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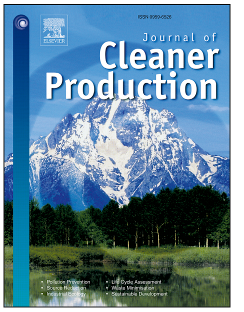

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Structural Performance and Sustainability Assessment of Cold Central-Plant and In-Place Recycled Asphalt Pavements: A Case Study

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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.

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

1. Introduction

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

The existing studies primarily focused on the laboratory and field evaluation of cold recycled asphalt mixtures. For instance, Kim and Lee (2006) and Wirtgen (2012) developed mix design methods for cold recycled asphalt mixtures with foamed asphalt binder. These mix design methods not only define the requirements for RAP materials, foamed asphalt binder, and chemical additives, but also provide the procedures to design the optimum binder system. With the increase of field experience in cold recycling, Asphalt Recycling and Reclaiming Association (ARRA) (2015) developed new mix design methods for cold recycled asphalt mixtures with foamed and emulsified asphalt binders, which redefined the material requirements and the performance criteria for asphalt mixtures. Kim et al. (2009), Khosravifar et al. (2015), Diefenderfer et al. (2016), and Lin et al. (2017) conducted the dynamic modulus laboratory test for various cold recycled asphalt mixtures. They found that the cold recycled asphalt mixtures exhibited less temperature and frequency dependencies compared to hot mix asphalt (HMA), but still should be classified as thermo-viscoelastic materials. Niazi and Jalili (2009), Kim et al. (2009), and Khosravifar et al. (2015) evaluated the rutting resistance of cold recycled asphalt mixtures using the permanent deformation tests. They pointed out that the rutting resistance of cold recycled asphalt mixtures was dependent on the type and dosage of binders, in particular on the dosage of cement. If the dosage of cement is less than 1.5%, the cold recycled asphalt mixtures generally have less rutting resistance than the HMA (Bocci et al. 2011, Grilli et al. 2012, Stimilli et al. 2013, Leandri et al. 2015). Yan et al. (2010) investigated the fatigue cracking resistance of cold recycled asphalt mixtures. They concluded that the fatigue properties of foamed and emulsified asphalt treated mixtures were similar to the HMA. Diefenderfer et al. (2012, 2016) evaluated the CIR and CCPR projects in I-81 highway in Virginia and National Center for Asphalt Technology (NCAT) Test Track, respectively. They reported that all of the cold recycling sections exhibited excellent performance in terms of rutting and fatigue cracking resistance.

Although a great deal of studies have comprehensively characterized the performance of cold recycled asphalt mixtures, limited research has dealt with the structural assessment of cold recycled asphalt pavements. Diefenderfer et al. (2015) and Diaz-Sanchez et al. (2017) determined the layer coefficients of cold in-place and central-plant recycled asphalt pavements for use in AASHTO 93 Design. Their methodologies relied on an empirical relationship between the layer coefficient and the back-calculated resilient moduli. This relationship was originally developed for HMA (Huang 2004), but whether it is suitable for cold recycled asphalt mixtures is still not clear. Moreover, more highway agencies are abandoning the AASHTO 93 Design method and adopting the Mechanistic-Empirical Pavement Design Guide - now available as the AASHTOWare Pavement ME Design program (Smith and Braham 2018, Shirzad et al. 2018). In the current Pavement ME Design program, the cold recycled asphalt mixture is considered as a bound base material, which means that users only need to assign a constant resilient modulus. However, this assumption contradicts the fact that cold recycled asphalt mixture exhibits thermo-viscoelastic characteristics being functional as an asphalt layer. Therefore, there is a need to develop a mechanistic-empirical structural assessment methodology, which will take into account the mechanical characteristics (e.g., viscoelasticity) of cold recycled asphalt pavements. Furthermore, the developed methodology should discriminate the pavement performance by using different cold recycling technologies. The methodology should also be capable of evaluating the effects of structural properties and climatic conditions on the long-term performance of cold recycled asphalt pavements. These analyses will facilitate the use of cold recycling technologies for different pavement structures in different climate regions.

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

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

2. Mix Design

This study followed the ARRA mix design guidelines to design cold recycled asphalt mixtures with foamed and emulsified asphalt binders. The RAP materials were collected from a previous construction project on US Highway 280 in Opelika, Alabama. The RAP binder content ranged from 4.9 – 5.2% and was performance graded as PG 100-10. The base asphalt binder used for foaming and the emulsion were PG 67-22 binder from Birmingham, Alabama and PG 64-22 binder from Parsons Tennessee, respectively.

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

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

Figure 1 showed the gradations of the cold recycled asphalt mixtures before and after ignition. The figure legend used “RAP” to represent source RAP before burning, “F” to stand for foamed mixtures, and "E" for emulsion mixtures. The RAP materials were sampled after crushing and fractionation using the CIR and CCPR processes. As presented in Figure 1, the CCPR had coarser gradations than the CIR before and after ignition. After ignition, the foamed and emulsion mixtures had similar aggregate gradations for both CIR and CCPR technologies.

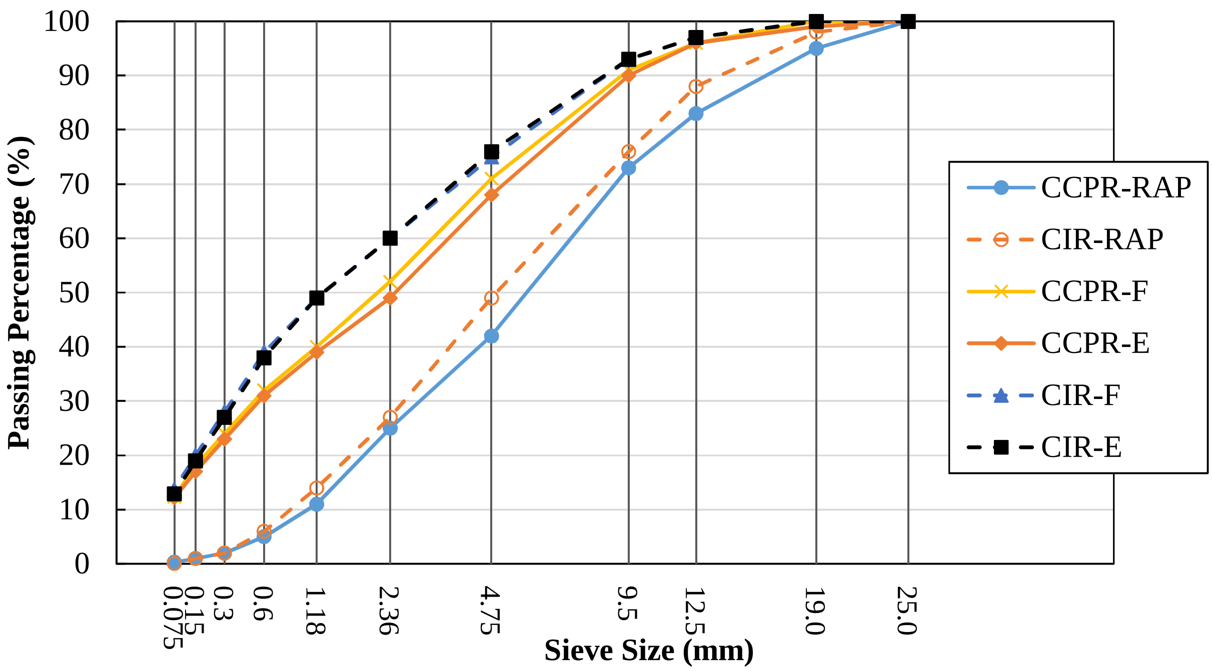


Figure 1. Aggregate Gradations of Cold Recycled Asphalt Mixtures

3. Laboratory Characterization of Cold Recycled Asphalt Mixtures

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

3.1 Dynamic Modulus Test

The dynamic modulus test was used to determine the viscoelastic inputs of cold recycled asphalt mixtures for the Pavement ME Design program. These tests were conducted in an asphalt mixture performance tester (AMPT) in accordance with AASHTO TP79 with some modifications. Three temperatures (4, 20, and 40°C) and three frequencies (0.1, 1, and 10 Hz) were selected for testing. The small-scale specimens (i.e., 50-mm diameter and 110-mm height) were fabricated following a method proposed by Bowers et al. (2015). Two replicates were used in this test. Figure 2 presented the dynamic modulus master curves for HMA and cold recycled asphalt mixtures at a reference temperature of 20°C. Herein, the HMA mixture contained 5.2% PG 64-22 asphalt binder and 94.8% virgin aggregates. The air void content was 7% and the corresponding nominal maximum aggregate size was 9.5mm. In the log-scale frequency space, the low frequency range (10^{-5} to 10^{-3} Hz) corresponds to the high temperature range, the mid-frequency range (10^{-3} to 10^{3} Hz) corresponds to the intermediate temperature range, and the high frequency range (10^{3} to 10^{5} Hz) corresponds to the low temperature range (Gu et al. 2018). As shown in Figure 2, the cold recycled asphalt mixtures generally had lower dynamic moduli than the HMA in the entire frequency range. In the high frequency (or low temperature) range, the cold recycled asphalt mixtures showed comparable dynamic moduli. While in the low frequency (or high temperature) range, the CCPR foamed asphalt mixture showed a much higher dynamic modulus than the other cold recycled materials. In the Pavement ME Design program, the dynamic moduli of HMA and cold recycled asphalt mixtures were tabulated according to the specified temperatures and frequencies in the test. The software was able to automatically predict the dynamic moduli of asphalt mixtures at any given temperature and load frequency.

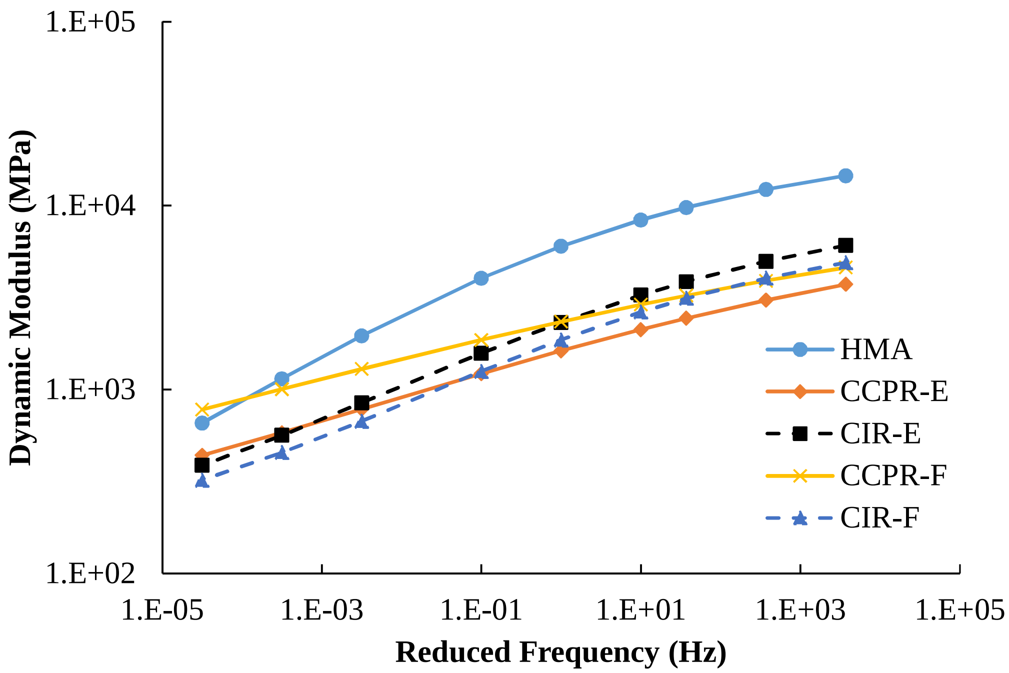


Figure 2. Dynamic Modulus Master Curves for Cold Recycled Asphalt Mixtures

3.2 Permanent Deformation Test

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

$$\frac{\varepsilon_p}{\varepsilon_r} = aN^b \tag{1}$$

where ε_p is the accumulated plastic strain, ε_r is the resilient strain, N is the number of load repetitions, and a and b are the model coefficients. Table 1 showed the determined rutting model coefficients for these asphalt mixtures. In the Pavement ME Design program, the rutting potential of asphalt mixture was calculated by Equation 2.

$$\frac{\varepsilon_p}{\varepsilon_r} = \beta_{r1} 10^{k_1} T^{k_2 \beta_{r2}} N^{k_3 \beta_{r3}} \tag{2}$$

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

$$k_{1-CR} = k_{1-HMA} - \log_{10}\left(\frac{a_{HMA}\varepsilon_{r_{CR}}}{a_{CR}\varepsilon_{r_{HMA}}}\right) \tag{3}$$

$$k_{3-CR} = k_{3-HMA} - \left(b_{HMA} - b_{CR}\right) \tag{4}$$

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.

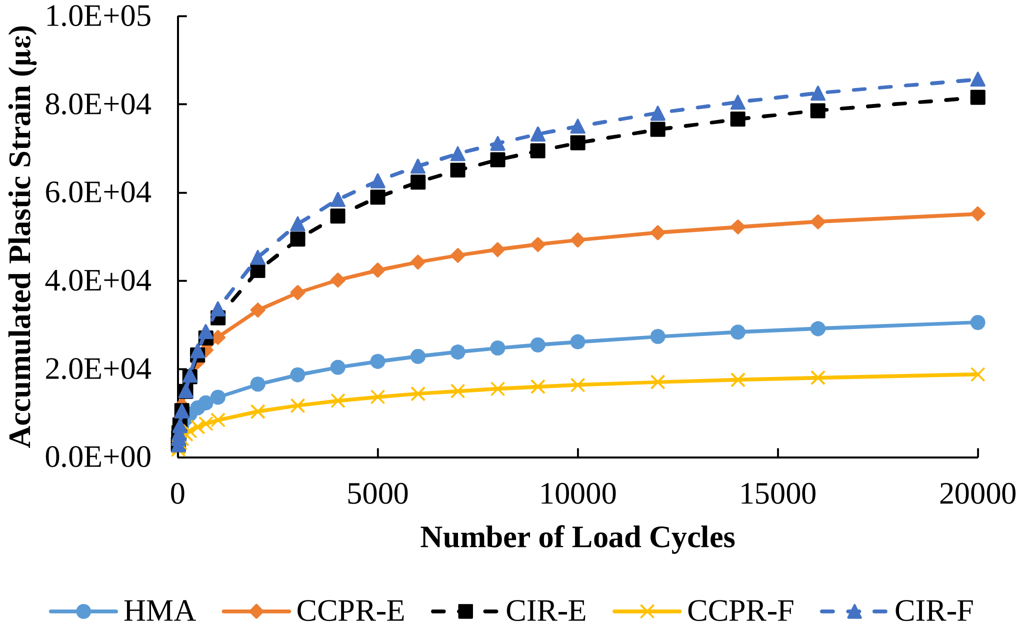


Figure 3. Accumulated Plastic Strain Curves for Cold Recycled Asphalt Mixtures

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

$$N_f = 0.00432 * C * \beta_{f_1} * k_1 \left(\frac{1}{\varepsilon_1}\right)^{k_2 * \beta_{f2}} \left(\frac{1}{E_1}\right)^{k_3 * \beta_{f3}} \quad (5)$$

where N_f is the fatigue life of asphalt pavement, C is the laboratory to field adjustment factor, ε_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 fatigue properties, β_{f_1}, β_{f_2} and β_{f_3} are calibration factors. The default values of fatigue properties are: k_1 = 0.007566, k_2 = 3.9492, and k_3 = 1.281. In this study, these default fatigue properties were used to represent the fatigue cracking resistance of cold recycled asphalt mixtures.

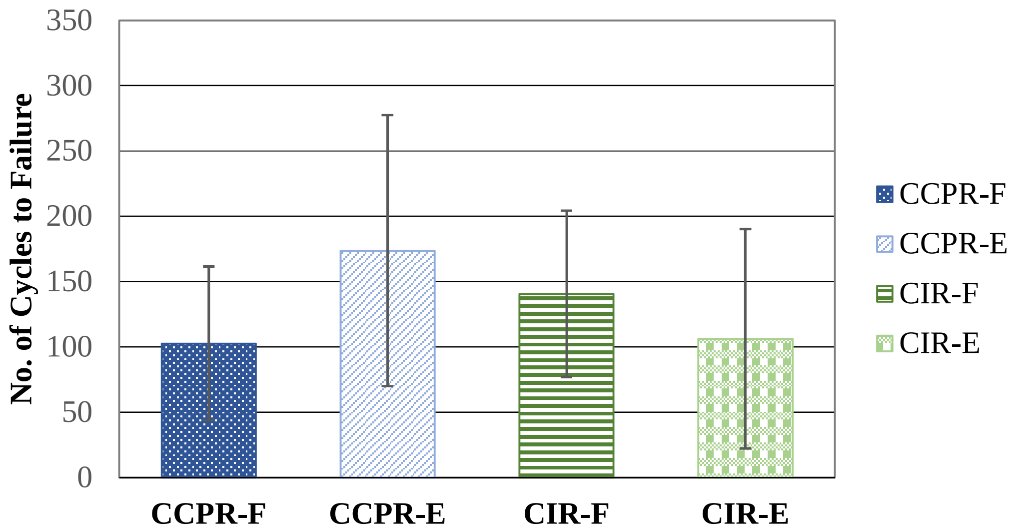


Figure 4. Overlay Test Results of Cold Recycled Asphalt Mixtures

4. Field Performance Prediction of Cold Recycled Asphalt Pavements

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

Layer No.	Control		Cold Recycling	
	Material	Layer Thickness (mm)	Material	Layer Thickness (mm)
1	HMA Thinlay	25	HMA Thinlay	25
2	HMA Binder Course	90	Cold Recycled Asphalt	90
3	Asphalt Treated Base	254	Asphalt Treated Base	254
4	Unbound Granular Subbase	203	Unbound Granular Subbase	203
5	Subgrade	NA	Subgrade	NA

NA= Not Available

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

In this study, the level 1 inputs were used for characterizing the HMA overlay, the cold 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 presented in the previous section. The level 2 inputs were used for unbound aggregates subbase and subgrade soil. The resilient moduli of unbound aggregates and subgrade soil were 206 MPa and 103 MPa, respectively. The analysis period was assigned as 15 years.

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

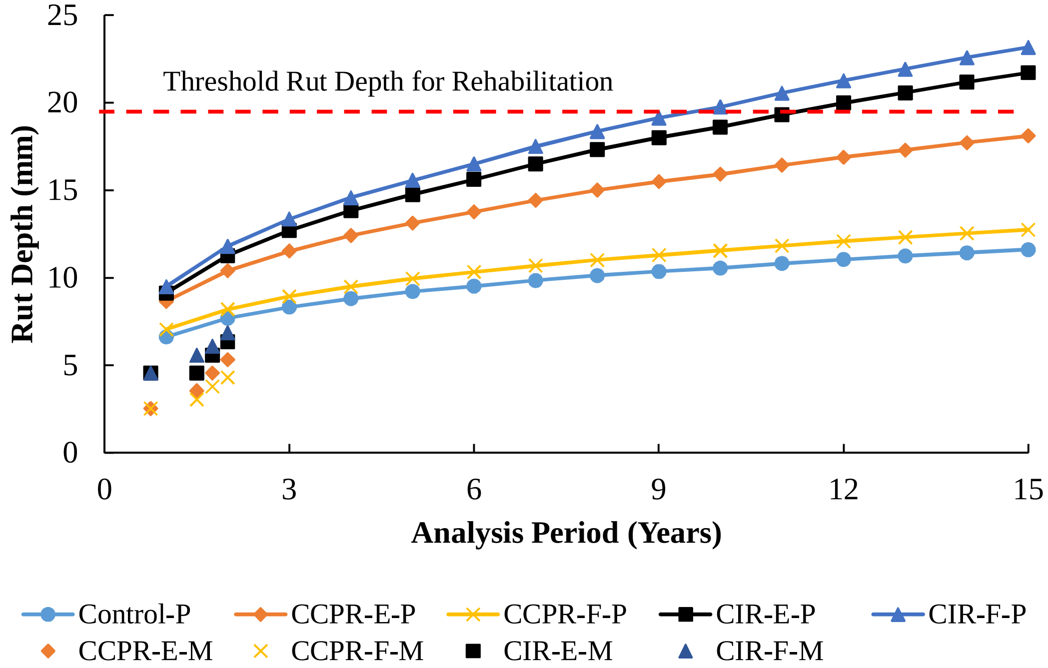


Figure 6. Predicted and Measured Rut Depths for Cold Recycled Asphalt Pavements

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

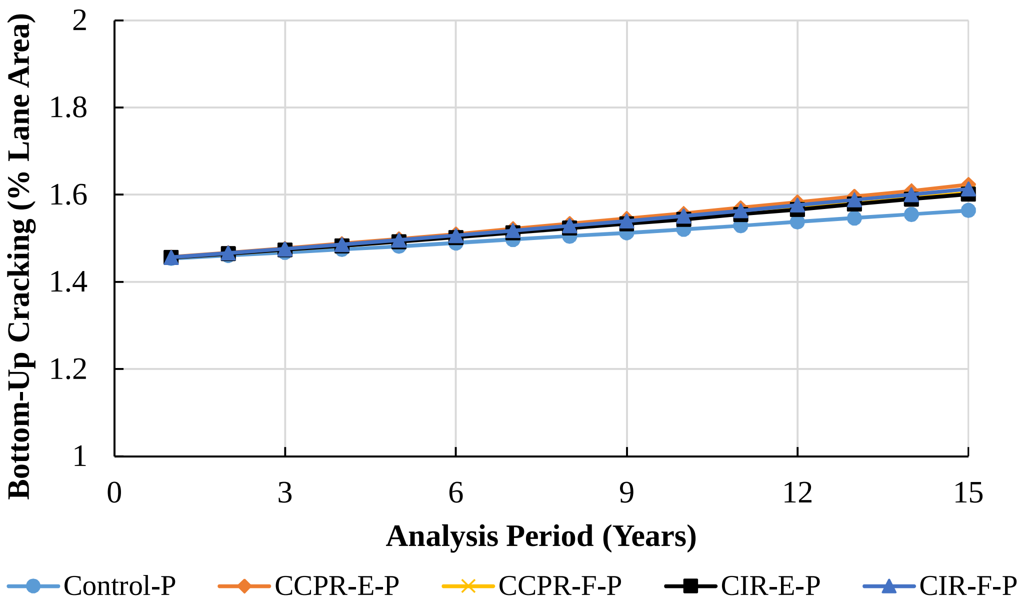


Figure 7. Predicted Fatigue Cracking for Cold Recycled Asphalt Pavements

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

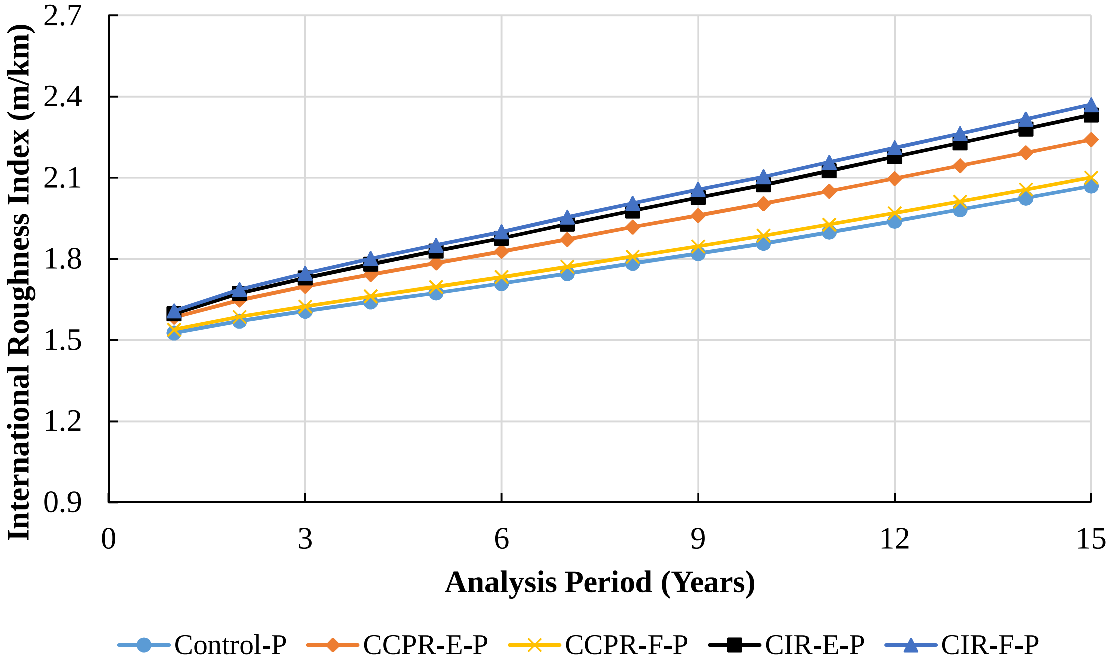


Figure 8. Predicted International Roughness Index for Cold Recycled Asphalt Pavements

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

5. Sustainability Assessment of Cold Recycled Asphalt Pavements

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

5.1 Life Cycle Cost Analysis

To enable a fair comparison among competing pavement alternatives, all future anticipated costs and salvage value were discounted to the present to take into account the time value. The net present value (NPV) of initial construction and discounted future costs and salvage value was then determined for each alternative using the common economics formula shown in Equation 6. Finally, the alternative with the lowest NPV was considered to be the most economical choice.

$$NPV = Initial\ Const.\ \mathrm{Cos}\,t + \sum_{k=1}^{N} Future\ \mathrm{Cos}\,t_k \left[\frac{1}{(1+i)^{n_k}} \right] - Salvage\ Value \left[\frac{1}{(1+i)^{n_e}} \right] \quad (6)$$

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

Table 2. Comparison of Life Cycle Costs of Pavement Alternatives

Pavement Alternatives	Initial Construction Cost ($/LKM[1])	Salvage Value ($/LKM[1])	Net Present Value ($/LKM[1])
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

Note: [1] LKM = Lane Kilometer

5.2 Life Cycle Assessment

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

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[1]	275	22	
	CCPR Mix	14	1	
	CIR Mix	15	1.13	
Milling		12	0.8	
Transport (km/ton)		1.3	0.06	(EPA, 2014)
Placement	HMA	9	0.6	(Chappat and Bilal, 2003)
	Cold Mix Asphalt	6	0.4	

Note: [1] 20% RAP was used in the HMA

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

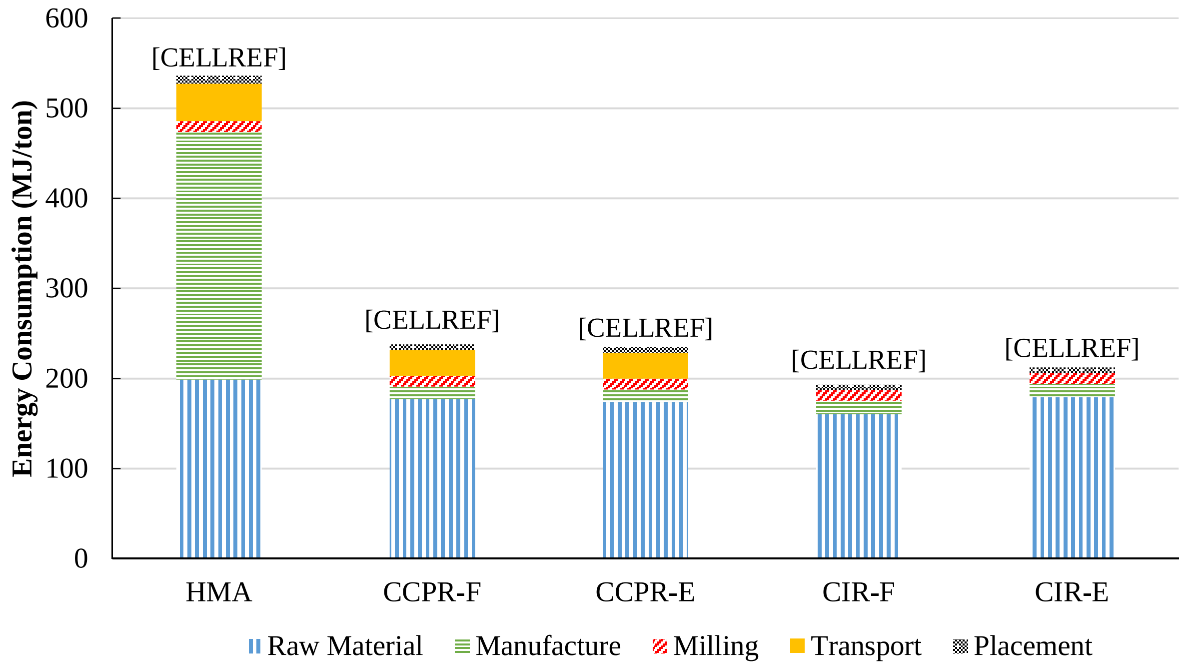


Figure 9. Energy Consumption of Cold Recycling Projects

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

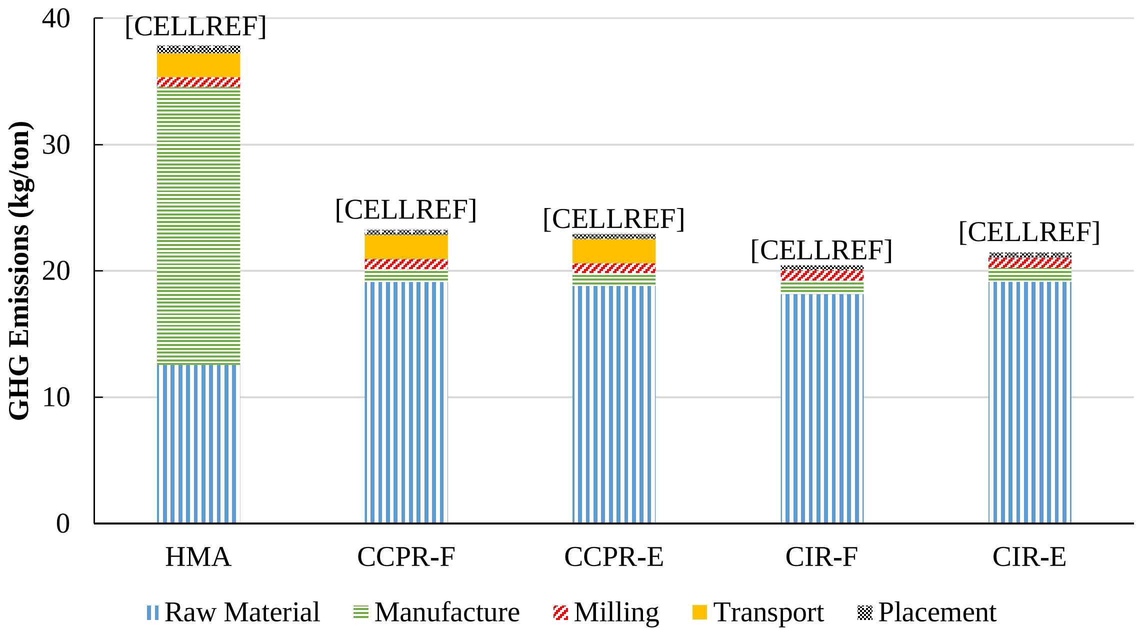
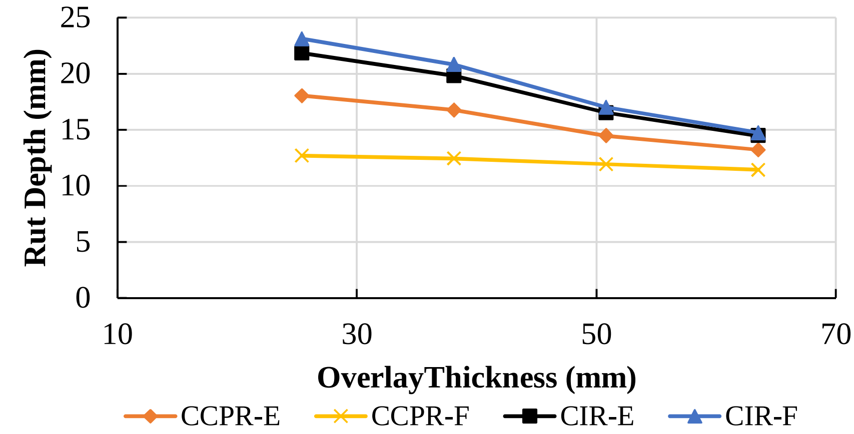


Figure 10. Greenhouse Gas Emissions of Cold Recycling Projects

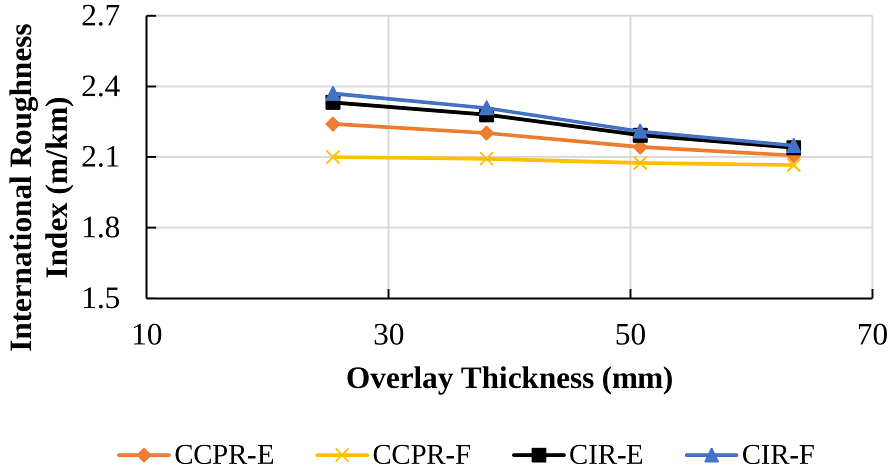
6. Structural Performance Assessment of Cold Recycled Asphalt Pavements

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

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



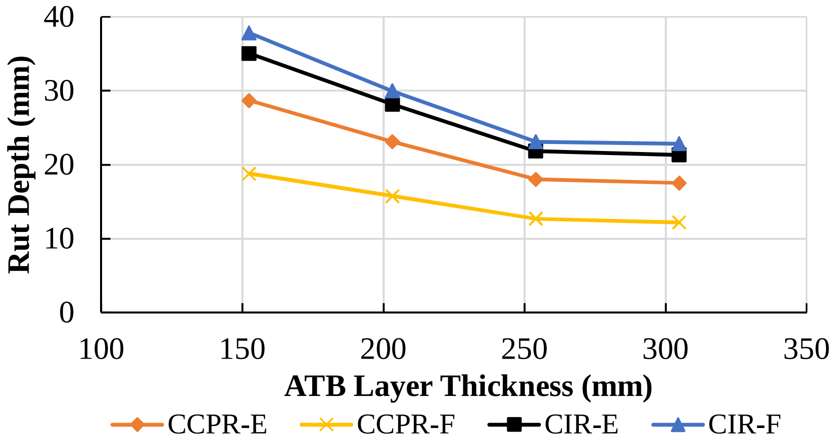
(a) Rut Depth



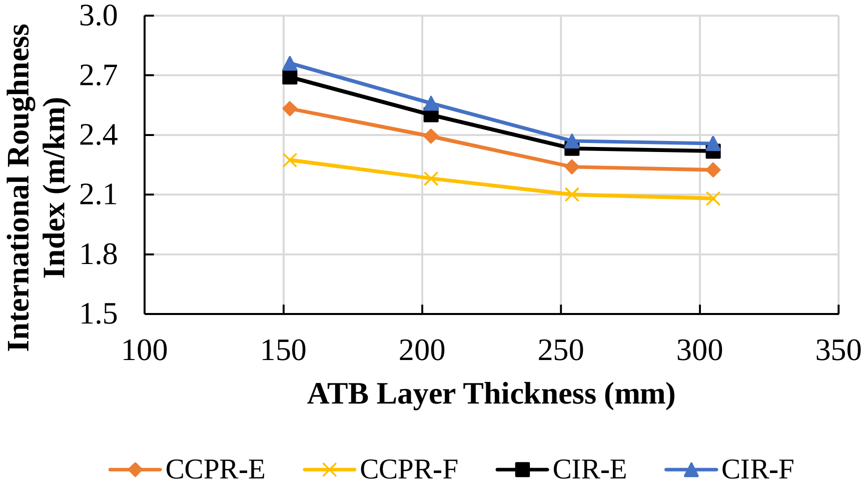
(b) International Roughness Index

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

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



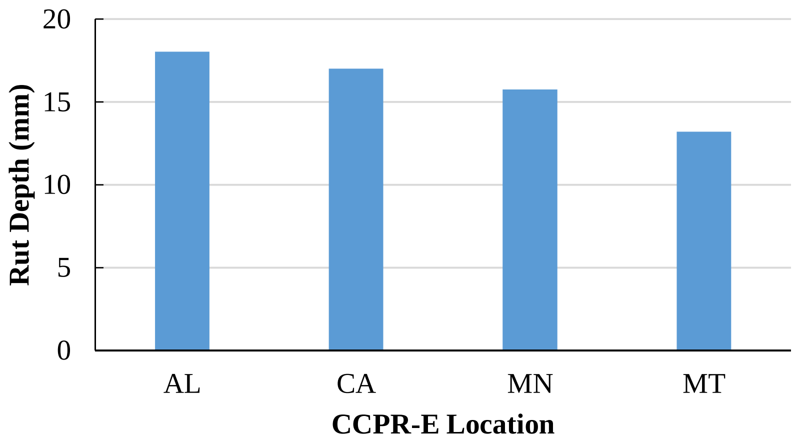
(a) Rut Depth



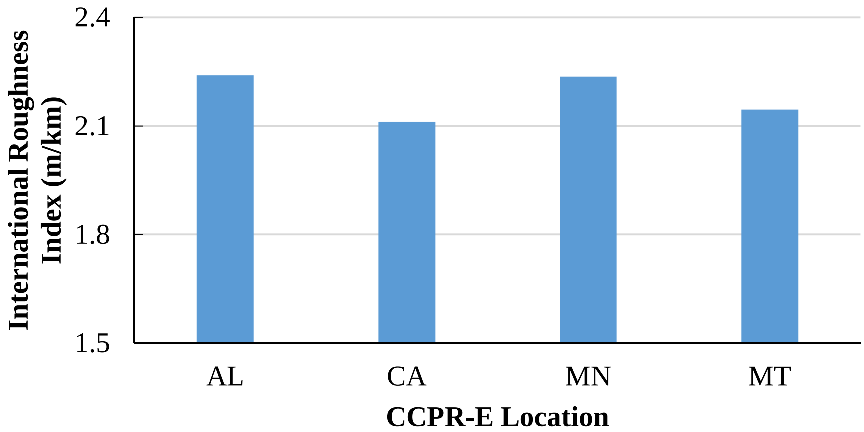
(b) International Roughness Index

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

In the Long-Term Pavement Performance (LTPP) database, the climate in the United States is divided into four zones, namely, wet-freeze, wet-no-freeze, dry-freeze and dry-no-freeze. The aforementioned cases were located in the State of Alabama (AL), which was classified in wet-no-freeze zone. To evaluate the impact of climate condition on structural design, other three weather stations were also analyzed in this study, which included Los Angeles in California (CA, dry-no-freeze), Bozeman in Montana (MT, dry-freeze), and Minneapolis in Minnesota (MN, wet-freeze). Figure 13 showed the impact of climate conditions on the performance of CCPR-E sections. As presented in Figure 13a, the MT section had the lowest rut depth when compared against other sections. The AL and CA sections exhibited similar resistances to rutting. Compared to the no-freeze zones (i.e., AL and CA sections), the freeze zones (i.e., MT and MN sections) resulted in less rutting distress. This might be because the asphalt materials in freeze zones were much stiffer than those in no-freeze zones. As shown in Figure 13b, the CA section had the lowest IRI value in comparison to other sections. Compared to wet zones (i.e., AL and MN sections), the dry zones yielded lower IRI values at the end of analysis period. In this case study, the CCPR-E structures shown in Figure 5 passed both the rutting and IRI design criteria in the all four climatic zones. It is worth mentioning that the current Pavement ME Design considers the influence of climate on pavement performance by varying the mechanical properties of asphalt material and unbound material. The influence of climate on moisture damage and freeze-thaw effects are not included in the analysis.



(a) Rut Depth



(b) International Roughness Index

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

7. Conclusions and Future Work

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

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

Cold recycled asphalt mixtures are evolutive materials whose properties change due to the physical and chemical processes, such as moisture evaporation, emulsion setting, and cement hydration. The future studies should focus on the development of laboratory curing protocol to simulate these long-term physical and chemical changes. The developed curing protocol will be crucial to determine the material properties of cold recycled asphalt mixtures for pavement structural design.

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