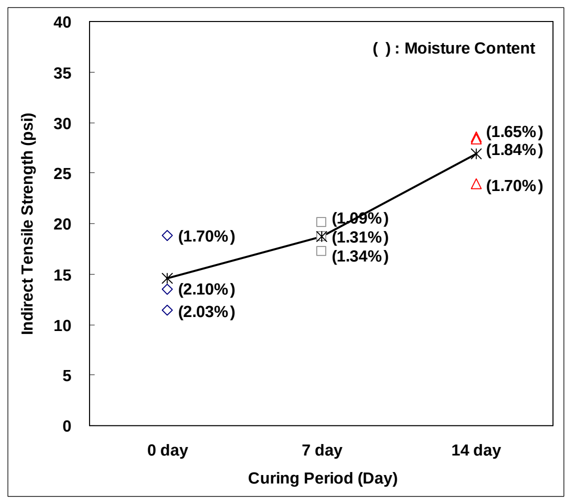
(a) Initial air curing: 0 hr



(b) Initial air curing: 1 hr

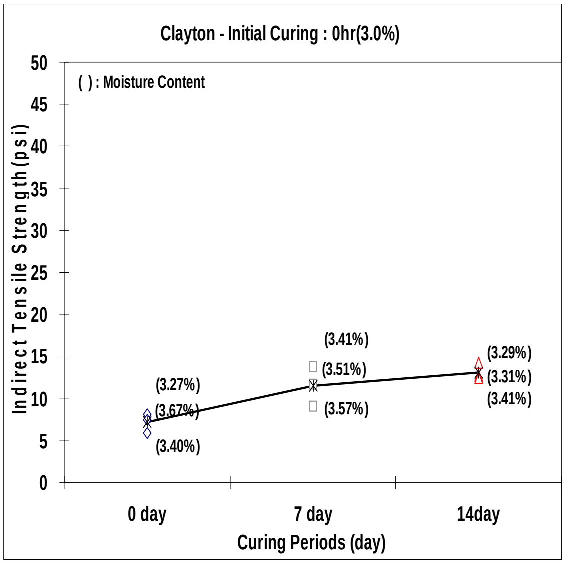


(c) Initial air curing: 3 hrs

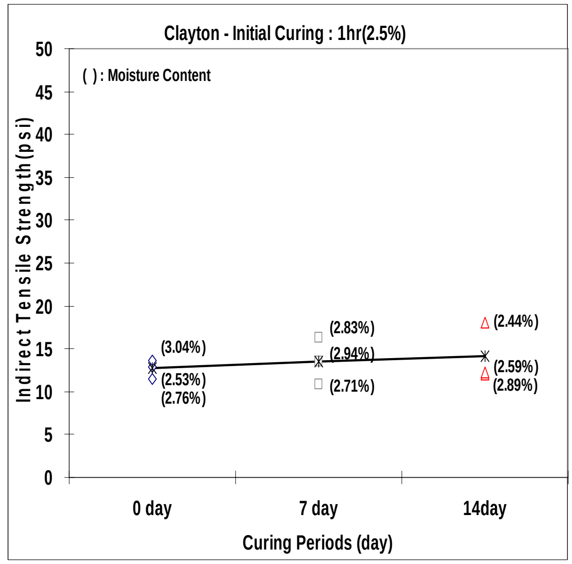


(d) Initial air curing: 5 hrs

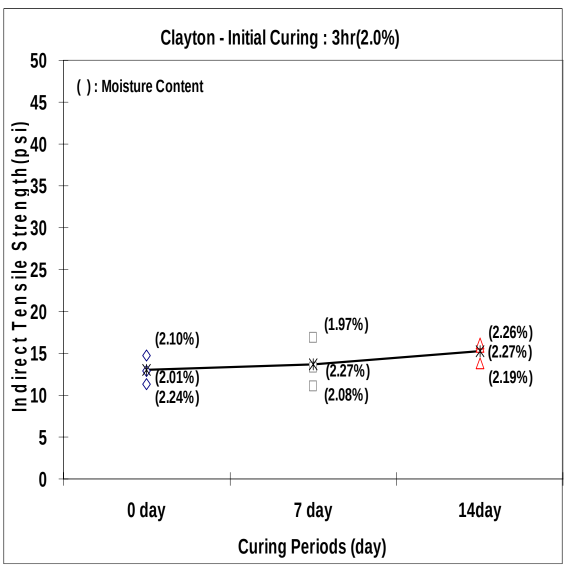
Figure 6-8. Relationships between ITS and curing period for CIR-emulsion specimens cured at 45°C using RAP materials from Story County



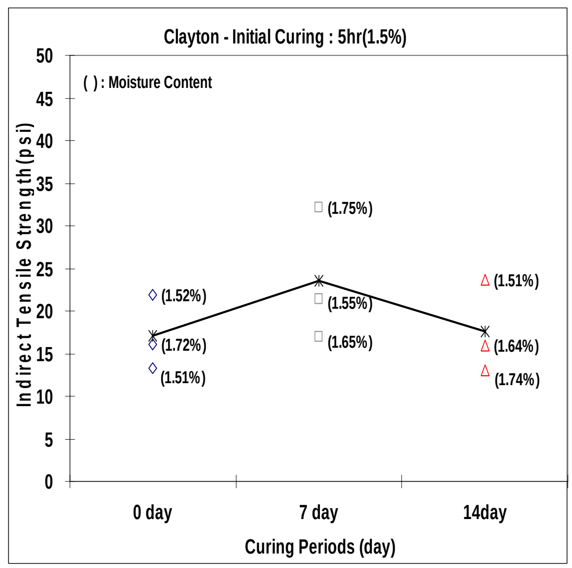
(a) Initial air curing: 0 hr



(b) Initial air curing: 1 hr

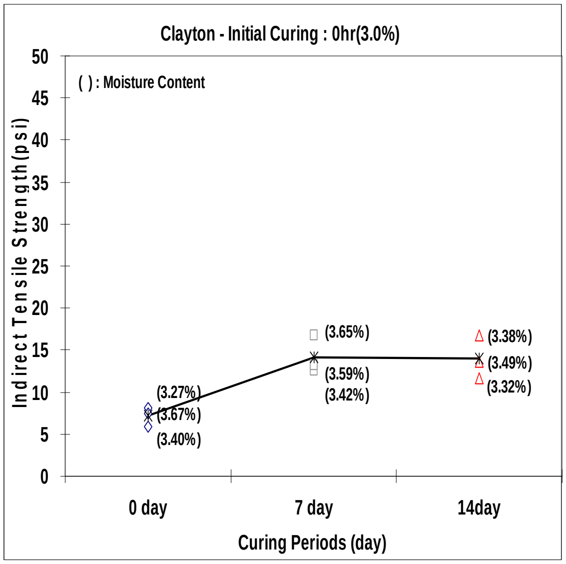


(c) Initial air curing: 3 hrs

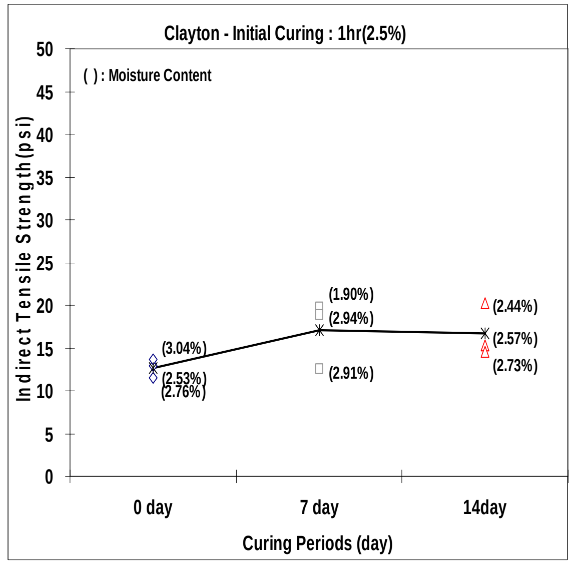


(d) Initial air curing: 5 hrs

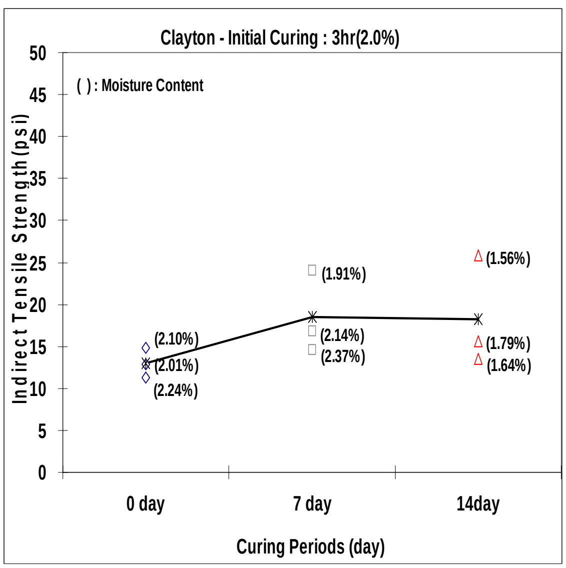
Figure 6-9. Relationships between ITS and curing period for CIR-foam specimens cured at 25°C using RAP materials from Clayton County



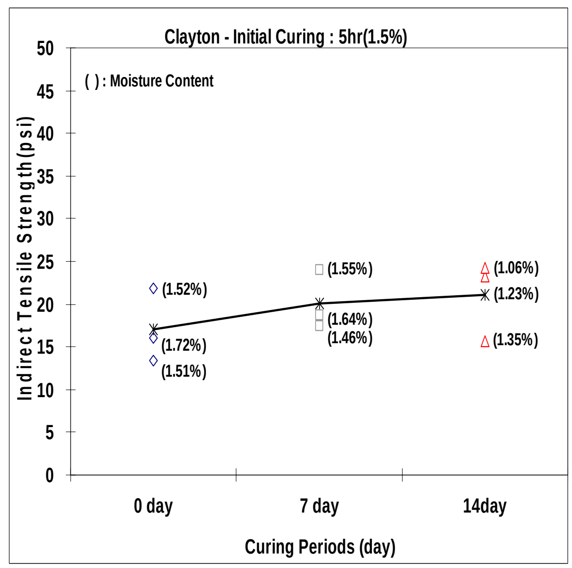
(a) Initial air curing: 0 hr



(b) Initial air curing: 1 hr

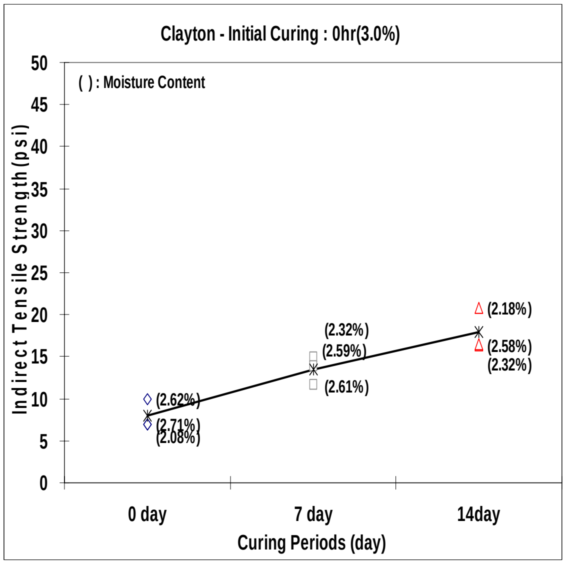


(c) Initial air curing: 3 hrs

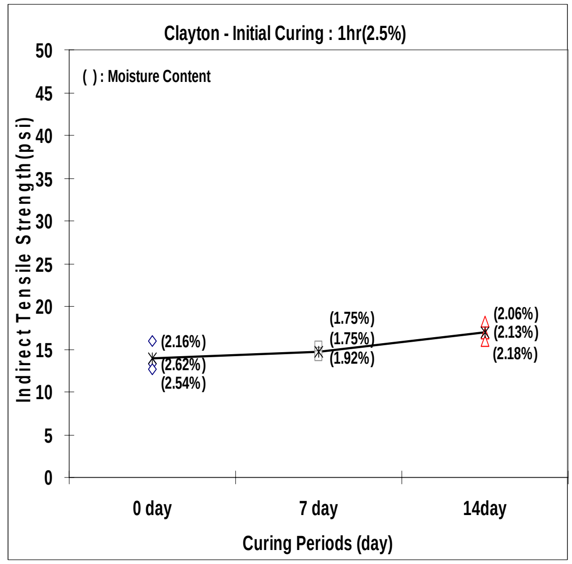


(d) Initial air curing: 5 hrs

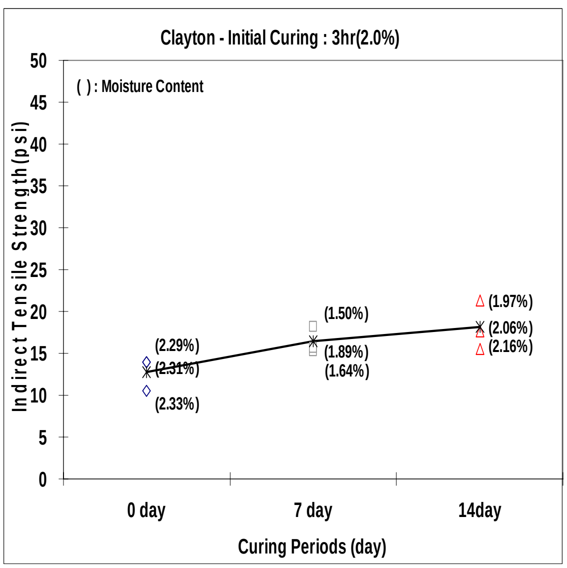
Figure 6-10. Relationships between ITS and curing period for CIR-foam specimens cured at 45°C using RAP materials from Clayton County



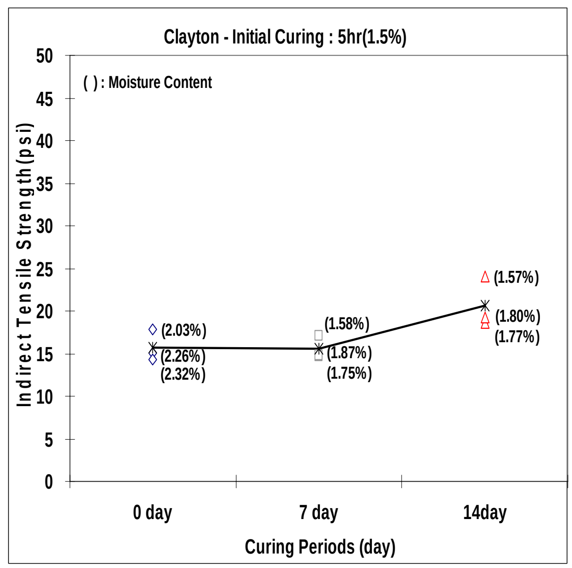
(a) Initial air curing: 0 hr



(b) Initial air curing: 1 hr

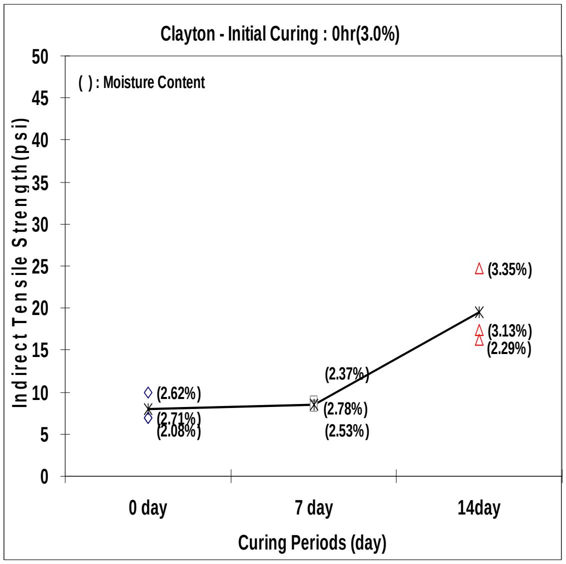


(c) Initial air curing: 3 hrs

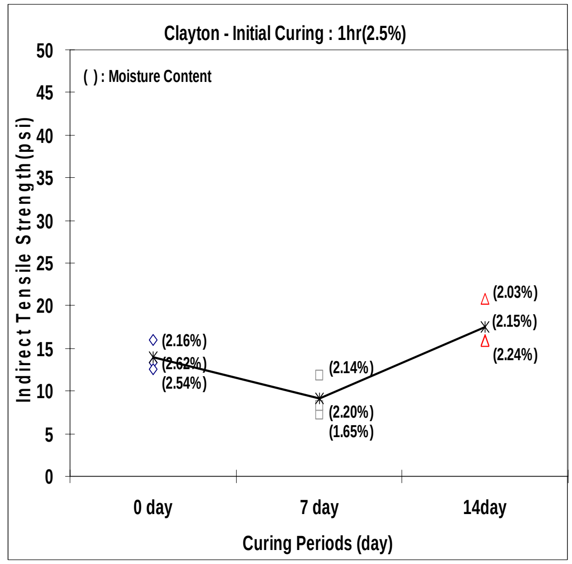


(d) Initial air curing: 5 hrs

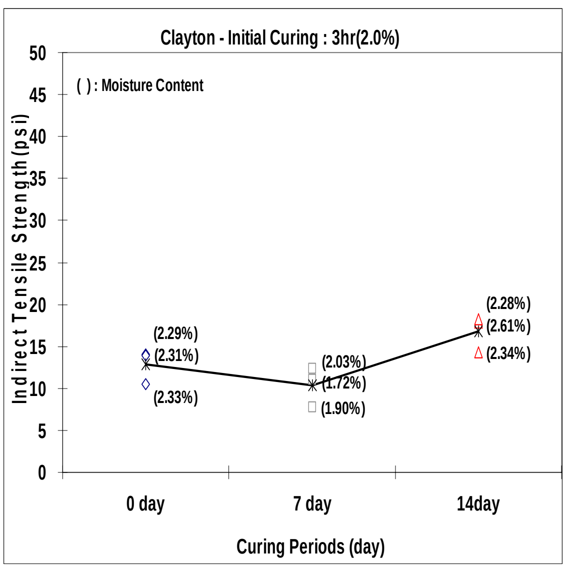
Figure 6-11. Relationships between ITS and curing period for CIR-emulsion specimens cured at 25°C using RAP materials from Clayton County



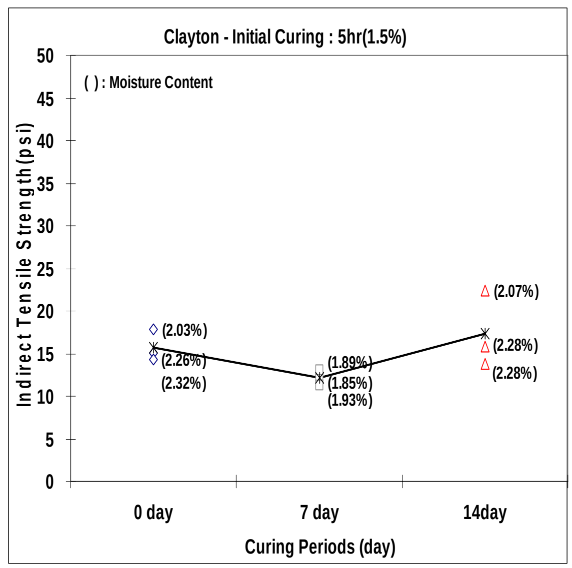
(a) Initial air curing: 0 hr



(b) Initial air curing: 1 hr



(c) Initial air curing: 3 hrs

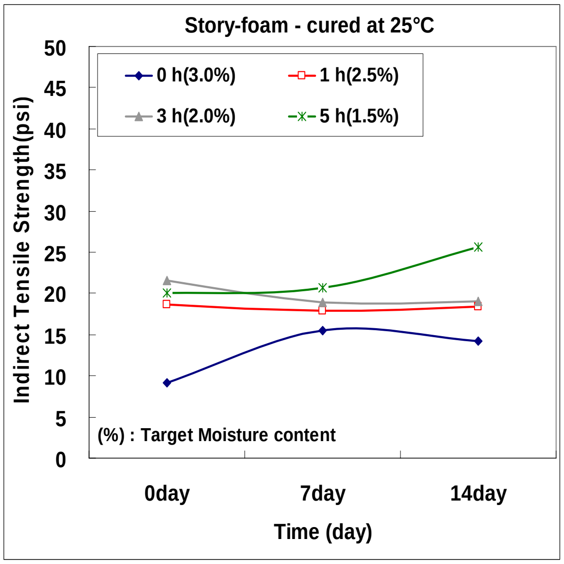


(d) Initial air curing: 5 hrs

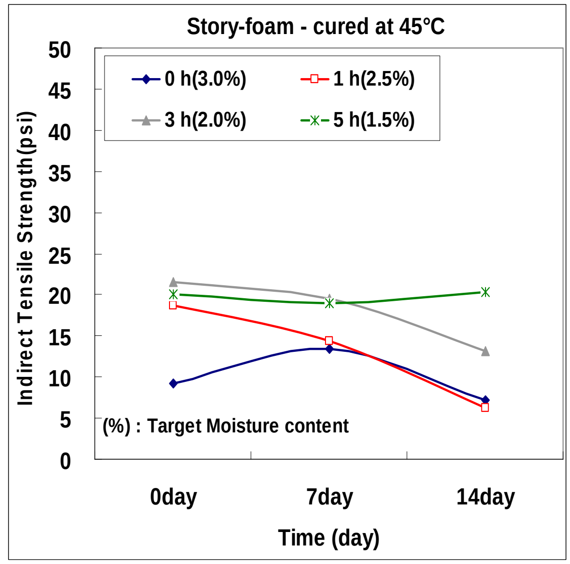
Figure 6-12. Relationships between ITS and curing period for CIR-emulsion specimens cured at 45°C using RAP materials from Clayton County

The average indirect tensile strength value of three specimens prepared for each of four initial curing conditions are plotted against curing periods for two RAP sources in Figure 6-13 and Figure 6-14, respectively. As discussed earlier, indirect tensile strength stayed constant or decreased as the curing time increased up to 14 days. However, the indirect tensile strength of CIR-foam and CIR-emulsion specimens increased as the initial curing time in the air increased.

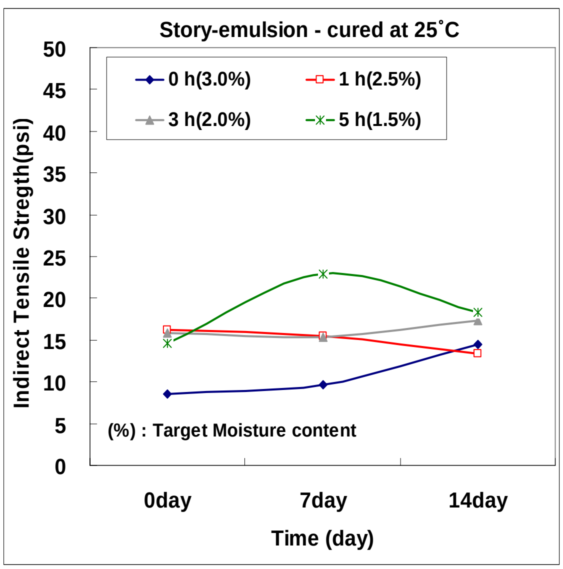
Figure 6-15 and Figure 6-16 show plots of indirect tensile strengths of CIR-foam and CIR-emulsion specimens against moisture contents for twelve combinations of initial and oven curing conditions for RAP materials from Story County and Clayton County, respectively. Overall, the indirect tensile strengths increases as the moisture contents decrease except the CIR-emulsion cured in the oven at 45˚C with RAP materials from Clayton County. For the given moisture content, covered CIR-foam specimens exhibited the slightly higher indirect tensile strength than covered CIR-emulsion specimens.



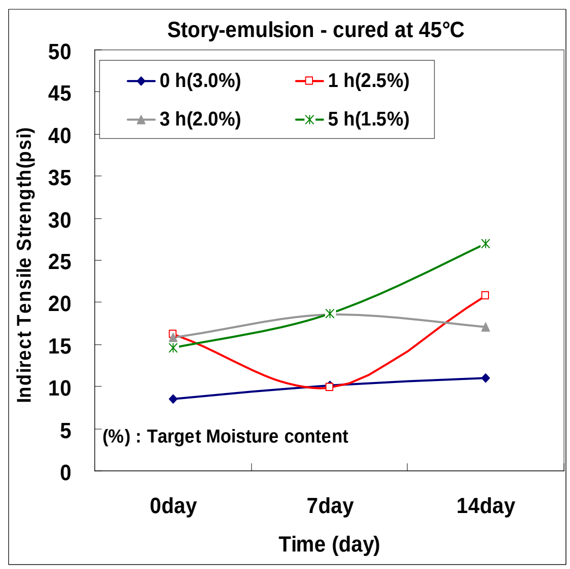
(a) CIR-foam cured at 25˚C



(b) CIR-foam cured at 45˚C

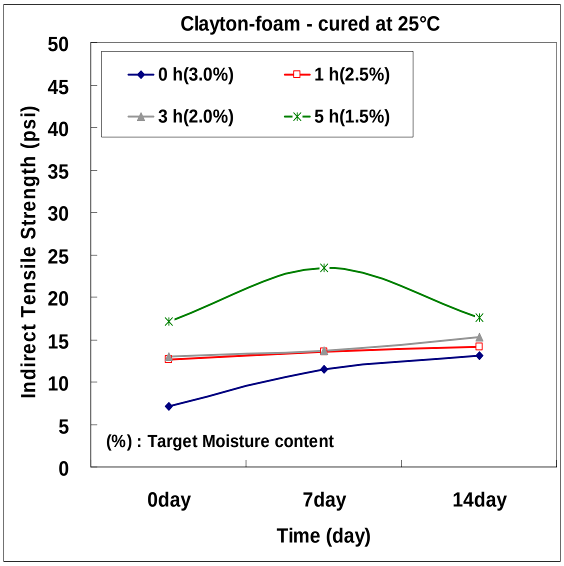


(c) CIR-emulsion cured at 25˚C

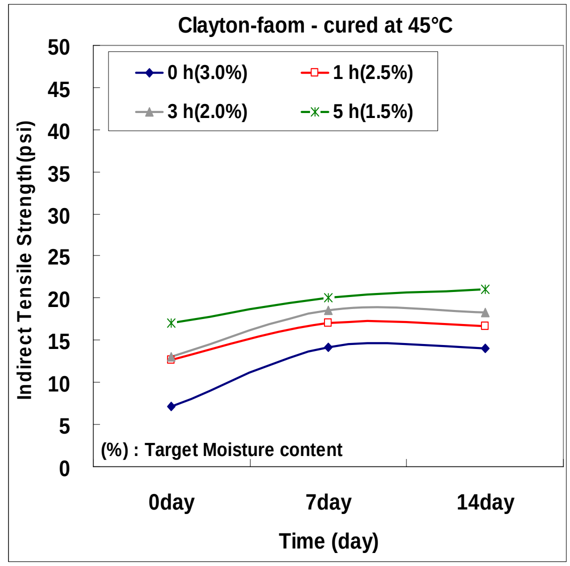


(d) CIR-emulsion cured at 45˚C

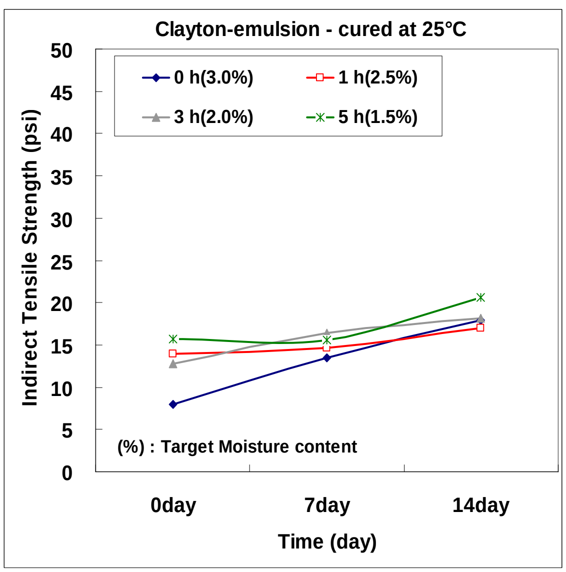
Figure 6-13. Plots of ITS against curing time for different initial curing conditions using RAP materials from Story County



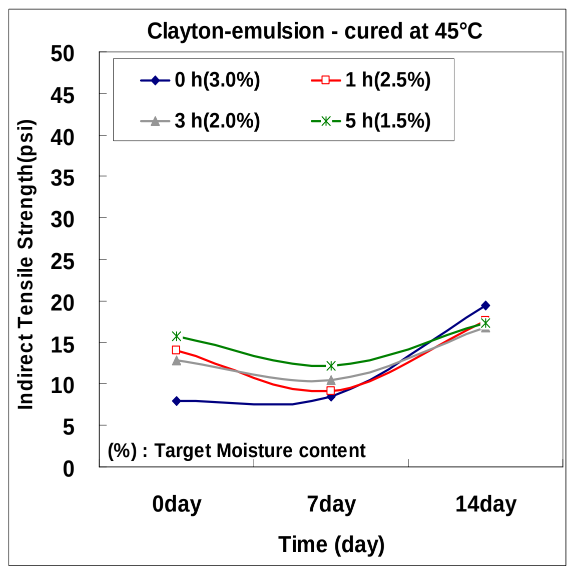
(a) CIR-foam cured at 25˚C



(b) CIR-foam cured at 45˚C

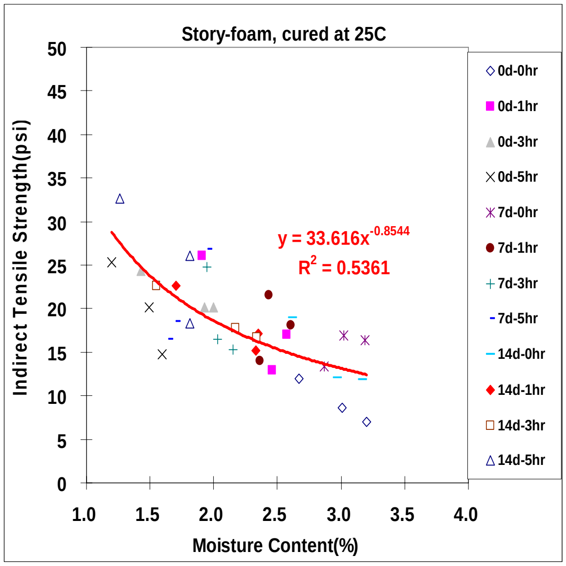


(c) CIR-emulsion cured at 25˚C

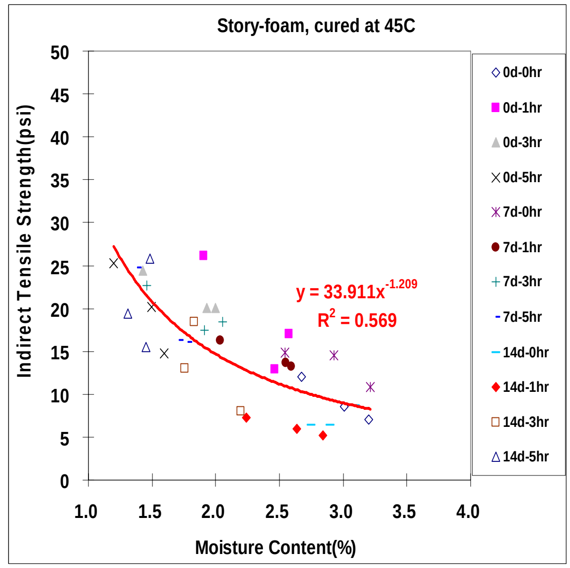


(d) CIR-emulsion cured at 45˚C

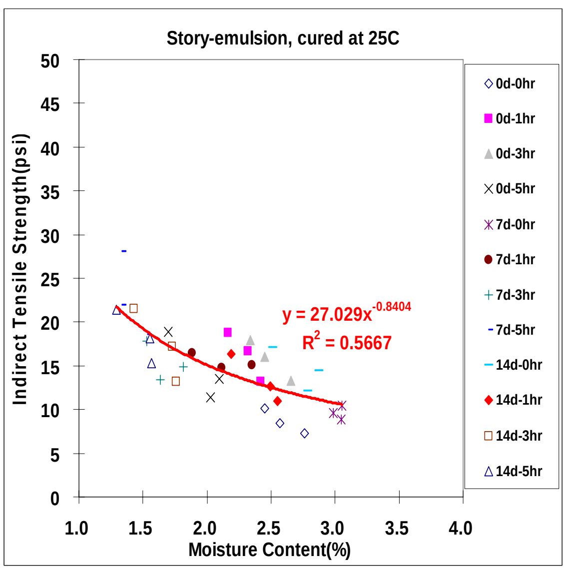
Figure 6-14. Plots of ITS against curing time for different initial curing conditions using RAP materials from Clayton County



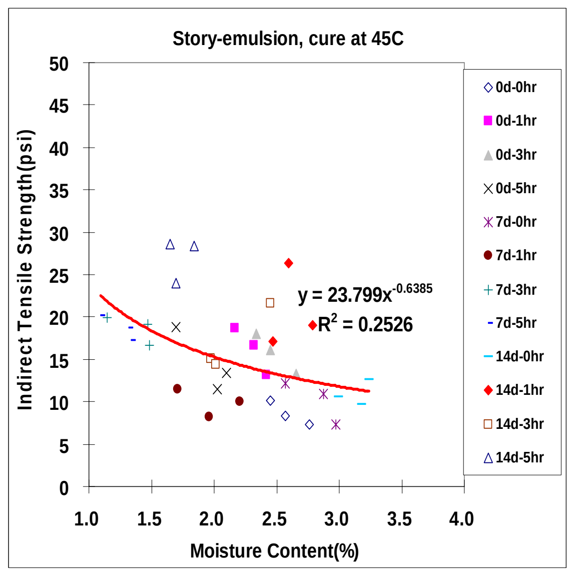
(a) CIR-foam cured at 25˚C



(b) CIR-foam cured at 45˚C

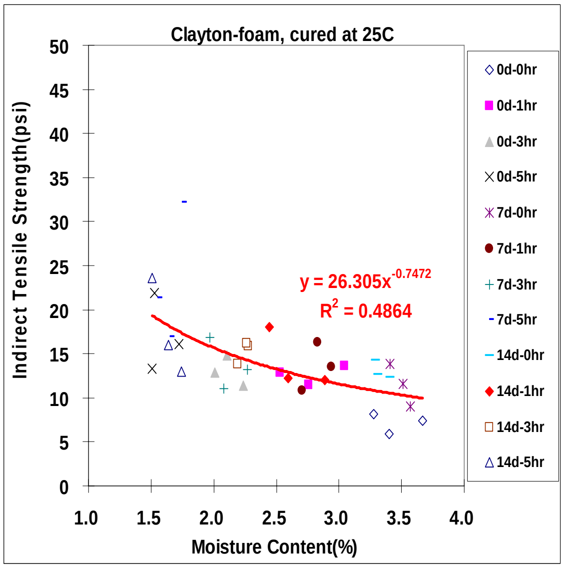


(c) CIR-emulsion cured at 25˚C

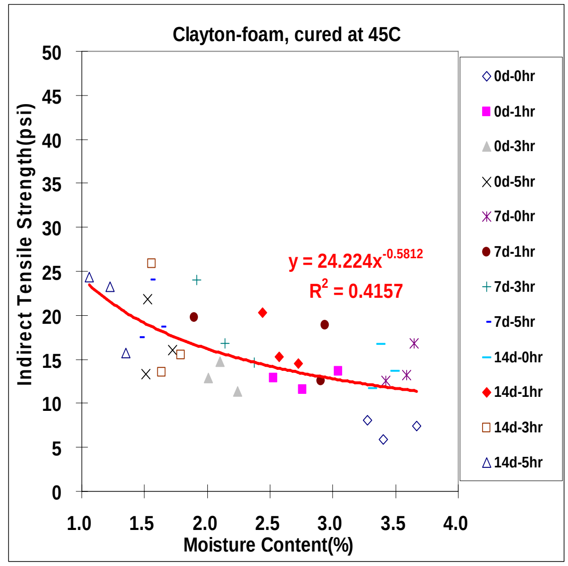


(d) CIR-emulsion cured at 45˚C

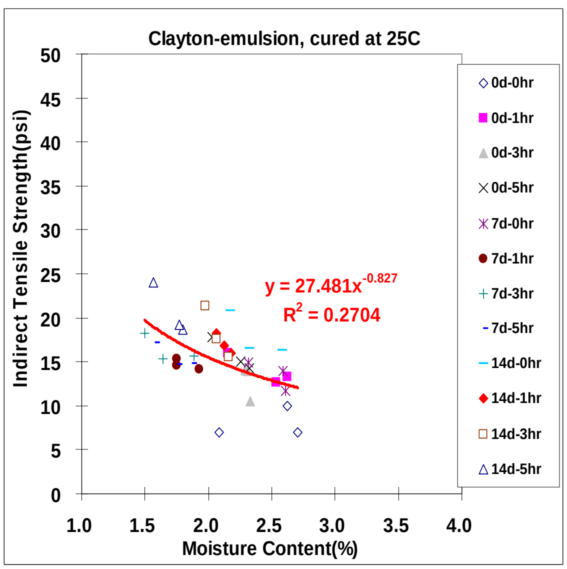
Figure 6-15. Plots of ITS against moisture content for CIR-foam and CIR-emulsion specimens cured at 25°C and 45°C using RAP materials from Story County



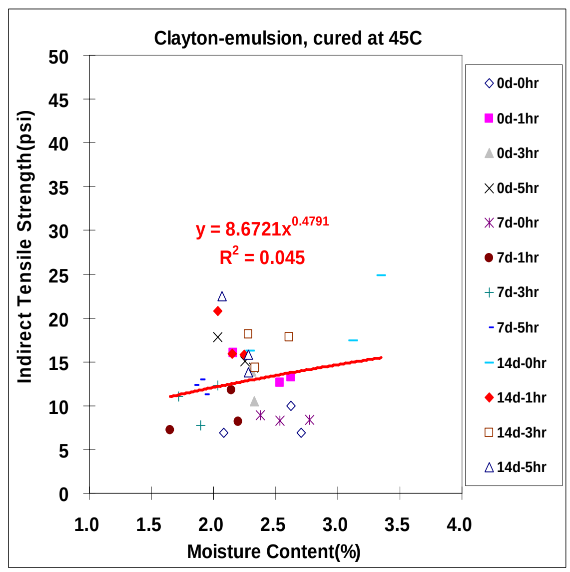
(a) CIR-foam cured at 25˚C



(b) CIR-foam cured at 45˚C



(c) CIR-emulsion cured at 25˚C



(d) CIR-emulsion cured at 45˚C

Figure 6-16. Plots of ITS against moisture content for CIR-foam and CIR-emulsion specimens cured at 25˚C and 45˚C using RAP materials from Clayton County

Table 6-10 and Table 6-11 summarize the ratio of the indirect tensile strength gain over the moisture reduction (ΔITS/ΔMC) of each batch of the three covered CIR-foam and CIR-emulsion specimens with RAP materials from Story County and Clayton County, respectively. As shown in Figure 6-17, for RAP materials from Story County, there is a consistent trend of increase in indirect tensile strength as the reduction in moisture content by taking two representative data points to define a linear slope among three identical samples within a batch. However, as shown in Figure 6-18, for RAP materials from Clayton County, there is no consistent trend of increase in indirect tensile strength as the reduction in moisture content. It can be postulated that this inconsistency might have been caused by the fact that RAP materials from Clayton County were collected from the stockpile instead of the job site.

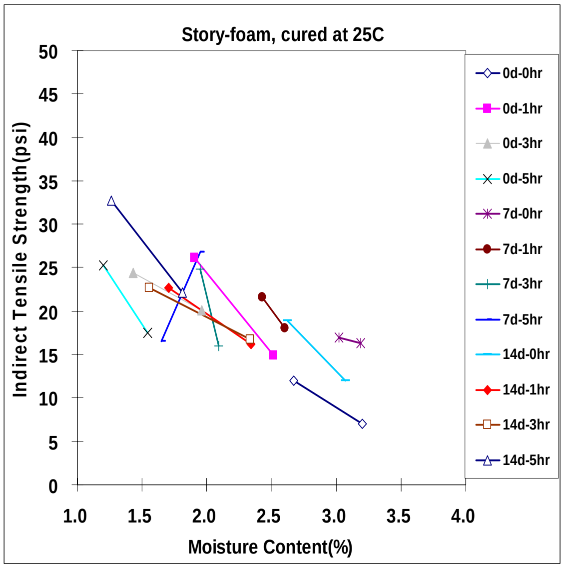
The average indirect tensile strengths for each of seven ranges of moisture contents are summarized in Table 6-12 and plotted in Figure 6-19. It can be observed that there is a gradual increase in the indirect tensile strength as the moisture content decreases 3.5% to 1.0%. It is interesting to note that the specimens with RAP materials from Clayton County exhibited the overall higher moisture content than ones from Story County. It can be postulated that the specimens with high moisture contents might have contributed to the overall weak indirect tensile strength of specimens prepared with RAP materials from Clayton County.

Table 6-10. Slope of ΔITS/ΔMC of CIR-foam and CIR-emulsion specimens for given curing period using RAP materials from Story County

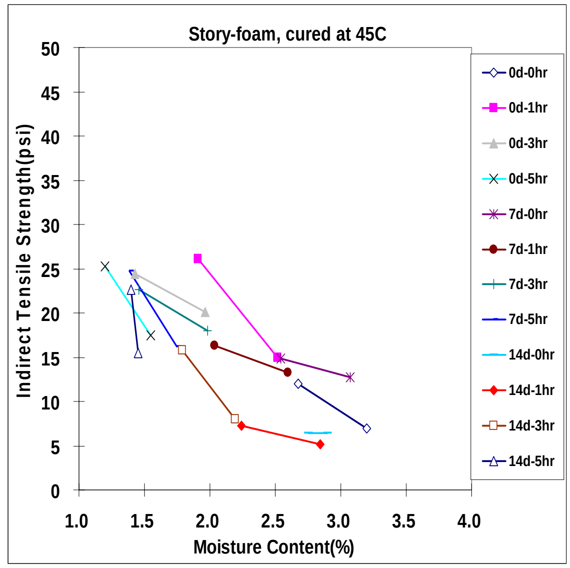
Types of Mixture	Air Curing Time / Oven Curing Time	0 h	1 h	3 h	5 h	AVG
Story-foam, Cured at 25°C	0 day	9.5	18.2	8.1	22.6	14.6
	7 days	3.4	20.1	62.8	-33.8	13.1
	14 days	15.4	10.1	7.5	19.1	13.1
	AVG	9.4	16.2	26.2	2.6	-
Story-foam, Cured at 45°C	0 day	9.5	18.2	8.1	22.6	14.6
	7 days	4.1	5.4	9.0	23.8	10.6
	14 days	-0.3	3.5	19.3	123.8	36.6
	AVG	4.4	9.0	12.1	56.8	-
Story-emulsion, Cured at 25°C	0 day	7.9	25.8	14.3	17.4	16.4
	7 days	-297.9	3.0	3.2	46.6	-61.2
	14 days	8.4	13.6	25.1	17.7	16.2
	AVG	-93.8	14.2	14.2	27.2	-
Story-emulsion, Cured at 45°C	0 day	7.9	25.8	14.3	17.4	16.4
	7 days	16.8	6.2	6.0	9.3	9.6
	14 days	-2.4	241.7	-15.0	-94.0	32.6
	AVG	7.4	91.2	1.8	-22.4	-

Table 6-11. Slope of ΔITS/ΔMC of CIR-foam and CIR-emulsion specimens for given curing period using RAP materials from Clayton County

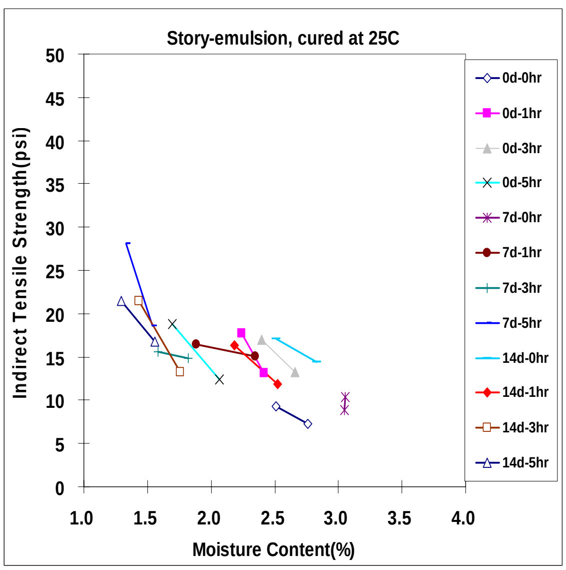
Types of Mixture	Air Curing Time / Oven Curing Time	0 h	1 h	3 h	5 h	AVG
Clayton-foam, Cured at 25°C	0 day	5.6	0.9	13.7	79.2	24.8
	7 days	26.2	-23.0	22.7	-86.5	-15.2
	14 days	22.2	19.6	-25.1	50.7	16.9
	AVG	18.0	-0.8	3.8	14.5	-
Clayton - foam, Cured at 45°C	0 day	5.6	0.9	13.7	79.2	24.8
	7 days	-27.4	4.0	24.4	2251.9	563.2
	14 days	185.8	25.3	73.5	38.3	80.7
	AVG	54.7	10.1	37.2	789.8	-
Clayton - emulsion, Cured at 25°C	0 day	-2.7	7.1	108.8	12.4	31.4
	7 days	3.6	4.9	10.2	7.8	6.6
	14 days	16.1	20.1	41.4	23.0	25.2
	AVG	5.7	10.7	53.5	14.4	-
Clayton - emulsion, Cured at 45°C	0 day	-2.7	7.1	108.8	12.4	31.4
	7 days	2.1	-5.3	4.1	2.9	0.9
	14 days	-5.1	41.6	-34.5	36.5	9.6
	AVG	-1.9	14.5	26.1	17.2	-



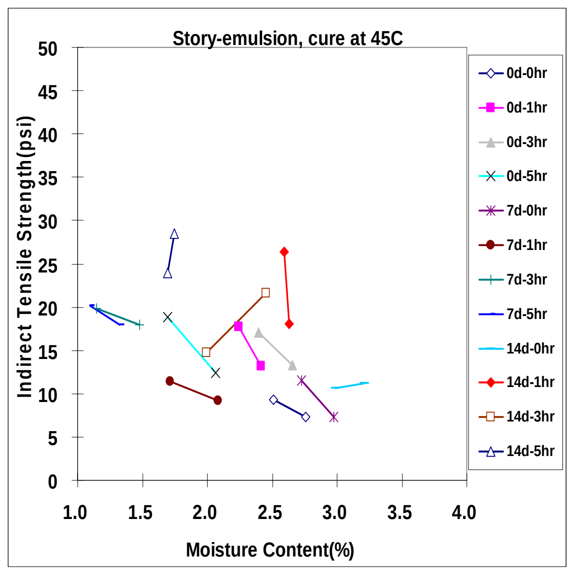
(a) CIR-foam cured at 25˚C



(b) CIR-foam cured at 45˚C

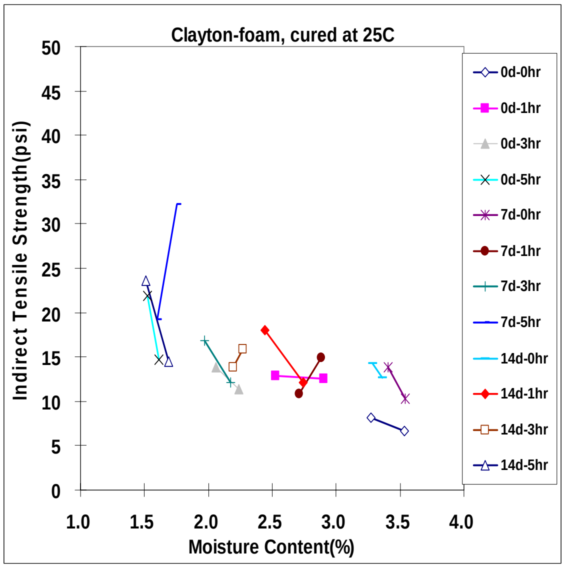


(c) CIR-emulsion cured at 25˚C

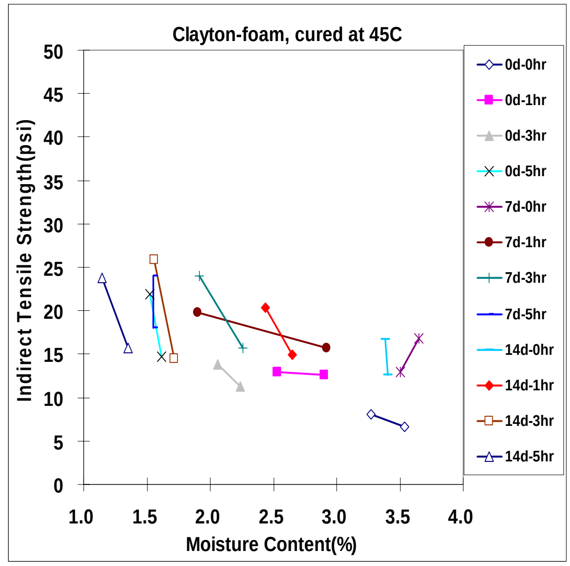


(d) CIR-emulsion cured at 45˚C

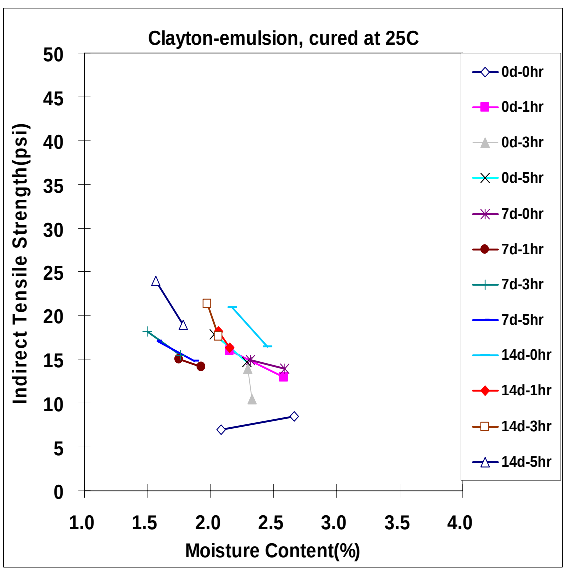
Figure 6-17. Linear slopes of ITS over moisture content for each batch of covered CIR-foam and CIR-emulsion specimens using RAP materials from Story County



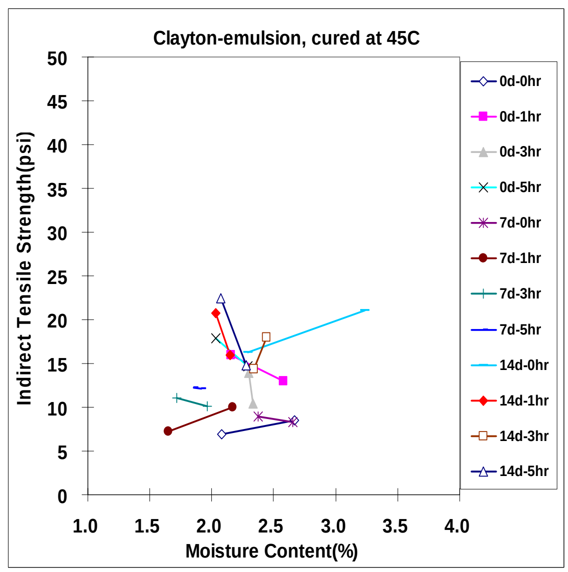
(a) CIR-foam cured at 25˚C



(b) CIR-foam cured at 45˚C



(c) CIR-emulsion cured at 25˚C

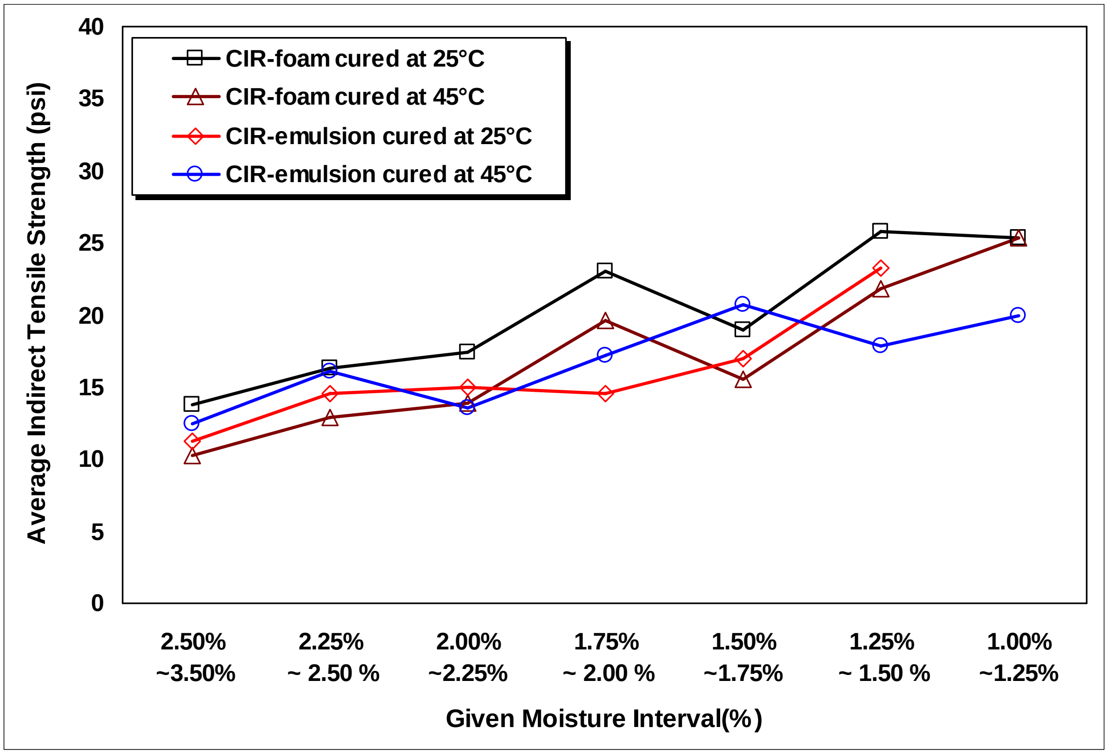


(d) CIR-emulsion cured at 45˚C

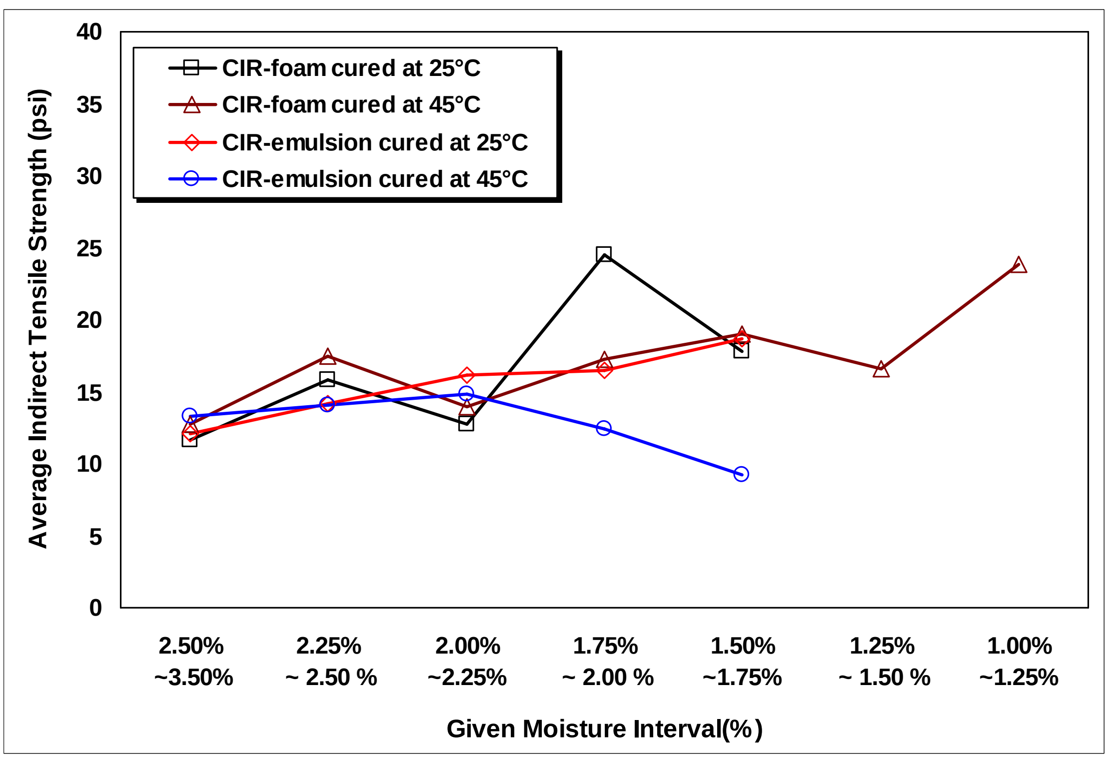
Figure 6-18. Linear slopes of ITS over moisture content for each batch of CIR-foam and CIR-emulsion specimens using RAP materials from Clayton County

Table 6-12. Summary of average ITS values at each range of moisture contents

Given Moisture Interval	2.50% ~ 3.50 %	2.25% ~ 2.50 %	2.00% ~ 2.25%	1.75% ~ 2.00 %	1.50% ~ 1.75 %	1.25% ~ 1.50 %	1.00% ~ 1.25%
CIR-foam Cured at 25°C (Story County)	13.8	16.3	17.4	23.0	19.0	25.8	25.3
CIR-foam Cured at 45°C (Story County)	10.3	12.9	13.9	19.6	15.5	21.8	25.3
CIR-emulsion Cured at 25°C (Story County)	11.2	14.5	15.0	14.5	17.0	23.2	-
CIR-emulsion Cured at 45°C (Story County)	12.5	16.1	13.6	17.2	20.7	17.9	20.0
CIR-foam Cured at 25°C (Clayton County)	11.7	15.8	12.8	24.5	17.8	-	-
CIR-foam Cured at45°C (Clayton County)	12.8	17.5	14.0	17.3	19.0	16.6	23.8
CIR-emulsion Cured at 25°C (Clayton County)	12.1	14.2	16.2	16.5	18.7	-	-
CIR-emulsion Cured at 45°C (Clayton County)	13.3	14.1	14.8	12.4	9.2	-	-



(a) Story County



(b) Clayton County

Figure 6-19. Average ITS values against ranges of moisture contents

7. EFFECT OF MOISTURE ON CURED SPECIMENS

The current practice in Iowa simply controls the maximum moisture content in the CIR below 1.5%. There is a critical issue that whether HMA overlay can be placed or not if it rained on the CIR layer after its moisture content had reached 1.5%. This chapter presents the effect of moisture on the cured CIR specimens.

In order to simulate a raining condition during the curing period of CIR pavement in the field, as shown in Figure 7-1, the CIR specimens were cured for 5 hour in the air to reach moisture content of 1.5%. The cured CIR specimens were then placed in the water bath at 25°C for 24 hours to represent rain on CIR layer in the field. Finally, the weight of CIR specimens at dry and saturated surface dry conditions were measured to compute the saturation level during the submerged procedure and indirect tensile strength test was conducted to evaluate the influence of the moisture soaking on indirect tensile strength in the laboratory.

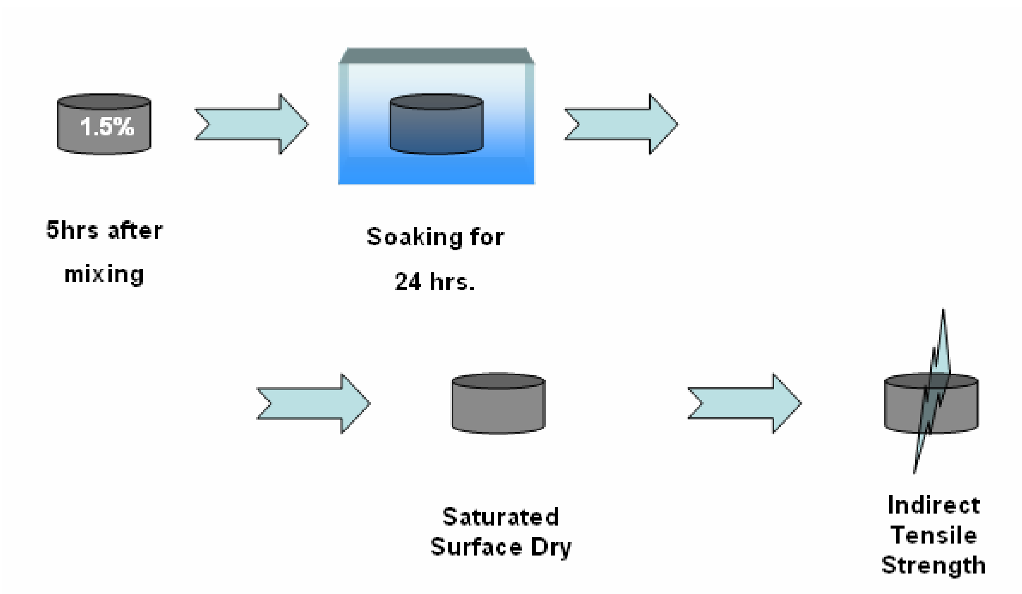


Figure 7-1. Testing process of submerged CIR specimens

Table 7-1 summarizes mix design parameters and number of specimens used for the submerged CIR specimens. As can be seen in Table 7-1, CIR-foam mixtures were produced at 2.0% FAC and 4.0% MC and the CIR-emulsion mixtures were produced at 3.0% EAC and 3.0% MC. All specimens were compacted using gyratory compactor at 25 gyrations using RAP materials from RAP materials from Story County and Clayton County.

Table 7-1. Design parameters selected for submerged CIR-foam specimens

CIR-foam Mixture		CIR-emulsion Mixture	
Asphalt Binder	PG 52-34	Emulsion Type	HFMS-2S
Foaming Temperature (ºC)	170ºC	-	-
Foaming Water Content (%)	1.3%	-	-
Foamed Asphalt Content (%)	2.0%	Emulsion Content (%)	3.0% (mix of asphalt and water in 2:1 ratio)
Moisture Contents of RAP (%)	4.0%	Moisture Contents of RAP (%)	3.0%
Compaction Method	Gyratory compactor at 25 gyrations	Compaction Method	Gyratory compactor at 25 gyrations
RAP Source	Story County Clayton County	RAP Source	Story County Clayton County
Curing Condition	In the air for 5 hrs	Curing Condition	In the air for 5 hrs
Submerged Condition	Under water for 24 hrs	Submerged Condition	Under water for 24 hrs
Testing Method	Indirect tensile strength test	Testing Method	Indirect tensile strength test
Number of Specimen	3 specimens	Number of Specimen	3 specimens

7.1 Test Results of Submerged CIR Specimens

Table 7-2 summarizes moisture contents and indirect tensile strengths of CIR-foam and CIR-emulsion specimens cured in the air for 5 hours before and after submerged under water for 24 hours.

Table 7-2. Summary of moisture content and bulk specific gravities of submerged CIR specimens and Un-submerged CIR specimens

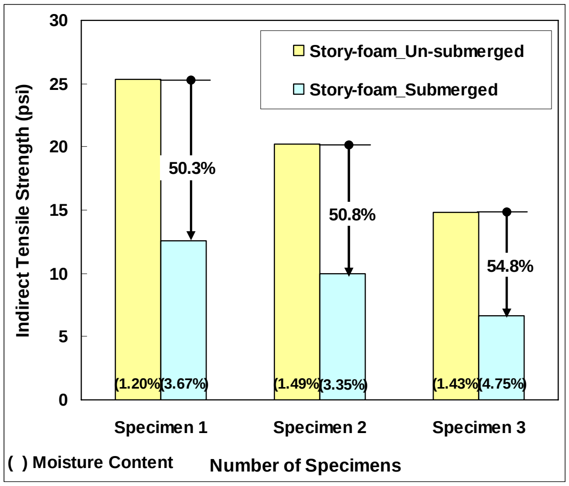
Submerged CIR Specimens

Type of mixture	Initial Moisture (%)	Moisture Content (%)		Gmb		ITS (psi)	
		Cured in air for 5 hours	Submerged for 24 hours	Cured in air for 5 hours	Submerged for 24 hours		
Story-foam	3.24	2.39	3.67	2.179	2.206	12.6	9.7
	3.27	1.74	3.35	2.157	2.191	9.9	
	3.59	2.08	4.75	2.069	2.123	6.7	
Story-emulsion	2.67	1.18	3.11	2.163	2.205	11.0	8.9
	3.19	1.66	3.45	2.142	2.180	9.1	
	3.05	1.56	3.92	2.114	2.163	6.4	
Clayton-foam	2.65	1.17	3.16	2.190	2.233	14.3	10.1
	3.67	2.30	4.03	2.173	2.210	6.0	
	N/A						
Clayton-emulsion	3.13	2.45	2.98	2.251	2.262	16.9	15.0
	3.19	1.66	3.45	2.218	2.257	14.2	
	3.05	1.56	3.92	2.211	2.262	13.9	

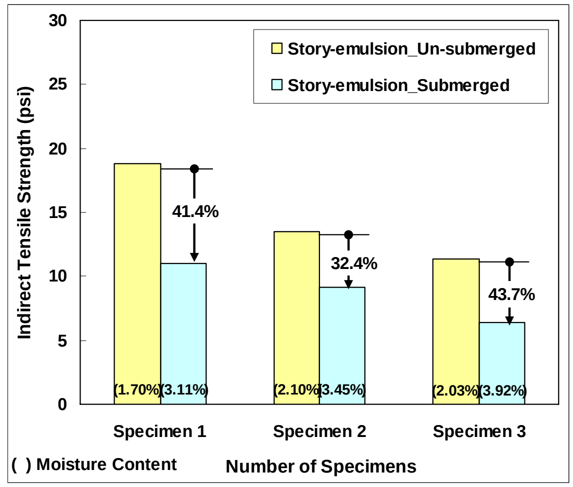
Un-submerged CIR Specimens (Data from Chapter 6)

Type of mixture	Initial Moisture (%)	Moisture Content (%)		Gmb		ITS (psi)	
		individual	Average	Individual	Average		
Story-foam	2.77	1.20	1.43	2.222	2.204	25.3	20.1
	2.86	1.49		2.180		20.2	
	2.85	1.60		2.209		14.8	
Story-emulsion	2.95	1.70	1.94	2.153	2.130	18.8	14.6
	3.16	2.10		2.117		13.5	
	3.30	2.03		2.121		11.4	
Clayton-foam	3.52	1.52	1.59	2.152	2.134	21.9	17.1
	3.57	1.72		2.136		16.1	
	3.54	1.51		2.114		13.3	
Clayton-emulsion	2.61	2.03	2.20	2.235	2.218	17.9	15.7
	2.96	2.26		2.205		15.0	
	3.01	2.32		2.214		14.3	

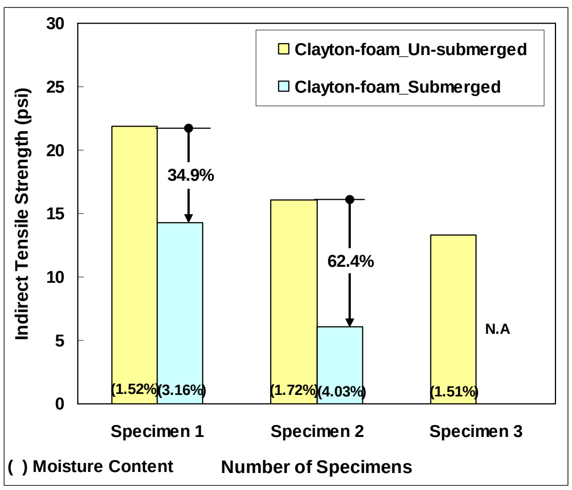
Figure 7-2 shows plots of indirect tensile strengths of un-submerged and submerged CIR specimens. When the specimens were submerged under water for 24 hours, the indirect tensile strength decreased by 32.4% to 62.4%, except CIR-emulsion specimens with RAP materials from Clayton County. Based on the limited test result, it can be concluded that although CIR layer once reached 1.5% moisture content requirement, it is cautioned for an overlay if it rained on.



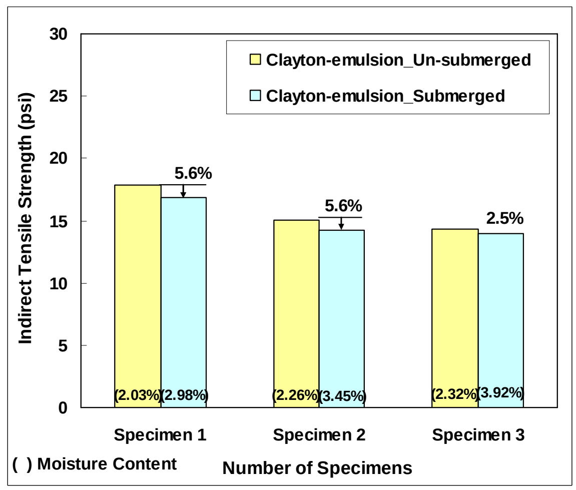
(a) CIR-foam (Story County)



(b) CIR-emulsion (Story County)



(c) CIR-foam (Clayton County)



(d) CIR-emulsion (Clayton County)

Figure 7-2. Comparison of ITS between un-submerged and submerged CIR specimens

8. IMAPCTS OF CURING PROCEDURES ON FLOW NUMBER AND DYNAMIC MODULUS OF CIR SPECIMENS

To predict the field performance of CIR pavements during the curing process, the dynamic creep and dynamic modulus tests were conducted using Superpave simple performance equipment as shown in Figure 8-1. The CIR-foam and CIR-emulsion specimens for the dynamic creep test were prepared under three different curing conditions. The CIR-foam and CIR-emulsion specimens for the dynamic modulus tests were prepared at six different curing time periods and tested to examine effects on the dynamic modulus when curing time increases and the moisture content decreases.

Figure 8-1. Simple performance testing equipment at the University of Iowa

8.1 Dynamic Creep Test

As shown in Figure 8-2, CIR specimens for dynamic creep test were compacted using the gyratory compactor at 25 gyrations and cured initially for 10 hours at room temperature. After 10-hour air curing, covered CIR specimens were cured in the oven at 45°C for 7-day and 14-day. Table 8-1 summarizes the mix design parameters for specimens for dynamic creep test.

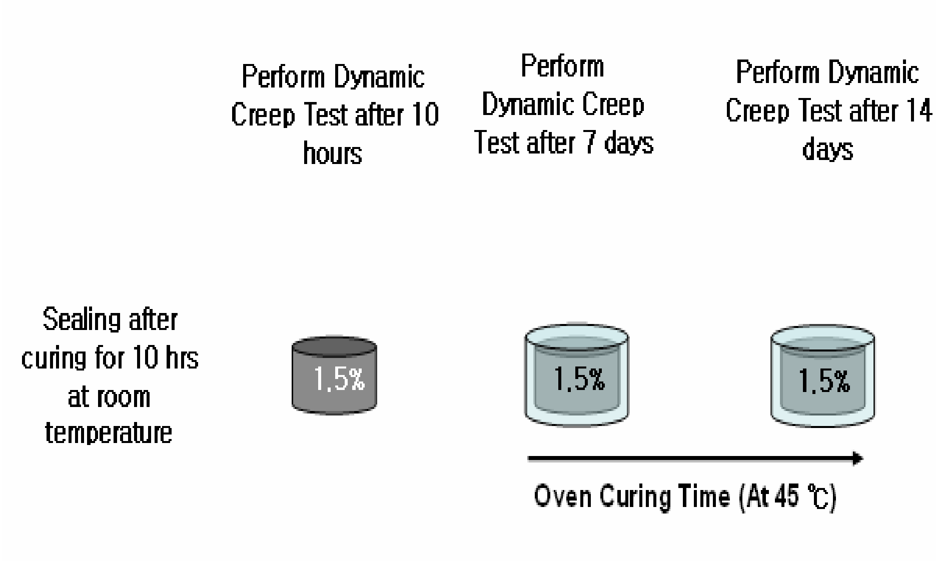


Figure 8-2. Test plan of curing process for dynamic creep test

Table 8-1. Design and testing parameters selected for dynamic creep test

CIR-foam Mixture		CIR-emulsion Mixture	
Asphalt Binder	PG 52-34	Emulsion Type	HFMS-2S
Foaming Temperature (ºC)	170ºC	-	-
Foaming Water Content (%)	1.3%	-	-
Foamed Asphalt Content (%)	2.0%	Emulsion Content (%)	3.0% (mix of asphalt and water in 2:1 ratio)
Moisture Contents of RAP (%)	4.0%	Moisture Contents of RAP (%)	3.0%
Compaction Method	Gyratory compactor at 25 gyrations	Compaction Method	Gyratory compactor at 25 gyrations
RAP Source	Story County Clayton County	RAP Source	Story County Clayton County
Curing Condition	In the air for 10 hrs	Curing Condition	In the air for 10 hrs
Oven Curing Condition	0-day 7-day, 14-day	Oven Curing Condition	0-day, 7-day, 14-day
Testing Method	Dynamic Creep	Testing Method	Dynamic Creep
Number of Specimen	2 specimens	Number of Specimen	2 specimens

8.1.1 Dynamic Creep Testing Procedure

Generally, the dynamic creep test was developed to identify the permanent deformation characteristics of asphalt mixtures, by applying several thousand repetitions of a repeated load and recording the cumulative deformation as a function of the number of load cycles. The load is applied for 0.1 second with a rest period of 0.9 second in one cycle and repeated up to 10,000 loading cycles. As shown in Figure 8-3, results from the dynamic creep test are normally presented in terms of the cumulative permanent strain (ε_p) versus the number of loading cycles. The cumulative permanent deformation strain curve is generally defined by three stages: 1) primary stage, 2) secondary stage and 3) tertiary stage (EI-Basyoung et al. 2005):

1. Primary stage: high initial level of rutting, with a decreasing rate of plastic deformations, predominantly; associated with volumetric change.
2. Secondary stage: small rate of rutting exhibiting a constant rate of change of rutting that is also associated with volumetric changes; however, shear deformations start to increase at increasing rate.
3. Tertiary stage: high rate (level) of rutting predominantly associated with plastic (shear) deformations under no volume change conditions.

The permanent deformation increase rapidly in the primary stage and the incremental deformation decreases in the secondary stage. In the tertiary stage, the permanent deformations increase rapidly. The flow number (FN) is defined as number of loading cycles at the beginning of tertiary stage.

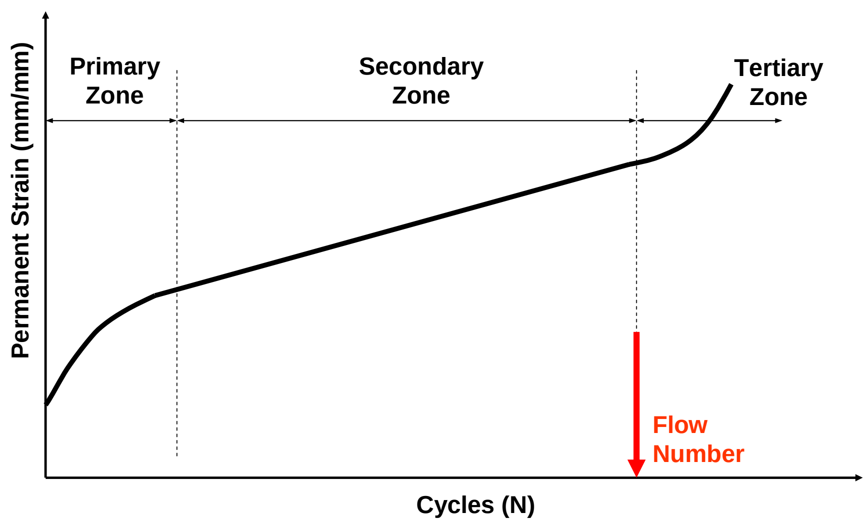


Figure 8-3. Permanent deformation behavior against loading cycles

Two loading stress level of 10 psi and 20 psi were selected to attain tertiary flow in a reasonable number of cycles not exceeding 10,000. Testing temperature of 45˚C was selected as a typical temperature of CIR layer.

8.1.2 Results and Discussion

Table 8-2 and Table 8-3 summarize the volumetric characteristics and moisture contents of CIR-foam and CIR-emulsion specimens for two different testing strain levels, which are 10 psi and 20 psi, respectively. As shown in Table 8-2 and Table 8-3, the air voids of CIR specimens with RAP materials from Story County were higher than those of CIR specimens with RAP materials from Clayton County. The moisture content of CIR-foam specimens was lower than those of CIR-emulsion for both RAP materials.

Table 8-2. Bulk specific gravities (G_{mb}), moisture content, and air voids of CIR specimens for dynamic creep test at 20 psi

RAP Source	Curing Period	G_{mb}				Moisture Content (%)		Air Void (%)	
		Individual		Ave.	G_{mm}	Initial	Tested	Individual	Ave.
CIR-foam (Story County)	0 day	# 1	2.129	2.108	2.391	3.16	1.18	10.9	11.8
		# 2	2.087			3.33	1.23	12.7	
	7 days	# 1	2.092	2.087		3.25	1.13	12.5	12.5
		# 2	2.082			3.25	1.24	12.7	
	14 days	# 1	2.090	2.074		3.29	1.09	12.6	13.3
		# 2	2.058			3.39	1.14	13.9	
CIR-emulsion (Story County)	0 day	# 1	2.118	2.102	2.418	3.32	1.47	12.4	13.1
		# 2	2.086			3.28	1.44	13.7	
	7 days	# 1	2.112	2.105		2.95	1.33	12.7	12.9
		# 2	2.098			3.27	1.53	13.2	
	14 days	# 1	2.088	2.080		3.06	1.27	13.6	14.0
		# 2	2.071			3.34	1.35	14.3	
CIR-foam (Clayton County)	0 day	# 1	2.142	2.131	2.390	3.61	1.75	10.4	10.9
		# 2	2.119			3.82	1.83	11.3	
	7 days	# 1	2.164	2.148		3.11	1.32	9.4	10.1
		# 2	2.132			3.46	1.56	10.8	
	14 days	# 1	2.183	2.168		2.95	1.23	8.7	9.3
		# 2	2.154			3.35	1.48	9.9	
CIR-emulsion (Clayton County)	0 day	# 1	2.215	2.215	2.423	3.04	2.39	8.6	8.6
		# 2	N/A			N/A	N/A	N/A	
	7 days	# 1	2.219	2.211		2.49	1.71	8.4	8.7
		# 2	2.203			2.82	1.97	9.1	
	14 days	# 1	2.219	2.206		2.90	1.95	8.4	9.0
		# 2	2.192			3.19	2.25	9.5	

Table 8-3. Bulk specific gravities (G_{mb}), moisture content, and air voids of CIR specimens for dynamic creep test at 10 psi

RAP Source	Curing Period	G_{mb}				Moisture Content (%)		Air Void (%)	
		Individual		Ave.	G_{mm}	Initial	Tested	Individual	Ave.
CIR-foam (Story County)	0 day	# 1	2.068	2.042	2.391	3.65	1.21	13.5	14.6
		# 2	2.016			3.46	1.18	15.7	
	7 days	# 1	2.087	2.076		3.45	1.25	12.7	13.2
		# 2	2.065			3.48	1.35	13.6	
	14 days	# 1	2.100	2.081		3.48	1.33	12.2	1.30
		# 2	2.062			3.40	1.27	13.8	
CIR-emulsion (Story County)	0 day	# 1	2.056	2.058	2.418	3.34	1.51	15.0	14.9
		# 2	2.059			3.45	1.59	14.8	
	7 days	# 1	2.073	2.079		3.30	1.60	14.3	14.0
		# 2	2.085			3.59	1.95	13.8	
	14 days	# 1	2.041	2.043		3.32	1.35	15.6	15.5
		# 2	2.044			3.25	1.21	15.5	
CIR-foam (Clayton County)	0 day	# 1	2.130	2.119	2.390	4.11	2.03	10.9	11.3
		# 2	2.109			4.41	2.14	11.8	
	7 days	# 1	2.086	2.079		3.16	1.14	12.7	13.0
		# 2	2.073			3.28	1.31	13.3	
	14 days	# 1	2.078	2.070		3.23	1.17	13.1	13.4
		# 2	2.062			3.39	1.23	13.7	
CIR-emulsion (Clayton County)	0 day	# 1	2.185	2.185	2.423	4.15	3.23	9.8	9.2
		# 2	2.184			4.44	3.47	8.6	
	7 days	# 1	2.107	2.100		3.29	3.29	13.0	13.4
		# 2	2.092			1.63	1.77	13.7	
	14 days	# 1	2.187	2.187		3.42	2.54	9.7	9.7
		# 2	2.186			3.32	2.36	9.8	

The first round of dynamic creep tests was performed on CIR specimens under a loading stress level of 20 psi at 45˚C and Table 8-4 summarizes flow number and cumulative strain at three different curing conditions using two RAP sources and two types of binder. The second round of dynamic creep tests were performed on CIR specimens under a loading stress level of 10 psi at 45˚C and Table 8-5 summarize flow number and cumulative strain at three different curing conditions using two RAP sources and two types of binder.

Table 8-4. Flow number and strain at flow number at 20 psi

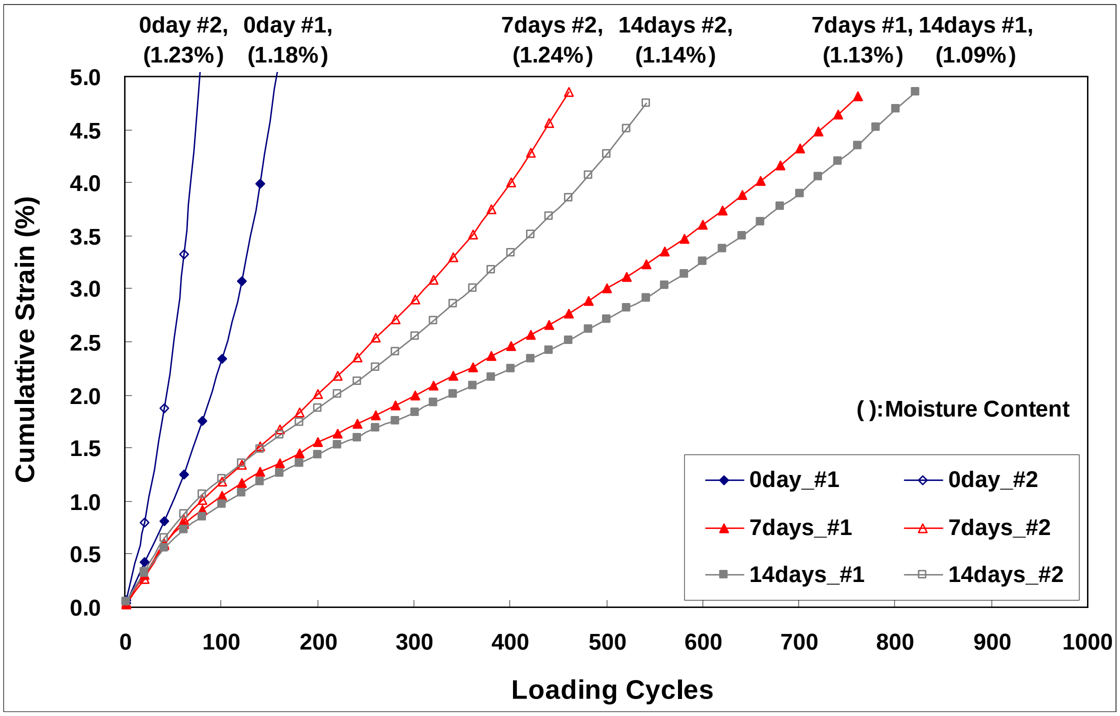
RAP Source	Curing Period	No. of Specimen	Flow Number		Stain at FN
			Individual	Average	
CIR-foam (Story County)	0 day	# 1	41	31	0.81%
		# 2	21		0.79%
	7 days	# 1	361	301	2.27%
		# 2	241		2.36%
	14 days	# 1	401	331	2.25%
		# 2	261		2.26%
CIR-emulsion (Story County)	0 day	# 1	261	151	3.23%
		# 2	41		1.39%
	7 days	# 1	161	131	2.25%
		# 2	101		2.93%
	14 days	# 1	121	131	1.95%
		# 2	141		2.19%
CIR-foam (Clayton County)	0 day	# 1	145	93	1.96%
		# 2	41		0.98%
	7 days	# 1	181	141	1.88%
		# 2	101		2.50%
	14 days	# 1	261	181	2.34%
		# 2	101		1.42%
CIR-emulsion (Clayton County)	0 day	# 1	21	21	0.93%
		# 2	N/A		N/A
	7 days	# 1	101	71	2.44%
		# 2	41		1.37%
	14 days	# 1	61	51	1.97%
		# 2	41		1.31%

Table 8-5. Flow number and strain at flow number at 10 psi

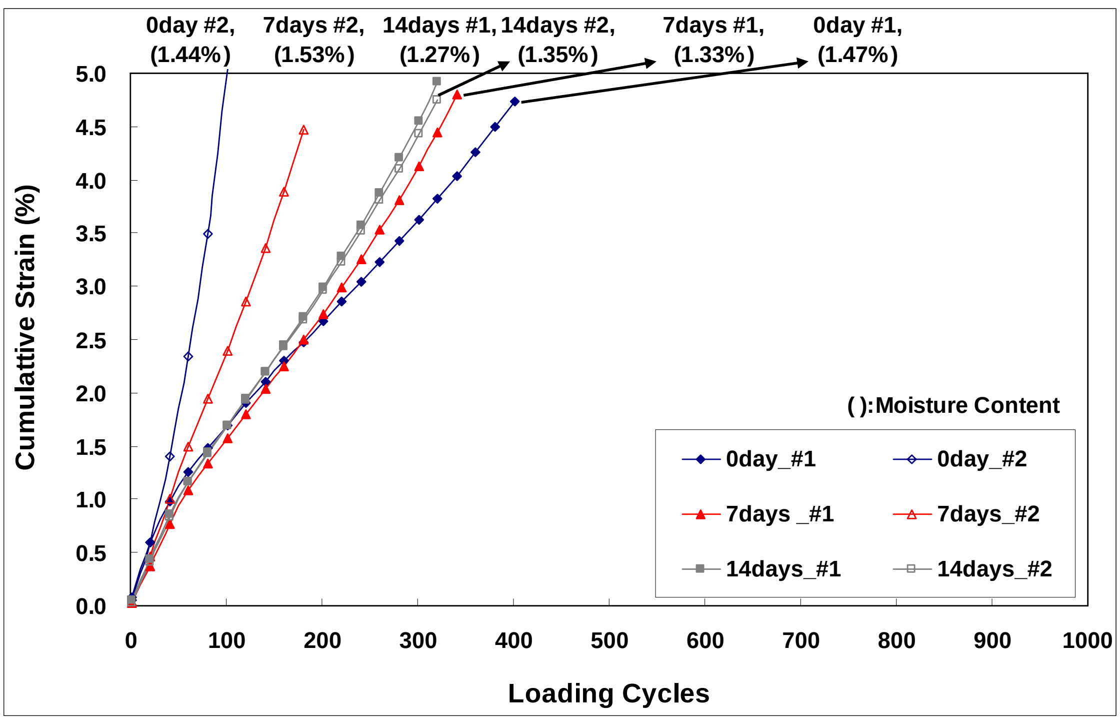
RAP Source	Curing Period	No. of Specimen	Flow Number Individual	Flow Number Average	Stain at FN
CIR-foam (Story County)	0 day	# 1	1041	761	1.61%
		# 2	481		1.60%
	7 days	# 1	1921	1501	2.14%
		# 2	1081		2.13%
	14 days	# 1	2061	1541	2.04%
		# 2	1021		2.17%
CIR-emulsion (Story County)	0 day	# 1	221	161	1.58%
		# 2	101		1.17%
	7 days	# 1	281	241	2.23%
		# 2	201		2.26%
	14 days	# 1	241	301	1.96%
		# 2	361		2.37%
CIR-foam (Clayton County)	0 day	# 1	401	341	1.75%
		# 2	281		2.01%
	7 days	# 1	661	531	2.29%
		# 2	401		1.17%
	14 days	# 1	701	671	2.00%
		# 2	641		2.20%
CIR-emulsion (Clayton County)	0 day	# 1	121	121	1.47%
		# 2	121		1.62%
	7 days	# 1	181	161	1.85%
		# 2	141		2.05%
	14 days	# 1	161	161	2.00%
		# 2	161		1.93%

Figure 8-4 and Figure 8-5 show plots of cumulative strain against the number of loading cycles measured at three different curing conditions under a loading stress level of 20 psi at 45˚C using RAP materials from Story and Clayton Counties, respectively. As shown in these figures, CIR-foam specimens exhibited a higher resistance to permanent deformation than CIR-emulsion specimens. It should be noted that all CIR specimens have failed before the loading cycle of 1,000 because the applied loading stress level was too high for the specimens. Due to the early failure, it is difficult to observe the impacts of different curing procedures on the flow number of all CIR specimens.

Figure 8-6 and Figure 8-7 show plots of cumulative strain against the number of loading cycles measured at three different curing conditions under a loading stress level of 10 psi at 45˚C using RAP materials from Story and Clayton Counties, respectively. As shown in these figures, CIR-foam specimens with RAP materials from Story County failed at the highest number of loading cycles whereas CIR-emulsion specimens with RAP materials from Clayton County failed at the lowest number of cycles. Due to the early failure, it is difficult to observe the impacts of different curing procedures on the flow number of CIR-emulsion specimens. Based on the limited test result, it can be concluded that the CIR-foam specimens with longer the curing time are more resistant to permanent deformation.

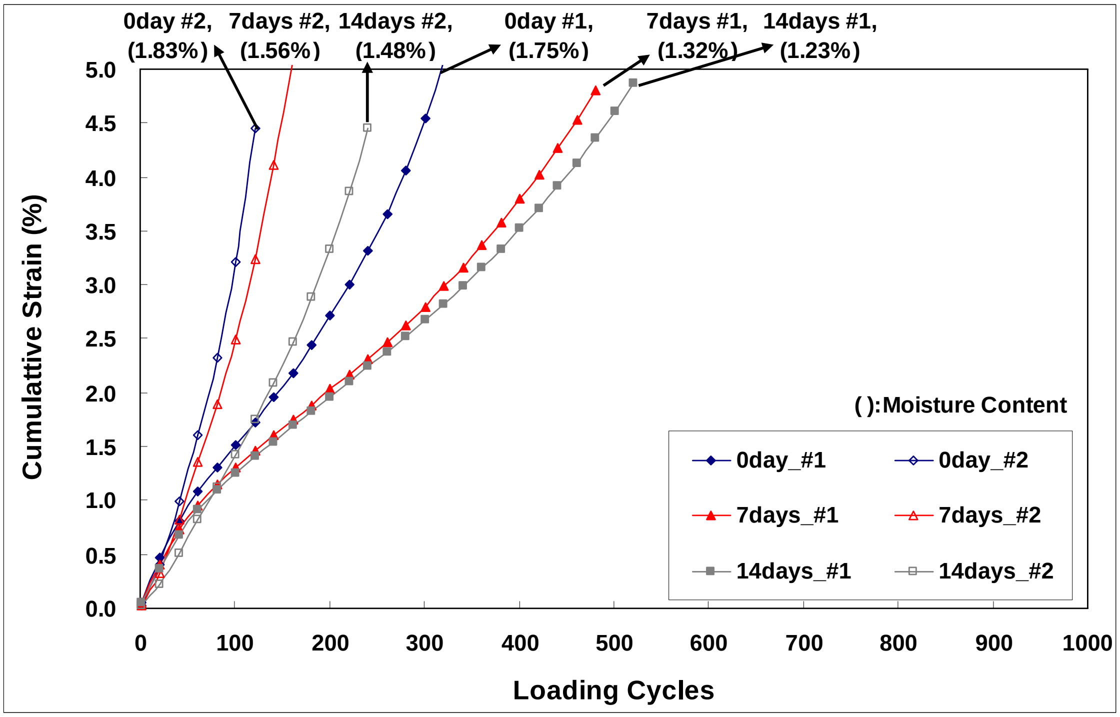


(a) CIR-foam (Story County)

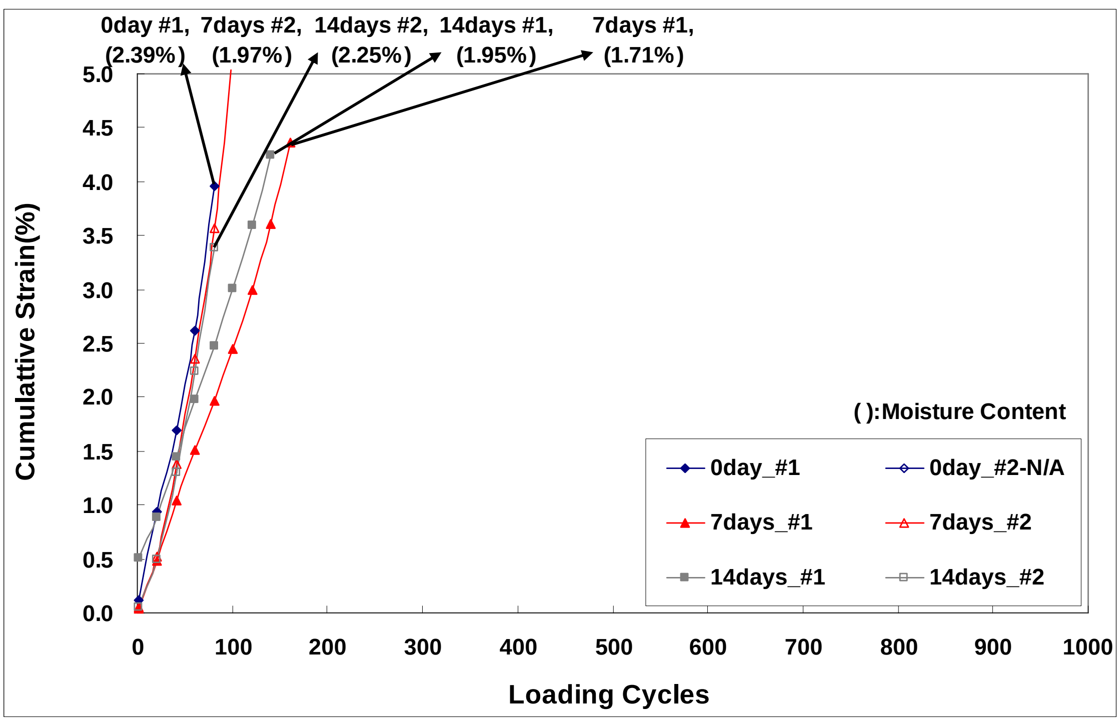


(b) CIR-emulsion (Story County)

Figure 8-4. Plots of permanent strain versus loading cycle at 20 psi using RAP materials from Story County

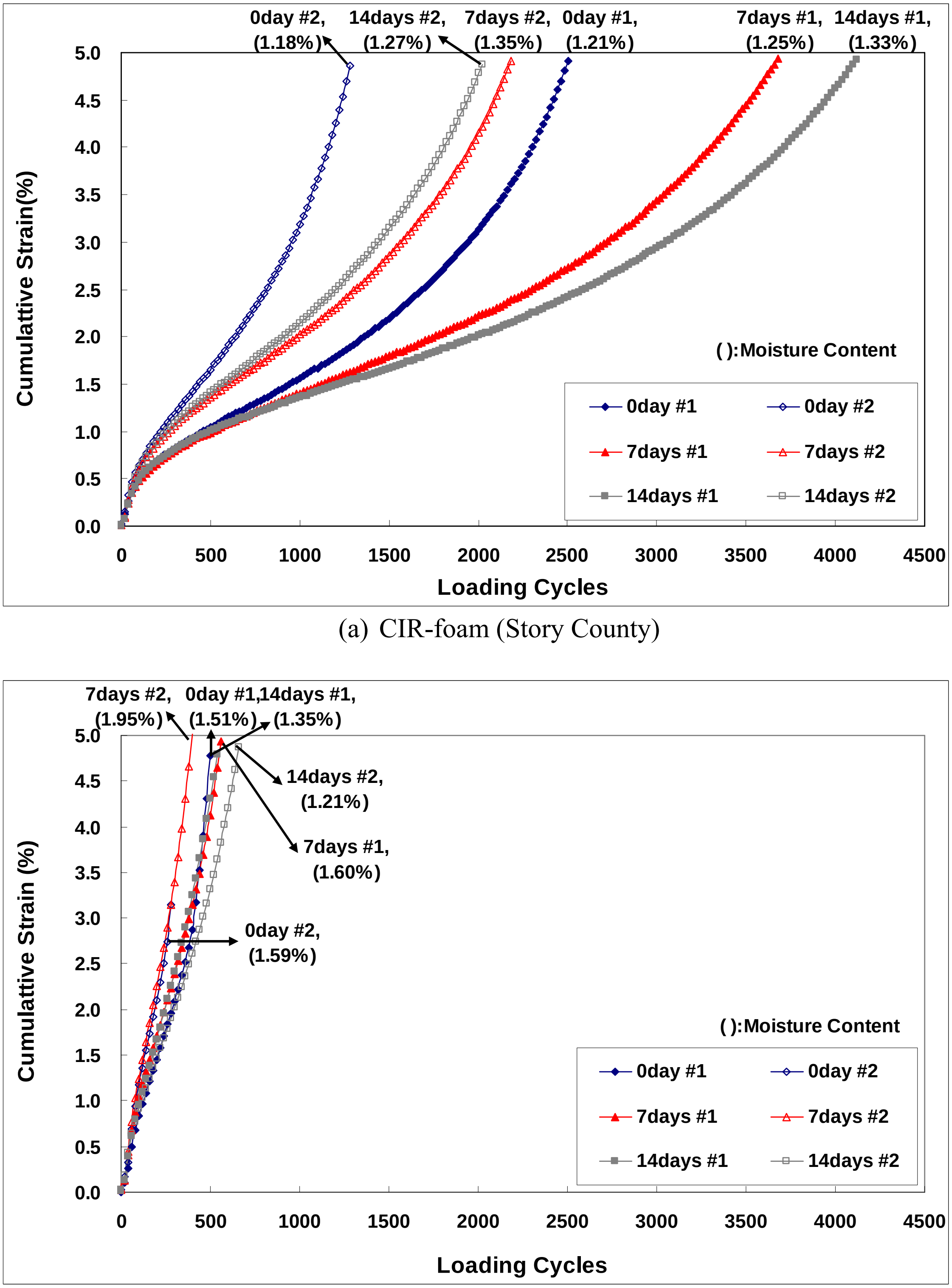


(a) CIR-foam (Clayton County)



(b) CIR-emulsion (Clayton County)

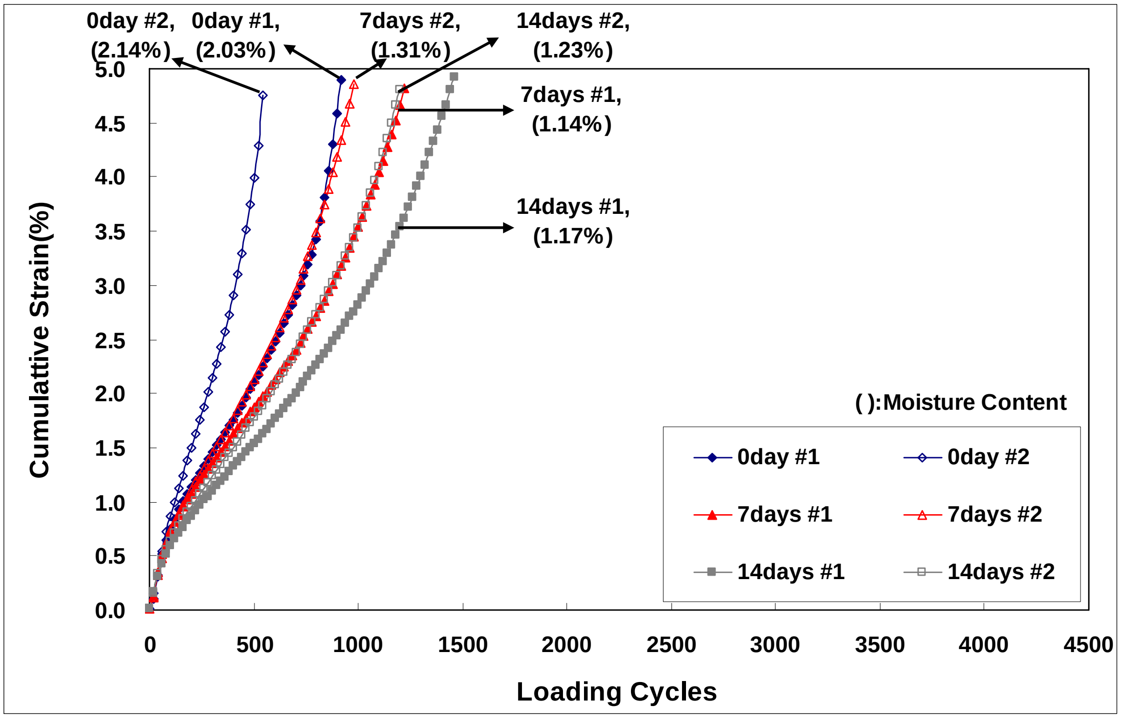
Figure 8-5. Plots of permanent strain versus loading cycle at 20 psi using RAP materials from Clayton County



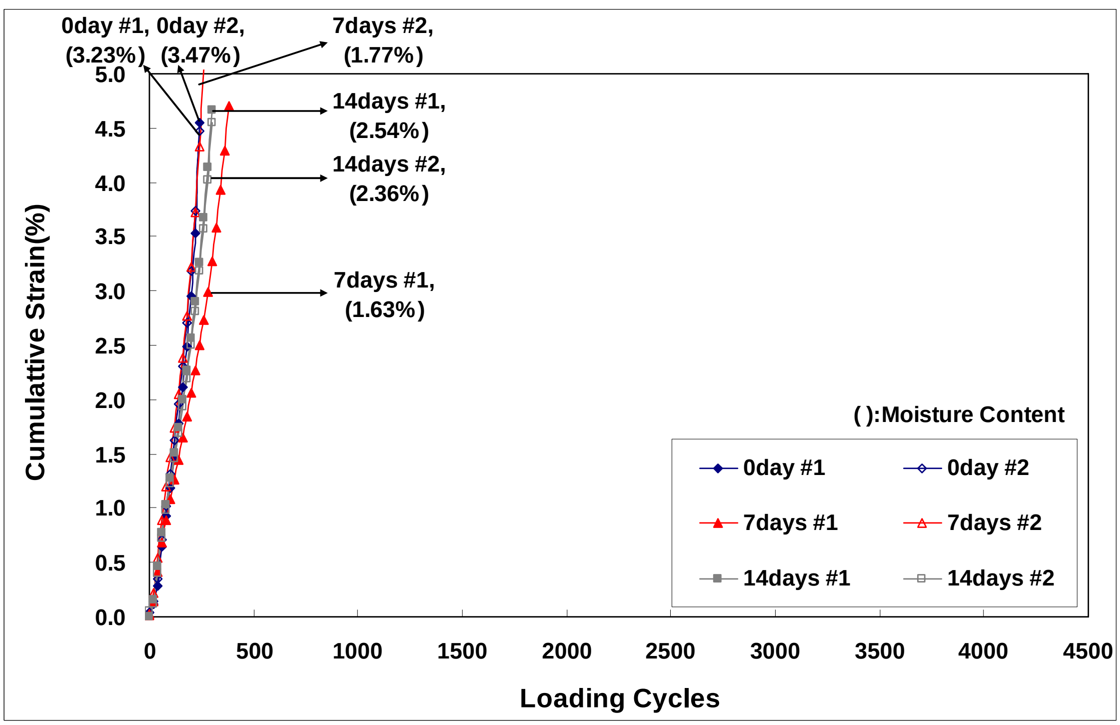
(a) CIR-foam (Story County)

(b) CIR-emulsion (Story County)

Figure 8-6. Plots of permanent strain versus loading cycle at 10 psi using RAP materials from Story County



(a) CIR-foam (Clayton County)



(b) CIR-emulsion (Clayton County)

Figure 8-7. Plots of permanent strain versus loading cycle at 10 psi using RAP materials from Clayton County

8.2 Dynamic Modulus Tests

Both CIR-foam and CIR-emulsion specimens for the dynamic modulus tests were prepared using the gyratory compactor at 25 gyrations and cured for 5, 10, 20, 30, 45, and 90 hours at a room temperature. The dynamic modulus was measured at each curing time to observe the change in the stiffness of CIR specimens as they are cured. Table 8-6 summaries the mix design and testing parameters, which were used to prepare specimens for the dynamic modulus test.

Table 8-6. Design parameters selected for dynamic modulus test

CIR-foam Mixture		CIR-emulsion Mixture	
Asphalt Binder	PG 52-34	Emulsion Type	HFMS-2S
Foaming Temperature (ºC)	170ºC	-	-
Foaming Water Content (%)	1.3%	-	-
Foamed Asphalt Content (%)	2.0%	Emulsion Content (%)	3.0% (mix of asphalt and water in 2:1 ratio)
Moisture Contents of RAP (%)	4.0%	Moisture Contents of RAP (%)	3.0%
Compaction Method	Gyratory compactor at 25 gyrations	Compaction Method	Gyratory compactor at 25 gyrations
RAP Source	Story County Clayton County	RAP Source	Story County Clayton County
Curing Condition	In the air for 5, 10, 20, 30, 45, and 90 hours	Curing Condition	In the air for 5, 10, 20, 30, 45, and 90 hours
Testing Method	Dynamic Modulus @ 21.1°C and 10 Hz	Testing Method	Dynamic Modulus @ 21.1°C and 10 Hz
Number of Specimen	2 specimens	Number of Specimen	2 specimens

8.2.1 Dynamic Modulus Testing Procedure

The dynamic modulus test was performed at one loading frequency of 10Hz and one testing temperature of 21.1°C. The dynamic moduli of CIR specimens were measured at six curing periods of 5, 10, 20, 30, 45, and 90 hours.

To begin testing, LVDT's were adjusted to near to the end of its linear range to allow the full range to be available for the accumulation of compressive permanent deformation. A minimum contact load equal to 5% of the dynamic load was applied to the specimen. A sinusoidal axial compressive load was applied to CIR specimens while maintaining the axial strain at 80 microstrain.

8.2.2 Results and Discussion

Table 8-7 summarizes the volumetric characteristics and moisture contents of CIR-foam and CIR-emulsion specimens at each of six curing periods for two different RAP sources. It should be noted that CIR-emulsion specimens with RAP materials from Clayton County failed during the dynamic modulus test. It is interesting to note that the CIR-emulsion specimens with RAP materials from Clayton County exhibited the smallest flow number and unreasonable ITS values.

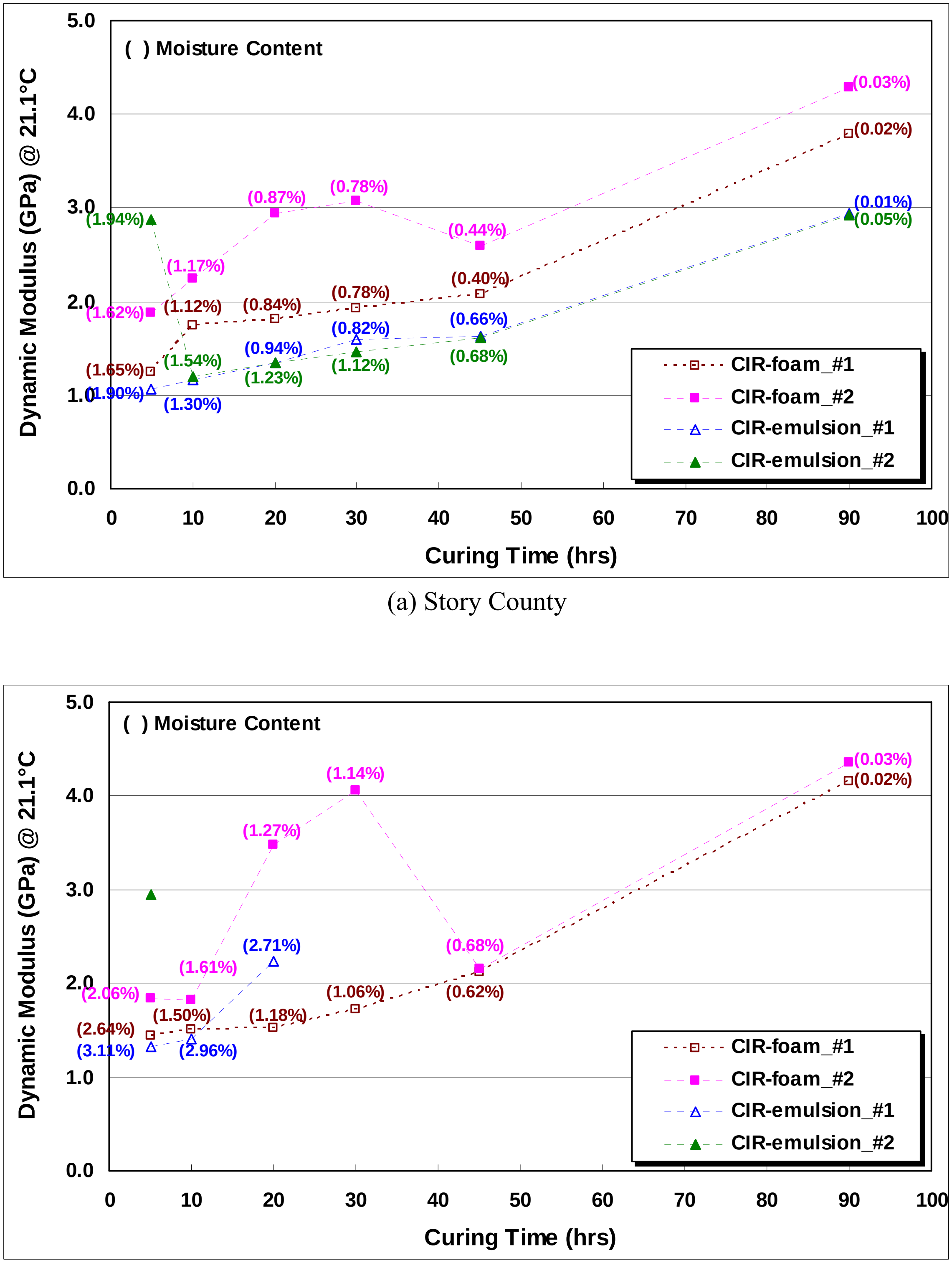
Table 8-7 Bulk specific gravities (Gmb), air voids and moisture contents of CIR-foam and CIR-emulsion specimens prepared for dynamic modulus test

RAP Source	Curing Time(h)	Gmb			Air Void (%)			Moisture Content (%)		
		#1	#2	AVG	#1	#2	AVG	#1	#2	AVG
Story-Foam	0	2.088	2.099	2.093	12.7	12.2	12.4	3.54	3.61	3.58
	5	2.050	2.059	2.054	14.3	13.9	14.1	1.65	1.62	1.63
	10	2.039	2.050	2.044	14.7	14.3	14.5	1.12	1.17	1.15
	20	2.033	2.051	2.042	15.0	14.2	14.6	0.84	0.87	0.85
	30	2.032	2.042	2.037	15.0	14.6	14.8	0.78	0.78	0.78
	45	2.024	2.036	2.030	15.3	14.8	15.1	0.40	0.44	0.42
	90	2.017	2.027	2.022	15.7	15.2	15.5	0.02	0.03	0.02
Story-emulsion	0	2.100	2.073	2.087	13.1	14.2	13.7	3.36	3.40	3.38
	5	2.071	2.044	2.057	14.4	15.5	14.9	1.90	1.94	1.92
	10	2.059	2.036	2.047	14.9	15.8	15.3	1.30	1.54	1.42
	20	2.051	2.030	2.041	15.2	16.0	15.6	0.94	1.23	1.08
	30	2.049	2.028	2.038	15.3	16.1	15.7	0.82	1.12	0.97
	45	2.046	2.019	2.032	15.4	16.5	16.0	0.66	0.68	0.67
	90	2.032	2.006	2.019	16.0	17.0	16.5	0.01	0.05	0.03
Clayton-Foam	0	2.163	2.150	2.157	9.5	10.0	9.8	3.56	3.81	3.69
	5	2.129	2.114	2.121	10.9	11.5	11.2	2.64	2.06	2.35
	10	2.120	2.105	2.112	11.3	11.9	11.6	1.50	1.61	1.56
	20	2.113	2.098	2.106	11.6	12.2	11.9	1.18	1.27	1.22
	30	2.111	2.095	2.103	11.7	12.3	12.0	1.06	1.14	1.10
	45	2.102	2.086	2.094	12.1	12.7	12.4	0.62	0.68	0.65
	90	2.089	2.072	2.084	12.6	13.1	12.8	0.02	0.03	0.02
Clayton-emulsion	0	2.168	2.186	2.177	10.5	9.8	10.2	3.26	N/A	3.26
	5	2.164	2.174	2.169	10.7	10.3	10.5	3.11	N/A	3.11
	10	2.161	2.170	2.166	10.8	10.4	10.6	2.96	N/A	2.96
	20	2.156	N/A	2.156	11.0	N/A	11.0	2.71	N/A	2.71
	30	2.154	N/A	2.154	11.1	N/A	11.1	2.60	N/A	2.60
	45	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	90	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 8-8 summarizes the dynamic moduli of CIR specimens of RAP materials from Story and Clayton Counties and they are plotted against the curing time in Figure 8-8 for two different RAP sources. As expected, the dynamic moduli increased as curing time increased and moisture contents decreased. The dynamic mouldi of CIR-foam specimens were higher than those of CIR-emulsion specimens for both RAP sources. This might have been caused by the higher moisture content in CIR-emulsion specimens than CIR-foam specimens for the equivalent curing time. Based on the limited test result, it can be concluded that the stiffness development of CIR-emulsion mixtures is slower than that of CIR-foam mixtures. Overall, due to the moisture present and the limited curing time, the dynamic modulus of test specimens seemed to be lower than a typical fully cured CIR specimen in the oven.

Table 8-8. Summary of dynamic moduli at six cases of curing time for CIR-foam and CIR-emulsion of RAP materials from Story and Clayton Counties

Dynamic Modulus (kPa) at 21.1°C, 10Hz				
Curing Time(hr)	CIR-foam (Story County)		CIR-emulsion (Story County)	
	# 1	# 2	# 1	# 2
5	1,245,758	1,882,620	1,067,664	2,877,391
10	1,738,229	2,248,671	1,170,384	1,201,888
20	1,805,150	2,945,769	1,343,618	1,352,813
30	1,932,946	3,079,193	1,597,976	1,454,851
45	2,083,712	2,591,391	1,635,403	1,604,940
90	3,784,089	4,281,810	2,933,311	2,927,907
Curing Time(hr)	CIR-foam (Clayton County)		CIR-emulsion (Clayton County)	
	# 1	# 2	# 1	# 2
5	1,437,706	1,838,039	1,318,447	2,941,610
10	1,510,693	1,818,314	1,408,526	N/A
20	1,518,344	3,476,526	2,239,563	N/A
30	1,723,637	4,060,231	N/A	N/A
45	2,126,323	2,159,383	N/A	N/A
90	4,158,903	4,355,893	N/A	N/A



(a) Story County

(b) Clayton County

Figure 8-8. Plots of dynamic moduli against six cases of curing time for two different RAP sources

9. DEVELOPMENT OF MOISTURE LOSS INDEX FOR CIR LAYERS

In order to develop a better analysis tool to monitor the CIR layer in preparation for a timely placement of the wearing surface, the concept of a moisture loss index was explored. The main objective of the moisture loss index is to estimate an optimum curing condition for a timely placement of wearing surface in the field, which can achieve the minimum strength required to carry the design traffic.

9.1 Concrete Pavement Curing

From the past research on concrete pavement, it has been shown that the three weather conditions; air temperature, humidity and wind velocity, are the best indicators to determine if plastic shrinkage cracks will develop. A nomograph to estimate the development of shrinkage cracks was developed by the Portland Cement Association. (Snell 2007). The rate of evaporation is a key consideration in monitoring the quality of the curing of concrete pavements. The effective curing thickness concept was introduced as a method to evaluate the effectiveness of a curing method. The surface relative humidity is known to have the biggest influence on both the effective curing thickness and the rate of evaporation. Thus, prediction of the rate of evaporation of the water from the concrete surface would depend on the relative humidity of the surface (Jeong 2003)

Numerous efforts have been made to develop empirical models to express evaporation as a function of atmospheric factors (Penman 1984). Dalton (1802) proposed the following model to predict the rate of evaporation.

$$E = (e_s - e_d)\, f(\upsilon)$$

Where,

E = rate of evaporation ($ML^{-2}T^{-1}$)

e_s = saturation vapor pressure of water surface (ML^{-2})

e_d = vapor pressure of air above water surface (ML^{-2})

$f(v)$ = wind function

v = wind speed (LT^{-1})

M = mass

L = length

T = time

Menzel (1954) developed the following equation, which has been accepted as one of the best methods for predicting evaporation of bleeding water on the surface of the concrete pavement.

$$E = 0.44(e_s - e_d)(0.253 + 0.096v)$$

Recently, Uno (1998) proposed the following equation to predict the evaporation rate.

$$E = [T_C^{2.5} - (r \times T_a^{2.5})][1 + 0.4V] \times 10^{-6}$$

Where,

E = evaporation rates, $lb/ft^2/h$

T_C =concrete temperature, °F

T_a = air temperature, °F

r= (relative humidity %)/100

V=wind speed, mph

A relatively simple procedure for determination of the rate of evaporation is the use of the chart in Figure 9-1. By drawing a line to intercept the appropriate air temperature, relative humidity, concrete temperature, and wind velocity values, in this order, the rate of evaporation can be approximated.

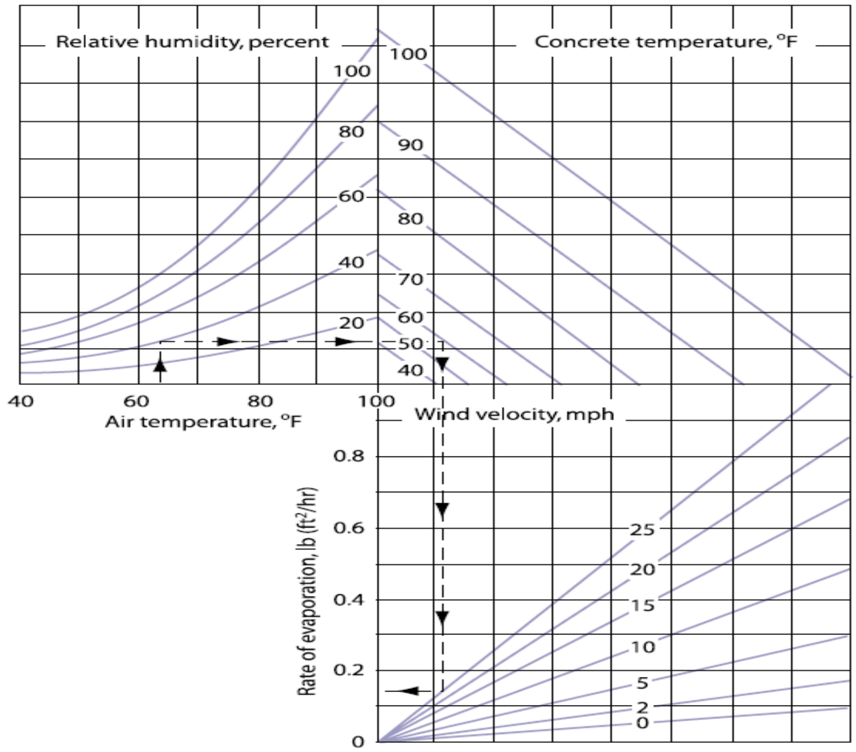


Figure 9-1. Nomograph for estimating the rate of evaporation of water from a concrete surface (ACI 1996)

Luke (2007) developed a computer program that makes this nomograph and equations easy to use where the user simply enters the air temperature, concrete temperature, relative humidity, and wind velocity. An evaporation calculator can be obtained from the website www.lavyconcrete.com.

9.2 Development of Moisture loss index for CIR Layer

The simplest approach for developing a moisture loss index for a CIR layer is to develop a multiple linear regression equation to predict the moisture change in the CIR layer as a function of initial moisture condition, cumulative air temperatures, cumulative humidity and the cumulative wind speed as follows:

$$\Delta MoistureContent = a_1 \times InitialMC + a_2 \times CTemp + a_3 \times CHumidity + a_4 \times CWindSpeed$$

Where,

InitialMC = the actual moisture content of CIR-layer right after construction
CTemp = Cumulative Air Temperature (°°F) since construction
CHumidity = Cumulative Humidity (%) since construction
CWindSpeed = Cumulated Wind Speed (mph) since construction
a_1, a_2, a_3, a_4 = multiple linear regression coefficients

9.3 Moisture loss index Based on Laboratory Data

To illustrate a process of developing a moisture loss index, a series of moisture data collected from the laboratory curing specimens are used. Tables from 9-1 to 9-4 summarize Δmoisture(%)/Δhour and initial moisture contents that were measured each time. Only two factors, Δmoisture(%)/Δhour and initial moisture content are considered because the laboratory has a constant temperature, a constant humidity and no wind. Figure 9-2 and Figure 9-3 show a relationship between Δmoisture(%)/Δhour and initial moisture content of uncovered CIR specimens for 6, 10, 22 and 50 hours and six different RAP sources. As can be seen from these figures, for a given initial moisture content of uncovered CIR specimens, Δmoisture(%)/Δhour varied for different curing periods and RAP sources. This result indicates that the moisture reduction rate is affected by curing periods and RAP materials.

Table 9-1. Summary of Δmoisture(%)/Δhour and initial moisture contents for 6 or 10 hours using different RAP sources

RAP Source	Curing Time (hour)	Specimen 1		Specimen 2		Specimen 3	
		Δmoisture(%)/Δ hour	Initial Moisture at each time	Δmoisture(%)/Δ hour	Initial Moisture at each time	Δmoisture(%)/Δ hour	Initial Moisture at each time
Lee County for 6 hours	0~1	0.65	3.42	0.59	3.27	0.57	3.14
	1~2	0.41	2.77	0.41	2.67	0.42	2.56
	2~4	0.31	2.36	0.33	2.26	0.28	2.15
	4~6	0.17	1.73	0.16	1.61	0.14	1.58
Hardin County for 10 hours	0~0.5	0.58	2.91	0.55	3.15	0.45	2.69
	0.5~1	0.39	2.62	0.39	2.87	0.35	2.46
	1~1.5	0.34	2.42	0.31	2.68	0.28	2.29
	1.5~2	0.31	2.25	0.32	2.52	0.27	2.15
	2~4	0.23	2.10	0.22	2.36	0.21	2.01
	4~6	0.20	1.63	0.20	1.91	0.18	1.60
	6~8	0.08	1.23	0.13	1.51	0.12	1.24
	8~10	0.10	1.08	0.10	1.26	0.06	1.00
Wapello County for 10 hours	0~0.5	0.83	3.49	0.76	3.30	0.75	3.29
	0.5~1	0.54	3.07	0.50	2.92	0.56	2.91
	1~1.5	0.46	2.80	0.44	2.67	0.47	2.63
	1.5~2	0.39	2.57	0.40	2.45	0.38	2.40
	2~3	0.29	2.38	0.33	2.25	0.31	2.20
	3~3.5	0.24	2.09	0.22	1.92	0.24	1.89
	3.5~4.5	0.08	1.72	0.08	1.60	0.08	1.53
	4.5~5	0.21	1.64	0.34	1.52	0.23	1.45
	5~6	0.07	1.53	0.07	1.35	0.08	1.34
	6~7	0.09	1.46	0.09	1.28	0.08	1.26
	7~8.5	0.04	1.38	0.04	1.19	0.05	1.18
	8.5~10	0.02	1.32	0.02	1.13	0.01	1.11

Table 9-2. Summary of Δmoisture(%)/Δhour and initial moisture contents for 10hours using different RAP sources

RAP Source	Curing Time (hour)	Specimen 1		Specimen 2		Specimen 3	
		Δmoisture(%)/Δ hour	Initial Moisture at each time	Δmoisture(%)/Δ hour	Initial Moisture at each time	Δmoisture(%)/Δ hour	Initial Moisture at each time
Webster County for 10 hours	0~2	0.44	3.08	0.46	3.27	0.47	3.28
	2~3	0.28	2.19	0.27	2.35	0.26	2.35
	3~4	0.24	1.91	0.26	2.09	0.25	2.08
	4~6	0.08	1.67	0.15	1.83	0.16	1.83
	6~8	0.14	1.51	0.11	1.53	0.09	1.51
	8~20	0.03	1.24	0.02	1.31	0.02	1.33
	20~24	0.00	0.93	0.01	1.02	0.02	1.08
	24~30	0.01	0.92	0.01	0.98	0.01	1.02
	30~50	0.01	0.83	0.01	0.88	0.01	0.92
Mont-gomery County for 10 hours	0~1	0.58	2.71	0.56	2.27	0.60	2.91
	1~2	0.34	2.12	0.37	1.71	0.39	2.32
	2~4	0.11	1.78	0.29	1.34	0.31	1.92
	4~5	0.13	1.57	0.14	0.76	0.11	1.30
	5~6	0.12	1.44	0.07	0.62	0.11	1.19
	6~8	0.02	1.32	0.02	0.55	0.03	1.08
	8~10	0.04	1.28	0.06	0.50	0.06	1.02
Muscatine County for 10 hours	0~1	0.35	1.94	0.36	2.49	0.50	2.57
	1~2	0.46	1.59	0.47	2.13	0.36	2.07
	2~4	0.15	1.13	0.23	1.66	0.22	1.71
	4~5	0.02	0.83	0.22	1.19	0.17	1.27
	5~6	0.09	0.81	0.09	0.97	0.22	1.11
	6~8	0.05	0.72	0.06	0.87	0.05	0.89
	8~10	0.08	0.63	0.12	0.76	0.10	0.79

Table 9-3. Summary of Δmoisture(%)/Δhour and initial moisture contents for 22 or 50 hours using different RAP sources

RAP Source	Curing Time(h)	Specimen 1		Specimen 2		Specimen 3	
		Δmoisture(%)/Δ hour	Initial Moisture at each time	Δmoisture(%)/Δ hour	Initial Moisture at each time	Δmoisture(%)/Δ hour	Initial Moisture at each time
Lee County for 22 hours	41	0.70	3.22	0.70	3.38	0.75	3.38
	1~4	0.32	2.52	0.32	2.68	0.33	2.63
	4~8	0.10	1.57	0.13	1.72	0.11	1.63
	8~22	0.03	1.17	0.03	1.22	0.03	1.19
Hardin County for 50 hours	0~0.5	0.62	2.52	0.66	2.72	0.70	2.71
	0.5~1	0.41	2.21	0.32	2.39	0.37	2.36
	1~4	0.21	2.00	0.21	2.23	0.22	2.18
	4~8	0.11	1.39	0.13	1.59	0.14	1.53
	8~20	0.03	0.96	0.03	1.07	0.03	0.95
	20~26	0.01	0.63	0.01	0.70	0.01	0.65
	26~33	0.01	0.55	0.01	0.62	0.01	0.56
	33~47	0.005	0.50	0.005	0.56	0.005	0.50
	47~50	0.004	0.43	0.005	0.48	0.004	0.43
Wapello County for 50 hours	0~0.5	0.84	3.34	0.74	3.28	0.68	3.36
	0.5~1	0.49	2.92	0.51	2.91	0.51	3.02
	1~1.5	0.47	2.68	0.46	2.65	0.47	2.76
	1.5~2	0.41	2.44	0.42	2.42	0.43	2.52
	2~2.5	0.36	2.24	0.35	2.21	0.33	2.30
	2.5~3	0.33	2.06	0.36	2.04	0.27	2.14
	3~5	0.22	1.89	0.21	1.86	0.21	2.01
	5~6	0.15	1.46	0.17	1.45	0.16	1.59
	6~8	0.03	1.31	0.03	1.28	0.03	1.43
	8~10	0.06	1.26	0.06	1.23	0.07	1.38
	10~20	0.02	1.13	0.02	1.10	0.02	1.25
	20~24	0.011	0.93	0.011	0.90	0.011	1.04
	24~30	0.014	0.88	0.012	0.86	0.014	1.00
	30~40	0.007	0.80	0.007	0.79	0.008	0.91
	40~50	0.002	0.73	0.003	0.72	0.003	0.84

Table 9-4. Summary of Δmoisture(%)/Δhour and initial moisture contents for 50 hours using different RAP sources

Sources	Curing Time(h)	Specimen 1		Specimen 2		Specimen 3	
		Δmoisture(%)/Δ hour	Initial Moisture at each time	Δmoisture(%)/Δ hour	Initial Moisture at each time	Δmoisture(%)/Δ hour	Initial Moisture at each time
Webster County for 50 hours	0~2	0.44	3.08	0.46	3.27	0.47	3.28
	2~3	0.28	2.19	0.27	2.35	0.26	2.35
	3~4	0.24	1.91	0.26	2.09	0.25	2.08
	4~6	0.08	1.67	0.15	1.83	0.16	1.83
	6~8	0.14	1.51	0.11	1.53	0.09	1.51
	8~20	0.03	1.24	0.02	1.31	0.02	1.33
	20~24	0.00	0.93	0.01	1.02	0.02	1.08
	24~30	0.01	0.92	0.01	0.98	0.01	1.02
	30~50	0.01	0.83	0.01	0.88	0.01	0.92
Mont-gomery County for 50 hours	0~2	0.57	2.57	0.59	2.93	0.60	3.01
	2~3	0.16	1.44	0.29	1.76	0.28	1.81
	3~4	0.18	1.28	0.21	1.47	0.20	1.53
	4~8	0.06	1.10	0.03	1.26	0.03	1.33
	8~10	0.010	0.87	0.049	1.13	0.041	1.19
	10~20	0.013	0.85	0.025	1.03	0.024	1.11
	20~24	0.013	0.73	0.018	0.78	0.016	0.86
	24~30	0.008	0.68	0.010	0.71	0.010	0.80
	30~40	0.009	0.63	0.005	0.65	0.008	0.74
	40~50	0.001	0.54	0.006	0.60	0.002	0.66
Muscatine County for 50 hours	0~2	0.41	2.32	0.39	2.21	0.44	2.40
	2~3	0.19	1.50	0.29	1.43	0.29	1.51
	3~4	0.11	1.31	0.16	1.14	0.14	1.22
	4~6	0.05	1.20	0.10	0.98	0.09	1.08
	6~8	0.03	1.09	0.05	0.77	0.04	0.90
	8~20	0.01	1.03	0.01	0.68	0.01	0.82
	20~24	0.002	0.91	0.008	0.52	0.004	0.66
	24~30	0.005	0.90	0.005	0.49	0.005	0.64
	30~50	0.003	0.87	0.004	0.46	0.004	0.61

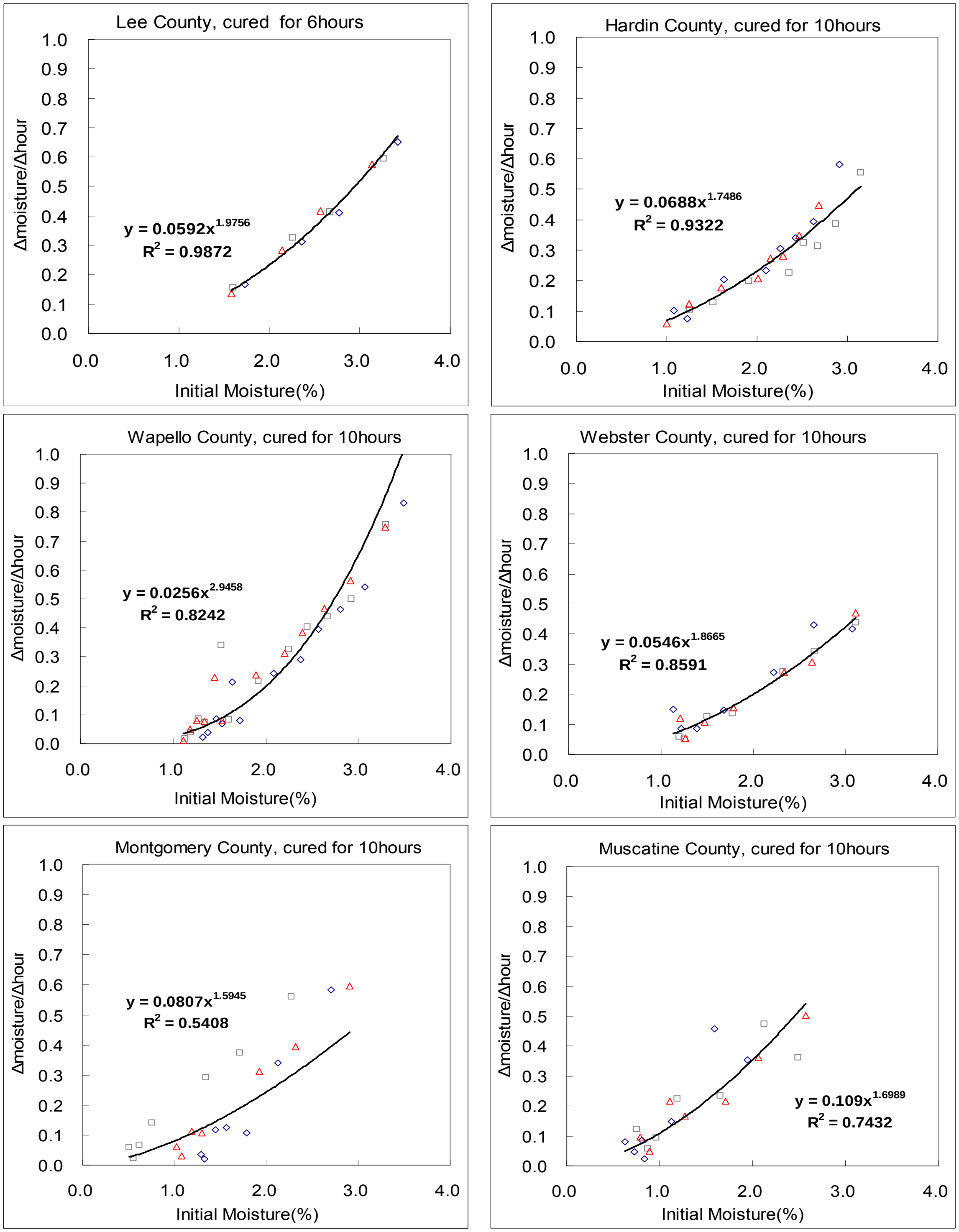


Figure 9-2. Plots of the relationship between Δmoisture(%)/Δhour and initial moisture for 6 or 10 hours using different RAP sources

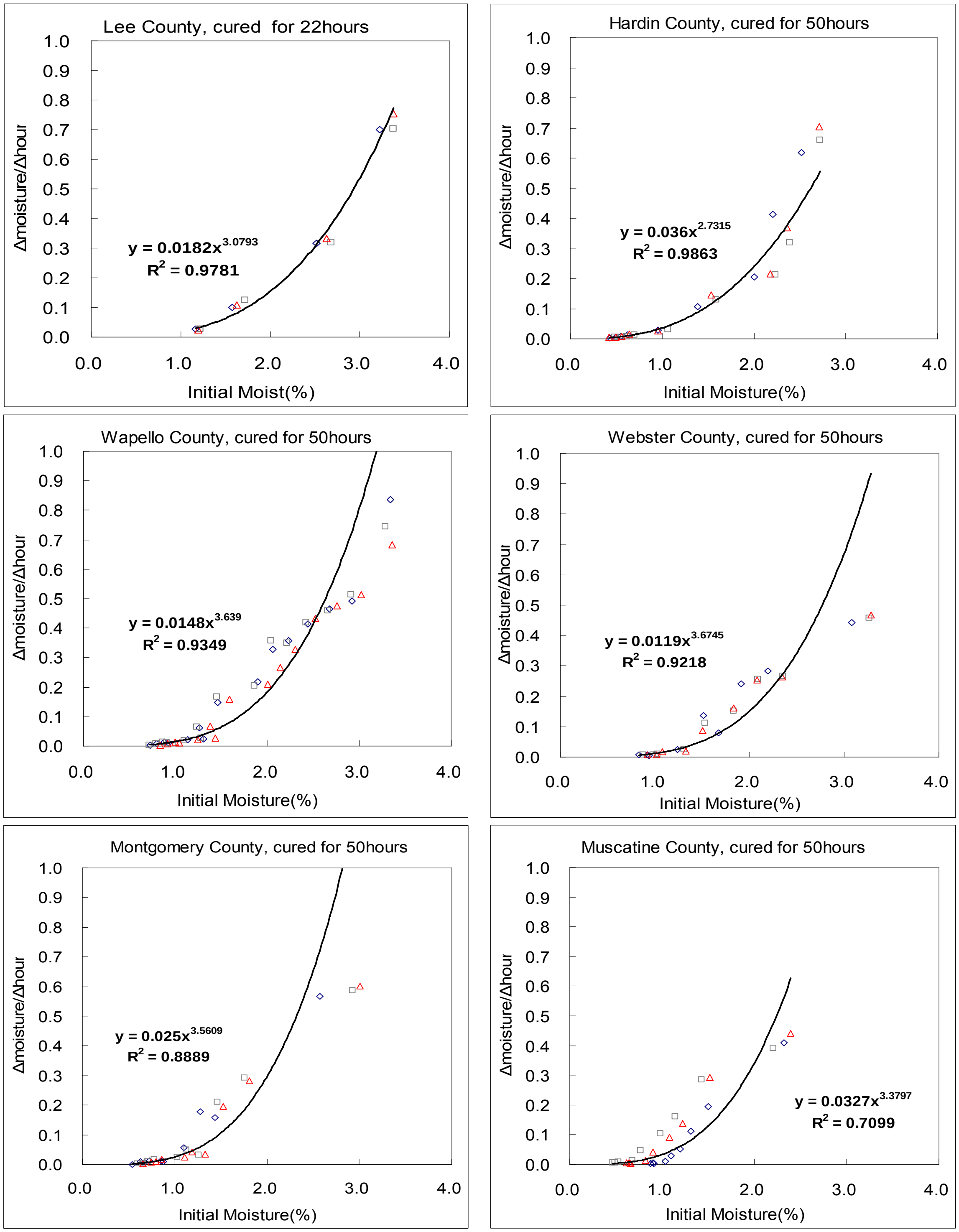


Figure 9-3. Plots of the relationship between Δmoisture(%)/Δhour and initial moisture for 22 or 50 hours using different RAP sources

9.4 Moisture loss index Based on Field Data

Moisture contents were measured from the CIR project located on State Highway 38 in Story County shown in Figure 9-4, which was constructed in September 2007. As shown in Table 9-5, moisture contents were measured three times from two different spots on the CIR-layer.

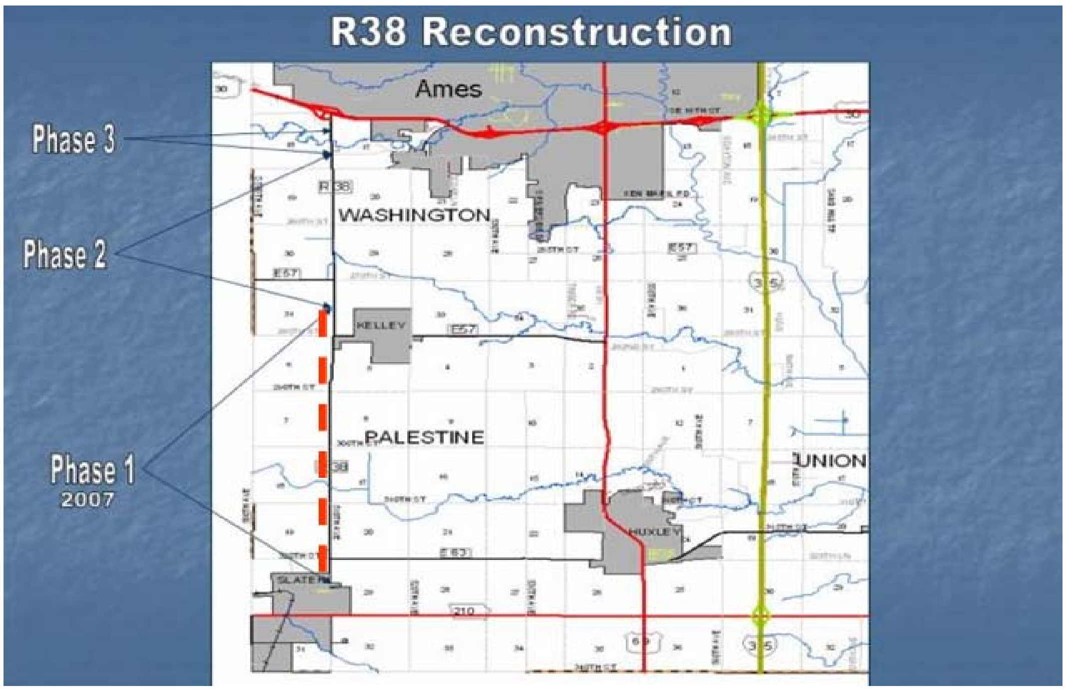


Figure 9-4. CIR project site where moisture data were collected

Table 9-5. Moisture contents measured from State Highway 38 in Story County

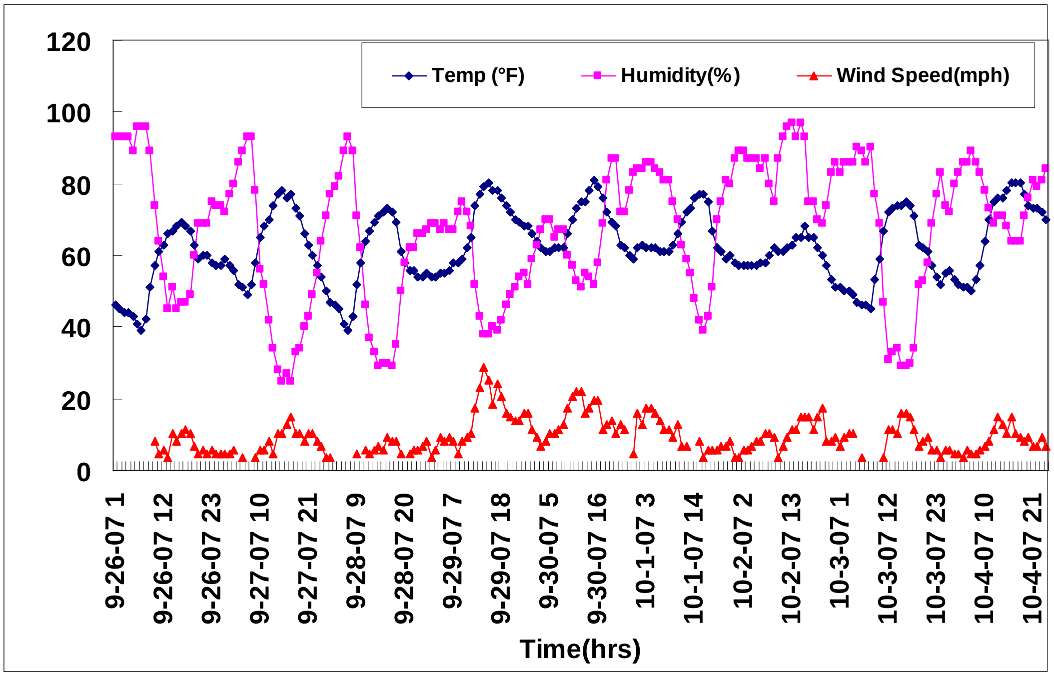
Location \ Date tested	9/26/07	10/04/07	10/10/07
103+89	10.7	4.2	3.8
152+26	9.6	3.8	3.6

A weather website, http://www.wunderground.com/, was then accessed to obtain the weather information on Slater Road 38. From the website, ambient temperature, humidity and wind speed data were available every hour. Table 9-6 shows an example to calculate cumulative temperature above freezing. Cumulative humidity and wind speed were also calculated in the units of cumulative percent humidity and cumulative mph, respectively.

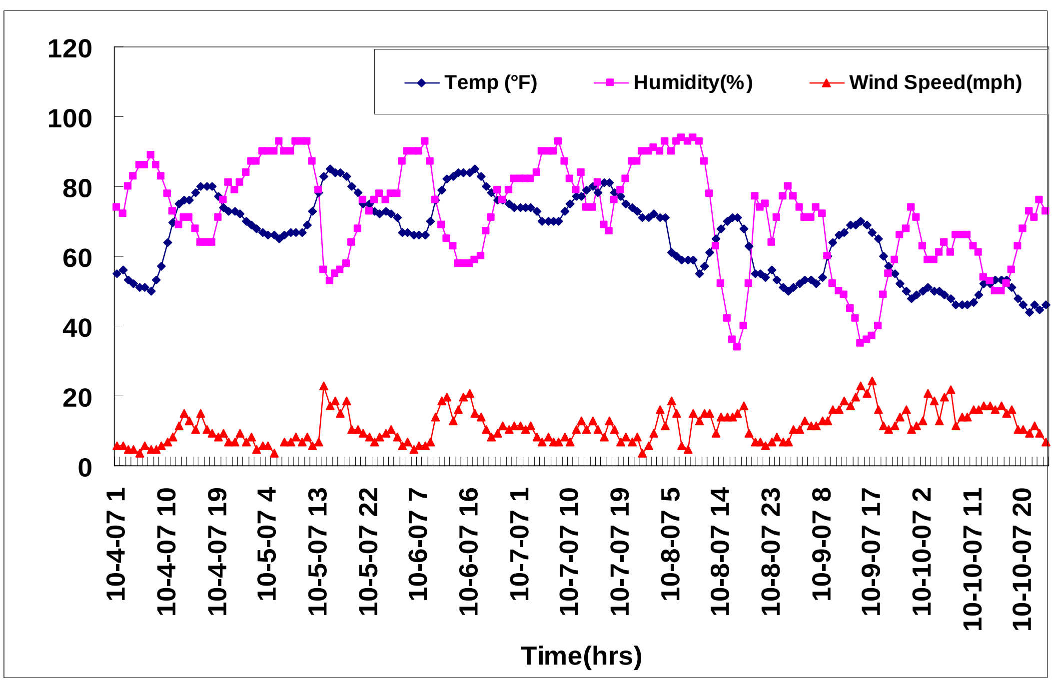
Table 9-6. Summary of calculating cumulated temperature

Date	Time	Temp (°F)	-32 (°C)	Cumulative Temperature
09/26/2007	12:53 AM	46	14	14
	1:53 AM	45	13	27
	2:53 AM	44.1	12.1	39.1
	3:53 AM	44.1	12.1	51.2
	4:53 AM	43	11	62.2
	5:53 AM	41	9	71.2
	6:53 AM	39	7	78.2
	7:53 AM	42.1	10.1	88.3
	8:53 AM	51.1	19.1	107.4
	9:53 AM	57	25	132.4

During two time periods, between 9/26/07 and 10/04/07, and between 10/04/07 and 10/10/07, cumulative temperature, humidity and wind speed data were calculated using the weather information available from the website. Figure 9-5 shows the weather conditions during two time periods and Figure 9-6 shows cumulative temperature, cumulative humidity and cumulative wind speed during 9 days, between 9/26/07 and 10/04/07, during 7 days between 10/04/07 and 10/10/07. Table 9-7 summarizes Δmoisture content, initial moisture content and cumulative data collected from the weather website.



(a) Between 9/26/07 and 10/04/07



(b) Between 10/04/07 and 10/10/07

Figure 9-5. Weather conditions during two time periods

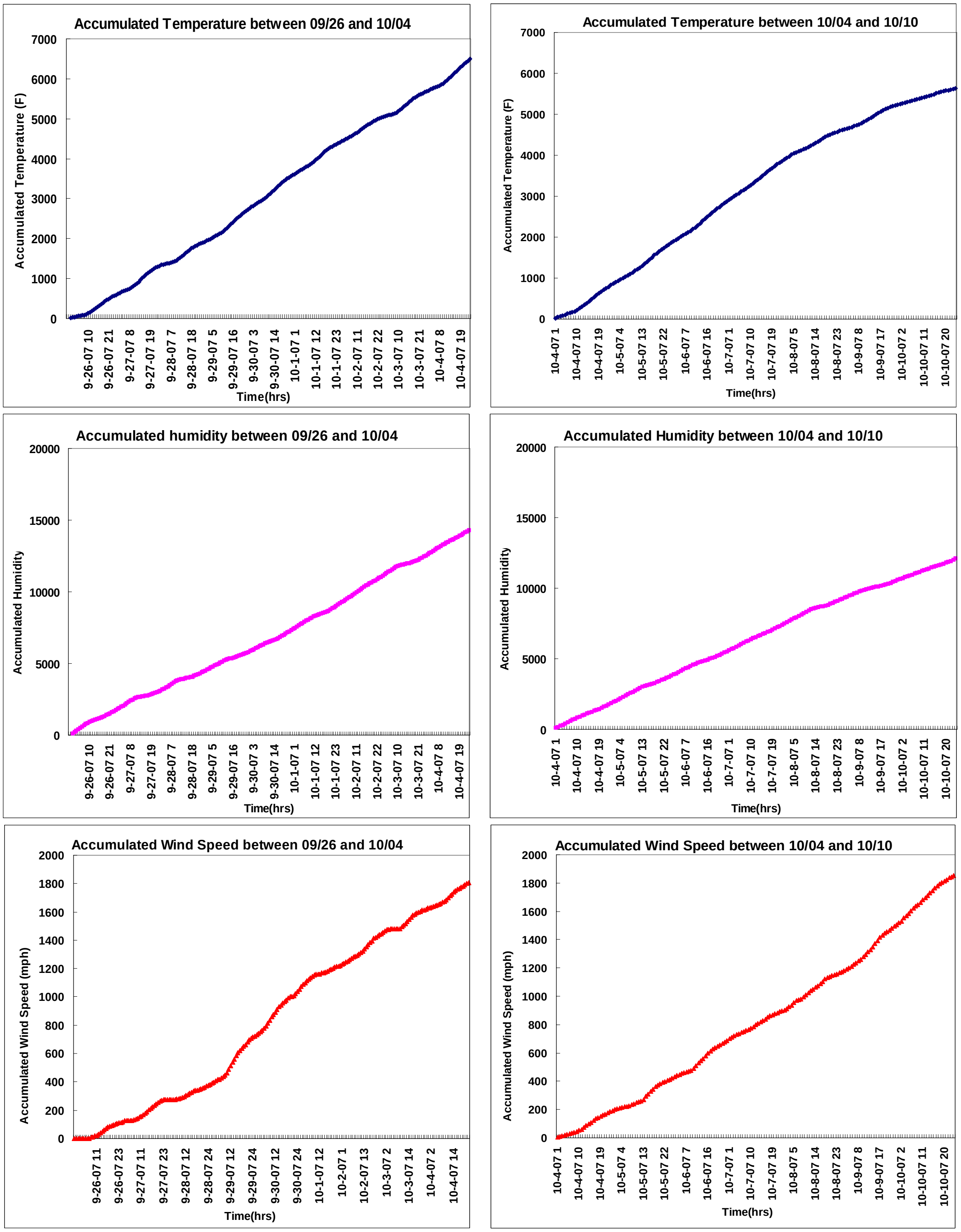


Figure 9-6. Plots of cumulative temperature, humidity and wind speed between 9/26/07 and 10/04/07, and between 10/04/07 and 10/10/07

Table 9-7. Summary of Δmoisture content, initial moisture content and cumulative temperature, humidity and wind speed

Project Site / Date	Δ moisture Content	Initial Moisture Content	Cumulative Temperature	Cumulative Humidity	Cumulative Wind Speed
Location (103+89) Between 09/26~10/04	6.5	10.7	6490.9	14277	1806.2
Location (103+89) Between 10/04~10/10	0.4	4.2	5632.2	12066	1852.2
Location (152+26) Between 09/26~10/04	5.8	9.6	6490.9	14277	1806.2
Location (152+26) Between 10/04~10/10	0.2	3.8	5632.2	12066	1852.2

Another set of moisture data on a 5.68-mile CIR project located on highway # 79 from Geode State Park east Middletown was obtained from Des Moines County. The CIR layer was constructed between May 21th and June 1st 2007 and HMA for an intermediate base was overlaid between June 19th and July 12th 2007. HMA for the surface was overlaid between June 28th and August 2nd 2007. Table 9-8 summarizes the moisture contents measured during the CIR construction and Table 9-9 summarizes Δmoisture content, cumulative temperature, humidity and wind speed. It should be noted that there are three negative values of Δmoisture content in the Table 9-9. According to the record of the weather website, there was heavy rain on May 31st between 3:30 a.m. to 3:50 a.m. and light rain on June 1st between 11:49 a.m. to 12:53 p.m. As a result, these three negative data points were removed for a further analysis.

Table 9-8. Moisture contents that measured at Highway #79, Geode State Park east Middletown

Location \ Date	05/22/07	05/24/07	05/25/07	05/29/07	05/30/07	05/31/07	06/01/07
Different Spots	4.2%	3.2%	3.1%	3.8%	3.3%	3.8%	4.1%

Table 9-9. Summary of Δmoisture content, initial moisture content and cumulative temperature, humidity and wind speeds

Date	Δ moisture content	Initial moisture content	Cumulative Temperature	Cumulative Humidity	Cumulative Wind Speed
05/22~05/24	1.0	4.2	3148.8	3720	979.3
05/24~05/25	0.1	3.2	1787.4	3006	423.5
05/25~05/29	-0.7	3.1	4691.2	8237	733.7
05/29~05/30	0.5	3.8	1921.0	2668	351.6
05/30~05/31	-0.5	3.3	1738.0	3113	286.2
05/31~06/01	-0.3	3.8	1924.9	3640	293.1

The following regression equation to predict Δmoisture content in CIR layer was developed based on initial moisture content, cumulative temperature, humidity and wind speed collected from two CIR project sites as summarized in Table 9-10.

$$\Delta MC = -2.98 + 0.949\ IMC + 0.00013\ CTemp - 0.000072\ CHumidity - 0.00019\ CWindSpeed$$

Based on a limited amount of field data, the R-square value was 99.3%, which indicates a strong correlation between moisture change with a combination of initial moisture content, cumulative temperature, cumulative humidity and cumulative wind speed. The highest positive correlation was observed between Δmoisture content and the initial moisture content whereas there was an unreasonable positive correlation between Δmoisture content and cumulative humidity. In the future, the more accurate moisture condition data should be collected from various depths of a CIR layer to validate this moisture loss index concept.

Table 9-10. Summary of Δmoisture content, initial moisture content and cumulative temperature, humidity and wind speeds

Project Site	Δ Moisture Content	Initial Moisture Content	Cumulative Temperature	Cumulative Humidity	Cumulative Wind Speed
Slater Road 38	6.5	10.7	6490.9	14277	1806.2
	0.4	4.2	5632.2	12066	1852.2
	5.8	9.6	6490.9	14277	1806.2
	0.2	3.8	5632.2	12066	1852.2
Highway #79	1.0	4.2	3148.8	3720	979.3
	0.1	3.2	1787.4	3006	423.5
	0.5	3.8	1921.0	2668	351.6

10. CONCLUSIONS AND FUTURE STUDIES

The Cold In-Place Recycling (CIR) has become one of the popular methods in rehabilitating the existing asphalt pavements due to its cost-effectiveness, the conservation of paving materials, and its environmental friendliness. Particularly, in Iowa, the CIR has been used widely in rehabilitating the rural highways because it improves a long-term pavement performance. A CIR layer is normally covered by a hot mix asphalt (HMA) overlay or chip seal in order to protect it from water ingress and traffic abrasion and obtain the required pavement structure and texture. Curing is the term currently used for the period of time that a CIR layer should remain exposed to drying conditions before an HMA overlay or chip seal is placed.

Currently, various agencies have different moisture content requirements prior to placement of the wearing surface based on the total moisture content in a CIR layer. The industry standard for curing time is 10 days to 14 days or a maximum moisture content of 1.5 percent. These criteria are well founded by historical experience, but appear to be very conservative. Often, the exposed CIR layer is required to carry traffic for many weeks before the wearing surface is placed. This increases the risk that the investment in the CIR layer may be damaged by extended periods of traffic and unfavorable climate.

To further Iowa's development of asphalt recycling technology, this study was performed to explore technically sound and more effective ways to identify minimum in-place CIR properties necessary to permit placement of the HMA overlay or chip seal. The research effort focused on procedures that optimize the CIR exposure time while retaining the potential for the owner agency's investment to succeed. The main objective of this research is to develop a better analysis tool that the industry and the owner agency can apply to monitor the CIR layer in preparation for a timely placement of the wearing surface.

10.1 Conclusions

Based on the literature reviews and extensive laboratory experiments of curing process for both CIR-emulsion and CIR-foam in the field and laboratory, the following conclusions are derived:

1. Iowa agencies adopted a curing requirement of 1.5% moisture condition in the field. However, based on the limited field data, CIR layers were some overlaid when the moisture content was well above 1.5%.

2. To represent the curing process of CIR pavement in the field construction, three different laboratory curing procedures were examined: 1) curing process of uncovered specimen, 2) curing process of semi-covered specimen and 3) curing process of covered specimen.

3. The laboratory test results confirmed that the method of curing temperature and length of the curing period significantly affect the properties of the CIR mixtures.

4. The uncovered CIR-foam specimens continued to gain the indirect tensile strength up to 28 days when cured in the oven at 25˚C, 40˚C and 60˚C after the moisture content is reduced to zero after two days.

5. For uncovered specimens, up to 10 hours of curing in the air, the indirect tensile strength did not increase but it increased when curing time increased from 10 hours to 50 hours. There was no good correlation between indirect tensile strength and moisture content in the early curing stage up to 10 hours.

6. For semi-covered specimens, up to 12 hours of curing, the indirect tensile strength did not increase but it increased when curing time increased from 12 hours to 14 days. Given the similar moisture content level, the indirect tensile strength of some specimens cured for 14-day was typically higher than those cured for 7-day.

7. For the given moisture content and curing time, semi-covered CIR-foam specimens exhibited the slightly higher indirect tensile strength than semi-covered CIR-emulsion specimens.

8. For covered specimens, the indirect tensile strength of covered CIR-foam specimens increased as the curing time increased. The indirect tensile strength of covered CIR specimens with the initial moisture content below 1.5%, when cured in the oven at 40˚C, increased over the curing period from zero to 14 days. However, the indirect tensile strength of covered CIR specimens with the initial moisture content of 1.5% or higher did not increase over the curing period from zero to 14 days.

9. For the given moisture content, covered CIR-foam specimens exhibited the slightly higher indirect tensile strength than covered CIR-emulsion specimens.

10. Overall, indirect tensile strength of CIR specimens with RAP materials from Clayton County was lower than ones from Story County. This might have been caused by the stiffer extracted asphalt binder and the higher moisture content.

11. When the specimens were submerged under water for 24 hours after reaching 1.5% moisture content, the indirect tensile strength decreased by 32.4% to 62.4%, except CIR-emulsion specimens with RAP materials from Clayton County.

12. CIR-foam specimens with RAP materials from Story County failed at the highest number of loading cycles whereas CIR-emulsion specimens with RAP materials from Clayton County failed at the lowest number of cycles. The CIR-foam specimens with a longer curing time are more resistant to permanent deformation.

13. Dynamic moduli increased as curing time increased and moisture contents decreased. The dynamic mouldi of CIR-foam specimens were higher than those of CIR-emulsion specimens. This might have been caused by the higher moisture content in CIR-emulsion specimens than CIR-foam specimens for the equivalent curing time.

14. To develop a better analysis tool to monitor the CIR layer in preparation for a timely placement of the wearing surface, a moisture loss index was developed based on the initial moisture content, cumulative temperature, cumulative humidity and cumulative wind speed.

10.2 Future Studies

To validate the developed moisture loss index against moisture conditions measured in the field, the following task should be performed.

- In the future, the more accurate moisture condition data should be collected from various depths of a CIR layer to validate the moisture loss index concept. As shown in Figure 10-1, moisture meter will be placed at the bottom of the CIR layer. Both CIR-emulsion and CIR-foam project sites will be identified for installation of the moisture meter, which can measure both moisture and temperature in the field. The moisture meter will be installed at the bottom of the CIR layer and monitored using a data acquisition device. The area measuring feature of the moisture meter will be very valuable given the inherent variability of moisture within a CIR layer caused by a non-uniformity of water application during construction.

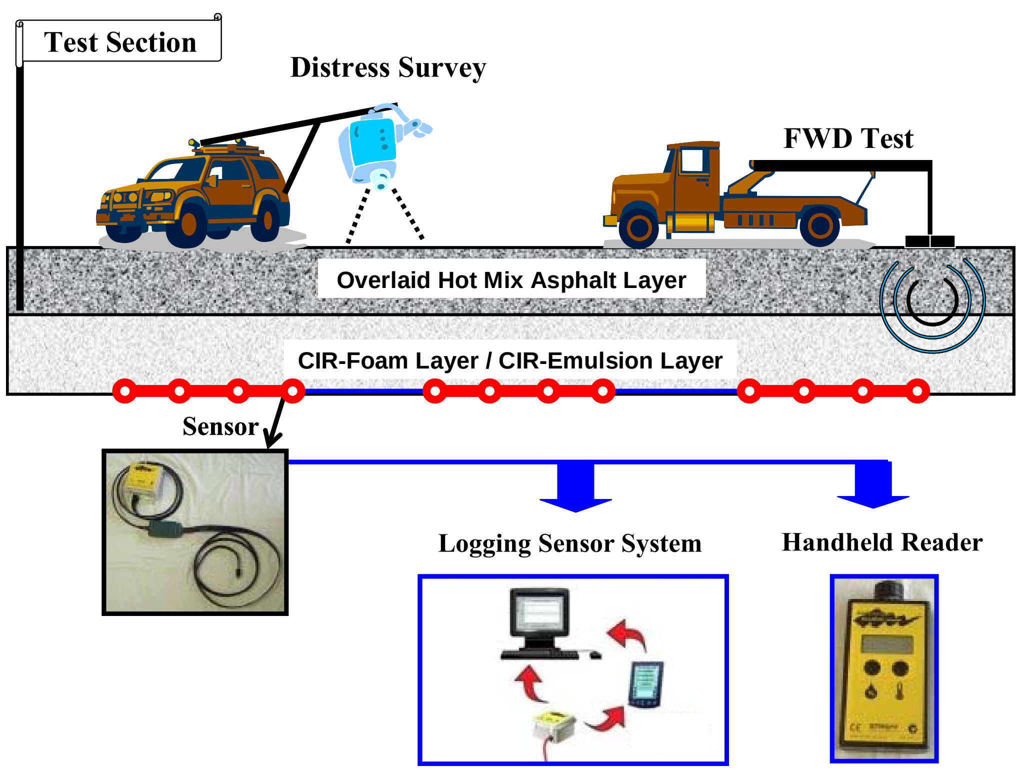


Figure 10-1. Measuring temperature, moisture, deflection and distress from test sections

- To examine the CIR curing process in the field, cores should be taken from the CIR project sites to determine relationship between indirect tensile strength and moisture content at various temperature conditions. The curing conditions of cores should be compared against the results of the specimens cured using the semi-covered curing procedure in the laboratory.

- The developed moisture loss index concept should be validated against the actual CIR construction projects. The density and the moisture content should be monitored in the field by the contractors using a nuclear gauge and they should be compared against the moisture contents measured using moisture meter installed at the bottom of CIR layer.

- The moisture loss index based on the curing temperature and moisture content should be validated against various CIR projects. The validation project sites should be monitored to see if there is a difference in performance for the CIR projects for different moisture contents and curing indices.

- The validation sections should be evaluated for their initial conditions before and after HMA overlay using FWD and a distress survey vehicle. These conditions should be used as a reference points to measure the deterioration levels in the future.

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