Creep performance evaluation of Cold Mix Asphalt patching mixes

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Abstract

Cold Mix Asphalt (CMA) is commonly used in lieu of typical Hot Mix Asphalt (HMA) for localized pavement patching due to the quantities, intermittent locations and times when repairs need to be executed. The objective of this investigation was to evaluate the resistance of CMA to accumulate permanent deformation under cyclic loading, and to present an alternative to assess stability potential from a portable device. Considering CMA is at its weakest state right after placement, and that its resistance to creep improves with curing, the study focused on evaluating the rutting performance of uncured CMA materials at different compaction levels in the laboratory by means of parameters $b$ and $FN$ from a Modified Cyclic Creep Test (MCCT) and by their resistance to penetration with a Light Cone Penetrometer (LCP), defined by the LCP penetration rate ($LPR$). Based on the experimental results, acceptable laboratory stability can be expected when values below 0.5 µm/load and over 1000 load cycles are observed for $b$ and $FN$, respectively. Considering the potential use of the LCP as a field-friendly quality control tool, models to estimate parameters $b$ and $FN$ from the MCCT as a function of $LPR$ and other CMA characteristics were developed using Multiple Linear Regression Analysis (MLRA). The results suggest that when $LPR$ values are limited to 0.50 mm/blow, CMA materials can be expected to show acceptable stability levels.

Keywords: Creep; Cold Mix Asphalt; Permanent deformation; Penetration test; Patching

1. Introduction

The constant need to repair localized pavement failures, and the nature of the repairs normally required in terms of material quantities and timing at which the repairs need to be executed, make necessary the use of materials that can be stored and used when needed. Although the behavior of Hot Mix Asphalt (HMA) is somewhat well understood and there is extensive knowledge about its performance, the inability to produce and store HMA in small quantities to be used as required make them unsuitable for pothole and other localized repairs. To fill this need, Cold Mix Asphalt (CMA) is normally used, as its characteristics allow users to have immediate availability in stock, and use it when and where needed.

Considering that the solvents that allow CMA’s mixing and compaction processes can take some time to evaporate, their ability to resist permanent deformation immediately after placement (i.e., fresh or “uncured”) is a major concern. The establishment of protocols to assess CMA’s performance in the uncured state is necessary to reduce concerns with their generalized implementation and use.

Once the CMA has been manufactured and is made available, compaction is the single most important factor affecting performance that is completely under the control of the contractor. Having the means to easily assess how compaction affects the ability of a given CMA to resist the accumulation of permanent deformation would be extremely useful, as minimum compaction levels could be established, and quality assessment of available CMA could be executed during procurement processes.
A methodology to establish rationally the ability of CMA to resist the accumulation of permanent deformation when subjected to cyclic loads, and a procedure with potential field use to quickly assess rutting performance in CMA is presented in the next sections of this document.

2. Literature review

The frequent need of localized small pavement repairs during the year, presents CMA as the perfect candidate for this type of work. Initial studies in the late 70’s evaluated the use of cold mixes in pavement patching operations [1]. Prowell and Franklin evaluated a wide variety of cold mixes in the mid 90’s for the Virginia DOT patching operations, and developed a performance rating system involving visual inspection of the patches for the presence of bleeding, dishe, debonding, raveling, and pushing/shoving, as well as measurements of workability and patch survival rate [2]. They concluded that mix instability is one of the major limitations preventing the use of cold mixes as successful patching materials.

Although there are different tests to characterize CMA, most characterization methods for these materials focus on mix workability rather than performance, mostly because these materials are often used as a temporary repair. However, research has been done to develop CMA that can be used as a permanent solution [3], although the ability to match the performance of its hot mixed counterpart (i.e., Hot Mix Asphalt) has been elusive.

Other characterization tests performed on cold mix materials include particle size gradation, residual asphalt content, and other aggregate tests such as surface area determination, specific gravity and absorption, soundness, and mechanical abrasion. Aggregate gradation, residual asphalt content, and workability are the most commonly used characterization tests for cold mixes.

Recommendations regarding aggregate gradation and shape are reported in the literature. Overall, finer and single sized gradations with low amount of fines (material passing the 0.075 mm sieve) are favored for increased workability [4], but recommendations to allow some coarser aggregate to promote greater stability have been made by Prowell and Franklin [2]. Low aggregate angularity has been connected with poor stability in the mixes.

Excessive initial instability right after construction is one of the main performance-related concerns related to cold mix use. Due to its properties, the workability needed during installation affects negatively the initial resistance against plastic deformation required in the repairs. Patch stability, understood as the ability of a CMA material to resist permanent deformation and shoving, is normally evaluated by primitive procedures (such as penetration with a screw driver, and turning the driving wheel of a passenger car), but the use of structured methods to relate initial stability with more elaborated permanent deformation performance parameters is not generalized. Some efforts to characterize workability and stability in cold asphalt mixtures have been recently reported in the literature [5,6], but cold mix stability characterization is far from becoming a standard procedure.

A recent NCHRP synthesis of practice published by the Transportation Research Board reports the use of tests to evaluate percent coating of aggregate, stripping potential and draindown susceptibility in cold asphalt patching mixes, and also indicate the use of workability tests using a workability box and a modified pocket penetrometer. The document also highlights the need for technical developments in patching practices, including the need to have rational ways to compare different patching materials as one of the areas of most interest in the United States [7].

Although some researchers have used load tests for CMA evaluation, most researchers have focused on measuring workability characteristics. Estakhri and Button report the use of unconfined compression tests and suggest limiting criteria from this test for assessing workability [8]. However, some research efforts have studied rutting performance in CMA products. Rosales-Herrera et al. evaluated locally produced and proprietary CMA patching materials using slumps tests for workability assessment and stability assessment in the laboratory using Hamburg Wheel Tracking tests and a local Texas Stability Tests [6].

Most efforts to understand permanent deformation behavior on bituminous mixes has been focused on Hot Mix Asphalt (HMA), and the majority of tests have been developed around this application. Different methods to characterize permanent deformation behavior in asphalt mixtures include incremental static, dynamic, and creep tests, and several models including binder and mix properties have been developed, although these days most tests use some form of dynamic load applied to confined or unconfined specimens. Although the triaxial test setup can simulate more effectively the stress states that may be expected in the field, its implementation requirements have made unconfined tests very popular.

The response of asphalt bound materials under uniaxial repeated loading can be separated into three stages: a primary stage, where high rates of deformation are present primarily for re-accommodation of the structure of the mix; a secondary stage, in which the rate of deformation per load cycle remains approximately constant; and a tertiary stage, where the rate of deformation increases dramatically with each load repetition until complete failure is reached. Lower strain rates during the secondary stage of deformation suggest a more stable mix after initial densification has been achieved, and the structure of the mixture has finished its relocation due to initial traffic compaction. The number of load cycles at which a mixture enters the tertiary deformation stage (also known as the Flow Number, or FN) has become also an accepted rutting performance parameter [9]; higher FN values suggest mixes with lower rutting susceptibility.

Arguably the most commonly used permanent deformation characterization model is the Power Model, expressed generally in the form:
The accumulated permanent strain due to cyclic axial loading, $N$ is the number of load applications that produced $\varepsilon_p$, and $a$ and $b$ are regression constants that depend on the material and stress state conditions. The usefulness of this model to properly characterize the permanent deformation behavior in asphalt mixes has been reported in the literature [10,11].

Uniaxial repeated loading with static confinement in cold mixes was reported by Anderson and Thompson [12]. They applied a haversine load (0.1 s, followed by a rest period of 0.9 s) to laboratory compacted Emulsion Aggregate Mixtures (EAM). They also utilized a Dynamic Cone Penetrometer (DCP) during laboratory testing, to obtain a rapid indication of in-situ shear strength. They found a considerable increase in shear strength for aggregate mixes after emulsion treatment.

Parameters obtained from permanent deformation tests have been found to be appropriate predictors of rutting performance. In particular, parameters from repeated confined and unconfined compression tests (such as coefficients $a$ and $b$ from the best-fit line on the log-log plot of accumulated strain vs. load repetitions, and Flow Number) have been identified as effective indicators of mixture sensitivity to permanent deformation [13,14].

It is widely recognized that an adequate aggregate structure is critical in the resistance of asphalt–aggregate mixtures against permanent deformation, especially at elevated temperatures, when the major contribution to stability in the mix is given by the aggregate skeleton, as the viscosity in the binder works against the stability of the HMA; it is considered that a similar effect occurs in cold mixes when tested at early curing stages; for CMA materials in particular, crushed, single sized aggregates with absorption values below 1.0% are recommended in the literature for improved stability [1,4].

Aggregate maximum nominal size alone does not appear to affect the permanent deformation performance of asphalt mixes, as reported by Hand and others after a study on 21 superpave mixtures was completed [15]. However, when combined with other aggregate characteristics, such as aggregate type and fine aggregate angularity, the study showed that it does indeed have an effect.

Kandhal and Parker reported the effect of aggregate maximum size, shape, angularity, and surface texture on rutting performance. Tests such as sieve analysis, uncompacted void content, and flat or elongated particles were found to be related to resistance to permanent deformation [16].

### 2.2. Field characterization of CMA used for localized repairs

As mentioned earlier, evaluating the suitability of a particular CMA to be used as a patching repair material has been generally based on primitive tests, including for instance penetration with a screwdriver, and power steering turns using a passenger car. Although these tests have provided useful information, lack of standard procedures makes it difficult for manufacturers and procurement officers to assess the potential performance that a particular repair could have.

Use of the Dynamic Cone Penetrometer for in-situ material characterization has been extensively researched, and is reported in the literature [22–25]. Models relating deviator stress at failure for granular materials during triaxial compression tests with DCP penetration rate were successfully developed by Ayers et al. [26]. Ford and Eliaison report DCP use in conjunction with sand cone tests for density control in subsurface drainage trenches [27]. Other researchers have used the DCP as the sole compaction control method for thermostatic pipe backfill installation (Jayawickrama et al. [28]). In general, the use of the DCP for backfill compaction control is fairly common, but its utilization with cold patching mixtures is limited. However, it is felt that as the stability and shear strength of CMA relies mainly on their aggregate structure in an uncured state, the use of the cone penetrometer can be suitable to assess their stability and shear strength characteristics.

The development of simple and field-friendly test methods able to estimate proven rutting indicators would be
extremely useful. Considering the cost and simplicity of tools such as the cone penetrometer, facilitating its use for CMA evaluation can be a practical solution to monitor compaction levels needed to reach minimum initial stability, increasing the chances of obtaining high quality localized repairs where CMA is used.

3. Methodology

3.1. Overview

The main objective of the study was to evaluate the ability of CMA products typically available in the market for pothole repair to resist the accumulation of permanent deformation under the application of cyclic loads. This was accomplished by determining the values of parameters \( b \) (power term in Eq. (1)) and \( FN \) (Flow Number), both obtained from uniaxial repeated load tests, widely accepted as appropriate to characterize rutting susceptibility in bituminous mixes.

Considering that the strength of CMA increases with time, the evaluation concentrated on characterizing permanent deformation resistance in an uncured state (i.e., fresh mixes right after unpacking).

In addition, in order to establish a rapid and field-friendly methodology to assess CMA rutting resistance, the test parameters from the uniaxial cyclic permanent deformation tests mentioned above (i.e., \( b \) and \( FN \)) were compared with the penetration rates obtained from testing replicate CMA specimens compacted from low to high densification levels with a Light Cone Penetrometer. Data were processed using Multiple Linear Regression Analysis (MLRA) to establish the relationships between the parameters from both tests. A total of six proprietary CMA products available in the market were investigated, and are identified in this document as mixes A, B, C, D, E and V (the latter used for validating the models developed).

3.2. Test description and results

The characterization tests used can be classified in two main categories: loose mix properties and compacted mix properties. Loose mix properties include gradation analysis, Total Fluid Content (TFC) and Total Binder Content (TBC) determined with the Ignition Oven Test in the uncured and fully cured state, respectively, uncompacted voids of the fine aggregate fraction (UVFine), and maximum theoretical specific gravity (\( G_{mm} \)). Properties of compacted specimens, identified as Performance Tests, include resistance to penetration with the Dynamic Cone Penetrometer, and resistance to permanent deformation after dynamic loading with a modified laboratory uniaxial repeated load test.

Specimens having a one to one (1:1) diameter to height ratio (diameter of 150 mm) were compacted by means of a gyratory compactor with density levels ranging from low to high, using an axial pressure of 600 kPa and an external angle of 1.25°. After compaction, the specimens were subjected to cyclic creep and penetration tests. Aggregate particle size distribution and loose mix properties for the CMA evaluated are summarized in Table 1.

Fine aggregate angularity (UVFine) and surface texture was evaluated on material passing the 4.75 mm opening sieve according to AASHTO T 304-96, Method C. The high UVFine results suggest the use of 100% crushed aggregate for all the CMA evaluated, and suggest significant differences between the mixes, particularly between mixes A and D and mixes B, C, and E (the former having uncompacted voids around 3% higher than the latter).

3.2.1. Performance Test 1: Modified Cyclic Creep Test (MCCT)

Considering CMA materials are at their weakest state early in their lives (i.e., immediately after placement), it is of the utmost importance to determine their ability to resist permanent deformation induced by repeated loads when they have not had the opportunity to cure.

Although triaxial cyclic test setups would be an immediate choice to account for this low initial strength, their somewhat complex implementation requires trained personnel and accessories that oftentimes are not readily available in asphalt laboratories (e.g., a triaxial confining cell). In order to keep the fundamental permanent deformation test for CMA as simple and practical as possible, and knowing the ability of the cyclic uniaxial compression tests to characterize the rutting performance of bituminous mixes, this test was modified in order to make it suitable to the particular low initial stability conditions observed in CMA at low curing levels.

The modification consists on providing confinement to the fresh CMA by means of two rubber membranes, each having 150 mm in diameter and thickness of 0.635 mm. In this way, the implementation of the test is kept simple, while allowing testing CMA specimens with a wide range of permanent deformation resistance to be evaluated under the same conditions.

Table 1
Summary of mixture characteristics.

<table>
<thead>
<tr>
<th>Mix property</th>
<th>Mix ID</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max (mm)</td>
<td></td>
<td>19</td>
<td>4.75</td>
<td>9.5</td>
<td>4.75</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>%Pass94</td>
<td></td>
<td>49.4</td>
<td>90.8</td>
<td>43.8</td>
<td>94.3</td>
<td>35</td>
<td>48.2</td>
</tr>
<tr>
<td>%Pass9500</td>
<td></td>
<td>4.53</td>
<td>2.72</td>
<td>3.23</td>
<td>4.71</td>
<td>4.37</td>
<td>2.35</td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td>25.1</td>
<td>2.4</td>
<td>2.4</td>
<td>2.6</td>
<td>24.4</td>
<td>13</td>
</tr>
<tr>
<td>Cc</td>
<td></td>
<td>2.8</td>
<td>1.3</td>
<td>0.9</td>
<td>1.4</td>
<td>7.7</td>
<td>2.1</td>
</tr>
<tr>
<td>D10 (mm)</td>
<td></td>
<td>0.29</td>
<td>1.5</td>
<td>2.46</td>
<td>1.29</td>
<td>0.28</td>
<td>0.7</td>
</tr>
<tr>
<td>D30 (mm)</td>
<td></td>
<td>2.39</td>
<td>2.61</td>
<td>3.69</td>
<td>2.46</td>
<td>3.78</td>
<td>3.04</td>
</tr>
<tr>
<td>D50 (mm)</td>
<td></td>
<td>7.19</td>
<td>3.56</td>
<td>5.88</td>
<td>3.38</td>
<td>6.74</td>
<td>5.94</td>
</tr>
<tr>
<td>TFC</td>
<td></td>
<td>7.44</td>
<td>5.89</td>
<td>3.86</td>
<td>10.16</td>
<td>6.77</td>
<td>8.30</td>
</tr>
<tr>
<td>TBC</td>
<td></td>
<td>5.86</td>
<td>5.08</td>
<td>2.95</td>
<td>4.75</td>
<td>5.09</td>
<td>5.77</td>
</tr>
<tr>
<td>Gmm</td>
<td></td>
<td>2.61</td>
<td>2.63</td>
<td>2.64</td>
<td>2.59</td>
<td>2.54</td>
<td>2.602</td>
</tr>
<tr>
<td>UVFine</td>
<td></td>
<td>44.4</td>
<td>41.7</td>
<td>41.1</td>
<td>44.3</td>
<td>41.4</td>
<td>41.9</td>
</tr>
</tbody>
</table>
The Modified Cyclic Creep Test (MCCT) consists in subjecting previously compacted CMA specimens with the gyratory compactor (GC) to a 0.1 s duration stress pulse with magnitude of 138 kPa, followed by a rest period of 0.9 s. Prior to subjecting the specimens to loading, they were transferred from the GC compaction molds to split PVC molds and transferred to a temperature controlled environment set to 25 °C for 2 h. After this, the samples were removed from the PVC molds, covered with the two rubber membranes, and positioned inside the temperature controlled load frame for the test. Detailed explanation of the MCCT test can be found in [29].

The power rutting model described in Eq. (1) was selected to describe the relationship between the accumulated permanent strain and the number of load repetitions obtained from the MCCT. The slope of the curve of ε_p vs. N in a log–log scale (i.e., power term b in Eq. (1)) was used as one indicator of the resistance to accumulate permanent deformation with repeated loading in CMA. An additional parameter from the MCCT test, namely the number of cycles to enter the tertiary stage of permanent deformation (i.e., FN), was used as an indicator of the life of a CMA. Mixes showing a combination of lower slope b values and higher FN values are expected to be better suited to resist permanent deformation under the action of repeated loads.

Fig. 1 shows the relationship between the slope b and FN during the MCCT for all the mixes evaluated. The results suggest that when CMA specimens show FN values under around 1000 cycles, major instability can be expected, as indicated by the consistently higher b values. In general, when the term b is under 0.5 με/load, CMA specimens are more stable and last longer, as indicated by higher FN values. Although the overall trend indicates that lower b values can be expected when higher FN values are present, the somewhat small variation in b for FN values greater than 1000 is a clear indication of a more stable mix.

Based on the MCCT trend observed in Fig. 1, maximum average values of 0.5 με/load and 1000 load repetitions for the slope b and FN, respectively, were selected as threshold values to separate acceptable from unacceptable resistance to permanent deformation under cyclic loading in the laboratory.

3.2.2. Performance Test 2: LCP penetration test

The Light Cone Penetrometer (LCP) is a smaller version of the Army Corps of Engineers Dynamic Cone Penetrometer, and is currently used by some utility companies as a backfill compaction quality control tool. The conical tip is driven into the material whose compaction is to be verified by the impact of a free falling mass which applies a constant impact energy to an anvil located at the upper end of the rod where the conical tip is attached. The parameter from the LCP penetration test (identified herein as LPR) is defined as the rate at which the tip of the LCP penetrates the CMA specimen with each impact of the free falling mass, and is expressed in units of depth of penetration per blow (mm/blow). Lower LPR values are associated with higher shear strength, as more impacts of the falling mass are required to penetrate a given depth.

Penetration tests with the LCP were executed on replicate specimens of all CMA materials from where MCCT data were available, with the objective of having a set of data that included parameters b and FN and associated values of the parameter LPR from the LCP penetration tests of an identical specimen.

3.3. CMA rutting susceptibility assessment with the Light Cone Penetrometer (LCP)

Results suggest that the parameters b and FN from the MCCT provide useful information to assess the ability of CMA with varying characteristics and compaction levels ranging from low to high to resist permanent deformation due to repeated loading, and provide a reference from where a methodology to quickly assess rutting susceptibility in these types of materials with potential field applicability could be developed.

Recognizing that the rutting resistance and the magnitude of the penetration rate from a penetration test with the LCP are both dependent on how well packed are the particles in a CMA (i.e., both are dependent on the degree of compaction), models to estimate the MCCT parameters b and FN as a function of the parameter LPR from LCP tests were developed. The usefulness of establishing these relationships lies in the fact that as the LCP test is a simple, low cost activity that lends itself to be used in the field, it could potentially serve as an on-site quality control tool when CMA materials are used during localized pavement repairs. For instance, if minimum acceptable stability is considered to be reached when the slope of the secondary stage of permanent deformation b is less than 0.500 με/load, maximum penetration rates ensuring this slope value is not exceeded could be determined.

Multiple Linear Regression Analysis (MLRA) was used to develop the relationships between the parameters from the MCCT test (slope b, and Flow Number FN) and the LCP penetration rate (LPR) with other mixture properties...
that could serve as additional predictor variables to explain the variability in MCCT parameters. The theory behind the principles and assumptions utilized during MLRA is extensively reported in the literature [30–34], and is not discussed in detail in this paper. The definitive variables included in each of the models were determined after stepwise and best $R^2$ predictor selection procedures. After the models were fitted, MLRA assumptions about equality of variance, linearity, and normality of residuals were verified. For specific details regarding the statistical analysis procedure, including software outputs, variable transformations, and the final models with all the checks for model assumption violations, the reader is referred to Appendix A in [29]. The Pearson correlation coefficients among the final variables included in the models are included in Table 2. A summarized discussion of the results from the MLRA is included in the following sections for each of the models developed.

3.3.1. Resistance to accumulate permanent deformation with repeated loading: Slope $b$

The relationship between $LPR$ and the slope of the accumulated permanent deformation curve from the MCCT can be seen in Fig. 2, while the results from the MLRA procedure are included in Table 3.

As expected, lower penetration rates are related with better stability, but it is evident that there is not a unique relationship between $b$ and $LPR$, as similar $b$ values are observed for very different penetration rates.

The unique relationship between $LPR$ and $b$ for each CMA suggests that other mixture characteristics play an important role in the strain rate values that could be expected when specific LCP penetration rates are observed. After statistical analysis that included variable selection procedures, Multivariate Linear regression Analysis (MLRA) and model’s statistical assumptions check (i.e., equality of variance, linearity, and normality of residuals), the equation to estimate the rate of accumulation of permanent strain under cycling loading $b$ is given by Eq. (2):\

$$b = -1.48 + 0.42LPR + 0.037Cc + 0.037UVFine$$ (2)

As expected, the model suggests that higher penetration rates ($LPR$) are related to higher $b$ values (meaning lower rutting resistance). The effect of $UVFine$ on $b$ seems to be contradictory, as intuitively one would expect that higher uncompacted voids would result in lower $b$ values ($r = -0.51$, in Table 2), due to rougher particle surface texture and angularity. The somewhat high correlation between $LPR$ and $UVFine$ ($r = -0.72$) may explain this contradiction, as interpretation of partial regression coefficients becomes difficult when predictors are not fully independent from each other. However, the use of $UVFine$ as a predictor increases the overall predictive power of the model, improving its accuracy for stability assessment ($R^2$ increases from 0.72 to 0.78 by inclusion of $UVFine$ as a predictor variable).

Taking into account the domains for the predictor variables, the possible estimated values for $b$ would fall between 0.174 and 1.122 $\mu$m/load. This has to be kept in mind when using the model, as the minimum and maximum observed values of $b$ were 0.266 and 0.779 $\mu$m/load, respectively, and extrapolation should be avoided when possible. It is felt, however, that the model can satisfactorily differentiate between low, medium, and high stability CMA. Overall, acceptable stability was observed when samples showed slope values under 0.5 $\mu$m/load.

3.3.2. Onstage of permanent deformation failure: Flow Number ($FN$)

The relationship between the number of cycles to enter the tertiary stage of permanent deformation ($FN$) and LCP penetration rate ($LPR$) can be seen in Fig. 3.

The trend shows that lower $LPR$ values are associated with higher number of load cycles to the onset of failure (i.e., CMA with longer “life”). MCCT results suggest that all CMA evaluated can potentially survive long periods of cyclic loading without failure, if adequate compaction is provided. Logarithmic transformation of $FN$ was required to meet MLRA assumptions. The analysis of variance and the parameters for the prediction of $LogFN$ as a function of $LPR$ and mix characteristics are summarized in Table 4.

The equation for estimating the number of cycles for the onset of flow failure ($LogFN$) from the MCCT test is given by:

$$LogFN = 13.23 - 2.021LPR - 0.099Cc - 0.196UVFine$$ (3)

Significance of the predictors to estimate $LogFN$ is confirmed by the model’s $p$ value below 0.0001 (last column in Table 4). While $LPR$ alone serves as a satisfactory pre-

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson correlation coefficients between MCCT parameters and predictor variables.</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>$b$</td>
</tr>
<tr>
<td>$LogFN$</td>
</tr>
<tr>
<td>$LPR$</td>
</tr>
<tr>
<td>$Cc$</td>
</tr>
<tr>
<td>$UVFine$</td>
</tr>
</tbody>
</table>
dictor of LogFN (coefficient of determination of 0.71), adding UVFine and Cc improve considerably the power of the estimation ($R^2 = 0.82$).

It comes as no surprise that the signs of the parameter estimates are consistent with the previous model, as both are estimating mix stability characteristics. The inverse proportionality between FN and LPR was expected, as samples with higher penetration rates are expected to fail earlier. As was the case with the signs of the coefficients for the slope $b$, the sign in the coefficient for UVfine in Table 4 would suggest an inverse relationship between LogFN and UVFine, which is counterintuitive (as mentioned before). The high negative correlation between LPR and UVFine ($r = -0.72$ in Table 2) may explain this situation.

Taking into account the domains for the predictor variables, the prediction range for FN could vary theoretically between 5 and 56,000 load cycles. Observed FN values were between 80 and 20,500 load cycles. Care must be taken when interpreting the estimated number of cycles to failure from the model, as the numbers may be misleading for very unstable or extremely strong mixes. For practical purposes, rather than estimating the actual Flow Number of the mixes, the model could be useful for rating as satisfactory or unsatisfactory a particular compacted mixture. For the CMA evaluated, acceptable stability was observed for FN values above 1000 load cycles.

### Table 3
ANOVA and parameters for $b = f(LPR, Cc, UVFine)$.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>$F$ Value</th>
<th>$p &gt; F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3</td>
<td>0.63751</td>
<td>0.21250</td>
<td>79.81</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>63</td>
<td>0.16774</td>
<td>0.00266</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>66</td>
<td>0.80525</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root MSE</td>
<td></td>
<td>0.05160</td>
<td></td>
<td>$R$-Square</td>
<td>0.7917</td>
</tr>
<tr>
<td>Dependent mean</td>
<td></td>
<td>0.47894</td>
<td></td>
<td>Adj $R$-Sq</td>
<td>0.7818</td>
</tr>
<tr>
<td>Coeff Var.</td>
<td></td>
<td>10.77384</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4
ANOVA and parameters for LogFN = $f(LPR, Cc, UVFine)$.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>$F$ Value</th>
<th>$p &gt; F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
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<td>12.20293</td>
<td>4.06764</td>
<td>79.09</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>47</td>
<td>2.41738</td>
<td>0.05143</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected total</td>
<td>50</td>
<td>14.62030</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root MSE</td>
<td></td>
<td>0.22679</td>
<td></td>
<td>$R$-Square</td>
<td>0.8347</td>
</tr>
<tr>
<td>Dependent Mean</td>
<td></td>
<td>3.16350</td>
<td></td>
<td>Adj $R$-sq</td>
<td>0.8241</td>
</tr>
<tr>
<td>Coeff Var.</td>
<td></td>
<td>7.16895</td>
<td></td>
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</tbody>
</table>

### Parameter estimates

| Parameter estimates | DF | Parameter estimate | Standard error | $t$ value | $Pr > |t|$ | Standardized estimate | Variance inflation |
|---------------------|----|--------------------|----------------|-----------|---------|----------------------|--------------------|
| Intercept           | 1  | -1.47608           | 0.35243        | -4.19     | <.0001  | 0                    | 0                  |
| LPR                 | 1  | 0.42414            | 0.03338        | 12.71     | <.0001  | 1.45261              | 3.95302            |
| Cc                  | 1  | 0.03704            | 0.00415        | 8.93      | <.0001  | 0.71175              | 1.92264            |
| UVFine              | 1  | 0.03716            | 0.00777        | 4.79      | <.0001  | 0.45756              | 2.76516            |

![Fig. 3. Relationship between LPR and Flow Number (FN).](image-url)

Different procedures for model validation are mentioned in the literature [32,34]. The models presented in this doc-
agement were validated using two methods: first, by implementing the jackknife elimination procedure to perform cross-validation using the PRESS procedure, and second, by comparing measured vs. predicted stability parameters on a CMA not used for model development (identified in this document as mix V).

The cross validation from the jackknife elimination procedure (leave-one-out) uses the Predicted Residual Sums of Squares (PRESS statistic) to evaluate the validity of the model when applied to the general population. The PRESS statistic is defined as:

$$ PRESS = \sum c_i^2 $$

(4)

where \( c_i \) is the residual for observation \( i \) computed as the difference between the measured value of the dependent variable and the prediction from a regression model calibrated on the set of \( n - 1 \) measurements from which measurement \( i \) was excluded. The PRESS statistic can also be interpreted as the Sum of Squared Errors from Validation (SSEv) used to calculate a “validation” coefficient of determination (\( R_v^2 \)). The PRESS procedure suggests that \( R_v^2 \) values similar to the model’s \( R^2 \) can be considered as evidence of validation.

In order to account for uncertainties in both the predicted values and in the estimates of the regression coefficients, Weisberg suggests the use of the Root-mean-squared error of validation from the PRESS procedure (RMSEv) for the construction of prediction confidence intervals [34]. A 95% confidence interval is given by \( \pm 2RMSE_v \), where \( yp \) is the predicted value for the dependent variable. Relevant statistics from the PRESS validation procedure for the two stability models are included in Table 5.

The similarity between the coefficient of determination from the model and from the PRESS procedure for estimating the permanent deformation rate suggests that the model for estimating \( b \) is appropriate (a difference between \( R^2 \) and \( R_v^2 \) of 0.03 for \( b \), as indicated in Table 5). Furthermore, the difference between the residual standard error from validation and the original model for \( b \) is 0.0033 \( \mu \text{e}/\text{load} \), which can be considered negligible.

The difference between the residual standard error from the PRESS procedure (RMSEv) and from the original model (RMSE) for \( \log FN \) is 0.1008, which translates into a difference of around 500 load cycles in the estimated value of \( FN \). The difference in Table 5 between the coefficients of determination from the original model and from validation using the PRESS procedure (\( R^2 \) and \( R_v^2 \) of 0.83 and 0.65, respectively), suggests that applicability of the model may be reduced when using materials different to those from where the model was developed. Taking into account that the reduction in \( R^2 \) is not severe, it is felt that the model can still be applicable with some precautions.

To confirm the suitability of the models to estimate the resistance of CMA materials to accumulate permanent deformation, specimens of a mix not used in the MLRA (mix V) were prepared at different compaction levels and tested using the MCCT and to penetration with the LCP.

The parameters \( b \) and \( FN \) measured for mix V during MCCT tests, along with their predicted values using the models from Eqs. (2) and (3), respectively, are shown in Figs. 4 and 5. Comparison between measured and predicted values for both \( b \) and \( FN \) suggest the models accurately estimate both the rate of accumulation of permanent strain under repeated loading and the Flow Number.

Estimated \( b \) values for mix V ranged between 0.354 and 0.625 \( \mu \text{e}/\text{load} \), while measured values ranged between 0.231 and 0.547 \( \mu \text{e}/\text{load} \). Although a somewhat larger difference between estimated and measured \( b \) values was detected in one case (for an LPR of 0.43 mm/blow, the predicted and measured \( b \) values were 0.36 \( \mu \text{e}/\text{load} \) and 0.22 \( \mu \text{e}/\text{load} \), respectively), overall the model provides reasonable estimates of the strain rate measured during testing within a 95% confidence interval.

The estimated values for \( FN \) ranged between 364 and 8893 load cycles, while measured values ranged from 530 to 33,000 load cycles. Although the model was not able to predict accurately the \( FN \) in one instance (measured \( FN \) of 33,000), the model would still accurately classify this specimen as having satisfactory stability.
5. Conclusions and limitations

The rutting performance of Cold Mix Asphalt (CMA) materials commonly used for pavement localized patch repairs was analyzed in the laboratory by means of the Modified Cyclic Creep Test (MCCT) and by their resistance to penetration with a Light Cone Penetrometer (LCP). Taking advantage of the potential use of the LCP as a field-friendly quality control tool, two predictive equations to estimate the parameters $b$ and $FN$ from the MCCT as a function of the resistance to penetration with the LCP (i.e., $LPR$) were developed using Multiple Linear Regression Analysis (MLRA):

$$b = -1.48 + 0.42LPR + 0.037C_c + 0.037UV_{fine}$$  \hspace{1cm} (2)

$$LogFN = 13.23 - 2.021LPR - 0.099C_c - 0.196UV_{fine}$$  \hspace{1cm} (3)

The equations are useful to estimate the ability of fresh (i.e., non-cured) CMA to resist permanent deformation caused by the action of repeated axial loading in a laboratory setting. Based on the results available, acceptable laboratory stability can be expected when values below 0.5 $\mu$m/load and over 1000 load cycles are observed for $b$ and $FN$, respectively.

While the maximum $LPR$ penetration rate that needs to be established to ensure acceptable laboratory stability in a particular mixture depends on aggregate characteristics such as $C_u$, $C_c$, and $UV_{fine}$, the data suggest that when $LPR$ values are limited to 0.50 mm/blow, mixes similar to those evaluated during the investigation can be expected to show acceptable stability levels. Due to the fact that CMA’s rutting resistance improves with time as curing takes place, the results suggest that the LCP can potentially be used to control compaction levels during patch installation, ensuring minimum initial stability levels.

From a mixture stability standpoint, gradation changes to maximize the aggregate particle interaction are encouraged. However, such changes may slow the curing rate of the mixes, and this may be a factor due to environmental regulations. Rapid curing is not a crucial feature regarding stability, as long as minimum stability levels can be guaranteed.

It is recognized that even though the validation process provided encouraging results, the limited number of mixes used during the development of the models demands a careful and conservative approach in their use. While the models can estimate quantitatively the stability parameters from the MCCT, their primary purpose is to differentiate between satisfactory and unsatisfactory stability.

References


[29] Luis G. Diaz, Simplified Test Methodology for Stability Assessment of Asphalt Cold Mixes (Doctoral dissertation), University of Illinois at Urbana-Champaign, 2005.


