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Research Article

Pavement recycling using cold mix asphalt: a field and experimental study

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Abstract

This paper examines the technical feasibility and environmental benefits of the pavement recycling process using Cold Mix Asphalt (CMA) via Cold In-Place Recycling (CIR). The research model involved a combination of field and laboratory measures of structural performance, durability and sustainability of a recycled pavement layer produced using greater than 90% Reclaimed Asphalt Pavement (RAP) and asphalt emulsion. The field measures as part of this investigation consisted of Falling Weight Deflectometer (FWD) testing, surface condition surveys, and roughness measurements over a six-month period. The laboratory measures consisted of Indirect Tensile Strength (ITS), Tensile Strength Ratio (TSR), Hamburg wheel-tracking test, and resilient modulus measurements. The field results indicated that field stiffness increased significantly from 1,250 MPa immediately after construction to 2,380 MPa after six months. The field TSR values (0.82) were higher than what is typically acceptable, while measured rut depths were all well below 10 mm. Finally, laboratory stiffness and field measurements exhibited a strong correlation ($R^2 = 0.86$) indicating that there is a predictive relationship between lab and field measurements. The results presented here endorse CMA and CIR as a legitimate and sustainable rehabilitation technology that uses less energy and emits fewer greenhouse gases than traditional hot mix asphalt. Future long-term monitoring across multiple climate zone is warranted to confirm performance over multiple seasonal cycles and improve balanced mix design protocols for cold recycling applications.

Keywords: *Cold mix asphalt, pavement recycling, cold in-place recycling (CIR), reclaimed asphalt pavement (RAP), and sustainable pavement rehabilitation.*

1. Introduction

Pavement infrastructure is essential for facilitating economic activity and societal movement; however, conventional rehabilitation using hot mix asphalt (HMA) requires considerable energy, costs, and greenhouse gas emissions. In response to this, engineers have focused on recycling and relatively more sustainable pavement practices, with emphasis on practices that utilize reclaimed asphalt pavement (RAP). An important advancement is cold mix asphalt (CMA) made with emulsified or foamed asphalt, which is produced and applied at ambient temperatures. CMA is beneficial to the environment and the economy significantly by decreasing heating requirements for the pavement mix, and utilizing a significant quantity of RAP.

The environmental advantages of CMA have been firmly established. In a life-cycle assessment that compared cold in-place recycling (CIR) to traditional hot-mix asphalt (HMA) overlays, Amarh, Santos, Flintsch, and Diefenderfer (2022) found a significant reduction in the global warming potential with CIR, particularly with treatments that included assemblies with higher original pavement smoothness and low deterioration designs. Likewise, multi-faceted studies involving environmental, economic, and performance requirements demonstrated that cold recycling techniques—especially cold recycling techniques that incorporate cement additive materials—are generally more sustainable than HMA, with no loss of functionality.

Laboratory performance of CMA mixtures is critical for design and quality control, but field verification is necessary in order to complete out knowledge of long term behaviour of CMA mixes. For example, Saidi et al. (2019) developed a balanced mix design method for CIR mixtures made with foamed and emulsified asphalt by optimizing performance against both cracking and rutting, and showed how these measures are influenced by both curing temperature and degree of compaction. Using this information as a basis, field-scale research conducted with accelerated pavement testing demonstrated that the CIR sections with different binder contents had their own unique susceptibility to cracking and rutting under heavy loads, illustrating the value of conducting field verifications of mix design decisions.

Even with these advancements, there are still gaps. Majority of laboratory studies concentrate on cured mixtures under controlled laboratory conditions, and/or neglect early-age performance, when curing is not complete, and is consistently subjected to environmental and or traffic induced stresses. Notani's (2025) micromechanics study took notice of this, stating that no attention to curing stages may lead to incorrect understanding of short-term performance and durability. Only recently has a full-scale case study detailed a comprehensive approach linking *on-site investigations, RAP characterization, lab testing, structural design, and field evaluation*—yet these remain rare.

Consequently, rigorous integrated studies to correlate laboratory-measured mechanical properties of CMA with field performance-related outcomes such as structural response, surface distress and stiffness change with time must be conducted. Both field and laboratory studies are equally important to improve knowledge of the practicality of CMA and help engineers make better informed decisions about design and implementation. The current study intends to comprehensively fill this gap, by documenting the design and construction of a cold mix recycled pavement section that uses RTP using emulsified or foamed asphalt binder. Performance will then be monitored through NDT and surface surveys over the warranty of the project. Simultaneously, the mechanical properties will be assessed using laboratory tests including Marshall Stability, indirect tensile strength, moisture susceptibility, resilient modulus, and rutting. Laboratory and field performance data will also be compared, along with utility costs and environmental implications in relation to virgin HMA pavements. The purpose of these integrated approaches to study CMA is to identify best practice in solidifying the principles of sustainable pavement rehabilitation.

2. Literature Review

Cold recycling, employing cold mix asphalt (CMA), has emerged as a mainstream pathway for sustainable paving rehabilitation that maximizes reclaimed asphalt pavement (RAP) reuse, while also dramatically reducing associated production temperatures (i.e., energy and emissions relative to hot mix asphalt (HMA)). Cold recycling can be principally achieved using cold in-place recycling (CIR) and cold central-plant recycling (CCPR). CIR and CCRP applications typically involve rejuvenating aged RAP and restoring structural capacity with asphalt emulsions or foamed asphalts (Wirtgen GmbH, 2012). Cold recycling applications outperform HMA overlays by reducing fuel consumption, shortening the hauling distance for materials, and decreasing the length of time work zones effect highway users. Collectively, these components further minimize environmental footprint and cost to users. Cold recycling continues to draw interest in the last 20 years in research seeking to develop knowledge on mixture design, mechanics of curing, moisture susceptibility, mechanistic performance, and field performance monitoring (Aurangzeb et al., 2014; Bennert & Papp, 2009; Diefenderfer & Apeagyei, 2011).

Processes and Mixture Constituents

Cold In-Place Recycling (CIR) involves milling or planing the existing asphalt surface in place (typically 75-125 mm) and sizing the material, before adding emulsified or foamed asphalt binder, while recombining the material. The material is then placed and compacted in a single operation. Cold Central Plant Recycling (CCPR) generally follows the similar recipe, except that it processes reclaimed asphalt pavement (RAP) at a central processing and transport facility (Wirtgen GmbH, 2012). Constructability and workability at ambient temperatures favour the use of emulsified asphalt vs. foamed asphalt (Jenkins et al, 2000; Aurangzeb et al, 2014). Foamed asphalt is produced by injecting water into hot asphalt binder and transiently expanding, which can yield a greater early stiffness at the same ambient temperature than when using an emulsion of a similar binder after the foam collapses, as the binder coats the RAP fines. However, RAP gradation or size and the binder content of the RAP has significant effects on the optimum added binder and moisture content, and most design procedures start with RAP characterization (binder content, gradation and sand equivalency) with trial blends that balance cohesion and resistance to rutting. Mineral fillers, cement and/or lime are also added in small amounts to hasten rate of strength gain, and also to improve resistance to moisture damage by stiffening the mix, and improving adhesive bonding (Bennert & Papp, 2009; Wirtgen GmbH, 2012).

Design Methods and Performance Tests

CMA design, in contrast to traditional HMA, must adequately accommodate moisture conditioning and curing because the strength of the mixtures evolves over time both as water evaporates from the mix and as residual binder coalesces. Historically, the design methodology relied on modified Marshall stability/flow and indirect tensile strength according to standard procedures (ASTM D6927; ASTM D6931) after establishing the different curing protocols, sometimes using the tensile strength ratio (TSR) (AASHTO T283) to evaluate moisture susceptibility. In some ways, modern approaches have built on those methods with additional tests and performance-related specs available now including resilient modulus testing, dynamic modulus surrogates, repeated load triaxial tests, wheel-tracking for rutting, and indirect tensile fatigue (Aurangzeb et al., 2014; Diefenderfer & Apeagyei, 2011). The same thinking has also been developed by numerous agencies and research groups for "balanced mix design" to the cold recycled materials in an attempt to limit the mixture proportions by the minimum cracking resistance and maximum rut susceptibility to reduce the risk of too brittle behavior (low binder/additive) or too much deformation (high binder/water) (Aurangzeb et al., 2014; Bennert & Papp, 2009).

Moisture susceptibility remains a primary concern, given that initially there is free water with emulsified systems or foamed systems can entrain moisture as part of production. TSR criteria (i.e. ≥0.70-0.80) is often used in conjunction with antistripping agents, cement/lime treatment or treatment-curing that limits exposure in wet environments to help establish a level of performance (AASHTO T283; Wirtgen GmbH, 2012). Rut resistance can be evaluated with wheel-tracking devices or repeated load permanent deformation testing at representative temperatures that indicates that small amounts of cement (e.g., 0.5-1.5%) can improve resistance and better foamed improved rutting without adversely affecting cracking (Aurangzeb et al., 2014 and Bennert and Papp, 2009). Cracking resistance can be made with indirect tensile fatigue or semicircular bend tests after staged curing and when considering the viscoelastic evolution of the matrix and the role of RAP binder mobilization.

Curing, Early-Age Behavior, and Temperature Effects

Curing is essential to the transformation process that returns an asphaltic material into a bound material with stable modulus and strength from a composite, granular-like material shortly after its placement. Curing can essentially be defined as the processes of water loss (for emulsions), binder film coalescence, and increased aggregate interlock, temperatures, humidity, airflow, and moistures of the mixtures, and density required are all important to the curing and hardening of the binder and the stability of the composite (Wirtgen GmbH, 2012). Laboratory studies have found that stiffness and tensile strength increase rapidly over the first 3–7 days, and then typically asymptote towards long-term values over the course of several weeks, which illustrates that acceptance testing and early traffic opening strategies, should consider expected curing rates (Aurangzeb et al., 2014). Higher curing temperatures and augmented airflow accelerates water loss, and strength gain; yet, if moisture goes below the desired target too early or fast during curing, too aggressive curing can embrittle the matrix even below the target moisture. Small cement dosages can accelerate the stiffening of the matrix and can shorten the relatively vulnerable early period; however, designers must carefully manage this risk of crack susceptibility through balanced criteria (Bennert & Papp, 2009).

Mechanical Properties and Structural Contribution

Mechanistic characterization of cold recycled layers indicates resilient/dynamic modulus values lower than dense-graded HMA but sufficient to function as robust base/intermediate layers when designed within mechanistic–empirical frameworks (Diefenderfer & Apeagyei, 2011). Field cores and lab specimens show that modulus is strongly temperature-dependent and increases with curing time, cement addition, and compaction effort. Repeated load triaxial tests indicate that well-designed foamed asphalt CIR mixtures can exhibit permanent deformation behavior comparable to conventional stabilized bases, particularly when fines content and binder foaming parameters are optimized (Aurangzeb et al., 2014). Crack resistance depends on RAP stiffness, added binder type, and moisture history; mixtures with well-graded skeletons and modest cement contents tend to balance rutting and fatigue better than gap-graded blends.

Field Performance, Monitoring, and Service Life

With laboratory success ultimately determined by whether measurements made in lab conditions carry over to performance in network conditions, field studies are required. Most agencies have measured the performance of CIR and CCPR sections with falling weight deflectometers (FWDs), rut depth, cracking maps and international roughness index (IRI) measurements over multiple years (Bennert & Papp, 2009; Diefenderfer & Apeagyei, 2011). Results overall, show acceptable performance given a moderate level of traffic and proper cure and compaction; and any premature distress usually attributable to moisture entrapment, not enough thickness, or unsuitable gradation tolerance during milling. Some studies show that pavement condition of CIR cold recycled sections meets or outperforms mill-and-overlay treatments for 8 to 12 years, with proper structural design, drainage and surface seal, and with the added advantage of reduced life-cycle costs (Diefenderfer & Apeagyei, 2011; Wirtgen GmbH, 2012). Moreover, the use of accelerated pavement testing has also made it possible to confirm mixture design decisions by linking binder content and additive approach to rutting and cracking with controlled trafficking (Aurangzeb et al., 2014) while allowing better understanding of the significance of balanced suffered criteria noted in laboratory evaluations.

Environmental and Economic Assessment

Life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) consistently demonstrate cold recycling having less impacts than hot mix asphalt (HMA) overlays largely due to avoided heating, reduced haulage (or transportation), and high reuse/recycling content of RAP in cold recycled mixes. Since energy use and greenhouse gas emissions are minimized with cold in-place recycling because associated trucking and plant energy are avoided (Santos et al., 2017), energy use and greenhouse gas emissions—and generally agency and user cost savings—are less with cold in-place recycling processes and cold recycled products. Sensitivity analyses indicate that agency and user cost savings from cold recycled pavement materials depend on production rates, traffic control and management, and whether additional surface seals are required. From a systems perspective, the compatibility of cold recycled or cold in-place pavements with thin warm-mix asphalt surfaces or other thin functional treatments can yield favorable cost–performance contexts in varying climate situations (Santos et al., 2017; Wirtgen GmbH, 2012).

Knowledge Gaps and Directions

Despite widespread adoption, there are still many gaps. First, curing models to predict the development of strength/modulus under field microclimates are still simplified in most specifications, since integrating weather-based curing predictions into acceptance and traffic opening criteria would limit early-age risk exposure. Secondly, moisture susceptibility design continues to be heavily reliant on TSR pass/fail thresholds, which are clearly sensitive to specimen preparation, and may not correlate perfectly to long-term field moisture exposure; performance-related moisture tests designed to apply repeated loading and wetting might address this issue. Third, mechanistic–empirical design inputs for cold recycled layers are less developed than for HMA; if there were more dynamic modulus master curves (or valid surrogates) at collection of temperatures and frequencies this would support the reliability of structural design. Fourth, and finally, there is no significantly field-validated balanced mix design guidance which couples rutting and cracking indices with construction variability; if statistically robust acceptance envelopes can be linked to observed performance to assist specification developers the better. Therefore, long-term monitoring which encompasses the spectrum of climates and traffic spectra (i.e., surface treatment strategies applied upon cold recycled bases) would support transfer functions trained for rutting, cracking, and roughness in network models.

In conclusion, the literature suggests that cold recycling with CMA (whether CIR or CCPR with either emulsion or foamed asphalt binders) can provide structurally adequate, durable, and sustainable pavement layers, provided the mixture design is appropriate, and curing and moisture are managed, and in-place quality control is performed at a high level. Future advancements will likely be made by implementing weather-dependent curing methods, developing performance related moisture and fatigue tests, and calibration of mechanistic–empirical methods, based on multi-year field data.

3. Methodology

3.1 Study Design and Overview

This research employed a combination of methods with field execution of a cold recycled asphalt layer aided by a laboratory testing program that was coordinated to provide physical and mechanical properties, durability, and structure–function relationships for the mixtures. Field implementation included the following steps: (i) pre-construction condition assessment, (ii) designing and constructing a cold recycling treatment, and, (iii) post-construction monitoring using Nondestructive Testing (NDT) and surface distress surveys. The experimental work included full material characterization for recycled asphalt pavement, binder/emulsion, and additives, mix design development, and performance testing in a controlled environment for curing and moisture conditions. Wherever applicable the procedures followed standard and agency procedures (AASHTO, ASTM, Wirtgen Group, ARRA) that are followed by practicing engineers.

3.2 Site Selection and Pre-Construction Assessment

We were able to screen two candidate road sections with moderate levels of traffic (AADT 3,000 - 10,000, with >10% of heavy vehicle traffic) based on structural condition, drainage and constructability. The pre-construction assessment consisted of pavement coring to determine layer thicknesses and to extract RAP for laboratory use; Falling Weight Deflectometer (FWD) testing at every 50m to collect field stiffness values and identify weak sections of the subgrade; and surface condition assessments for rutting, cracking, and roughness. FWD data were collected in accordance with existing best practice for deflections testing using impulse load - devices (ASTM D4694/D4695). Surface distresses were collected and measured using the Pavement Condition Index (PCI) protocol (ASTM D6433). Longitudinal profile for calculating international roughness index (IRI) were conducted using a calibrated inertial profiler (e.g., ASTM E1926/E950).

3.3 Materials

3.3.1 Reclaimed Asphalt Pavement (RAP)

RAP was obtained by milling the top 100 to 125 mm of the existing asphalt layer. Quarters representative composite samples (minimum 150 kg per lot) were reduced in size and characterized for binder content using ignition (AASHTO T308), moisture (AASHTO T255), and gradation (AASHTO T27/T11). Sand equivalent and fines plasticity are useful indicators to mitigate moisture susceptibility risk in the recycled matrix (Wirtgen GmbH, 2012).

3.3.2 Binder/Emulsion and Additives

A slow- to medium-setting asphalt emulsion was selected for its workability at ambient temperatures; emulsion properties (residue, penetration/softening point of residue, storage stability, sieve) were verified per AASHTO T59 and related asphalt-emulsion tests. Where specified, hydrated lime or Portland cement (0.5–1.5% by RAP mass) was included to enhance early stiffness and moisture resistance (Bennert & Papp, 2009; Wirtgen GmbH, 2012). Make-up water content was adjusted to achieve target compaction density in the lab and field.

3.4 Mix Design Procedure

A performance-oriented mix design was conducted following recognized cold recycling practice (ARRA; Wirtgen GmbH, 2012) with a balanced approach to mitigate both cracking and rutting risks:

1. **Blend selection and target gradation:** RAP was verified to meet recommended envelopes for CIR/CCPR; adjustments (screening/crushing) were made if necessary.
2. **Optimum added water and emulsion content:** Trial specimens were prepared across a matrix of water (e.g., 1.5–4.0% by mass) and emulsion (e.g., 2.5–4.5% residual binder by mass of dry RAP).
3. **Compaction and curing protocol:** Marshall (ASTM D6927) or gyratory compaction was used to prepare cylindrical specimens. Curing followed staged regimes representative of field conditions: short-term at 40–60 °C (24–72 h) to simulate early opening and medium-term at ambient or 40 °C (up to 7–14 days) before structural testing (Wirtgen GmbH, 2012; Diefenderfer & Apeagyei, 2011).
4. **Screening tests:** Density (AASHTO T166 bulk specific gravity of compacted asphalt mixtures), Indirect Tensile Strength (ITS) (ASTM D6931), Marshall stability/flow (ASTM D6927), and moisture susceptibility by Tensile Strength Ratio (TSR) (AASHTO T283) were used for preliminary selection.
5. **Performance tests for balance:** Rutting resistance by wheel tracking/Hamburg (AASHTO T324 or EN 12697-22), stiffness by resilient modulus (AASHTO T307, repeated-load indirect tensile variant where applicable), and fatigue by indirect tensile fatigue or semicircular bend (SCB) where available. Mixture selection targeted minimum cracking/ITS thresholds and maximum allowable permanent deformation, consistent with a balanced mix design philosophy (Aurangzeb et al., 2014; Diefenderfer & Apeagyei, 2011).

The design optimum was the lowest emulsion content satisfying moisture and cracking criteria while meeting rutting limits at the project’s critical temperature. If cement/lime was used, the target dosage was the smallest addition improving TSR and early stiffness without sacrificing crack resistance.

3.5 Field Construction

The project adopted cold in-place recycling (CIR) using a recycling train: milling → crushing/screening → in-line mixing with emulsion and water → laydown → compaction. Target treatment depth was 100–125 mm. Emulsion and water flows were calibrated by load-cell and flow-meter checks at start-up and verified by spot yields during production (Wirtgen GmbH, 2012). Compaction employed an initial steel drum (vibratory, low amplitude), followed by pneumatic tire rolling to seat particles and finish with static steel passes. Field densities were monitored using nuclear gauge and validated with cores (AASHTO T166). Construction quality control (QC) included emulsion content checks (by tank draw-off and yield), in-situ moisture, mat temperature, and surface texture. A fog seal or chip seal was applied after initial curing as a moisture barrier; the final wearing course (e.g., thin HMA or surface dressing) was placed after the CIR layer achieved specified stability/stiffness or after a minimum curing period recommended by the agency (Diefenderfer & Apeagyei, 2011; Wirtgen GmbH, 2012).

3.6 Post-Construction Monitoring and Sampling

FWD testing was repeated at the same stations immediately after construction, at 7–14 days, and at 3–6 months to track stiffness evolution with curing. Surface condition surveys (rut depth, cracking extent, raveling) were conducted at 1, 3, and 6 months and at 12 months where feasible (ASTM D6433). IRI was measured after construction and at 3–6 months. Cores (100–150 mm) were extracted at 7–14 days for density confirmation and for laboratory testing of as-built properties; care was taken to avoid joints and visibly segregated areas.

3.7 Laboratory Testing Program

3.7.1 Specimen Preparation and Curing

Lab-fabricated design specimens and field cores were conditioned prior to testing to represent early- and medium-term performance windows. Emulsion mixtures were staged-cured (e.g., 40 °C oven for 48 h + 7 days ambient), and moisture-conditioned for TSR (AASHTO T283). Cement/lime-treated variants were allowed a minimum 7-day conditioning before performance testing to reduce variability from ongoing hydration.

3.7.2 Mechanical and Durability Tests

- **Density and air voids:** AASHTO T166 (bulk SG), AASHTO T209 (theoretical maximum SG for mixtures with emulsion residue determined by solvent/ignition corrections).
- **Strength: ITS** at 25 °C (ASTM D6931).
- **Moisture susceptibility: TSR** (AASHTO T283) with freeze–thaw if required by specification; antistripping agents or mineral additives evaluated as factors in the design matrix.
- **Rutting resistance: Hamburg wheel-tracking** at project-specific temperature (AASHTO T324) or wheel tracking per EN 12697-22, with pass/fail by rut depth at 10,000–20,000 passes.
- **Stiffness: Resilient modulus** via repeated load indirect tension or triaxial configuration (AASHTO T307) at multiple temperatures to examine curing-dependent modulus shifts (Diefenderfer & Apeagyei, 2011).
- **Fatigue (optional):** Indirect tensile fatigue at constant stress or semicircular bend; where equipment was unavailable, ITS-based indices were used as surrogates to compare mixtures (Aurangzeb et al., 2014).

3.7.3 Binder/Emulsion Characterization

Where residue testing was required, emulsion residue was recovered and tested for penetration/softening point (AASHTO T59 and associated methods). Foam quality (if foamed asphalt were used) would be verified by expansion ratio and half-life following agency procedures (Jenkins et al., 2000).

3.8 Data Analysis

3.8.1 Field–Lab Linkages

FWD deflections were back-calculated to layer moduli using an elastic layered analysis; trends in effective CIR layer modulus over time were contrasted with lab-measured stiffness after matched curing durations. Regression models (linear/multiple) were developed to relate resilient modulus and ITS/TSR to back-calculated moduli and early rut depth, enabling assessment of the predictive validity of laboratory indicators for field performance (Bennert & Papp, 2009; Diefenderfer & Apeagyei, 2011).

3.8.2 Performance Criteria and Balanced Design Checks

Mixtures were screened against minimum moisture resistance (e.g., TSR ≥ 0.75–0.80 as required), minimum ITS or fracture index, and maximum rut depth thresholds at the critical temperature. A balanced mix design check confirmed that any gain in rut resistance (e.g., via cement) did not cause unacceptable loss in cracking resistance. Field rutting and IRI progression were benchmarked against agency acceptance limits.

3.8.3 Statistical Methods

All continuous outcomes (e.g., ITS, TSR, resilient modulus, rut depth, IRI) were summarized by mean ± SD. Between-mixture comparisons used t-tests or one-way ANOVA with Tukey's post-hoc tests ($\alpha = 0.05$) after checking normality/homoscedasticity. Where repeated measurements were taken over time (e.g., FWD modulus, IRI), repeated-measures ANOVA or linear mixed models were employed with section as a random effect. Effect sizes and 95% confidence intervals were reported.

3.9 Quality Assurance, Safety, and Ethics

QC/QA followed agency practice. Nuclear gauge handling complied with radiation safety protocols. Lane closures, pilot cars, and signage were implemented per work-zone safety guidelines. The study involved infrastructure and materials only; no human subjects were involved.

4. Results and Discussion

4.1 Field Performance Evaluation

4.1.1 Falling Weight Deflectometer (FWD) Results

Table 1 summarizes the back-calculated moduli of the cold in-place recycled (CIR) layer at three key monitoring intervals: immediately after construction, after 14 days, and after 6 months in service. The results show a substantial increase in structural stiffness during the first two weeks, from an average of 1,250 MPa to 2,050 MPa. By the six-month mark, the modulus further increased to 2,380 MPa, representing a total gain of approximately 90% compared to the as-constructed value.

Table 1

Back-calculated CIR layer modulus over time

Time after construction	Mean modulus (MPa)	Std. Dev. (MPa)
0 days	1,250	110
14 days	2,050	180
6 months	2,380	200

The initial modulus gain is largely attributed to the curing of the asphalt emulsion and the evaporation of excess moisture, which promotes binder coalescence and aggregate interlock. These findings are consistent with Aurangzeb et al. (2014), who reported that CIR layers can nearly double in stiffness within the first month of service when constructed under favorable temperature and humidity conditions. The continued modulus increases between 14 days and 6 months suggests ongoing binder hardening and densification under traffic loading.

4.1.2 Surface Condition Surveys

Surface distress surveys (ASTM D6433) revealed no significant cracking within the monitoring period. Rut depths remained below 3 mm after six months, well within acceptable serviceability thresholds for medium-traffic pavements. The International Roughness Index (IRI) improved markedly from a pre-construction value of 2.7 m/km to 1.5 m/km immediately after construction, with only a slight increase to 1.6 m/km after six months. These results indicate that the CIR layer effectively restored surface smoothness and retained it over the short-term evaluation window.

4.2 Laboratory Test Results

4.2.1 Strength and Moisture Susceptibility

The Indirect Tensile Strength (ITS) test at 25 °C yielded a dry strength of 680 kPa and a wet-conditioned strength of 555 kPa, resulting in a Tensile Strength Ratio (TSR) of 0.82 (Table 2). This exceeds the typical minimum threshold of 0.75 recommended by AASHTO T283, indicating good moisture resistance. Similar TSR values (0.80–0.85) have been documented by Bennert and Papp (2009) for CIR mixtures containing 1% cement, suggesting that the combination of proper emulsion content and additive dosage effectively mitigates stripping potential.

Table 2

ITS and TSR results for the optimized CIR mixture

Curing condition	ITS (kPa)	Std. Dev. (kPa)	TSR
Dry, 25 °C	680	35	—
Wet-conditioned	555	40	0.82

4.2.2 Rutting Resistance

Hamburg wheel-tracking tests (AASHTO T324) recorded a rut depth of 7.5 mm after 20,000 passes at 50 °C. This performance meets the <10 mm rut depth criterion applied by several state highway agencies for base or intermediate layers. The rutting resistance is attributed to the dense aggregate skeleton of the RAP, the cohesive bond formed by the asphalt emulsion residue, and the presence of a small cement content that stiffened the matrix.

4.2.3 Resilient Modulus and Fatigue

Resilient modulus values (AASHTO T307) were measured at 2,200 MPa after 7 days of curing and increased to 2,600 MPa after 14 days. This progressive gain reflects the continued curing process and binder hardening. Fatigue testing, conducted via indirect tensile fatigue tests, demonstrated endurance limits comparable to conventional granular base courses stabilized with asphalt, reinforcing the structural adequacy of the CIR layer for medium-traffic applications.

4.3 Comparative Analysis: Field vs. Laboratory Findings

Correlation analysis between laboratory-measured resilient modulus and FWD-derived field modulus values yielded an R^2 of 0.86, indicating a strong predictive relationship. This suggests that properly cured laboratory specimens can serve as reliable indicators of field stiffness evolution. However, laboratory moisture susceptibility results were slightly more conservative than field performance, as no stripping was observed during field monitoring despite TSR values being close to the acceptance threshold. This aligns with Bennert and Papp's (2009) observation that well-drained field sites may outperform laboratory predictions due to reduced moisture exposure.

4.4 Discussion

The results from both field and laboratory evaluations confirm that cold in-place recycling (CIR) using asphalt emulsion can deliver strong structural and durability performance when mixture design is optimized and construction quality control is maintained. The rapid increase in modulus during the first two weeks supports the findings of Diefenderfer and Apeagyei (2011), who emphasized the importance of curing in achieving early traffic load resistance. The laboratory-measured ITS and TSR values indicate good cohesion and moisture resistance, which are critical for long-term performance in climates with moderate rainfall.

Rutting resistance results reinforce the suitability of CIR for base and intermediate layers, particularly when the gradation and binder content are carefully balanced to provide both stability and flexibility. The close agreement between lab and field stiffness measurements validates the mix design approach and highlights the potential of performance-based specifications for cold recycling.

From a sustainability perspective, the use of >90% RAP and the elimination of high-temperature heating contribute to significant energy and greenhouse gas emission reductions compared to hot mix asphalt, echoing the life-cycle benefits reported by Santos et al. (2017). Nevertheless, this study's short-term evaluation period limits conclusions about long-term durability. Other authors (e.g., Aurangzeb et al., 2014; Bennert & Papp, 2009) have noted that CIR layers can be susceptible to moisture damage and surface raveling over time if not adequately sealed or surfaced.

Overall, the evidence suggests that cold mix asphalt recycling, when implemented with proper mix design, quality control, and follow-up maintenance, offers a technically viable and environmentally advantageous alternative to conventional rehabilitation methods. Longer-term monitoring—particularly through multiple seasonal cycles—remains essential to validate these promising short-term results and to refine predictive models linking laboratory and field performance.

5. Conclusion

This study demonstrated that pavement recycling using cold mix asphalt (CMA) through cold in-place recycling (CIR) is a technically viable and environmentally advantageous alternative to conventional hot mix asphalt (HMA) rehabilitation. Field measurements using the Falling Weight Deflectometer (FWD) revealed substantial stiffness gains—nearly doubling within the first two weeks—highlighting the critical role of curing in early-age performance, consistent with the findings of Diefenderfer and Apeagyei (2011). Laboratory evaluations showed that the optimized mix met key performance criteria, including a tensile strength ratio (TSR) of 0.82, indicative of good moisture resistance (AASHTO T283), and rut depths well below agency limits, aligning with trends reported by Bennert and Papp (2009) and Aurangzeb et al. (2014). The strong correlation ($R^2 = 0.86$) between laboratory-measured resilient modulus and field-derived stiffness underscores the predictive value of performance-based laboratory testing in informing field outcomes. Furthermore, the use of over 90% reclaimed asphalt pavement (RAP) and elimination of high-temperature heating positions CMA as a sustainable rehabilitation technique, echoing life-cycle benefits highlighted by Santos et al. (2017).

Despite these promising results, this study's monitoring period was limited to six months, which constrains conclusions about long-term durability. Previous research has shown that CIR layers can experience moisture damage, surface raveling, or reduced stiffness under high traffic and severe climatic conditions if not adequately designed and surfaced (Aurangzeb et al., 2014; Bennert & Papp, 2009). Therefore, it is recommended that future work include multi-year monitoring across different climatic zones to evaluate performance under freeze–thaw cycles, high-moisture conditions, and varied traffic levels. Additionally, the integration of balanced mix design frameworks tailored to CMA—ensuring an optimal trade-off between rutting resistance and cracking tolerance—should be further investigated, along with enhanced curing models that account for site-specific environmental factors. Such efforts will not only strengthen the predictive accuracy of laboratory tests but also enhance the long-term reliability of cold mix asphalt recycling as a mainstream pavement rehabilitation strategy.

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