INTRODUCTION
One of the most common distresses in composite pavements is reflective cracking. The reaction of thermal and traffic loading causes the concrete to expand inherently, contract and shift vertically which consequently ruptures the bonded overlaying hot-mix-asphalt (HMA) at pavement joints. These recurring movements of the pavement substructure subsequently result in the upward progression of the rupture through to the driving surface within a time frame. Accelerated by freeze-thaw cycles, reflective cracking shortens a pavement’s service life. This enables the development of potholes and/or cracks, thus requiring premature maintenance or full pavement restoration.

Several strategies to mitigate pavement distress, particularly reflective cracking, have been explored. The effectiveness of each technique varies tremendously depending on the number of factors, particularly climate conditions. The saw and seal method is a technique that creates incisions of uniformly-spaced saw-cuts in the overlaying HMA surface directly above the underlying concrete joints in the concrete base and is filled with a rubberized low modulus sealant. This method accommodates the movements of the underlying concrete in the HMA overlay instead of cracking at these joint locations. Saw-cuts are often made in transverse or longitudinal directions, or both. Other standard techniques that are used to mitigate reflective cracking include the reinforcement of the HMA overlay with geosynthetic material, placing new asphalt directly on the distressed pavement, and resurfacing the pavement increasing asphalt thickness. Under the same traffic and environmental conditions, each strategy could be successfully replicated. Another notable finding is that, the success of the most frequently used reflective crack prevention methods tend to decrease with increasing traffic volumes. In fact, according to the literature, several methods fail after experiencing only medium-level traffic volumes.

Major factors that cause reflective cracking include temperature, traffic volume, and pavement age. The success of the saw-cut sealant method depends on the changes in the widths of the both types of saw-cuts made in the HMA. The widths of the saw-cuts were measured at 22 saw-cut points on a quarterly basis. Statistical tests of the relationship between the saw-cuts and the changes in average daily air temperature, average daily traffic (ADT), and pavement age were conducted. From the results, the maximum daily temperature and ADT had a statistically significant effect on changes in both of saw-cut types.

LITERATURE REVIEW
Reflective cracking may occur in composite pavements as well as flexible pavements. It is more common in a composite pavement which has been studied and documented in the literature. Reflective cracking is typically classified into two categories:
1. Cracks caused by underlying joints in the concrete slab base
2. Cracks caused by underlying cracks either in the concrete base or old HMA overlay.
Reflective cracking come about due to a combined effect of recurring horizontal and vertical deflections at the underlying joints in the composite (jointed) pavements or the original HMA layer that has been overlaid with additional HMA.\textsuperscript{4} Presented in Fig. 1 are the commonly known mechanisms of reflective cracking.

Saw and seal is a reflective cracking modification method that involves constructing incisions across and along the direction of travel of approximately half of an inch in width in a bituminous overlay and sealing them with rubberized modified material.

Fig. 2 shows the details of a typical saw-cut joint. These joints in the bituminous overlay are found directly over the structural joints or cracks in the underlying concrete base. The purpose for saw and seal treatment is to assist the concrete’s movement in reacting to temperature and other changes caused by its expansion and contraction. Sealing of the joints avoids the intrusion of moisture and incompressible materials, which could lead to pavement distresses such as rutting.

If the overlay cannot accommodate the movement of the underlying joint or crack, the tensile stresses developed at the interface of the bituminous overlay and concrete base overcomes the tensile strength of the bituminous overlay causing a crack to develop. The frequency of these cracks throughout a concrete slab depends on the HMA overlay stiffness, traffic loading, and the friction properties at the interface between the overlay and underlying pavement layer.\textsuperscript{3}

Smaller joint spacing (slab length) suitably accommodates the stresses in the pavement and is more efficient than longer ones.

In New York, joint spacing distances as small as fifteen feet has been used with high levels of success in preventing reflective cracking, and in Minnesota, thirty to fifty feet is the optimal joint spacing distance for the saw and seal method to be effective.\textsuperscript{1,3} In these two states, it has been reported that the depth of the saw-cut needs to be depth of at least 5/8 of an inch for the underlying reflective cracks to coincide with the HMA overlay joints.\textsuperscript{3}

To resolve the problem of reflective cracking, Mostafa et al. recommended the use of saw and seal method to control the distressed composite pavements. In Louisiana, they evaluated the performance of a HMA overlay built with the saw and seal method and compared the results with available untreated segments across the state. Over a span of 12 years, the researchers attained a detailed performance and economic evaluation. Along with varying climate conditions, the sections experienced average annual daily traffic (AADT) ranging from 1,800 to 50,250, along with changing climate conditions. Temperatures ranged between 18°F and 106°F in the northern of the state while temperatures ranged between 46°F and 100°F in the southern part. Saw-cuts made in the HMA overlay were both transverse and longitudinal. The study found that the saw and seal method was an overall success in increasing the service life of the pavement.\textsuperscript{5} Seven test sections indicated an increase in service life ranging from 4 to 12 years and six of the test sections showed an increase in service life of 3 years resulting in an expected average increase in service life of 4 years. When compared with regular HMA overlays, the saw and seal treatment method appeared to be more affordable for low to medium traffic volumes. The field evaluation revealed that HMA overlay constructed with the saw and seal method can allow the underlying layer dissipate the energy generated by the expansion and contraction of the concrete layer and traffic loading without cracking. Although the saw and seal method can prolong the life of pavement, minor reflective cracking may occur if cuts are made more than 25 mm away from the joint. Also, high increase in traffic loading may lead to minor rutting in the wheel paths which may cause a decrease in the serviceability of the pavement structure.

A study on a composite pavement test section that consisted of 54 sawed and sealed joints was conducted to determine its effect on controlling reflective cracking in North Dakota.\textsuperscript{6} That study began in 1994 and yearly evaluations were performed until 2001. The pavement consisted of an underlying concrete base that had very little transverse and longitudinal cracking with a four-
inch thick HMA overlay. Joints in the HMA overlay were sawed directly over the joints in the concrete base at 28 feet apart. The study found that all joints were in good condition and they experienced no adhesion failure between the sealant and the sidewalls of the joints despite extreme temperature cycling. The findings also suggested that the saw and seal method is effective when joints in the HMA overlay are located within one inch of the underlying concrete joint. The saw and seal method was found to be successful since after seven years, the test section experienced no cracking even though 59% of the shoulders at the joints experienced reflective cracking.

This article expands previous work on saw-cut methods for mitigating reflective cracking by examining factors that affect the widths of saw-cuts and to predict the difference in widths over time based on those factors.

METHODOLOGY

Based on the literature review, the most notable influence on reflective cracking is climate. Most of the studies that were conducted in warmer climates produced more effective results than the studies conducted in areas that experienced drastic changes temperature. In addition, the studies conducted in Louisiana, Nevada, Massachusetts and Virginia indicated that traffic volume also impacts the progression of reflective cracking. Considering these observations, air temperature (measured in degrees Fahrenheit) and ADT were chosen as two variables to be used in evaluating their impact on longitudinal and transverse saw-cuts in preventing reflective cracking. A control and experimental pavement segments were used for this study. A particular street segment, that is, southbound North Capitol Street in Washington DC was used. The experimental and control sections were therefore subjected to the same conditions.

Hypothesis and Visual Observations

To gauge the effectiveness of the saw and seal method in the prevention of reflective cracking, the impacts of changes in maximum daily temperature and ADT on transverse and longitudinal HMA saw-cut widths were evaluated. The following hypotheses were developed:

1. It is hypothesised that changes in average transverse saw-cut widths are related to the changes in average daily temperature and average daily traffic (ADT). The hypothesis is defined as follows:
   \[ H_0: X_{\text{avg}} \neq f(\Delta^\circ F, \text{ADT}) \]
   \[ H_1: X_{\text{avg}} = f(\Delta^\circ F, \text{ADT}) \]
   where:
   \[ \Delta^\circ F = \text{Changes in average daily temperature} \]

  ADT = Average daily traffic
  \[ X_{\text{avg}} = \text{Average change in width of HMA saw-cut over transverse concrete joints} \]

2. It is hypothesised that changes in average longitudinal saw-cut widths are related to mean daily temperature and average daily traffic. The hypothesis is defined as follows:
   \[ H_0: L_{\text{avg}} \neq f(\Delta^\circ F, \text{ADT}) \]
   \[ H_1: L_{\text{avg}} = f(\Delta^\circ F, \text{ADT}) \]
   where:
   \[ L_{\text{avg}} = \text{Average change in width of HMA saw-cut over longitudinal concrete joints} \]

3. Visual Observations: By visual inspection, it is hypothesised that reflective cracking will be mitigated more at the treated (experimental) section compared to the untreated (control) section.

Data Collection

The experiment was conducted on North Capitol Street, in the District of Columbia which is a heavily traveled three-lane divided roadway oriented in the north and south direction and carries an ADT of approximately 30,000 vehicles. The experimental site, shown in Fig. 3, is approximately 150 feet long of which 15 transverse and 7 longitudinal HMA saw-cut observation points were selected. The transverse saw-cuts covered all three lanes and were equally spaced at 30 feet while the longitudinal saw-cuts are located along the centerline between each southbound lane. The HMA saw-cuts were filled with sealant to the exact level of the pavement. The adjacent northbound lanes, constructed at the same time as the experimental section but without saw-cuts, were used for comparison purposes. It was assumed that the ADT for both the northbound and experimental sections was the same.
Reflective cracking

Three types of data were collected on a quarterly basis: HMA saw-cut widths (for transverse and longitudinal), average daily traffic; and average daily temperature. These data were obtained by field observations and records from the district department of transportation.

A field reconnaissance was conducted to select the road segment for the study and to locate the joints of concrete slabs for the study. The saw-cuts in the HMA were installed after pavement construction to establish individual measurement points of each saw-cut located in each lane. Saw-cut widths of up to 0.6 inches were made along the longitudinal and transverse joints in the travel lanes. The joints were sealed, and subsequently, 22 points for measuring joint expansion were selected: 7 longitudinal and 15 transverse points. The points for measurement were marked with spray-painted for ease of re-identification upon repeat visits for measuring their widths. On each day of site observations, the average daily temperature for Washington DC was recorded from the National Climatic Data Center. The data collection spanned a 4½ year period. Visual observations of the experimental and “control” sections were conducted during each field visit. Distress to the pavement surfaces of both sections were noted and photographed.

The average of the 15 initial transverse saw-cut widths and the 7 initial longitudinal saw-cut widths were calculated. These were used as initial observation values for transverse and longitudinal saw-cut widths respectively. The change in daily temperature, in degrees Fahrenheit, on the day of the data collection was obtained by subtracting the daily temperature on the day of installation of the saw-cuts and sealants from the average daily temperature recorded for each day of observation.

### RESULTS

#### Hypothesis No. 1

It was hypothesised that the changes in average transverse saw-cut widths are related to temperature and ADT. Table 1 presents the results of the statistical analysis using the changes in average transverse HMA saw-cut width as the dependent variable. The impact of each independent variable (changes in maximum temperature and ADT) on the dependent variable (changes in HMA saw-cut widths) were inferred from the R square, F-ratio, standard of error in prediction, and the p-values. A p-value of less than 0.05 indicates statistical significance of the model. From the results of the analysis, the alternative hypothesis that the changes in average transverse HMA saw-cut width is related to changes in mean daily air temperature and ADT cannot be rejected.

<table>
<thead>
<tr>
<th>Model summary</th>
<th>ANOVA</th>
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<tbody>
<tr>
<td>Independent variables in model</td>
<td>Unstandardised coefficients (b)</td>
</tr>
<tr>
<td>Change in mean daily temperature (\Delta T)</td>
<td>-0.0005251</td>
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<tr>
<td>Change in maximum temperature ((\Delta T)^2) &amp;</td>
<td>1.613 × 10^{-5} &amp; 0.057</td>
</tr>
<tr>
<td>ADT² &amp;</td>
<td>6.983 × 10^{-10} &amp; 0.930</td>
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Note: \(R^2 = 0.411\) and standard error of the estimate = 0.043 inches.

#### Hypothesis No. 2

It was hypothesized that the changes in the average longitudinal saw-cut widths are related to temperature and ADT. Presented in Table 2 is the summary of the results of the regression analysis using the changes in average longitudinal HMA saw-cut width as the dependent variable. The viability of the model was derived from the F-ratio and the p-values. A p-value of less than 0.05 for the associated F-statistic indicates statistical significance of the model. Based on the results of the analysis, the alternative hypothesis that the changes in average longitudinal HMA saw-cut width is related to changes in the maximum daily temperature and ADT cannot be rejected.

<table>
<thead>
<tr>
<th>Model summary</th>
<th>ANOVA</th>
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<tbody>
<tr>
<td>Independent variables in model</td>
<td>Unstandardised coefficients (b)</td>
</tr>
<tr>
<td>Change in mean daily temperature (\Delta T) &amp;</td>
<td>0.000125</td>
</tr>
<tr>
<td>Change in maximum temperature ((\Delta T)^2) &amp;</td>
<td>-0.00001037 &amp; -0.084</td>
</tr>
<tr>
<td>ADT² &amp;</td>
<td>3.297 × 10^{-10} &amp; 1.014</td>
</tr>
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</table>

Note: \(R^2 = 0.489\) and standard error of the estimate = 0.026 inches.
Visual Observations

Visual inspections of the experimental and control sites were conducted over the period of the study. As shown in Fig. 4, the experimental section which was treated with the saw-cut sealant was found to be in good condition compared to the control section. It was also observed that the experimental section experienced minor reflective cracking (or of low severity) while the control section experienced significant cracks as shown in Fig. 4.

Regression Model

From the results of the multiple regression analyses presented in Sections Hypothesis No. 1 and No. 2 (i.e., Tables 1 and 2), the following regression models were respectively developed for the average transverse and longitudinal saw-cut widths which were measured over a four-and-a-half year period:

\[
T_{\text{saw-cut width}} = \left( -0.00005251 \Delta T + 0.00001613 \Delta T^2 \right) + \left( 6.983 \times 10^{-10} \text{ADT}^2 \right)
\]

where:

- \( T_{\text{saw-cut width}} \) = Change in Average Transverse Saw-cut Width
- \( \Delta T \) = Change in Maximum Daily Temperature (°F)
- \( \text{ADT} \) = Average Daily Traffic

\[
L_{\text{saw-cut width}} = \left( 0.000125 \Delta T - 0.00001037 \Delta T^2 \right) + \left( 3.297 \times 10^{-10} \text{ADT}^2 \right)
\]

where:

- \( L_{\text{saw-cut width}} \) = Change in Average Longitudinal Saw-cut Width

CONCLUSION

This research explored the effectiveness of the saw and seal method in mitigating the impacts of reflectively cracking in a composite pavement. Based on the results of the statistical analyses and the visual assessment of the test and comparison sections, the saw and seal method effectively controlled reflective cracking. Confirming this finding is the statistically significant relationship found between the interaction of air temperature, \( \text{ADT} \), and the changes in the saw-cut widths; which explained 98.1% and 94.4% of variations in transverse and longitudinal movement at the saw-cuts respectively. This finding indicated that the variations in saw-cuts did not occur by chance but due to the impacts of air temperature, and \( \text{ADT} \). The study presents a model for predicting changes in the saw-cut widths based on \( \text{ADT} \) and temperature, at 95% confidence interval.

REFERENCES


Statement of originality of work: The manuscript has been read and approved by all the authors, the requirements for authorship have been met, and that each author believes that the manuscript represents honest and original work.

Sources of funding: None.

Competing interest / Conflict of interest: The author(s) have no competing interests for financial support, publication of this research, patents, and royalties through this collaborative research. All authors were equally involved in discussed research work. There is no financial conflict with the subject matter discussed in the manuscript.

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