Development of Moisture Loss Index Based on Field Moisture Measurement using Portable Time Domain Reflectometer (TDR) for Cold In-place Recycled Pavements

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Abstract

The practice of asphalt pavement recycling has grown rapidly over the decade, one of which is the cold in-place recycling with the foamed asphalt (CIR-foam) or the emulsified asphalt (CIR-emulsion). Particularly, in Iowa, the CIR has been widely used in rehabilitating the rural highways because it significantly increases the service life of the existing pavement. The CIR layer is typically overlaid by the hot mix asphalt (HMA) to protect it from water ingress and traffic load and obtain the required pavement structure and texture. Most public agencies have different curing requirements based on the number of curing days or the maximum moisture contents for the CIR before placing the overlay. The main objective of this study is to develop a moisture loss index that the public agency can use to monitor the moisture content of CIR layers in preparation for a timely placement of the wearing surface. First, the moisture contents were measured in the field using a portable time domain reflectometry (TDR) device. Second, the weather information in terms of rain fall, air temperature, humidity and wind speed was collected from the same location. Finally, a moisture loss index was developed as a function of initial moisture content, air temperature, humidity and wind speed. The developed moisture loss index based on the field measurements would help the public agency to determine an optimum timing of an overlay placement without continually measuring moisture conditions in the field.

Keywords
cold in-place recycling (CIR), time domain reflectometer (TDR), moisture content, moisture loss index
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 used widely in rehabilitating the rural highways because it improves a long-term pavement performance. Curing is the term currently used for a time period such that a CIR layer must remain exposed in the air for drying before the hot mix asphalt (HMA) overlay or the 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 mixture 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 the HMA overlay (AI 1998).

Various agencies have different moisture content requirements prior to placement of the wearing surface based on either the total moisture content in the mix or the increase in moisture content from the pavement prior to recycling. The industry standard for curing period is 10 days to 14 days or maximum moisture content of 1.5%. These criteria are well founded by historical experiences, but appear to be very conservative. 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.

2. LITERATURE REVIEW

Curing process can be fairly rapid under favorable weather conditions, but high humidity, low temperatures, or rainfall soon after CIR application can increase the curing time significantly. AIPCR (Association Mondiale de la Route) and PIARC (World Road Association) recommended that the application of the HMA overlay should be delayed until the residual water has largely evaporated (AIPCR and PIARC 2002). 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 is used to determine the timing of placing the HMA overlay ranging from 1.0% to 1.5%. Particularly, in Spain, it is recommended to place an HMA overlay only after the moisture content of 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.

Based on the FHWA’s survey (2005), each state has different moisture content or curing period requirement. As shown in Figure 1, Arizona, Iowa, South Dakota, Vermont and Washington recommend that the CIR layer shall be allowed to cure until the moisture of the CIR mixes is reduced to 1.5% or less. Colorado recommends the moisture content of 1.0% and Kansas recommends 2.0%. Delaware, Idaho, Maine, Maryland, Nebraska, Nevada, New Hampshire, New York, Ohio, Ontario and Pennsylvania require a curing period between 4 days and 45 days.

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

3. MOISTURE LOSS OF CIR-FOAM MIXTURES IN THE LABORATORY

To illustrate a process of developing a moisture loss index, a series of moisture data were collected from the laboratory cured
specimens. As shown in Figure 2, six different RAP materials were used to produce CIR-foam mixtures. Table 1 summarizes the mix design parameters used in the curing experiments of CIR-foam. As seen in Table 1, CIR-foam mixtures were produced with 2.0% foamed asphalt content (FAC) and 4.0% moisture content (MC), and were compacted by 25 gyrations of the gyratory compactor. Twelve CIR-foam specimens with each RAP source were cured in the air at 25°C to allow water to evaporate and their moisture contents were measured every 0.5 hour or 1 hour for up to 50 hours.

![Fig 2. Gradation plots from six different RAP sources passing 25mm sieve](image)

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

<table>
<thead>
<tr>
<th>Table 1. Design parameters selected for curing experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt Binder</td>
</tr>
<tr>
<td>Foaming Temperature(°C)</td>
</tr>
<tr>
<td>Foaming Water Content(%)</td>
</tr>
<tr>
<td>Foamed Asphalt Content(%)</td>
</tr>
<tr>
<td>Moisture Contents of RAP(%)</td>
</tr>
<tr>
<td>Compaction Method</td>
</tr>
<tr>
<td>Number of Specimen</td>
</tr>
</tbody>
</table>

Figure 3 shows a relationship between \( \frac{\text{moisture content}}{\text{hour}} \) and initial moisture content at 22 hours and 50 hours of the curing period for CIR-foam specimens made from six different RAP sources. Only two factors, \( \frac{\text{moisture content}}{\text{hour}} \) and initial moisture content, were considered here because the laboratory temperature and humidity were constant and no wind below. As can be seen from Figure 3, for a given initial moisture content of CIR-foam specimens, \( \frac{\text{moisture content}}{\text{hour}} \) varied according to different curing periods and RAP sources. This result indicates that the moisture reduction rate is affected by curing periods and RAP materials. Particularly, it can be concluded that \( \frac{\text{moisture content}}{\text{hour}} \) content is highly affected by the initial moisture content.

4. TIME DOMAIN REFLECTOMETRY (TDR) DEVICE

The time domain reflectometry (TDR) probes are initially used in the agricultural field and have been widely used to detect the in-situ moisture content in soils since the late 1970s. The TDR uses propagation of electromagnetic wave to measure materials properties and structural responses. Jiang and Tayabji (1999) reported that TDR has proved to be a reliable means to determine in-situ soil moisture content and developed four empirical models to compute volume of water. Yu et al. (2008) developed a method to directly estimate the degree of freeze/thaw from a TDR measurement. Hanek et al. (2001) reported that monitoring subsurface soil moisture using TDR can provide an efficient alternative method for determining when the damage susceptibility is reduced and heavy loads can
be resumed. Liang et al. (2006) found that variations in the moisture content at the base and the subbase layers can give an indication on how fast the overlying materials can drain the infiltrated water. Lee et al. (2008) applied a micromechanical scheme since existing methods for computing volumetric water content ignored variations of dry density.

For this study, as shown in Figure 4, a portable TDR was used to measure the moisture content of the CIR layer. TDR 300 reads directly the volumetric water content (VWC) that was converted to the gravimetric water content by using the following formula.

\[
w = \theta \times \left( \frac{\rho_w}{\rho_s} \right)
\]

Eq. 1

where,

- \( w \) = gravimetric water content
- \( \theta \) = volumetric water content
- \( \rho_w \) = density of water
- \( \rho_s \) = dry bulk density of soil

Fig 4. Portable TDR device used to measure in-situ moisture content

5. MEASUREMENTS OF FIELD MOISTURE CONTENTS USING TDR DEVICE

The CIR-foam project site is located from south of the city of West Branch to the Cedar-Muscatine County line, Iowa. The 7 km section of County Road X 30 was rehabilitated from I-80 to SH-6 by using the CIR-foam process from May 5th to May 9th, 2008. The top 10cm of the existing 23cm-thick Type B HMA layer were milled and mixed with foamed asphalt to produce the 10cm-thick CIR-foam layer.

5.1. Measurements of Loose CIR-foam Mixtures

Loose CIR-foam mixtures before compaction were collected from six different stations between 10:00 a.m. and 12:00 p.m. and between 4:00 p.m. to 6:00 p.m. on May 6-8, 2008. They were brought to a laboratory, dried at 40°C oven for 3 days and measured their in-situ moisture contents. Table 2 summarizes of the loose CIR-foam mixtures from the field. As seen in Table 2, the average moisture content of 2.2% measured at University of Iowa is in a good agreement with 2.4% as measured by a contractor. It is interesting to note that the moisture contents of the loose CIR-foam mixtures collected before compaction are relatively small, all to be less than 2.7%.

Table 2. Laboratory moisture contents of loose CIR-foam mixtures from the field

<table>
<thead>
<tr>
<th>Station No.</th>
<th># 1</th>
<th># 2</th>
<th># 3</th>
<th>Average</th>
<th>Contractor</th>
</tr>
</thead>
<tbody>
<tr>
<td>95+00</td>
<td>2.0%</td>
<td>1.7%</td>
<td>2.0%</td>
<td>1.9%</td>
<td>2.2%</td>
</tr>
<tr>
<td>45+00</td>
<td>1.7%</td>
<td>3.8%</td>
<td>2.0%</td>
<td>2.5%</td>
<td>2.2%</td>
</tr>
<tr>
<td>9+50</td>
<td>2.5%</td>
<td>2.3%</td>
<td>1.7%</td>
<td>2.2%</td>
<td>2.7%</td>
</tr>
<tr>
<td>43+50</td>
<td>2.3%</td>
<td>2.1%</td>
<td>1.8%</td>
<td>2.1%</td>
<td>2.6%</td>
</tr>
<tr>
<td>54+00</td>
<td>2.0%</td>
<td>1.5%</td>
<td>2.2%</td>
<td>1.9%</td>
<td>2.6%</td>
</tr>
<tr>
<td>125+00</td>
<td>2.7%</td>
<td>2.4%</td>
<td>2.1%</td>
<td>2.4%</td>
<td>2.6%</td>
</tr>
<tr>
<td>Total Average</td>
<td>2.2%</td>
<td></td>
<td></td>
<td></td>
<td>2.4%</td>
</tr>
</tbody>
</table>

5.2. Effect of Drilling Holes for TDR Measurement

Because two rods of a portable TDR device could not penetrate the hard CIR-foam layer during cool days, the layer was drilled to create small holes for penetration of TDR probes. As seen in Table 3, making holes for TDR probes did not properly detect the moisture content of the CIR-foam layer but did its temperature.

Table 3. Effect of drilling holes for TDR measurement
Thus, it can be postulated that drilling holes for TDR probes may not be a good method of detecting moisture loss but may be used to determine the optimum timing of an overlay.

5.3. Measurements of Field Moisture Contents

As shown in Figure 5, moisture contents were measured by the portable TDR device from seven different locations (9 moisture contents at each location) between 10:00 a.m. to 12:00 p.m. and between 4:00 p.m. to 6:00 p.m. for eleven days between May 5th and 15th, 2008. By penetrating the portable TDR probe into the CIR-foam layer, the volume water contents (VWC) were detected. CIR densities were also measured at each station using a nucleargauge. VWC were measured every day until the HMA overlay is applied. The densities measured at each station were used to convert VWC to WWC (average weight water contents).

![Figure 5](image)

Fig 5. Locations of moisture measurement using a portable TDR device

Table 4 summarizes WWC at each station. It is interesting to note that initial moisture contents measured in the field station are consistently higher than those of loose CIR-foam mixtures measured in the laboratory.

Figure 6 shows plots of field moisture contents (MC) measured by a potable TDR device against a nuclear gauge. As seen in Figure 6, it should be noted that the moisture contents measured using a portable TDR device and a nuclear gauge represent the average moisture condition between the surface and 3cm to 5cm below from the surface and they were all above the minimum moisture content of 1.5% that is required for an HMA overlay.

![Figure 6](image)

Fig 6. Plots of field moisture content measured by a portable TDR device against field moisture content measured by a nuclear gauge

5.4. Collection of Climatic Information

The climatic information on the CIR-foam project site was obtained from the website of weather information in Iowa. From the website, as shown in Figure 7, rainfall, ambient temperature, humidity, and wind speed data were collected every hour. As can be seen from Figure 7(a), rainfalls were recorded as 0.2cm, 1.8cm, and 0.5cm on the 7th, 11th, and 13th of May respectively. After raining on the project site, the moisture content measured by a portable TDR device increased. At station 125+00, the moisture content increased up to 50% between the 10th and the 11th of May.

![Figure 7](image)

Table 4, Summary of average weight water contents at each station

<table>
<thead>
<tr>
<th>Date</th>
<th>Station Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/5/2008(sunny)</td>
<td>2.6% - - - - - -</td>
</tr>
<tr>
<td>5/6/2008(sunny)</td>
<td>2.6% 2.9% 2.7% - - - -</td>
</tr>
<tr>
<td>5/7/2008(rain)</td>
<td>2.8% 3.5% 3.2% 2.2% 2.6% - -</td>
</tr>
<tr>
<td>5/8/2008(sunny)</td>
<td>- - - - - 2.3% 2.5% 2.8%</td>
</tr>
<tr>
<td>5/9/2008(sunny)</td>
<td>- 3.0% 3.3% 1.7% 2.0% 2.6% 2.7%</td>
</tr>
<tr>
<td>5/10/2008(rain)</td>
<td>2.8% 3.9% 3.3% 2.4% 2.7% 2.9% 2.7%</td>
</tr>
<tr>
<td>5/11/2008(rain)</td>
<td>4.2% 4.7% 4.9% 3.4% 4.8% 5.0% 5.8%</td>
</tr>
<tr>
<td>5/12/2008(sunny)</td>
<td>3.6% 4.0% 4.1% 3.1% 3.6% 3.9% 4.1%</td>
</tr>
<tr>
<td>5/13/2008(rain)</td>
<td>4.1% 4.6% 4.6% 3.0% 4.0% 4.3% 4.4%</td>
</tr>
<tr>
<td>5/14/2008(sunny)</td>
<td>3.2% 4.2% 3.3% 2.5% 3.2% 3.6% 3.6%</td>
</tr>
<tr>
<td>5/15/2008(sunny)</td>
<td>2.7% 3.2% 3.2% 1.9% 2.8% 3.0% 3.4%</td>
</tr>
</tbody>
</table>

Table 4 summarizing WWC at each station. It is interesting to note that initial moisture contents measured in the field station are consistently higher than those of loose CIR-foam mixtures measured in the laboratory.
To predict the moisture condition in the CIR layer, a moisture loss index was developed empirically as a function of initial moisture content, cumulative air temperature, cumulative humidity and the cumulative wind speed as following:

\[
\Delta \text{MC/hr} = a_1 \times \text{IMC} + a_2 \times \frac{\text{CTemp}}{\text{hr}} + a_3 \times \frac{\text{CHumidity}}{\text{hr}} + a_4 \times \frac{\text{CWindSpeed}}{\text{hr}}
\]

\[\text{Eq. 2}\]

\( \text{IMC} = \) the initial moisture content of CIR layer measured in the field

\( \text{CTemp} = \) cumulative air temperature(°C) between moisture measurements

\( \text{CHumidity} = \) cumulative humidity(%) between moisture measurements

\( \text{CWindSpeed} = \) cumulative wind Speed(km/h) between moisture measurements

\( a_1, a_2, a_3, a_4 = \) multiple linear regression coefficients

A total of twenty-one sets of data collected from the CIR-foam project site on County Road X 30, Cedar County, Iowa, and related weather information were used to develop the moisture loss index in Equation 2. The regression result is displayed below. In the equation, \( \Delta \text{MC/hr} \) in the CIR layer can be best fitted as a function of initial moisture content, cumulative temperature/hr, and humidity/hr and wind speed/hr. Even though considerable errors are contained in the regressed equation, it will help to predict the approximate moisture content when a direct measurement is not available.

\[\Delta \text{MC/hr} = -0.139 + 0.0215 \text{IMC} + 0.00957 \frac{\text{CTemp}}{\text{hr}} + 0.000963 \frac{\text{CHumidity}}{\text{hr}} -0.00669 \frac{\text{CWindSpeed}}{\text{hr}}
\]

\( R^2 = 66.1\% \)

Figure 8 shows plots of \( \Delta \text{MC/hr} \) against each variable. Each relationship shows positive slope in those fitting indicates increase of the moisture loss in the CIR layer with increase of initial moisture content, cumulative temperature, cumulative humidity and cumulative wind speed. Although it is seemingly unreasonable to expect that the moisture loss could increase as the humidity increases, for the limited set of data. It is acceptable here as it is.

\( \text{a, b, c, d, e} = \) multiple linear regression coefficients

\( \Delta \text{MC/hr} \) vs. \( \text{IMC} \)

\( \Delta \text{MC/hr} \) vs. \( \text{CTemp/hr} \)

\( \Delta \text{MC/hr} \) vs. \( \text{CHumidity/hr} \)

\( \Delta \text{MC/hr} \) vs. \( \text{CWindSpeed/hr} \)
7. CONCLUSIONS

The cold in-place recycling (CIR) is a process of rehabilitating existing asphalt pavements. The viability of such a process is justified by its conservation of paving materials and 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. This paper presents the efforts to optimize the CIR curing time while retaining the potential for the agency’s investment to be succeeded. The main objective of this research is to develop a better analysis tool that the industry and the agency can monitor the CIR layer in preparation for a timely placement of the wearing surface.

A series of moisture data were collected from the laboratory cured specimens to develop a moisture loss index. On the basis of the moisture measurements in the laboratory, it is concluded that the moisture reduction rate is significantly affected by curing periods and RAP materials. Particularly, moisture content is highly affected by the initial moisture content.

On the basis of the moisture measurements in the field using a portable TDR device and weather information obtained from the website, a new moisture loss index was developed using the initial moisture content, cumulative temperature, cumulative humidity and cumulative wind speed. The developed sets of moisture loss indices based on the field measurements will help pavement engineers determine an optimum timing of an overlay without continuous measurement of moisture in the field using a nuclear gauge.

In the future, the moisture loss index developed here should be validated more in additional CIR-foam construction projects. The field density and the moisture content monitored by contractors using a nuclear gauge should be compared against the moisture contents measured by a portable TDR device at the middle of the CIR layer to check future mutual agreement. In addition, the moisture index should be also developed for CIR-emulsion project sites.

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REFERENCES