# Behavior of Lime-Treated Cold In-Place Recycled Asphalt Pavements

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ABSTRACT: Use of recycled materials has great potential for rehabilitation of low to medium volume roads effectively and inexpensively. However, cold in-place recycling (CIR) technology lacks performance data and field demonstration projects. In this study, the design and performance characteristics of the CIR materials from two sites namely, Salina and Osborne sites in Kansas are determined in the laboratory. The laboratory tests include physical property (e.g., moisture, gradation, air voids, and emulsion) and performance-related (e.g., resistance to deformation, and rutting) testing. Relative performances of the CIR mixes from these two sites are then analyzed. Results show that the CIR mixes from both Salina and Osborne sites exhibited good resistance to deformation, and other criteria for low to medium volume roads. Addition of lime slurry into a milling-emulsion mix caused a significant improvement in the dry and wet rutting. Samples with 2.5% Reflex emulsion and 4.0% lime slurry additive used in the Salina site exhibited lower rut depths compared to the samples with 2.0% Reflex emulsion and 2.5% lime slurry additive used in the Osborne site. The resistance to deformation values varied only slightly between the initial cured and fully cured samples, indicating that R-values may not be a suitable property or indicator of the quality of a mix. It is believed that the data and results presented in this study will be useful in implementing the CIR technology for pavement rehabilitation.

KEY WORDS: Cold in-place recycling, reflex emulsion, lime, asphalt pavement, rutting.

## 1 INTRODUCTION

Recycling operations can be performed by either cold-mix recycling or hot-mix recycling. In hot-mix recycling, recycled asphalt pavements (RAP), or asphalt millings, are combined with new aggregates and asphalt cement to produce hot mix asphalt (HMA). In cold recycling, RAP materials are processed and laid under normal temperature. Cold recycling, in general, can be divided into two categories: cold central plant recycling and cold in-place recycling (CIR). In cold central plant recycling, the RAP materials are mixed with other materials in a plant to facilitate high rates of production. Where as, the CIR process is accomplished at the job site without hauling the RAP materials from an exiting pavement to the roadside or in a processing plant. A typical CIR process includes milling, crushing, sieving, mixing, laying, and compacting at the job site. Unlike hot-mix recycling, CIR technology is fairly new and extensive studies on it are not available (FHWA 2004). In this study, standardized and new methods for testing and design of CIR materials are addressed.

While there are many CIR design procedures available, there are no universally accepted design standards or guidelines. There is a need for widely accepted CIR design and performance testing methods (Forsberg 2002). Specifically, performance data with regards to rutting and moisture-susceptibility are needed. In this study, the design and performance characteristics of the CIR materials from Salina and Osborne sites in Kansas are determined in the laboratory. Specifically, physical property, strength and performance-related tests of laboratory-processed mixes and field-processed mixes were conducted. Laboratory data are analyzed and interpreted for design and performance evaluation of CIR mixes in partial depth pavement (base) rehabilitation. Due to length restriction, only selected results are presented here.

## 2 SITE DESCRIPTION

*Salina site* is a partial depth CIR project located in Salina, Kansas, 0.5 km (0.3 mile) west of K-140 and K-141. The site is on a two-lane road, which anticipates low volume traffic but high loads due to its agricultural topography. The existing pavement has an asphalt concrete surface thickness between 75 mm (3 in) and 125 mm (5 in), which shows evidence of transverse cracking. The intent of the project is to rehabilitate a 22 km (14-mi) stretch of the existing pavement with cold in-place recycling of the milled surface to be used as lime-treated cold-mix base course and overlaying a new 40 mm (1 1/2 in) hot-mix asphalt surface. The project has been conducted by Kansas DOT and all constructions by the Koss Construction Co., from Topeka, Kansas. The expected design life of the new pavement is 6-7 years. Reflex (i.e., ReFlex0type) emulsion with lime additive is used in this project. Better coating and early strength allows Reflex a quicker return time for traffic and earlier placement of a wearing course compared to the conventional emulsion (Koch Materials Company 2001). Hydrated lime additive is introduced into the moist aggregate before adding the emulsion to the mixture. The most effective method of applying lime is through the presence of moisture in the aggregate, i.e., in a slurry form. The design lime (dry) content in this project is 1.5% by weight of aggregate. In slurry form, this amount of lime is present in 4% lime slurry, which contains 38% hydrated lime and 62% water. Finally, the design mix from this site contains 2.5% Reflex emulsion and 4% lime slurry (i.e. 1.5% lime solids) by weight of total millings. The cold in-place recycling is performed using a continuous milling machine with lime feeder tank, followed by the emulsion storage tank.

*Osborne site* is also a CIR project constructed by the Kansas Department of Transportation and Brown and Brown, Inc. of Salina, Kansas. The project site is located approximately 6.4 km (4 mi) north of Osborne, Kansas along Highway 24. The total length of the project is approximately 8 km (5 mi) northward from the intersection of Highway 24 and Highway 281. The existing pavement is a two-lane low-volume high-load traffic system, largely due to the agricultural interchange in the region. In this project, a total of 100 mm (4 in) of the existing asphaltic concrete surface is milled. The millings are rejuvenated with 2.0% Reflex emulsion (i.e. non-solvent CSS-1 asphalt emulsions) and 2.5% lime slurry, which contains 31% limestone and 69% water. The millings are processed for use as a 127 mm (5 in) thick base layer. The recycled asphalt surface is overlaid with 40 mm (1.5 in) of hot-mix asphalt. The rehabilitation process is performed using cold in-place mobile recycling operation or a single pass equipment train. The major components of a single pass machine train are a cold-milling machine, portable crusher, travel-plant mixer, and laying down machine.

## 3 MIXING, COMPACTION AND CURING

*Mixing* of the loose laboratory samples consists of splitting RAP materials using an aggregate splitter to obtain a representative sample, and adding required amounts of reflex emulsion and lime slurry to the samples at room temperature (22-23°C).

*Compaction* of cold mix samples is performed using a Texas Gyratory Compactor (TGC) and Superpave Gyratory Compactor (SGC). The 100 mm (4-in) x 63.5 mm (2.5-in) cylindrical samples were compacted by TGC and used in strength-related tests such as resistance to deformation. Cylindrical samples of 150 mm (6-in) diameter and 75 mm (3-in) height are compacted by SGC and used rut testing in an Asphalt Pavement Analyzer (APA).

*Curing* (both initial and full curing) was used to evaluate the strength gain of the field- and laboratory- processed samples with time (Tarefder et al. 2003). Each of these curing can be performed in dry or wet (moisture-induced) conditions. The curing sequences performed in dry or wet (moisture-induced) conditions are listed in Table 1 (Asphalt Institute 1997). In dry curing, the compacted samples are placed in a draft oven for 24 hours at a specific temperature before testing. In wet (also called preconditioned) curing, samples are subjected to wetting under vacuum so that it can simulate the effect of prolonged exposure to subsurface water in the field. The curing sequence for fully cured samples aims to evaporate all the moisture within the samples, based on the recommendations of the Koch Pavement Solutions, Inc. (Koch Materials Co., 2001). Also, samples can be cured for an extended period of time (e.g., 3-days, 14-days, 28-days in this study) followed by an initial or full curing.

Table 1: Curing Sequence for Performance Tests of RAP Material

| Curing Type | Performance Tests | Curing Condition | Curing time and Sequence |
|---|---|---|---|
| Initial-Cured | Resistance to Deformation (R-value) | Dry | 1. Cured for 24 hours at room temperature after compaction. |
| | | Preconditioned | 1. Cured for 24 hours at room temperature after compaction<br>2. Cured in a forced-air oven for an additional 24 hours at 40°C<br>3. Followed by water immersion for one hour under vacuum pressure of 100 mm Hg and another hour without vacuum pressure before testing |
| Fully-Cured | R-value and Rut | Dry | 1. Cured for 24±2 hours at 60° C, or until the difference in mass is less than 0.05% within 2 hours |
| | R-value and Rut | Preconditioned | 2. Cured for 24±2 hours at 60° C, or until the difference in mass<br>is less than 0.05% within 2 hours<br>3. Precondition as in accordance with AASHTO T283 method.<br>No freezing and thawing procedures were studied<br>3. Followed by 2 hours in cool water bath before testing |
| Extended Cured | R-value and Rut | Dry or Preconditioned | Any one of the above standard curing (initial cured or Fully cured) is performed for an extended period of time (3, 14, and 28 days) |

## 4 PHYSICAL PROPERTIES

Table 2 shows sample processing, percentage emulsion, percentage lime, curing, and test methods used to characterize CIR materials from the Salina and Osborne sites.

Table 2: Test Matrix

| Site | Sample Type | % Reflex Emulsion | % Dry Lime | Curing | Tests |
|---|---|---|---|---|---|
| Salina at Kansas | Laboratory Processed | 1.5, 2.0, 2.5 | 0.0, 1.5, 2.0 | Initial-curing, Full-curing, and extended curing (3-day, 14-day, 28-day) | Resistance to Deformation, Dry Rut at 50°C, Wet Rut at 40°C, |
| | Field Processed | 2.5 | 1.5 | | |
| Osborne at Kansas | Laboratory Processed | 1.5, 2.0, 2.5 | 2.5 (Lime Slurry) | Initial-curing, Full-curing, and extended curing (3-day, 14-day, 28-day) | Resistance to Deformation, Dry Rut at 50°C, and Wet Rut at 40°C |

Salina site: *Field processed* CIR materials, transferred from the field to the laboratory in sealed bags, contain 2.5% Reflex emulsion and 1.5% dry lime in the form of slurry. In addition to processed millings, raw millings are collected from each site. They are crushed, graded, and rejuvenated with emulsion, water, and lime slurry, and used to prepare *laboratory processed* samples. The optimum liquid content is determined to be 4.75% using a standard proctor test (ASTM D 698). The raw (unrejuvenated) millings are combined with varying Reflex emulsion contents of 1.5%, 2.0% and 2.5%, with 1.5% dry lime in the form of slurry. Samples with 0.0% and 2.0% dry lime in the form of slurry are also fabricated at varying emulsion contents for comparison.

Osborne Site: *Field processed* samples compacted in the laboratory contain 2.0% Reflex emulsion with 2.5% lime slurry. *Laboratory processed* samples are prepared using three different emulsion contents. The design emulsion contents are 1.5%, 2.0% and 2.5% by weight of the total millings with lime slurry of 2.5%. Samples without lime slurry are also made at varying emulsion contents for comparison.

## 5 RESISTANCE TO DEFORMATION

The resistance value of the compacted bituminous mixtures is determined by measuring the lateral pressure developed due to vertical pressure by means of Hveem stabilometer. A resistance value of 70 for preconditioned and 78 for dry are the recommended minimum for initial-cured samples (Asphalt Institute 1989).

### 5.1 Salina Site

Figure 1 shows the resistance to deformation (i.e. R-value) of field-processed samples (with 1.5% dry lime) at different initial curing conditions for an extended period of time (3-days, 14-days, and 28-days). It can be seen that there is a very slight gain in strength (R-value) with respect to the increase in curing time from 3-days to 28-days. Dry samples have shown higher strength than the preconditioned samples (i.e., moisture-induced or wet samples).

Figure 2 shows the corresponding R-values of the laboratory processed samples. Clearly, 3-day cured samples have much lower R-values compared to the 14-days, 28-days, and fully cured samples. Apparently, the samples cured at 60oC (140°F) reflect the 28-days cured R-values. That is, curing at 60oC (140°F) accelerates gain in strength. Comparing Figures 1 and 2, it can be seen that the R-values of field processed samples (average R-value = 94.5) and laboratory processed samples (average R-value = 95.0 to 95.2) yield nearly identical results after 28 days curing period. This may justify the effectiveness of the process in recreating field mixes in the laboratory. The R-values obtained satisfy the minimum of 78 required for initial-cured dry samples as well as 70 for initial-cured moisture-induced samples (i.e. preconditioned) for base course application.

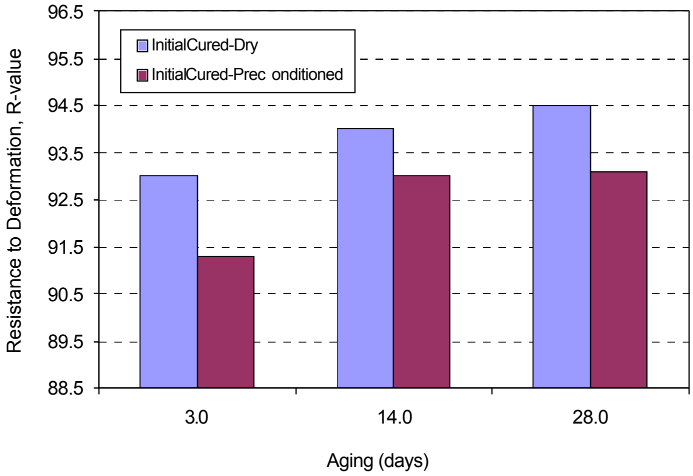


Figure 1: Variation of Resistance to Deformation of Field Processed Samples (2.5% Reflex Emulsion and 4% Lime Slurry) with Aging [Salina Site]

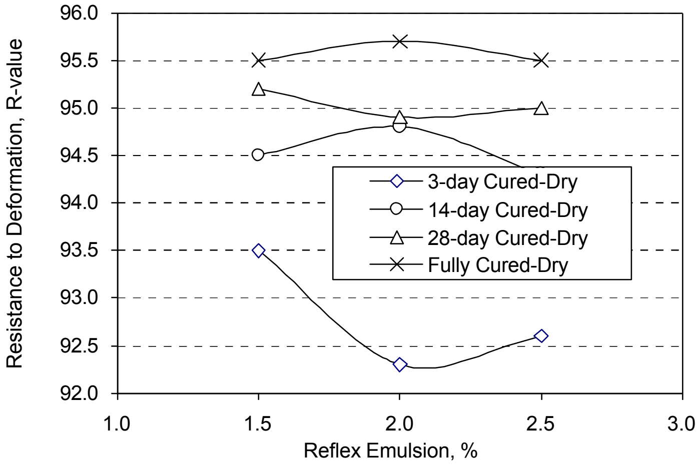


Figure 2. Variation of Resistance to Deformation of Laboratory Processed Samples (4% Lime Slurry) with %Emulsion [Salina Site]

Figure 3 shows the average resistance values at varying lime contents (0.0%, 1.5%, and 2.0%) for fully cured *laboratory processed* samples. Overall, there is significant change in R-values for differing lime contents. The R-values decreased by a maximum of 1% when no lime slurry is added, for all the emulsion contents.

5.2 Osborne Site

Figure 4 shows the variation of R-values with emulsion content for laboratory processed samples containing 2.5% lime slurry. The results are reported for dry, preconditioned, initial, and fully cured conditions. The initial cured R-values range from 85 to 83 with three different emulsion contents. The corresponding average R-values for the preconditioned samples are 84 to 81. It can be seen that the average initial R-values for dry and preconditioned samples are very similar. In a specific curing condition, the R-values vary by about 1 to 2 values for a change in emulsion content from 1.5 to 2.5%. The R-values are not significantly reduced when the samples are exposed to moisture intrusion.

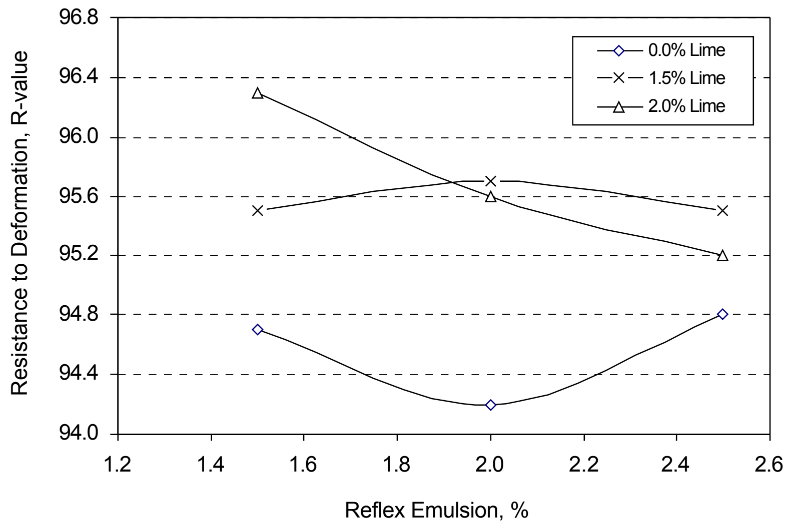


Figure 3: Effect of %Lime (dry) on the Resistance to Deformation of Laboratory Processed Samples (Fully Cured-Dry samples) [Salina Site]

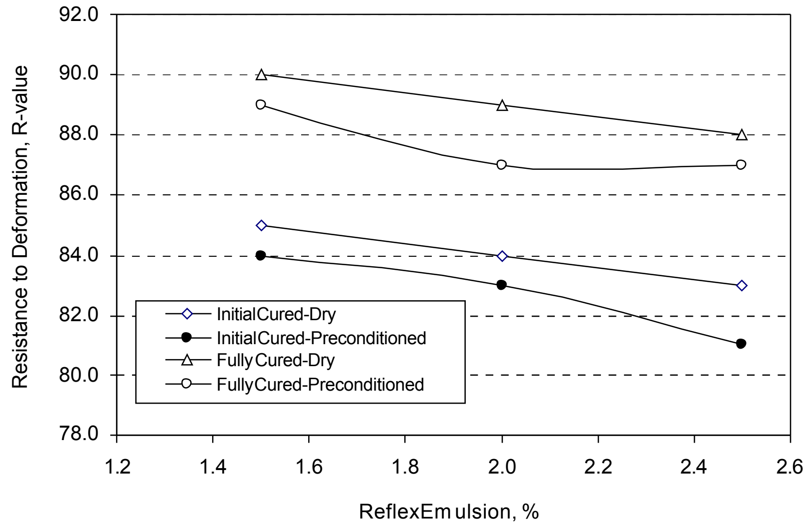


Figure 4: Resistance to Deformation of Laboratory Processed Samples (2.5% lime slurry) [Osborne Site]

Figure 5 shows that the average R-values of *field processed* samples are 88, 85, 92, and 92 for initial cured-dry, initial cured-precondition, fully cured-dry, and fully cured-precondition, respectively. Here, R-values of field processed samples differ slightly from those of laboratory-processed samples. The difference ranges from 1 to 5 for both the initial cured and fully cured samples, and it may be attributed to the non-homogeneity of the mixture. All samples meet the minimum requirement of 78 for dry samples and 70 for moisture-induced samples, as recommended by the Asphalt Institute (Asphalt Institute 1989).

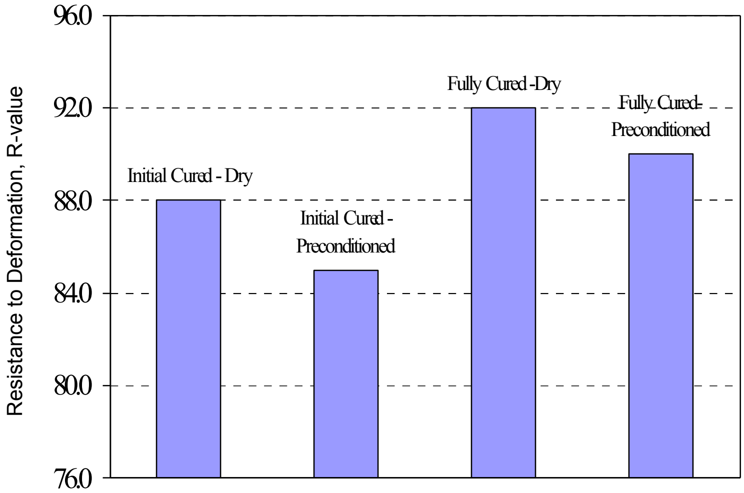


Figure 5: Resistance to Deformation of Field Processed Samples (2.5% lime slurry) [Osborne Site]

## 6 RUTTING POTENTIAL

In the APA, mix rutting potential is evaluated by subjecting CIR samples to moving wheel loads through pressurized hoses (i.e. tire pressures) and measuring rut depths at selected points along the wheel path as a function of the number of loading cycles. The magnitude of the applied vertical wheel load is kept at 445 N (100 lbs). The hose pressure is kept at 689.5 kPa (100 psi), and load is applied for 8000 cycles. The rut depth in millimeters at 8000-cycle is reported as the rutting potential of a mix. Figure 6 shows a set of rut samples at the end of the APA test.


Figure 6: Laboratory Processed Cylindrical Samples After Rut Test in the APA [Salina Site]

In the APA, the dry samples are preconditioned at a testing temperature of 50°C (122°F) for a minimum of 5 hours, but not exceeding 6 hours, before proceeding with the test. The dry samples are tested at 50°C (122°F). For a wet rut test, samples are first subjected to vacuum saturation for preconditioning the samples in accordance with the AASHTO T 283 method. Next, the preconditioned samples are tested under 40°C (104°F) or 50°C (122°F) water in the APA machine. The temperatures used approximate the pavement temperature that is expected in the field. Currently, only few state transportation departments have developed minimum specifications for APA rut depth. These specifications are usually for hot-mix asphalt pavements with high traffic volumes. For hot mix, the suggested maximum rut depths range from 5 mm (0.20 in) to 7 mm (0.28 in) (Koch Materials Company 2001, Cross 2000). Other studies (Tarefder and Zaman 2002) have suggested that the rut depths for good performing asphalt samples be between 7 mm (0.28 in) and 8 mm (0.32 in). In essence, rut depth criteria for CIR pavements with low volume traffic need to be established.

## 6.1 Salina Site

Table 3 shows the rut depths of *laboratory processed* samples with and without lime. It can be seen that the samples with lime perform better (i.e. low rut) than the samples without lime. The maximum rut observed is 5.9 mm (0.23 in.) versus 8.7 mm (0.34 in.) for the 4% lime slurry and 0% lime slurry, respectively. The maximum rut observed for the submerged case is 3.2 mm (0.13 in.) versus 8.6 mm (0.34 in.) for the 4% lime slurry and 0% lime slurry, respectively. Both have similar air voids in the range of 6 to 7%. It is to be noted that **Table** 4 shows the air void range but not a specific value. Two samples required to produce one rut value in an APA test do not have identical air voids.

Table 3: Rut Depths of Laboratory, Field, and Core Samples [Salina Site]

| Sample Type | % Air Voids | % Reflex Emulsion | % Lime Slurry | Dry Rut Depths (mm) at 50°C | Wet Rut Depths (mm) at 40°C |
|---|---|---|---|---|---|
| Laboratory Processed | 6 - 7 | 2.5 | 0 | 6.8 - 8.7 | 6.7 - 8.6 |
| | | | 4 | 4.7 - 5.9 | 2.2 - 3.2 |
| Field Processed | 10 - 11 | 2.5 | 4 | 5.6 - 7.5 | 3.5 - 5.0 |

Table 3 shows that dry rut depths (rut depths = 5.6 to 7.5 mm) of the *field processed* samples are higher than the wet rut depths (rut depths = 3.5 to 5.0 mm). This is due to the low temperature in submerged rut tests. Overall, rut depths obtained are below the 8 mm (0.31 in) requirement for the field and laboratory samples with 2.5% Reflex emulsion and 4.0% lime slurry.

## 6.2 Osborne Site

Table 4 shows the results of APA rut tests for field and *laboratory processed* samples. The maximum and minimum rut depths are shown with the percent air voids, %Reflex emulsion, and %lime slurry in the samples tested. Ideally, to compare rut depth of a set of samples with that of another set, the air voids in both sets should be identical. In practice, samples of identical air voids are rarely pursued to avoid tedious and time-consuming sample fabrication process.

Table 4: Rut Depths of Laboratory and Field Processed Samples [Osborne Site]

| Sample Type | % Lime Slurry | % Reflex Emulsion | % Air Voids in Dry Rut Sample | Dry Rut Depths (mm) at 50°C | % Air Voids in Wet Rut Sample | Wet Rut Depths (mm) at 50°C |
|---|---|---|---|---|---|---|
| Laboratory Processed | 2.5 | 1.5 | 9 -10 | 7.7 - 8.3 | 9 - 10 | 12.4 - 13.7 |
| | | 2.0 | 9 - 10 | 11.6 - 12.2 | 8.7 | 12.1 - 14.9 |
| | | 2.5 | 10 - 11 | 14.5 -14.6 | 7 - 8.3 | 16.3 - 18.1 |
| Field Processed | 2.5 | 2 | 10 - 11 | 6.7 - 8.2 | 10-11 | 6.5 - 8.7 |

As shown in Table 4, the dry rut depths between laboratory and *field prepared* samples vary significantly due to differences in air voids. This is also attributed to variations in gradations between the raw and the rejuvenated millings. The rejuvenated millings are taken directly from the hopper of an asphalt paver and the raw millings from a stockpile. **Table** 5 also shows the submerged rutting potentials of both the laboratory processed and field processed samples. The field-processed sample shows a slight increase in rut when subjected to moisture-induced damage; however, the laboratory-processed sample shows a 22 to 66% increase in rut depth.

Figure 7 shows the effect of emulsion content on the APA rut depths of the laboratory processed samples. It is noticeable that as the amount of emulsion is decreased, the rut depth is also decreased. Yet, the conclusion that emulsion should be minimized cannot be drawn, since at 1.5% emulsion content, the fine aggregates begin to strip off of the samples. This is caused by having too little emulsion to hold the fine aggregates together. In addition, at 2.5% emulsion, some bleeding is seen, where excess emulsion appears on the surface of the samples after extraction from the mold.

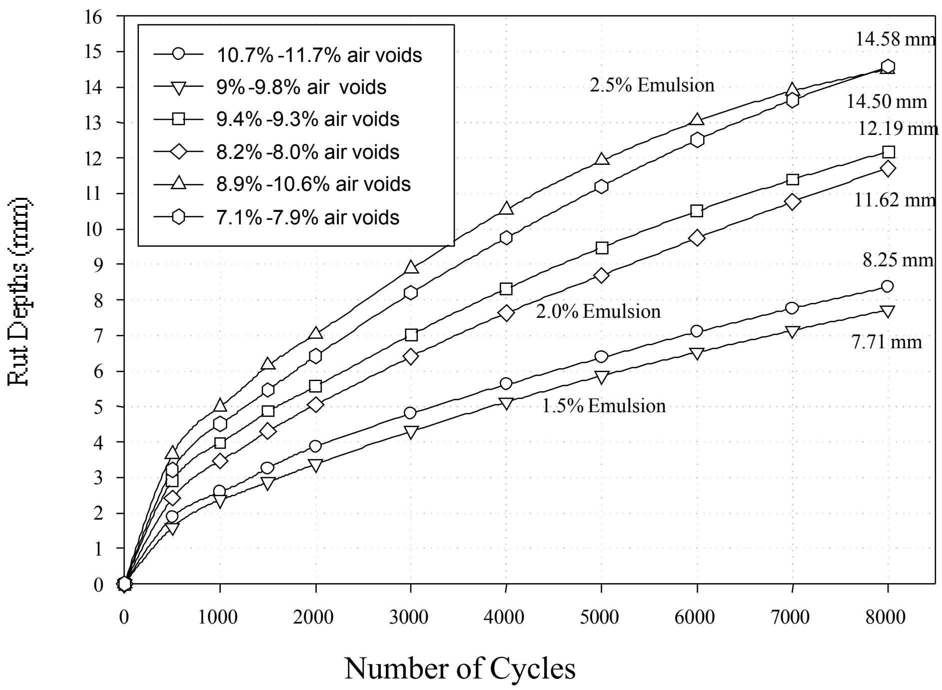


Figure 7: Variation of Rut Depths (Dry) of Field Processed Samples (2.5% Lime Slurry) with various Reflex Emulsion Contents [Osborne Site]

## 7 CONCLUDING REMARKS

### 7.1 Salina Site

- Addition of lime slurry in an emulsified CIR mix improves R-value, and both dry and submerged rutting significantly. A slight increase in resistance is observed when lime is present in the mix. Overall, the samples treated with lime slurry attain the minimum requirements (i.e. R-value, rut depths) for low volume roads.
- The attempt to simulate curing conditions has shown some potential for laboratory mix design.

- No clear trend is observed in the resistance to deformation (R-values) data for change in emulsion content of CIR mixes.

## 7.2 Osborne Site

- The difference in R-values between the dry and preconditioned (i.e., moisture-induced) samples is very small and therefore, negligible. The R-values satisfied the minimum design requirements for partial depth pavement with low volume traffic.
- Laboratory processed samples show higher rut depths as compared to the field processed sample. Only the field processed samples met the requirements of hot mix rut criteria (i.e., below 8 mm) in this study.

## 7.3 Overall

- The resistance to deformation values varied only slightly between the initial cured and fully cured samples, indicating that R-values may not be a suitable property or indicator of the quality of a mix.
- Samples with 2.5% Reflex emulsion and 4.0% lime slurry additive used in the Salina site exhibited lower rut depths compared to the samples with 2.0% Reflex emulsion and 2.5% lime slurry additive used in the Osborne site. The APA rut values of CIR samples from the Osborne site are significantly higher under wet (submerged) conditions than under dry conditions. The APA rut test, as a performance indicator, may be too severe since rutting is usually not a predominant problem in pavements rehabilitated with the CIR technology. The APA rut testing parameters such as: loading, hose pressure, etc for CIR mix/pavement need to be evaluated.
- Addition of lime slurry into a milling-emulsion mix caused a significant improvement in the dry and wet rutting. The CIR mixes from both Salina and Osborne sites exhibited good resistance to deformation, and other criteria for low to medium volume roads.

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