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# Structural Performance and Sustainability Assessment of Cold Central-Plant and In-Place Recycled Asphalt Pavements: A Case Study

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## Abstract

This paper aimed at assessing the structural performance and sustainability of cold recycled asphalt pavements. Four cold recycling technologies were investigated, including the cold central-plant recycling with emulsified and foamed asphalt binders (i.e., CCPR-E and CCPR-F), and the cold in-place recycling with emulsified and foamed asphalt binders (i.e., CIR-E and CIR-F). Firstly, the laboratory tests were conducted to comprehensively evaluate the dynamic modulus, rutting, and cracking performance of cold recycled asphalt mixtures. Subsequently, these laboratory results were used to determine the inputs of cold recycled asphalt mixtures for the Pavement ME Design program, which was employed to predict the pavement performance. Meanwhile, the National Center for Asphalt Technology also constructed four cold recycled pavement sections in the field. The monitored and predicted pavement performance showed similar trends in the first two years, but the Pavement ME Design program over predicted the rut depth of these sections. The pavement performance results confirmed that the bottom-up fatigue cracking was a negligible distress mode for cold recycled asphalt pavements. In the following, the life cycle cost analysis and life cycle assessment were conducted to evaluate the four different cold recycling projects. The life cycle cost analysis results demonstrated that all of the four cold recycling projects yielded less net present values than the HMA project. The life cycle assessment data indicated that the cold recycling technologies reduced the energy consumption by 56-64%, and decreased the greenhouse gas emissions by 39-46%. Finally, this study found that the overlay and asphalt treated base thicknesses and climatic conditions had significant impact on the performance of cold recycled asphalt pavements.

31 **Keywords:** *Cold Recycling; Laboratory Testing; Field Performance; Structural Assessment;*  
32 *Sustainability*

33

### 34 **1. Introduction**

35 Cold recycling is a rehabilitation method without the application of heat during the construction  
36 process. This is a cost-effective rehabilitation technique, which is not only effective in eliminating  
37 the rutting and fatigue cracking distresses of asphalt pavements (Alkins et al. 2008, Lane and  
38 Kazmierowski 2005, Buss et al. 2017), but also conserves non-renewable resources and energy  
39 (Thenoux et al. 2007, Tabakovic et al. 2016, Turk et al. 2016). Due to their merits in cost-  
40 effectiveness and sustainability, the cold recycling is currently attracting more and more attention  
41 in the United States. Traditionally, cold recycling consists of two subcategories, i.e., cold in-place  
42 recycling (CIR) and cold central-plant recycling (CCPR). CIR occurs within the roadway to be  
43 recycled and uses 100 percent of the reclaimed asphalt pavement (RAP) generated during the  
44 recycling process. CCPR is a process in which the asphalt recycling takes place at a central  
45 location using a stationary cold mix plant. The cold recycling usually requires multiple binders,  
46 including the bituminous material (e.g., foamed or emulsified asphalt binder), the chemical  
47 additives (e.g., lime, cement or fly ash), and water (Gomez-Meijide et al. 2016, Cox and Howard  
48 2016, Ma et al. 2017, Wang et al. 2018). A job mix formula defines the RAP gradation and the  
49 composition of the multiple-binder system for cold recycled asphalt mixtures. Due to the high void  
50 content of cold recycled asphalt mixtures, a surface course is required to protect the mixture from  
51 intrusion of surface moisture. Typically, the asphalt overlays are used for pavements with high  
52 traffic volumes, while the chip seals, slurry surfacing and micro surfacing are employed for  
53 pavements with low traffic volumes. Over the decades, the cold recycling has been an economical  
54 rehabilitation technique for low volume roadways. Recently, the Virginia Department of  
55 Transportation proved that cold recycling is also cost-effective for rehabilitation of heavy traffic  
56 volume roadways. To extend the use of cold recycling technologies, there is an urgent need to  
57 develop a pavement design methodology for cold recycled asphalt pavements with heavy traffic  
58 volume.

59 The existing studies primarily focused on the laboratory and field evaluation of cold  
60 recycled asphalt mixtures. For instance, Kim and Lee (2006) and Wirtgen (2012) developed mix  
61 design methods for cold recycled asphalt mixtures with foamed asphalt binder. These mix design  
62 methods not only define the requirements for RAP materials, foamed asphalt binder, and chemical

63 additives, but also provide the procedures to design the optimum binder system. With the increase  
64 of field experience in cold recycling, Asphalt Recycling and Reclaiming Association (ARRA)  
65 (2015) developed new mix design methods for cold recycled asphalt mixtures with foamed and  
66 emulsified asphalt binders, which redefined the material requirements and the performance criteria  
67 for asphalt mixtures. Kim et al. (2009), Khosravifar et al. (2015), Diefenderfer et al. (2016), and  
68 Lin et al. (2017) conducted the dynamic modulus laboratory test for various cold recycled asphalt  
69 mixtures. They found that the cold recycled asphalt mixtures exhibited less temperature and  
70 frequency dependencies compared to hot mix asphalt (HMA), but still should be classified as  
71 thermo-viscoelastic materials. Niazi and Jalili (2009), Kim et al. (2009), and Khosravifar et al.  
72 (2015) evaluated the rutting resistance of cold recycled asphalt mixtures using the permanent  
73 deformation tests. They pointed out that the rutting resistance of cold recycled asphalt mixtures  
74 was dependent on the type and dosage of binders, in particular on the dosage of cement. If the  
75 dosage of cement is less than 1.5%, the cold recycled asphalt mixtures generally have less rutting  
76 resistance than the HMA (Bocci et al. 2011, Grilli et al. 2012, Stimilli et al. 2013, Leandri et al.  
77 2015). Yan et al. (2010) investigated the fatigue cracking resistance of cold recycled asphalt  
78 mixtures. They concluded that the fatigue properties of foamed and emulsified asphalt treated  
79 mixtures were similar to the HMA. Diefenderfer et al. (2012, 2016) evaluated the CIR and CCPR  
80 projects in I-81 highway in Virginia and National Center for Asphalt Technology (NCAT) Test  
81 Track, respectively. They reported that all of the cold recycling sections exhibited excellent  
82 performance in terms of rutting and fatigue cracking resistance.

83 Although a great deal of studies have comprehensively characterized the performance of  
84 cold recycled asphalt mixtures, limited research has dealt with the structural assessment of cold  
85 recycled asphalt pavements. Diefenderfer et al. (2015) and Diaz-Sanchez et al. (2017) determined  
86 the layer coefficients of cold in-place and central-plant recycled asphalt pavements for use in  
87 AASHTO 93 Design. Their methodologies relied on an empirical relationship between the layer  
88 coefficient and the back-calculated resilient moduli. This relationship was originally developed for  
89 HMA (Huang 2004), but whether it is suitable for cold recycled asphalt mixtures is still not clear.  
90 Moreover, more highway agencies are abandoning the AASHTO 93 Design method and adopting  
91 the Mechanistic-Empirical Pavement Design Guide - now available as the AASHTOWare  
92 Pavement ME Design program (Smith and Braham 2018, Shirzad et al. 2018). In the current  
93 Pavement ME Design program, the cold recycled asphalt mixture is considered as a bound base  
94 material, which means that users only need to assign a constant resilient modulus. However, this

95 assumption contradicts the fact that cold recycled asphalt mixture exhibits thermo-viscoelastic  
96 characteristics being functional as an asphalt layer. Therefore, there is a need to develop a  
97 mechanistic-empirical structural assessment methodology, which will take into account the  
98 mechanical characteristics (e.g., viscoelasticity) of cold recycled asphalt pavements. Furthermore,  
99 the developed methodology should discriminate the pavement performance by using different cold  
100 recycling technologies. The methodology should also be capable of evaluating the effects of  
101 structural properties and climatic conditions on the long-term performance of cold recycled asphalt  
102 pavements. These analyses will facilitate the use of cold recycling technologies for different  
103 pavement structures in different climate regions.

104 In addition, the cold recycling is recognized as a cost-effective and sustainable  
105 rehabilitation technique. However, there is no study available to compare the different cold  
106 recycling technologies including CCPR and CIR in terms of life cycle costs and environmental  
107 benefits. These comparisons will be beneficial for pavement practitioners to select the right cold  
108 recycling technology for the given traffic volume, environment, and pavement structure.

109 To address the aforementioned research needs, this paper aimed at developing a  
110 mechanistic-empirical pavement design methodology for cold recycled asphalt pavements, and  
111 comparing the life cycle costs and environmental benefits of pavements when using different cold  
112 recycling technologies. In particular, the Pavement ME Design program was utilized to assess the  
113 structural performance of cold recycled asphalt pavements. The laboratory tests including dynamic  
114 modulus, permanent deformation and fatigue cracking tests were conducted to determine the  
115 appropriate inputs for cold recycled asphalt mixtures into the Pavement ME Design program. In  
116 order to validate the prediction accuracy, the software predicted pavement performance was  
117 compared against field performance measurements from test sections of the same material.  
118 According to the predicted performance, a case study was conducted to investigate the  
119 sustainability of asphalt pavements using different cold recycling technologies. Finally, a  
120 sensitivity analysis was conducted to evaluate the impacts of structural design parameters and  
121 climatic condition on the performance of cold recycled asphalt pavements.

122

## 123 **2. Mix Design**

124 This study followed the ARRA mix design guidelines to design cold recycled asphalt mixtures  
125 with foamed and emulsified asphalt binders. The RAP materials were collected from a previous  
126 construction project on US Highway 280 in Opelika, Alabama. The RAP binder content ranged

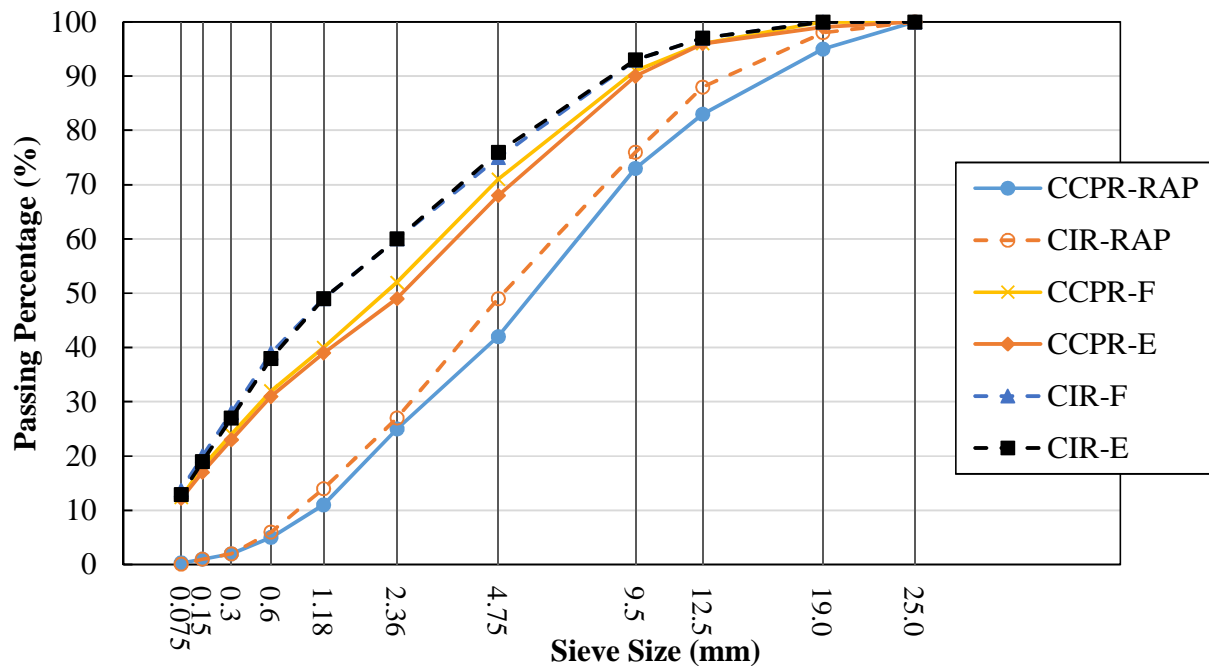
127 from 4.9 – 5.2% and was performance graded as PG 100-10. The base asphalt binder used for  
128 foaming and the emulsion were PG 67-22 binder from Birmingham, Alabama and PG 64-22  
129 binder from Parsons Tennessee, respectively.

130 The Wirtgen laboratory foaming plant was used to produce the foamed asphalt. The asphalt  
131 foaming process was produced at 170°C and 1.3% water to obtain a foamed asphalt with 8.5  
132 expansion ratio and 6-second half-life. A twin-shaft pug mill was used to mix RAP with foamed  
133 binder at room temperature  $25 \pm 2^\circ\text{C}$ . The mixing time should not exceed 60 seconds. Immediately  
134 after mixing, the specimens were compacted in a 100-mm diameter mold using a Superpave  
135 gyratory compactor. The design number of gyrations was 35, and the desired height of the  
136 specimens was  $63.5 \pm 2.5$  mm. The specimens were extruded from the molds after compaction, and  
137 then cured in a forced draft oven at  $40 \pm 1^\circ\text{C}$  for 72 hours and cooled at  $25 \pm 2^\circ\text{C}$  for 24 hours.  
138 Note that this curing protocol was used to condition specimens for both mix design and laboratory  
139 performance testing. The compacted and cured specimens were tested for indirect tensile strength  
140 in both dry and wet conditions following AASHTO T283 without freeze-thaw conditioning. The  
141 ARRA criteria requires a minimum dry strength of 310 kPa and a minimum tensile strength ratio  
142 of 0.7 for cold recycled asphalt mixtures. For central-plant recycled mixture, the foamed asphalt  
143 content was 2.2% by the weight of dry RAP, and the total water content was 7.2% by the weight of  
144 dry RAP. For in-place recycled mixture, the foamed asphalt content was 1.8% by the weight of dry  
145 RAP, and the total water content was 4.9% by the weight of dry RAP. A dosage of 1.5% Type I/II  
146 Portland cement was added for both central-plant and in-place recycled mixtures to reduce the  
147 moisture susceptibility.

148 A cationic slow-set emulsifier INDULIN w-5 at a dosage rate of 1.0% was used to produce  
149 the emulsified asphalt mixtures. The residue binder content was 62%. The pH value at room  
150 temperature is 2.98. The penetration of recovered residue at 25°C was 56.2, and the softening  
151 point of recovered residue was 48°C. Following similar mix design procedures of foamed asphalt,  
152 for central-plant recycled mixture, the emulsified asphalt content and total water content were  
153 determined as 3.0% and 7.0% by the weight of dry RAP, respectively. While for in-place recycled  
154 mixture, the emulsified asphalt content and the total water content were determined as 3.2% and  
155 4.4% by the weight of dry RAP, respectively. A dosage of 1.5% Type I/II Portland cement was  
156 also added for both central-plant and in-place recycled mixtures.

157 Figure 1 showed the gradations of the cold recycled asphalt mixtures before and after  
158 ignition. The figure legend used “RAP” to represent source RAP before burning, “F” to stand for

159 foamed mixtures, and “E” for emulsion mixtures. The RAP materials were sampled after crushing  
 160 and fractionation using the CIR and CCPR processes. As presented in Figure 1, the CCPR had  
 161 coarser gradations than the CIR before and after ignition. After ignition, the foamed and emulsion  
 162 mixtures had similar aggregate gradations for both CIR and CCPR technologies.



163  
 164 **Figure 1. Aggregate Gradations of Cold Recycled Asphalt Mixtures**

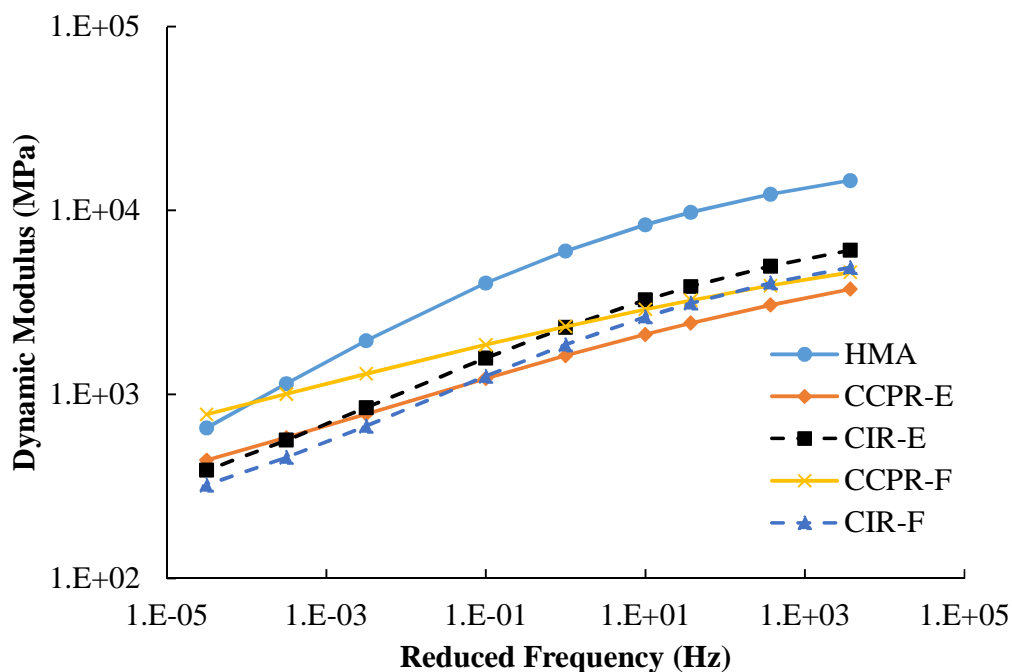
### 165 166 3. Laboratory Characterization of Cold Recycled Asphalt Mixtures

167 After mix design, the determined binder compositions were used in the CCPR and CIR processes.  
 168 The loose mixes were sampled from the central-plant and in-place, respectively, and then  
 169 compacted and cured in the laboratory. Three laboratory tests were conducted to characterize the  
 170 mechanical behavior of cold recycled asphalt mixtures, which included the dynamic modulus test,  
 171 permanent deformation test, and overlay test. The detailed test procedures and test results were  
 172 presented as follows.

#### 173 3.1 Dynamic Modulus Test

174 The dynamic modulus test was used to determine the viscoelastic inputs of cold recycled  
 175 asphalt mixtures for the Pavement ME Design program. These tests were conducted in an asphalt  
 176 mixture performance tester (AMPT) in accordance with AASHTO TP79 with some modifications.  
 177 Three temperatures (4, 20, and 40°C) and three frequencies (0.1, 1, and 10 Hz) were selected for  
 178 testing. The small-scale specimens (i.e., 50-mm diameter and 110-mm height) were fabricated

179 following a method proposed by Bowers et al. (2015). Two replicates were used in this test. Figure  
 180 2 presented the dynamic modulus master curves for HMA and cold recycled asphalt mixtures at a  
 181 reference temperature of 20°C. Herein, the HMA mixture contained 5.2% PG 64-22 asphalt binder  
 182 and 94.8% virgin aggregates. The air void content was 7% and the corresponding nominal  
 183 maximum aggregate size was 9.5mm. In the log-scale frequency space, the low frequency range  
 184 ( $10^{-5}$  to  $10^{-3}$  Hz) corresponds to the high temperature range, the mid-frequency range ( $10^{-3}$  to  $10^3$   
 185 Hz) corresponds to the intermediate temperature range, and the high frequency range ( $10^3$  to  $10^5$   
 186 Hz) corresponds to the low temperature range (Gu et al. 2018). As shown in Figure 2, the cold  
 187 recycled asphalt mixtures generally had lower dynamic moduli than the HMA in the entire  
 188 frequency range. In the high frequency (or low temperature) range, the cold recycled asphalt  
 189 mixtures showed comparable dynamic moduli. While in the low frequency (or high temperature)  
 190 range, the CCPR foamed asphalt mixture showed a much higher dynamic modulus than the other  
 191 cold recycled materials. In the Pavement ME Design program, the dynamic moduli of HMA and  
 192 cold recycled asphalt mixtures were tabulated according to the specified temperatures and  
 193 frequencies in the test. The software was able to automatically predict the dynamic moduli of  
 194 asphalt mixtures at any given temperature and load frequency.



195  
 196 **Figure 2. Dynamic Modulus Master Curves for Cold Recycled Asphalt Mixtures**

197

198 **3.2 Permanent Deformation Test**



199 The permanent deformation tests were performed on small-scale specimens to evaluate the  
 200 rutting resistance of cold recycled asphalt mixtures. The test procedures followed the AASHTO  
 201 Standard TP79. The tests were conducted at 54.5°C with a 483 kPa deviator stress and a 69 kPa  
 202 confining stress. Each specimen was subjected to the repeated compressive loading until the  
 203 accumulated plastic strain reached 100,000 microstrains or the number of loading cycles reached  
 204 20,000 cycles, whichever came first. The accumulated plastic strain curves were used to evaluate  
 205 the rutting susceptibility of asphalt mixtures. Three replicates were used in this test. Figure 3  
 206 showed the permanent deformation test results for HMA and cold recycled asphalt mixtures. As  
 207 presented, the CCPR foamed asphalt mixture exhibited the greatest rutting resistance, while the  
 208 CCPR emulsified, CIR foamed, and CIR emulsified asphalt mixtures had less rutting resistance  
 209 than the HMA. Compared to the CIR asphalt mixtures, the CCPR asphalt mixtures had much less  
 210 susceptibility to rutting. This might be because the CCPR asphalt mixtures had coarse gradations  
 211 than the CIR asphalt mixtures. The rutting curves were fitted by a power function, as shown in  
 212 Equation 1.

$$213 \quad \frac{\mathcal{E}_p}{\mathcal{E}_r} = aN^b \quad (1)$$

214 where  $\mathcal{E}_p$  is the accumulated plastic strain,  $\mathcal{E}_r$  is the resilient strain,  $N$  is the number of load  
 215 repetitions, and  $a$  and  $b$  are the model coefficients. Table 1 showed the determined rutting model  
 216 coefficients for these asphalt mixtures. In the Pavement ME Design program, the rutting potential  
 217 of asphalt mixture was calculated by Equation 2.

$$218 \quad \frac{\mathcal{E}_p}{\mathcal{E}_r} = \beta_{r1} 10^{k_1} T^{k_2 \beta_{r2}} N^{k_3 \beta_{r3}} \quad (2)$$

219 where  $T$  is the layer temperature,  $k_1$ ,  $k_2$  and  $k_3$  are the rutting coefficients, and  $\beta_{r1}$ ,  $\beta_{r2}$  and  $\beta_{r3}$   
 220 are the calibration factors, which are usually assumed as 1.0. For HMA, the default values of  
 221 rutting coefficients are:  $k_1 = -3.35412$ ,  $k_2 = 1.5606$ , and  $k_3 = 0.4791$ . In this study, both HMA  
 222 and cold recycled asphalt mixtures were assumed to possess comparable thermal characteristics,  
 223 which meant that the  $k_2$  value for cold recycled asphalt was also set as 1.5606. Accordingly, the  $k_1$   
 224 and  $k_3$  values for cold recycled asphalt were calculated by Equations 3 and 4, respectively.

$$225 \quad k_{1-CR} = k_{1-HMA} - \log_{10} \left( \frac{a_{HMA} \mathcal{E}_{rCR}}{a_{CR} \mathcal{E}_{rHMA}} \right) \quad (3)$$

$$k_{3-CR} = k_{3-HMA} - (b_{HMA} - b_{CR}) \quad (4)$$

where the subscript CR denotes the cold recycled asphalt, and the subscript HMA stands for the HMA. The calculated k-values of cold recycled asphalt were also shown in Table 1.

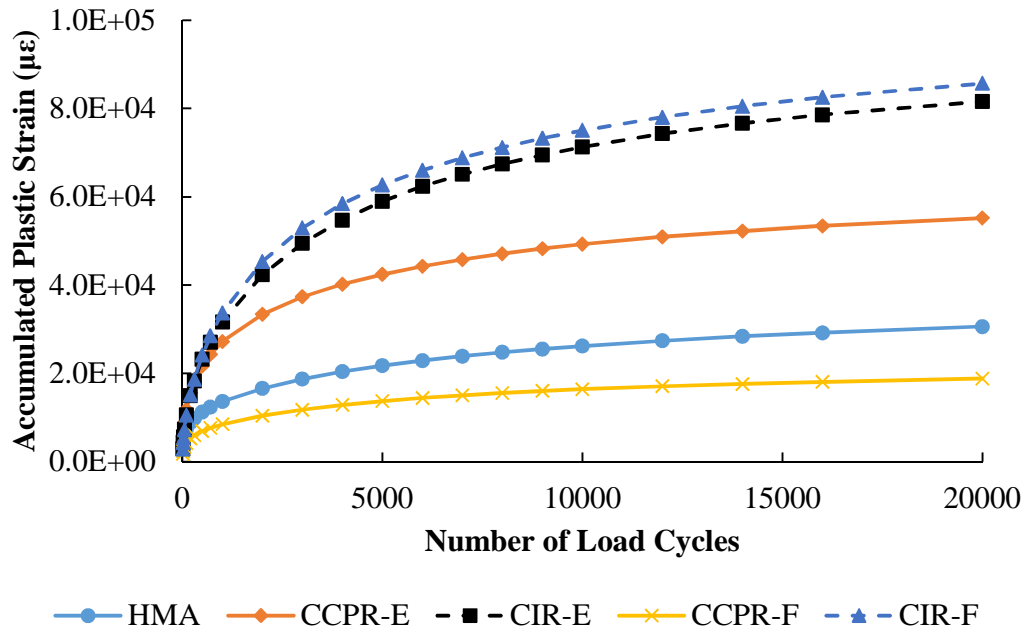


Figure 3. Accumulated Plastic Strain Curves for Cold Recycled Asphalt Mixtures

Table 1. Rutting Model Coefficients of Cold Recycled Asphalt Mixtures

Asphalt Mixture	Rutting Model Coefficients				
	Power Model		Pavement ME Design Model		
	a	b	$k_1$	$k_2$	$k_3$
HMA	2037	0.2813	-3.354	1.5606	0.4791
CCPR-F	1287	0.2718	-3.585	1.5606	0.4696
CCPR-E	3604	0.2753	-3.377	1.5606	0.4730
CIR-F	3018	0.3400	-3.569	1.5606	0.5378
CIR-E	2870	0.3358	-3.499	1.5606	0.5335

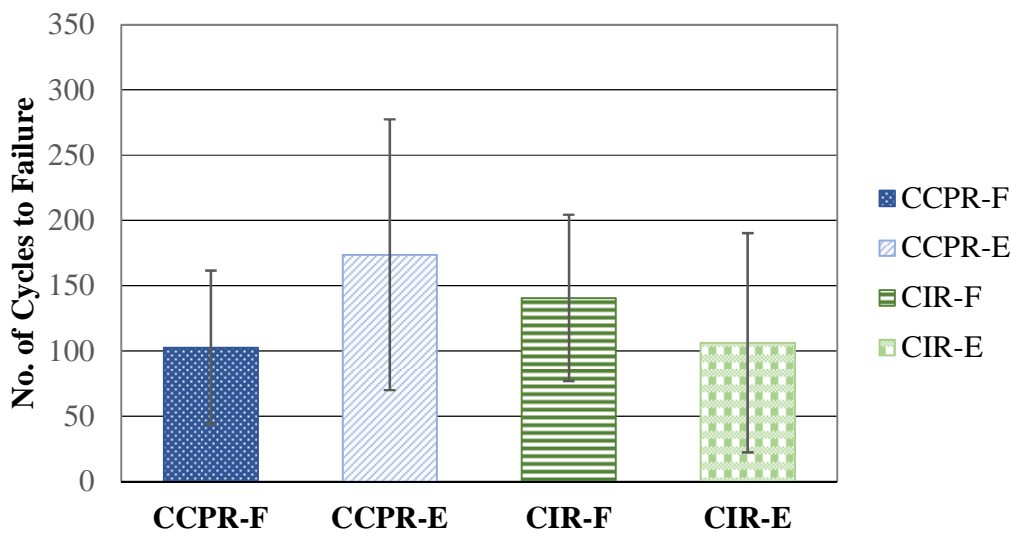
### 3.3 Overlay Test

To evaluate the fatigue cracking resistance of cold recycled asphalt mixtures, the overlay tests were conducted in accordance with the Texas Department of Transportation Standard Tex-248-F with some modifications. The field sampled and laboratory compacted specimens were tested at a frequency of 0.1 Hz with a maximum opening displacement of 0.381 mm. The load force and the plate opening displacement were recorded during the test. The number of failure cycles corresponds to 93% reduction of initial load. A higher number of failure cycles indicates a

241 better resistance to fatigue cracking. More details of overlay test can be found at Gu et al. (2015a  
 242 and 2015b). Four replicates were used in this test. Figure 4 showed the overlay test results for the  
 243 cold recycled asphalt mixtures. As illustrated, the CCPR foamed mixture had a better fatigue  
 244 cracking resistance than the CCPR emulsion mixture and the CIR foamed mixture had a lower  
 245 fatigue cracking resistance than the CIR emulsion mixture. The statistical analysis was conducted  
 246 to determine the significance of difference between these mixtures. Tukey's pairwise comparison  
 247 showed the differences of fatigue cracking resistance was insignificant at a significance level of  
 248 0.05 (p-value from analysis of variance). Moreover, Schwartz et al. (2017) stated that the bottom-  
 249 up fatigue cracking was not an important distress mode for cold recycled asphalt pavements. Thus,  
 250 this study did not consider the difference of fatigue properties among cold recycled asphalt  
 251 mixtures. In the Pavement ME program, the fatigue life of asphalt pavement was calculated by,

$$252 \quad N_f = 0.00432 * C * \beta_{f_1} * k_1 \left( \frac{1}{\epsilon_1} \right)^{k_2 * \beta_{f_2}} \left( \frac{1}{E_1} \right)^{k_3 * \beta_{f_3}} \quad (5)$$

253 where  $N_f$  is the fatigue life of asphalt pavement,  $C$  is the laboratory to field adjustment factor,  
 254  $\epsilon_1$  is the tensile strain at the critical location,  $E_1$  is the stiffness of material,  $k_1$ ,  $k_2$  and  $k_3$  are the  
 255 fatigue properties,  $\beta_{f_1}$ ,  $\beta_{f_2}$  and  $\beta_{f_3}$  are calibration factors. The default values of fatigue  
 256 properties are:  $k_1 = 0.007566$ ,  $k_2 = 3.9492$ , and  $k_3 = 1.281$ . In this study, these default fatigue  
 257 properties were used to represent the fatigue cracking resistance of cold recycled asphalt mixtures.



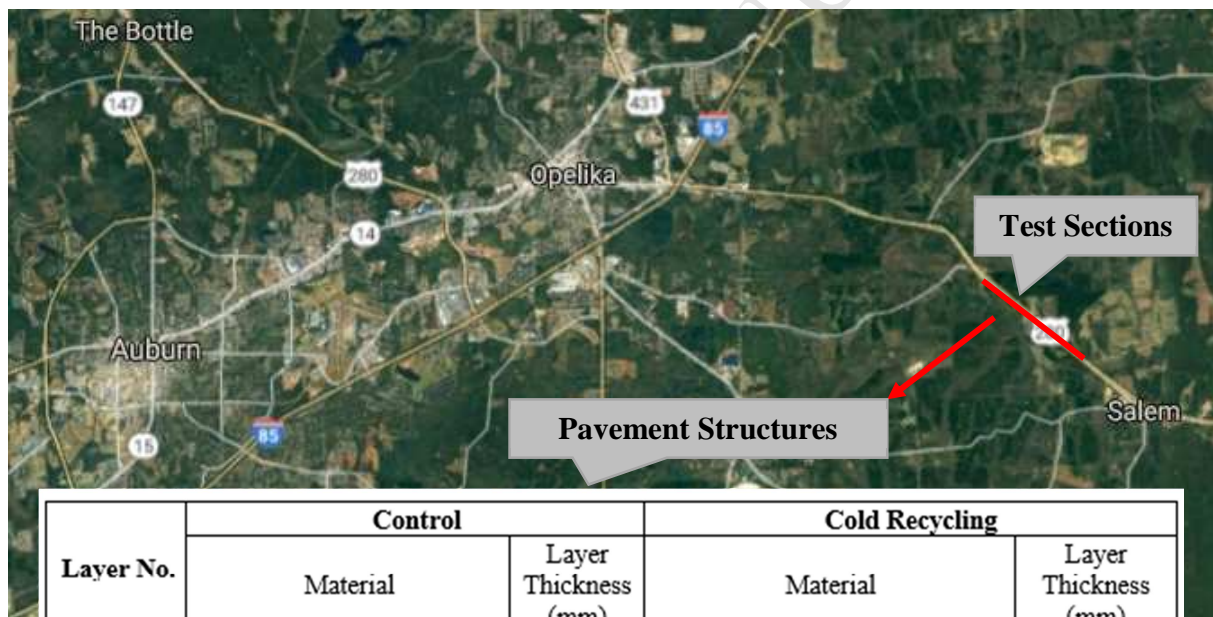
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259

Figure 4. Overlay Test Results of Cold Recycled Asphalt Mixtures

#### 260 4. Field Performance Prediction of Cold Recycled Asphalt Pavements

261 In 2015, the NCAT constructed four test sections on US280 in Lee County, Alabama, to evaluate  
 262 the field performance of cold recycled asphalt pavements. These sections included the CCPR with  
 263 emulsified binder (CCPR-E) and with foamed binder (CCPR-F), and the CIR with emulsified  
 264 binder (CIR-E) and with foamed binder (CIR-F). Figure 5 showed the location and structures of  
 265 these test sections. To compare with these cold recycled asphalt pavements, one HMA pavement  
 266 structure was assumed as the control section (Control) in this study. As illustrated in Figure 5, the  
 267 thickness of the cold recycled asphalt layer was 90 mm. The cold recycled asphalt layer was  
 268 surfaced with a 25-mm HMA overlay. The underlying layers included 254-mm asphalt treated  
 269 base (ATB), 203-mm unbound granular subbase, and subgrade soil. The annual average daily  
 270 traffic was 18,300 and 16% of the daily traffic was estimated to be heavy truck traffic. The traffic  
 271 speed limit was 105 km/h.



NA= Not Available

272

273

**Figure 5. Cold Recycled Asphalt Pavement Sections on US280 in Alabama**

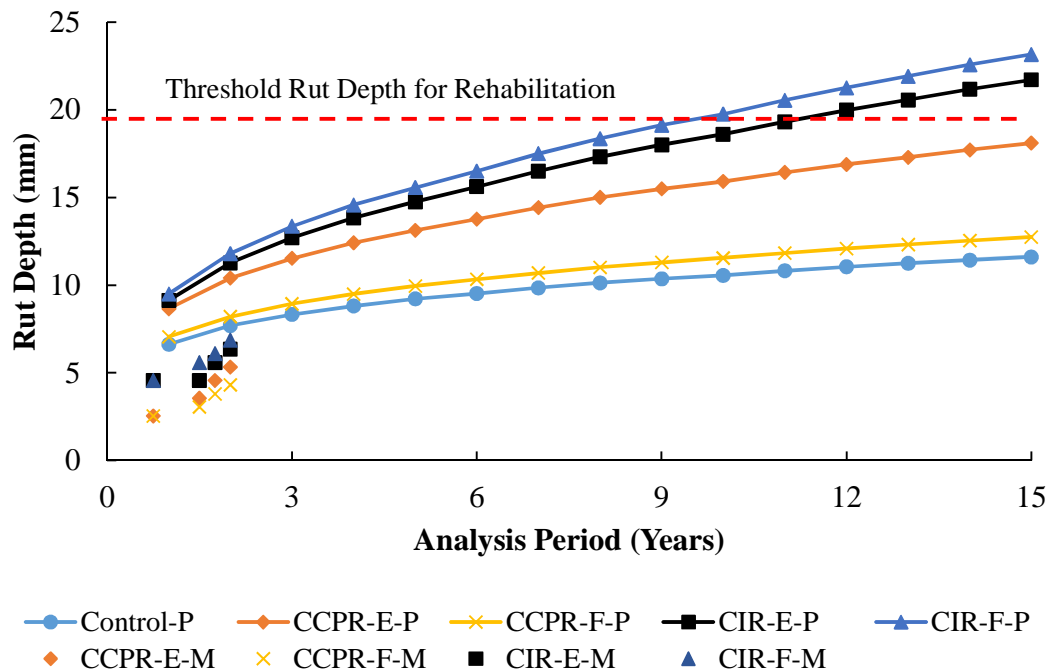
274

275 In this study, the level 1 inputs were used for characterizing the HMA overlay, the cold

276 recycled asphalt layer, and the asphalt treated base in the Pavement ME Design program. These inputs were determined from the dynamic modulus and permanent deformation test results

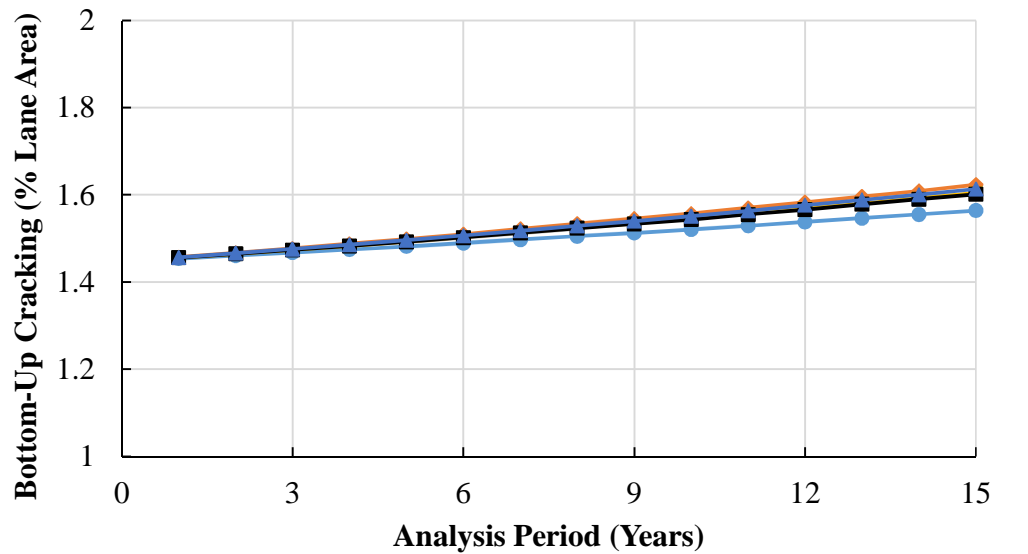
277 presented in the previous section. The level 2 inputs were used for unbound aggregates subbase  
278 and subgrade soil. The resilient moduli of unbound aggregates and subgrade soil were 206 MPa  
279 and 103 MPa, respectively. The analysis period was assigned as 15 years.

280 Figure 6 showed the predicted and measured rut depths using the Pavement ME Design  
281 program. In the legend, “P” stands for the predicted values, and “M” represents the measured  
282 results. As illustrated in Figure 6, the predicted rut depth of CCPR-F section showed comparable  
283 rut depth to the control section, which was around 10 mm after 15-year service life. Compared to  
284 the control section, the CCPR-E section had a higher predicted rut depth, but still satisfied the rut  
285 depth criterion, which allowed the rut depth less than 19 mm. While according to this rut depth  
286 criterion, both CIR sections required rehabilitation activities before the end of the analysis period.  
287 Specifically, the CIR-E section required the rehabilitation at the 10<sup>th</sup> year of service, and the CIR-F  
288 section needed the rehabilitation at the 11<sup>th</sup> year of service. Figure 6 also showed that the model  
289 predicted rut depths almost doubled those measured from the field thus far. This demonstrated that  
290 the Pavement ME Design program over predicted the rutting depth for asphalt pavements. The  
291 discrepancies between ME predictions and field measurements might be attributed to the lack of  
292 local calibration of ME coefficients. Another reason for the discrepancies is that the current  
293 laboratory curing protocol might not simulate the long-term physical and chemical changes of cold  
294 recycled asphalt mixtures in the field. In this study, the predicted performance did not consider the  
295 increase of material properties due to the long-term curing. However, both the model predictions  
296 and field measurements revealed the same sequence of rutting susceptibility for these cold  
297 recycled pavements, i.e., CCPR-F < CCPR-E < CIR-E < CIR-F. This finding was consistent with  
298 the permanent deformation test results in the laboratory.



299  
300 **Figure 6. Predicted and Measured Rut Depths for Cold Recycled Asphalt Pavements**

301 Figure 7 presented the predicted bottom-up fatigue cracking in asphalt pavements. It was  
302 shown that the bottom-up fatigue cracking distress was only 1.4-1.6 % lane area in cold recycled  
303 asphalt pavements, which was much less than the threshold value for rehabilitation (i.e., 25% lane  
304 area). This confirmed with the initial assumption that the bottom-up fatigue cracking was a  
305 negligible distress mode for cold recycled asphalt pavements. Within the 2-year service, no fatigue  
306 cracking had been observed from these cold recycled pavement sections. The measured fatigue  
307 cracking performance was consistent with the prediction from the Pavement ME Design program.

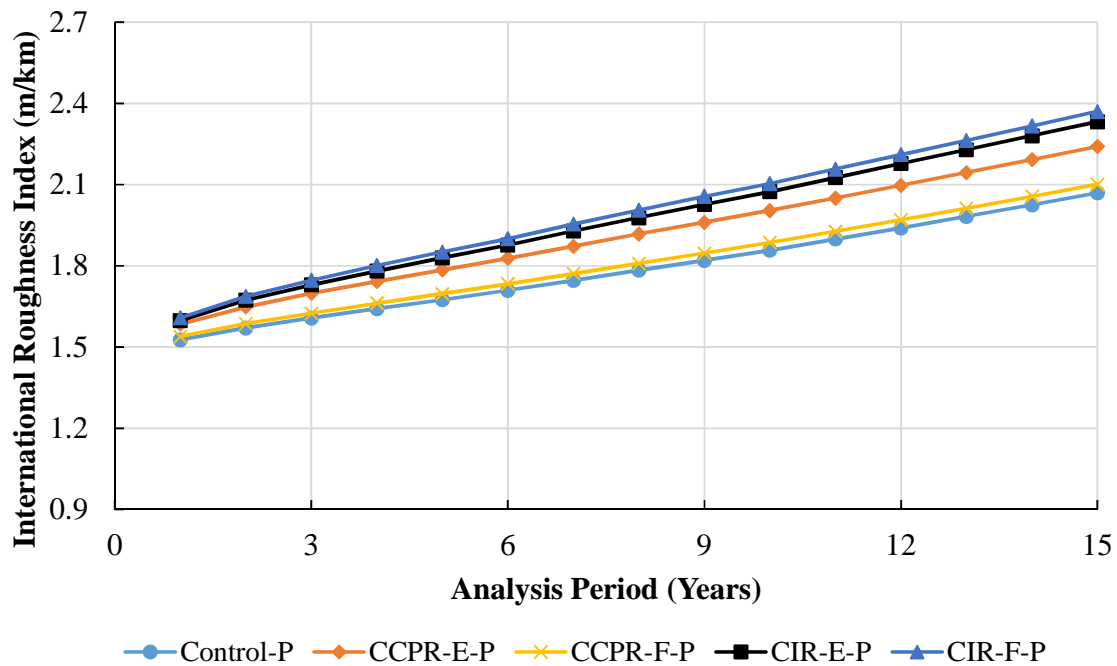


308 —●— Control-P    —◆— CCPR-E-P    —×— CCPR-F-P    —■— CIR-E-P    —▲— CIR-F-P

309 **Figure 7. Predicted Fatigue Cracking for Cold Recycled Asphalt Pavements**

310 Figure 8 illustrated the predicted international roughness index (IRI) for cold recycled  
 311 asphalt pavements. According to the Mechanistic-Empirical Pavement Design Guide (MEPDG),  
 312 the IRI reflects the ride quality of pavements, which is associated with the rutting and fatigue  
 313 cracking distresses (AASHTO 2008). As shown in Figure 8, the CCPR-F section had comparable  
 314 IRI values to the control section, but had lower IRI values than the CCPR-E section. Compared to  
 315 the CCPR sections, the CIR sections yielded much greater IRI values. In the Pavement ME Design  
 316 program, the threshold value for IRI was 2.7 m/km. Thus, all of the cold recycled asphalt  
 317 pavements satisfied the IRI criterion.

318



319  
320 **Figure 8. Predicted International Roughness Index for Cold Recycled Asphalt Pavements**

321 In general, the CCPR-F section exhibited much better performance than other cold  
322 recycled pavement sections, which was even comparable to the control section. Compared to the  
323 CCPR-F section, the CCPR-E section had much more rutting and fatigue cracking distresses, but  
324 still passed the performance criteria in the analysis period. According to the Pavement ME  
325 predictions, the CIR-F and CIR-E sections had severe rutting distresses, which may require major  
326 rehabilitation at 10<sup>th</sup> and 11<sup>th</sup> year of service, respectively. Note that these conclusions are drawn  
327 from the performance prediction results by the Pavement ME Design program. The designed  
328 material properties of cold recycled asphalt mixtures are dependent on the adopted mix design  
329 procedure and the laboratory curing protocol.

### 331 5. Sustainability Assessment of Cold Recycled Asphalt Pavements

332 Based on the predicted performance results, this section compared the life cycle costs and  
333 environmental benefits of the four different cold recycling technologies including CCPR-E,  
334 CCPR-F, CIR-E, and CIR-F.

#### 335 5.1 Life Cycle Cost Analysis

336 To enable a fair comparison among competing pavement alternatives, all future anticipated  
337 costs and salvage value were discounted to the present to take into account the time value. The net



338 present value (NPV) of initial construction and discounted future costs and salvage value was then  
 339 determined for each alternative using the common economics formula shown in Equation 6.  
 340 Finally, the alternative with the lowest NPV was considered to be the most economical choice.

$$341 \quad NPV = \text{Initial Const. Cost} + \sum_{k=1}^N \text{Future Cost}_k \left[ \frac{1}{(1+i)^{n_k}} \right] - \text{Salvage Value} \left[ \frac{1}{(1+i)^{n_e}} \right] \quad (6)$$

342 where  $i$  is the discount rate;  $n_k$  is the number of years from initial construction to the  $k^{\text{th}}$   
 343 expenditure; and  $n_e$  is the analysis period. For the sake of simplicity, this study did not consider  
 344 any user costs in the life cycle cost analysis, and assumed the analysis period is only 10 years.  
 345 According to the predicted performance results, there were no rehabilitation activities required for  
 346 all of the four cold recycling technologies. Herein, the discount rate was assigned as 4.0%, which  
 347 was a common value used by most of the Departments of Transportation in the United States  
 348 (West et al. 2013). Table 2 compared the life cycle costs of the HMA and cold recycled pavement  
 349 alternatives. The details of life cycle cost analysis can be found at Tables S1-S4 of the supporting  
 350 documents. As presented in Table 2, all of the cold recycled pavement sections had lower NPVs  
 351 than the HMA section. This confirmed that the cold recycling technique is more economical than  
 352 the replacement of HMA layer. By comparing the different cold recycling technologies, it was  
 353 found that the CCPR technologies were more cost-effective than the CIR technologies. This was  
 354 because the CCPR pavements had comparable initial construction cost, but much higher salvage  
 355 value than the CIR pavements. Table 2 also demonstrated that the CCPR-F was the most  
 356 economical choice in this case study, which reduced the NPV by 32% when compared to the  
 357 HMA replacement.

358 **Table 2. Comparison of Life Cycle Costs of Pavement Alternatives**

Pavement Alternatives	Initial Construction Cost (\$/LKM <sup>1</sup> )	Salvage Value (\$/LKM <sup>1</sup> )	Net Present Value (\$/LKM <sup>1</sup> )
HMA	34,257	15,225	23,971
CCPR-F	23,185	10,304	16,224
CCPR-E	23,754	7,918	18,405
CIR-F	19,866	0	19,866
CIR-E	22,467	2,043	21,088

359 Note: <sup>1</sup> LKM = Lane Kilometer

360 **5.2 Life Cycle Assessment**

361 The life cycle assessment was conducted to quantify the environmental benefits of the four  
 362 different cold recycling technologies. Table 3 listed the life cycle inventory (LCI) of asphalt  
 363 pavement. Note that this study only focused on the energy consumption and greenhouse gas (GHG)  
 364 emissions of the five processes, including raw material production, asphalt mixture manufacture,  
 365 pavement milling, material transport, and material placement. The material composition was  
 366 described in the previous sections. The transport distance was 32 km for all projects.

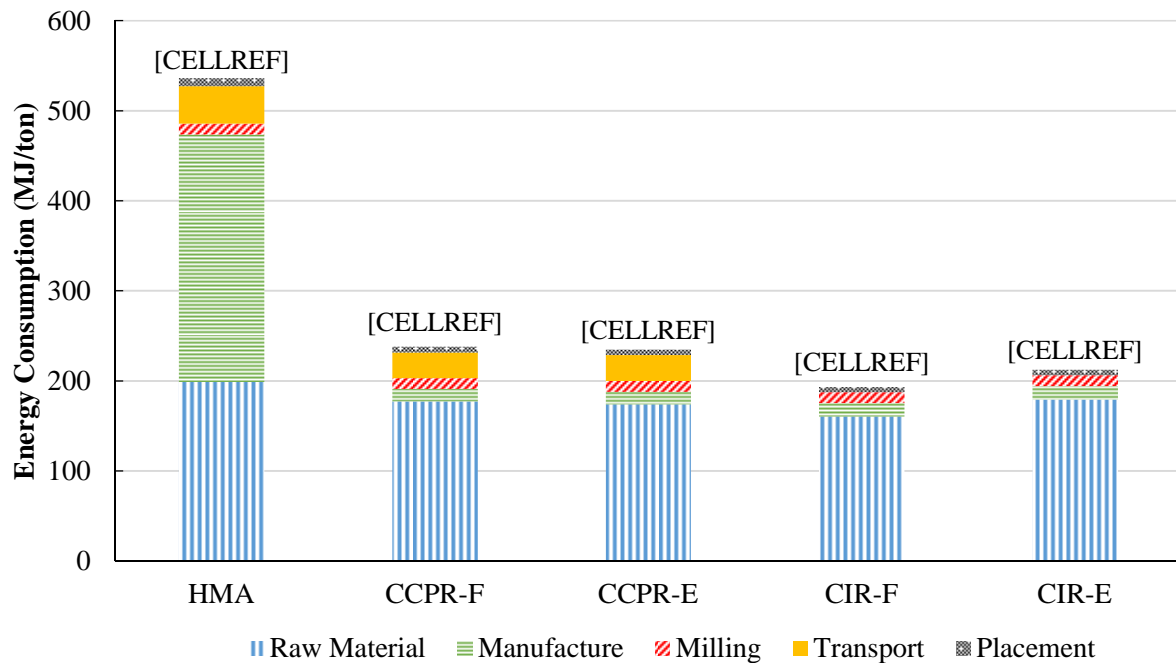
367 **Table 3. Life Cycle Inventory of Asphalt Pavement**

Processes		Energy Consumption (MJ/ton)	GHG Emissions (kg/ton)	LCI Source
Raw Materials	Asphalt Binder	4402	274	(EIA, 2013)
	Asphalt Emulsion (62% Residue)	3165	195	(Yang, 2014)
	Cement	5745	921	(PCA, 2007)
	Crushed Aggregates	30	2.1	(EarthShift, 2013)
	Water	10	0.3	(Chappat and Bilal, 2003)
Manufacture	HMA <sup>1</sup>	275	22	
	CCPR Mix	14	1	
	CIR Mix	15	1.13	
Milling		12	0.8	(EPA, 2014)
Transport (km/ton)		1.3	0.06	
Placement	HMA	9	0.6	(Chappat and Bilal, 2003)
	Cold Mix Asphalt	6	0.4	

368 Note: <sup>1</sup> 20% RAP was used in the HMA

369 Figure 9 presented the energy consumption of HMA and cold recycling projects. It was  
 370 shown that the cold recycling technologies reduced the energy consumption by 56-64%.  
 371 Compared to the HMA project, both CCPR and CIR projects exhibited similar reduction in energy  
 372 consumption. As shown in Figure 9, the cold recycling projects dramatically reduced the energy  
 373 consumption in the manufacture process, and slightly saved the energy from the production of raw  
 374 materials. By comparison of the cold recycling projects, the CIR projects consumed less energy  
 375 than the CCPR projects, which was mainly because that the CIR projects took the material  
 376 transport out of the entire process.

377



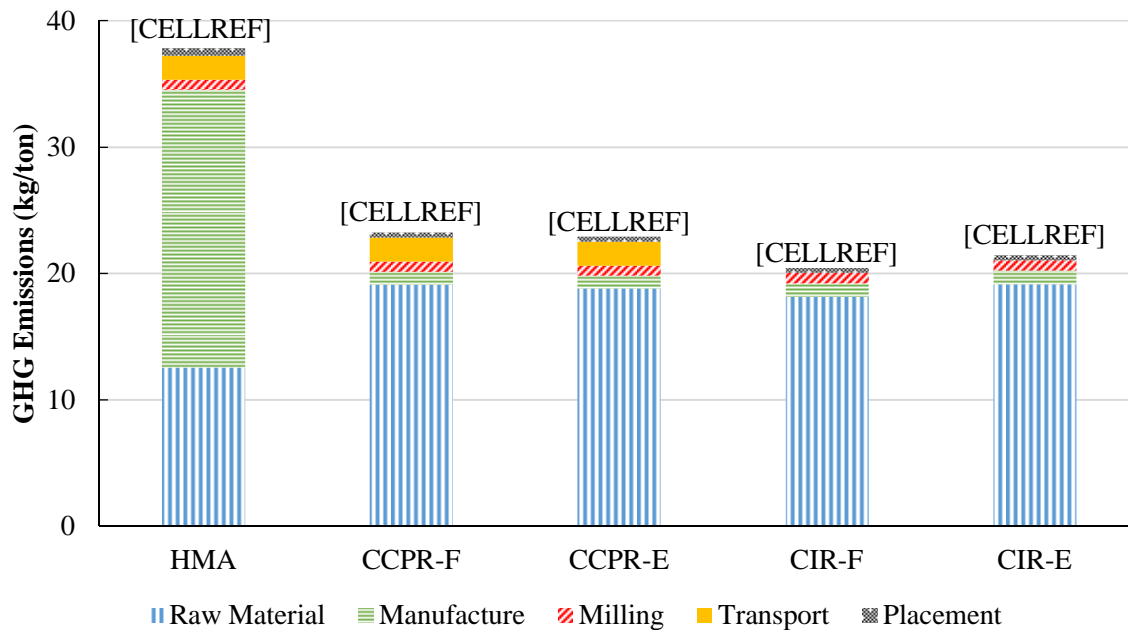
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**Figure 9. Energy Consumption of Cold Recycling Projects**

380 Figure 10 showed the GHG emissions of HMA and cold recycling projects. Compared to  
 381 the HMA project, the cold recycling technologies reduced the amount of GHG emissions by 39-  
 382 46%. Both CCPR and CIR projects exhibited similar reduction in GHG emissions. As  
 383 demonstrated in Figure 10, the cold recycling projects substantially reduced the GHG emissions in  
 384 the manufacture process, which was due to the significant decrease of manufacture temperature.  
 385 Although the cold recycling projects utilized less asphalt binder and crushed aggregates, they still  
 386 had higher GHG emissions than the HMA project in the production of raw materials. This was  
 387 because that the production of cement yielded much higher GHG emissions than other materials.  
 388 Compared among the cold recycling projects, the CIR projects had marginally lower GHG  
 389 emissions than the CCPR projects, which was still attributed to the remove of material transport  
 390 from the entire process.

391



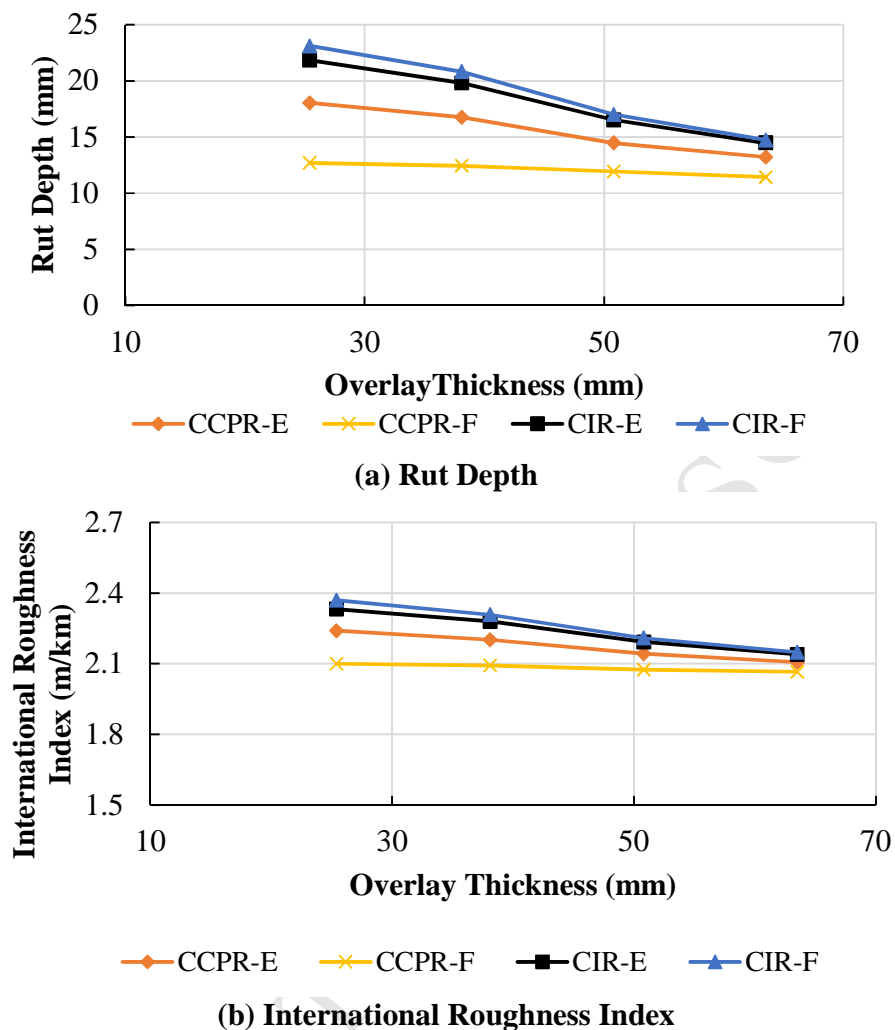
392  
393 **Figure 10. Greenhouse Gas Emissions of Cold Recycling Projects**  
394

### 395 6. Structural Performance Assessment of Cold Recycled Asphalt Pavements

396 The cold recycling treatment depths generally have a narrow range that is from 75 to 100 mm. For  
397 cold recycled asphalt pavement, an overlay is needed to place on top of the cold recycled layer to  
398 ensure good ride quality. To design a cost-effective cold recycled pavement structure, the  
399 thicknesses of overlay and ATB are dependent on the type of cold recycling technologies and the  
400 climate condition. This section discussed the influence of these design parameters on the  
401 performance of cold recycled asphalt pavements.

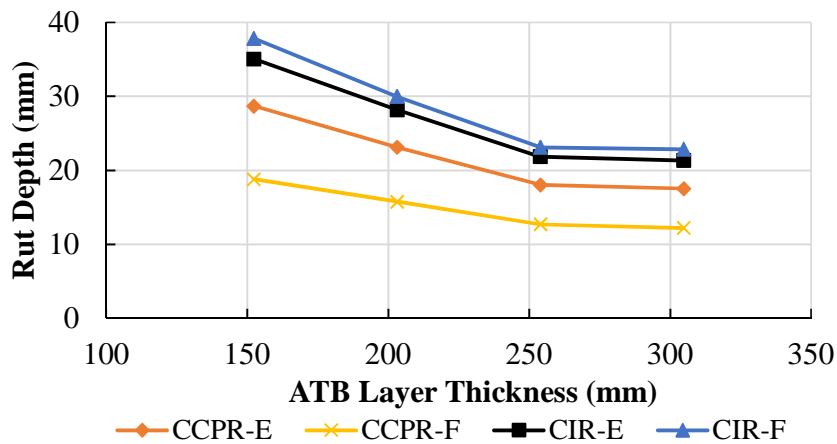
402 This study assumed the cold recycled pavement structure shown in Figure 5 as the base  
403 structure. The effect of overlay thickness on the performance of cold recycled asphalt pavements  
404 was shown in Figure 11. As presented in Figure 11a, the increase of overlay thickness significantly  
405 reduced the final rut depth of the CIR sections and the CCPR-E section, and slightly reduced the  
406 final rut depth of CCPR-F section. The pavements with 51 and 64 mm thick overlay could pass the  
407 design criterion for rutting regardless of which cold recycling technology is applied. Figure 11b  
408 showed that all of the pavement sections also met the requirement for IRI. It was demonstrated  
409 that the increase of overlay thickness was beneficial for the ride quality. Increasing overlay  
410 thickness from 25 to 64 mm reduced the IRI by 10.3% for the CIR-F section, 9.0% for the CIR-E  
411 section, 1.7% for the CCPR-F section, and 6.4% for the CCPR-E section.

412

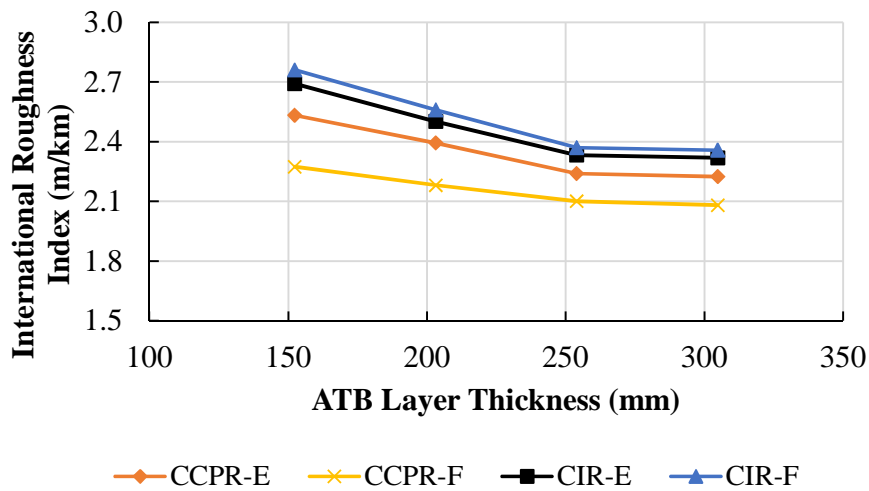


413 **Figure 11. Effect of Overlay Thickness on Cold Recycled Asphalt Pavement Performance**  
 414 **after 15-Year Service**

415 Figure 12 presented the effect of ATB layer thickness on the performance of cold recycled  
 416 asphalt pavements. It was shown in Figure 12a that the increase of ATB layer thickness from 152  
 417 to 254 mm substantially reduced the final rut depth for all the cold recycled pavements, while  
 418 increasing its thickness from 254 to 305 mm had a negligible influence on rutting. In these cases,  
 419 the sections passing the rut criterion included all the CCPR-F sections and CCPR-E sections with  
 420 254 and 305 mm ATB. Figure 12b demonstrated that the increase of ATB thickness was effective  
 421 in reducing the IRI of CCPR-E, CIR-E, and CIR-F sections, and the CCPR-F sections with thin  
 422 ATB still exhibited extraordinary ride quality.



(a) Rut Depth

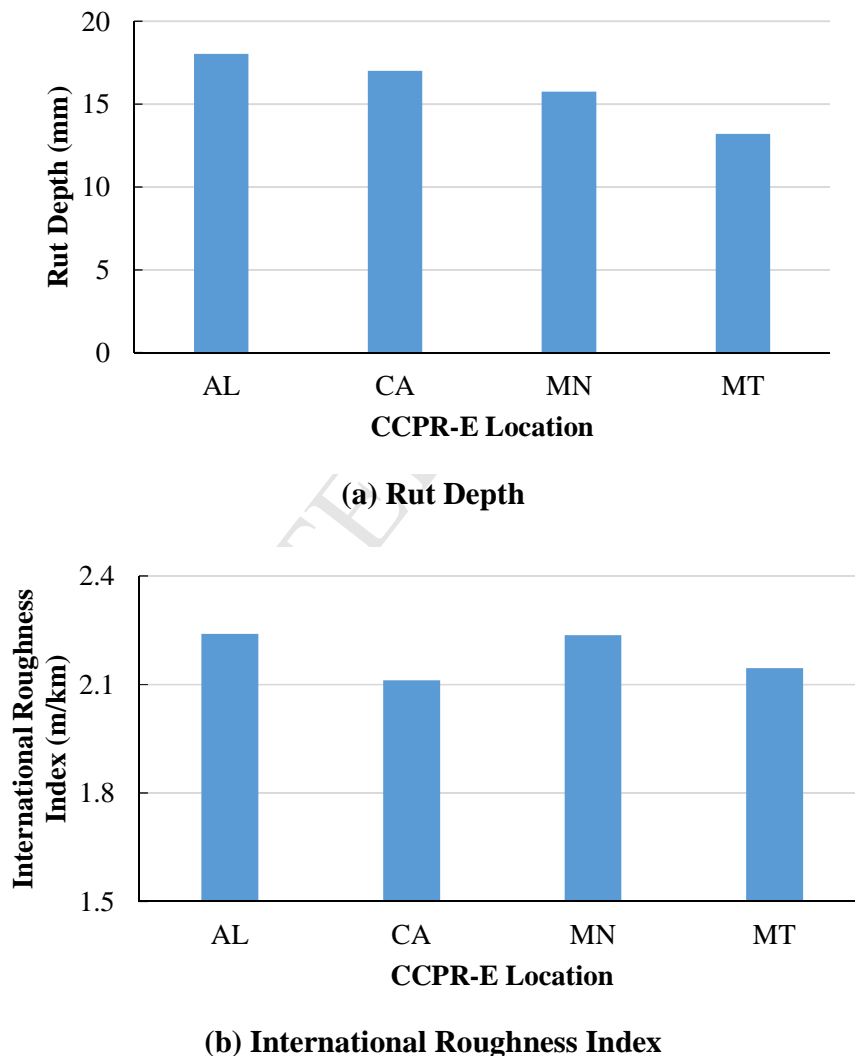


(b) International Roughness Index

423 **Figure 12. Effect of ATB Thickness on Cold Recycled Asphalt Pavement Performance after**  
 424 **15-Year Service**

425 In the Long-Term Pavement Performance (LTPP) database, the climate in the United  
 426 States is divided into four zones, namely, wet-freeze, wet-no-freeze, dry-freeze and dry-no-freeze.  
 427 The aforementioned cases were located in the State of Alabama (AL), which was classified in wet-  
 428 no-freeze zone. To evaluate the impact of climate condition on structural design, other three  
 429 weather stations were also analyzed in this study, which included Los Angeles in California (CA,  
 430 dry-no-freeze), Bozeman in Montana (MT, dry-freeze), and Minneapolis in Minnesota (MN, wet-  
 431 freeze). Figure 13 showed the impact of climate conditions on the performance of CCPR-E  
 432 sections. As presented in Figure 13a, the MT section had the lowest rut depth when compared  
 433 against other sections. The AL and CA sections exhibited similar resistances to rutting. Compared  
 434 to the no-freeze zones (i.e., AL and CA sections), the freeze zones (i.e., MT and MN sections)

435 resulted in less rutting distress. This might be because the asphalt materials in freeze zones were  
436 much stiffer than those in no-freeze zones. As shown in Figure 13b, the CA section had the lowest  
437 IRI value in comparison to other sections. Compared to wet zones (i.e., AL and MN sections), the  
438 dry zones yielded lower IRI values at the end of analysis period. In this case study, the CCPR-E  
439 structures shown in Figure 5 passed both the rutting and IRI design criteria in the all four climatic  
440 zones. It is worth mentioning that the current Pavement ME Design considers the influence of  
441 climate on pavement performance by varying the mechanical properties of asphalt material and  
442 unbound material. The influence of climate on moisture damage and freeze-thaw effects are not  
443 included in the analysis.



444 **Figure 13. Impact of Climate Conditions on the Performance of CCPR-E Sections**

445  
446  
447

## 448 7. Conclusions and Future Work

449 This study evaluated the structural characteristics of cold recycled asphalt pavements using a  
450 mechanistic-empirical approach, and assessed the sustainability of cold recycling technologies in  
451 terms of life cycle costs and environmental benefits. The major contributions of this paper were  
452 summarized as follows:

- 453 • The dynamic modulus test results confirmed that the cold recycled asphalt mixtures should  
454 be considered as thermo-viscoelastic materials (Kim et al. 2009). The permanent  
455 deformation test results demonstrated that the CCPR mixtures showed less rutting  
456 susceptibility than the CIR mixtures, and the CCPR-F mixture had comparable rutting  
457 resistance to HMA. The overlay test results showed that the cold recycled asphalt mixtures  
458 had comparable resistances to fatigue cracking.
- 459 • This study confirmed that the bottom-up fatigue cracking was a negligible distress mode  
460 for cold recycled asphalt pavements (Schwartz et al. 2017). Four cold recycled asphalt  
461 pavement sections (i.e., CCPR-E, CCPR-F, CIR-E, and CIR-F) were constructed in the  
462 State of Alabama, US. The monitored and predicted pavement performance showed similar  
463 trends in the first two years, but the Pavement ME Design program over predicted the  
464 rutting depth of these sections relative to the field measurements.
- 465 • The results of life cycle cost analysis demonstrated that all of the four cold recycling  
466 projects yielded less NPVs than the HMA project. Compared among the cold recycling  
467 projects, the CCPR-F was the most economical choice in this case study. The life cycle  
468 assessment data indicated that the cold recycling technologies reduced the energy  
469 consumption by 56-64%, and decreased the GHG emissions by 39-46%. Compared to the  
470 CCPR projects, the CIR projects had slightly less energy consumption and GHG emissions.
- 471 • The rut depth and IRI of cold recycled asphalt pavements were significantly affected by the  
472 overlay and ATB thicknesses and the climatic conditions.

473  
474 Cold recycled asphalt mixtures are evolutive materials whose properties change due to the  
475 physical and chemical processes, such as moisture evaporation, emulsion setting, and cement  
476 hydration. The future studies should focus on the development of laboratory curing protocol to  
477 simulate these long-term physical and chemical changes. The developed curing protocol will be



478 crucial to determine the material properties of cold recycled asphalt mixtures for pavement  
479 structural design.

480

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488

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