Effects of Pavement Design on Frost Heave at MnROAD

Paper #: 09-3181

Date: July 28, 2008

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Words: 6234
Figures: 3
Tables: 2
Photographs: 0
Total Word Count: 7484

Abstract

This paper presents the results of a study of the effect of different pavement design parameters on magnitude of frost heave, a major concern for pavements in cold climates. Elevations of frost pins embedded in MnROAD test sections measured over four years were analyzed, totaling to over 33,700 measurements used. Annual pin elevation changes were computed to evaluate the amount of frost heave and degree of frost heave uniformity within a cell. Statistical approaches such as visual analyses, Student-t hypothesis testing, and ANOVA analysis were used in this study to evaluate the effect of pavement design features on frost heave. The findings suggest that subgrade and base type, pavement thickness, and drainage capabilities are the major design factors that affect frost heave.

INTRODUCTION

Frost heave is the elevation change seen in cold climates caused by the formation of ice lenses in underlying soil layers. As water freezes in subgrade soil voids, ice crystals expand in volume by nine percent during the phase change and additional water is drawn from around the newly formed crystals by capillary action. The drawn water also freezes, causing the crystals to grow and interconnect into lenses. The additional volume in the soil exerts pressure on surrounding soil particles, causing the soil particles to displace towards the surface. This upward displacement causes the surface to heave up.

Frost action is a major concern for pavements in cold climates. Uniform heaving is not a concern because pavement response to the loading is small from the similar amount of heaving. However, differential frost heaving is a concern. Differential heaving loads the pavement different and leads to pavement deterioration like roughness and cracking [Dore 2001, Fradette 2005].

Although frost heave has been a subject of several theoretical, laboratory, and field investigation, the amount of field data concerning the magnitude of frost heave in pavements is still limited [Berg 1980, Michalowski 2006, Voller 2003]. One of the objectives of Minnesota Road Test research facility (MnROAD) was to fill this gap. MnROAD is a cold region pavement research facility outside of Albertville, MN constructed by MnDOT in 1993. It consists of the high volume [mainline] I-94 section that carries interstate traffic and the Low Volume Roadway [LVR] that simulates rural roads. Thousands of sensors, installed and operated by MnROAD personnel, record load response and environmental data.

To evaluate the effects of frost heave, MnROAD personnel installed frost pins in twenty pavement test sections. Of these test sections, thirteen are mainline sections and seven are low volume sections. Eight of the sections are portland cement concrete (PCC) and the remaining twelve are hot mix asphalt (HMA). Each cell has 5 to 7 pins centered in each traffic lane, spaced about 50 feet apart parallel to traffic. MnROAD personnel then used rod and level survey equipment to accurately measure the elevation of the embedded frost pins with respect to a benchmark reference point over a four year period. The pins were measured 75 times from November 1993 to February 1998. A majority of the measurements were taken during the late winter and spring thaw seasons, from mid February to the end of April. Pin information, locations and elevation data were stored in a MnROAD database, totaling over 33,700 frost pin elevation data points.
An advantage of this data set compared to frost heave data collected under similar studies is the quantity of data collected at a single testing location. Traditional studies use pavement sections located at different locations where different traffic and environmental loadings and in-situ soil conditions are similar, but not exactly the same. This lack of control within the field conditions and testing procedure introduces undesired lurking variables into the mix. These systematic and uncontrolled differences in the pavement sections in a comparative experiment cause bias. At the MnROAD test site, pavement sections are considered very controlled compared to one another and have a great deal of bias removed. All test cells within a test area see the same vehicle loading. The cells are in very close proximity to one another so each cell essentially experiences the same weather conditions and has the same soil composition and loading.

Also, traditional test sections may not be monitored on a frequent or prolonged basis. Taking multiple measurements on each test section reduces the variation seen in the magnitude and uniformity within the section values collected. In the MnROAD data, multiple pins in each cell were measured on a frequent basis over the course of four years. Repeating the measurements over four years shows that this event does not occur merely by chance.

A recent study sponsored by the Minnesota Department of Transportation examined frost heave as it relates to different pavement design parameters using the MnROAD frost pin database. The results of this study are described below.

**DATA REDUCTION**

The MnROAD frost pin elevation database was analyzed in this study. Change in pin elevation (CE) was first calculated. The earliest day where each elevation measurement was available for all the frost pins was defined as a reference day. Then the CE value for a corresponding day of measurement was calculated as a difference between the frost pin elevation on a certain day and the corresponding frost pin elevation on the reference day.

The CE for every pin was plotted as a function of time. Figure 1 shows typical plots of CE over time for both HMA and PCC pavements. Generally, every year CE starts to increase from the end of September and reaches its maximum around early March, after which it starts to decrease until approximately the middle of April. For a majority of cells, the CE changes little from May to September before it starts to increase again.

Although the same general trend is seen in all the figure 1 plots, the magnitude and uniformity between the pin measurements are different. Figure 1a shows the CE time plot for a full depth HMA mainline cell on a clay subgrade. The CE for cell 4 ranges from -0.1 to 1.1 inches. All the curves for each pin measured are quite similar. Figure 1b shows a CE time plot for a PCC mainline cell on a clay subgrade, with a class 5 base layer (MnDOT spec 3138 standard dense graded aggregate base). The CE values for cell 13 range from -0.6 to 1.4 inches. The pin measurements in cell 13 are much more spread out than those in cell 4, but the curves for each pin in the cell are fairly similar to one another. Figure 1c shows the CE time plot for a conventional HMA low volume cell on a clay subgrade. The CE values range from -0.6 to 0.6 inch. Cell 31 pins move just as much as the mainline cells described earlier, but the pin curves for this pin are spread out from one another. This shows differential pin movement between the pins. Figure 1d shows a PCC low volume cell on a sand subgrade with a class 5 base layer. The CE values for cell 36 range from -0.2 to 0.2 inch. This cell has pins that move the least of the four test cells shown and all pins move analogous to one another. Overall, the differences in CE
values for the different cells show that although the MnROAD test sections are subjected to the same environmental conditions, each cell responds differently to its surroundings.

To characterize the magnitude of seasonal variation in pin’s elevation, the yearly range of change of elevation (YRCE) for each frost pin was computed. YRCE is defined as the difference between the maximum and minimum values of the CE for an individual pin for a particular year. Assuming that frost heave action is the primary cause of seasonal changes in a frost pin’s elevation, YRCE is considered to be a parameter characterizing the seasonal magnitude of frost heave for a pin.
FIGURE 1 Change in individual frost pin elevation vs. time for selected cells
The variability in YRCE for the pins belonging to a particular cell contains information regarding differential frost heaving within the test section. Differential heaving across a cell is shown by the differences in individual pin elevations. Any differences in pin measurements across the cell would indicate the amount of non-uniformity in heaving. The data is considered uniform when the spread of the data is low [low differential heaving] and seen through the pins by having about equal elevations over time. Non-uniformity would be seen as the opposite of this.

Initially, it was planned to compute the mean value and standard deviation of the changes in pin values for each section to characterize the distribution of the pin elevation changes within a section. However, these parameters are very sensitive to extreme values and potential outliers in the data set. A preliminary analysis of the frost pin elevation data revealed that it would be very difficult to identify if tail measurements represented natural variability in frost heave. Removing these data points from the dataset could lead to a loss of significant information about pavement frost heave behavior if the measurements were not erroneous. To overcome this issue, it was decided to use more robust and resistive characteristics of the frost heave distributions, namely the median and interquartile range (IQR). IQR is the distance between the first (25th percentile) and third (75th percentile) quartile.

To test for the effect of frost heave on different design features, the YRCE and IQR values were statistically tested to investigate the response in the collected data. Statistical approaches were used to evaluate the effect of pavement design features on frost heave. Visual analyses of the datasets by plotting box plots and normal quantile plots, matched pairs student t-testing of the dataset means [bivariate analysis] and ANOVA testing of regression equations were completed in this study.

**Analysis and Results**

**Statistical Analysis**

Different major pavement design features’ effects on frost heave behavior were investigated in this study for both asphalt and concrete pavements. For each design feature, the analysis began with a visual and bivariate analysis where MnROAD cells were grouped in such a way that the groups would differ by a single design feature as best as possible. Further investigation on the interaction of design features within a design was statistically investigated by multivariate regression analysis and ANOVA testing on the selected data.

Comparing distributions of frost heave for two cells or groups of cells differing by a single design feature should give some preliminary idea about the contribution of the design feature on frost heave. A t-test was used to compare the distributions by performing hypothesis testing on the varying design characteristics of the test cells selected. The means of the two different groups for each design characteristic were tested in a matched pairs study to see if there was a difference between them. In this study, a two sample t-test was preformed in assuming an unequal variance between the groups.

The t-test requires data with an approximately normal distribution with independent variables. The data used was checked for normality using the normal quantile plots. Independence is maintained in design feature grouping. By breaking the analysis up into separate design features and carefully controlling test sections, the analysis forces results for a single design feature to reduce the interaction between features as much as possible.
As mentioned before, bivariate statistical analysis only considered one design feature at a time. However, a good pavement design is based on multiple design factors that must be balanced for optimal performance based on funding options and desired life cycle. The bivariate analysis does not take into account the interactions of the different variables and their effects on performance. The t-tests described earlier can not be used to isolate differences caused between the variables on pavement performance. Determining interrelationships between variables can only be statistically accomplished through a multivariate analysis.

Multiple linear regression was used in this study in an exploratory manner to identify the most significant variables. The linear coefficients were computer estimated by the method of least squares. Hypothesis testing used to test the significance of explanatory variable to a regression model and follows a similar procedure as in the bivariate analysis.

**Visual and Bivariate Analysis**

The details and of the tests are described and discussed below. The visual and bivariate analysis results for YRCE and IQR are summarized in tables 1 and 2, respectively. A more detailed analysis was given for the subgrade type variable as an example of the complete analysis procedure. A similar analysis was conducted for the six other design variables considered. A typical level of significance value of 0.05 will be used for this analysis [Moore 2006]. Cross section diagrams for the mainline and low volume road test cells indicating cell dimensions and materials are shown in figure 2.

1) **Subgrade Type**

Subgrade is a critical design feature when considering in frost heave action. It is well known that frost-susceptible soils typical contain large percentages of silts or clays [Michalowski 2006]. A previous study that monitored soil temperature, soil moisture movement and frost heave in silty clays found that a significant amount of moisture migration can cause frost heave within frozen soil at temperatures down to -2.4°C [Smith 2005]. The small size of capillaries in clay subgrade increases the ability of water to rise from the water table. The small particle size promotes formation of ice lenses when water freezes. Sand subgrades, which have a low surface area to volume ratio, are considered to be non-frost susceptible as they do not support capillary moisture movement as clay does. The larger particle size negatively affects an ability of ice lenses to grow [Voller 2003]. Both sand and clay subgrades were used for the LVR test cells. To isolate the effect of subgrade on frost heave, LVR cells with the same subgrade were grouped together for both HMA and PCC. The frost heave measurements for all the cells within a grouping were compared.
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### Key

- **Thickness**
  - **Type**
  - **Subgrade**
- **Thickness**
  - **Type**
  - **Base**
- **Surface**
  - **Type**
- **PG Grade**
  - **Type**
- **Base**
  - **Type**
- **Base**
  - **Type**
- **Subgrade**
  - **Type**

**FIGURE 2 MnROAD test cell cross sections**
## TABLE 2 MnDOT Aggregate Classification & Specification

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<th>Fine Content (%)</th>
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sp indicates special crushing requirements  
- Class 3 & 4: No crushed or fractured particles  
- Class 5: 10-15% crushed or fractured particles requires
Figure 3 show the box plot and normal quantile plot used in the subgrade type visual analysis. Figure 3a and 3b show that sand subgrade has a much lower median YRCE and IQR than the clay subgrade, respectively. The sand subgrade data is symmetric whereas the clay subgrade data has a right skew for both median YRCE and IQR. The normal quartile plot clearly shows the data distribution for the sand subgrade is normal whereas the clay subgrade has a distinctive right tail. The right tail seen in the clay subgrade data comes from data outliers. Of 238 data points within the clay subgrade group examined, 22 outliers were ignored in this portion of the study. The distribution of clay subgrade is close to normal without the 22 outliers. The star in tables 1 and 2 indicates multiple values were removed to achieve normality. The PCC visual analysis showed the same trend for the sand and clay subgrades.

FIGURE 3 Visual analysis plots for HMA subgrade type: a) YRCE and b) IQR
The results are consistent with findings from earlier studies and long held engineering knowledge that clay subgrades are more susceptible to the effects of frost heave than sand subgrades.

The amount of subgrade construction is an important difference that should be noted between the test sections at MnROAD and what is typically done on city and county roadways. The MnROAD cells were over excavated by about 6 feet and replaced with a more uniform silty clay or sand [Newcomb 1995]. This was done to limit the variability from differential subgrade soil properties across the cells. Due to the expense of over excavating soil, municipal governments typically use a cut and fill procedure with in-situ soils. In-situ soils are usually not high quality materials and will have more frost action compared to MnROAD cells. The additional subgrade work has some bias on the results and typical Minnesota pavements would yield different results.

2) Drainage

The presence of a permeable base, like the Permeable Asphalt Stabilized Base (PASB), may reduce the amount of free water that enters subgrade and/or minimize the dynamic pore pressures in the unbound materials under the bound layers. Using a drainage layer allows water to drain out of cross section instead of infiltrating through the subgrade, reducing any subgrade bearing capacity issues. Therefore, a permeable base could reduce the effects of frost heave. A permeable base could also provide an insulating effect keeping soil temperatures higher and pavement surface temperatures lower.

To examine this, three separate investigations were completed to test different drainage methods. Frost heave behavior in PCC pavements with different aggregate drainage layers was examined first using cells 6 and 7. Both cells have similar design features except that one cell has a dense graded aggregate base [no attempt to increase drainage] while the other has two smaller base layers, where part is a PASB layer on top of a dense graded aggregate base. The additional two investigations involved the use of a drainage structure compared to a PASB. Both HMA and PCC sections were chosen, represented by cell 18 against 23 and 10 against 12, respectively. Both cell groups tested against each other have similar design features except that one group has two smaller base layers, consisting of a PASB layer on top of a dense graded aggregate base and the other is a conventional pavement design with an edge drain.

Since water is a necessary component for frost heaving, it is expected that the pavement with better drainage would experience the less heaving. The statistical analysis suggests this idea is correct by showing that cells with a drainage layer had heaved less over the year and were more uniform than non-drainable cells. However, the amount of variables controlled in these tests is not very great and their confounding effects may change the outcome of the results. One example is in the second drainage case. Cell 18 has a conventional design that includes the use of higher quality base materials [class 6 base on a class 3 subbase] that have a low percentage of fines and is rather thick [31 inches] compared to cell 23 [PASB on a class 4 subbase and 16 inches]. The amount of difference in the selected cells may be too great to yield great results.

Also shown is that the use aggregate drainage layer perform better than a drainage structure and most likely more efficient because the aggregate drainage layers can serve an additional load bearing purpose in a pavement structure.
3) Total Pavement Thickness

Total pavement thickness is defined as the sum of thickness of surface layer, base layer, and sub-base layer. This design feature was chosen to see if there is any correlation between the amount of pavement constructed and frost heave. In addition to increasing the structural capacity of a pavement by utilizing better performing soils compared to in-situ, some states require the total depth of the pavement to extend to the frost depth to reduce the effects of frost heaving. Extending the depth into the frost susceptible subgrade soil reduces the amount of susceptible in-situ subgrade under the pavement incurring frost action and in turn reduces frost related damage.

To study this effect, a two phase approach was used. First, only cells 15 and 17 were compared. These cells have total thicknesses of 11.1 inches and 35.9 inches, respectively and investigated the difference between a relatively thin and thick HMA pavement section. The second part of this study includes more mainline HMA cells divided among the two groups based on total thickness. Cell 4, 14, 15 and 23 fell into the first group, where the total thickness was less than 17 inches. The second group consisted of cells 17, 18 and 22 where the total thickness was greater than 26 inches.

The statistical analysis shows that higher total thickness reduces frost heave the magnitude. It was found that the YRCE for thin cells is much higher than YRCE for thick cells. This could be expected since a thicker pavement structure had less frost penetration into subgrade than a thinner pavement structure. All other factors being equal, it is expected that the deeper pavement structures will experience less frost heave action than shallower pavement structures because of the selection of pavement materials. Typically, the quality of pavement materials decreases with increasing pavement depth. Gravels and sands [less frost susceptible] are placed on top of silts and clays [more frost susceptible]. The design construction helps to reduce formation of ice lenses in the subgrade, which in turn reduces frost heave. Additionally, a thicker pavement applies more weight on subgrade. Past research has shown that the magnitude of heave decreases as the external overburden pressure is increased [Voller 2003, Penner and Ueda 1977, and Nixon and Morgenstern 1973].

At the same time, surprisingly no significant effect of the pavement thickness on uniformity of frost heave was found. The research team could not find any plausible explanation of this phenomenon. It should be noted that in the comparison the thin pavements were represented by the full depth cells. The results could be different for conventional flexible pavements with thin aggregate bases.

4) Effect of Asphalt Binder Type

Asphalt binder type is a critical characteristic affecting HMA pavement performance. Although it was anticipated that asphalt binder or its Performance Grade (PG) rating would have no effect on frost heave, the variable was considered to investigate the possibility of secondary effects of frost heave due to changes in temperature distribution throughout the pavement system. Cells 14 and 15 were chosen to compare the effect of asphalt binder type. These cells are virtually the same minus the binder type used. The binder PG rating of cells 14 and 15 are 58-28 and 64-22, respectively.

The visual and bivariate results of this study suggest that the asphalt binder type has no effect on either the YRCE or the IQR, and therefore binder type would not affect pavement’s
frost heave behavior. Changes in temperature distribution throughout the pavement caused by differing binder type do not affect pavement response to frost heave.

5) **Base Material**

Cells 17 and 22 were chosen to investigate the effect of base material on frost heave. Typical changes in base material are due to differences in aggregate gradations used. Denser mixes have a higher unit weight [weight per volume] because more of the voids are filled. More voids are filled either by using smaller aggregates alone or adding smaller aggregates to larger aggregates. Less voids allow for more aggregate interlock between aggregates, increasing the strength and stability of the mix. However, the smaller voids decrease the amount of water that can flow through the soil and the void volume water can expand into when freezing. Water available to infiltrate into the subgrade can decrease its strength. The cells chosen have the same asphalt thickness. Cell 17 has 28 inches of class 3 base whereas cell 22 has 18 inches of class 6 base. Both are on a clay subgrade.

Base material seems to have an effect on the frost heave. Class 6 base material is found less frost susceptible compare to Class 3. This could be expected because Class 6 material has lower percentage of fines. More fines decreases the soil void volume and allows for less water drainage. More water in the soil can increase the chance for frost action. On the other hand, the analysis did not show any difference in frost heave uniformity when using a better base material.

It is important to point out that the cross sections were not equal in total thickness. Cell 22 has a more premium aggregate [class 6] compared to cell 17, but less is used. This observation from the IQR analysis is quite interesting. Both cells 17 and 22 are “thick” cells according to the classification used in the total pavement thickness. Although that analysis concluded that thicker cells did not exhibit more uniform frost heave than thinner sections, increases in the base thickness within the group of “thick” cells lead to improvement in frost heave uniformity. Some variation in the results seen in this section could be explained by a confounding effect of base thickness since the pavement sections used were not as controlled as the research team would have liked.

6) **Joint Spacing**

Contraction joints are made in concrete pavements to control the temperature and moisture stresses that are created during concrete curing. Without joint placement, the concrete will crack in an uncontrolled spacing at locations of high stresses and uncontrolled cracking can lead to a variety of PCC pavement distresses. Most importantly, more cracks allows for more water to enter the pavement system due to more surface openings. Joint spacing also affects the size of joint opening under temperature loading and structural capacity of the slab itself. To investigate the effect of joint spacing, PCC cells 11 and 12 were chosen. Both PCC cells have 1.25 inch diameter dowels and 5 inches of a dense graded base. The transverse joint spacing of cells 11 and 12 are 24 feet and 15 feet, respectively with 12 feet lane widths.

The observation that there is no apparent relationship between joint spacing and the magnitude of frost heave matches expectations. It is not surprising that longer joint spacing exhibited more uniform frost heave compare to shorter joint spacing cell. A longer joint spacing allows for a more adaptive pavement surface to the loading conditions and increase the uniformity of the data. Slabs covering a larger plan area would show less distresses as a result of
vertical shifts because the individual slab joints would be further apart. The vertical movement would be resisted because it must be distributed over a larger area. Shorter joint spacing would show more faulting because the soil uplift is more localized under the slab, make easier to vertically lift and cause higher roughness values.

7) Design Life

The MnROAD mainline HMA and PCC test sections were designed for either 5 or 10 year design life. Cell 4, a mainline full depth HMA section with a 5 year design life, was compared with cells 14 and 15, mainline full depth HMA sections with 10 year design life. Also, mainline PCC cells 6 and 7 with 5 year design lives were compared to 10 year design lives sections 10, 11, 12 and 13.

Pavement design life did not show any significance effect on either the YRCE or the IQR in PCC cells. However, greater design life seemed to have some effect on frost heave performance in HMA mainline cells. Designs with greater design life are constructed to withstand greater loadings. Depending on the design assumptions made, a more conservative approach is typically used to make sure the desired design life is reached. The increased strength from the conservative approach would explain the increase in performance.

Multivariate Regression Analysis

Multivariate linear regression analysis was completed individually for mainline HMA, mainline PCC, and LVR HMA sections. PCC LVR cells were not considered because there were only two cells with in the 20 selected for the study. A multiple linear fit was used with the YRCE analysis using the design features discussed earlier as dependant variables. The regression analysis was conducted only for this parameter because the results of the bivariate analysis indicated that the YRCE parameter yielded more reasonable and conclusive results.

This multivariable regression analysis was needed to determine any interaction between the design factors on frost heaving, if any, since the previous bivariate analysis was not able to so. The main purpose of this regression fit is to get an overall idea about the frost heave trend and relative contribution of different design features. Regression of each value began with the same basic model based on the key design features. Depending on the significance of each variable show in the coefficient estimates section of the ANOVA analysis, variables were removed if shown insignificant and the ANOVA analysis was repeated with the new model. Forward and backward regression was carried out to find the variables with significant effect on frost heave. Both types of regression have the same outcome: maximize the multiple correlation coefficient (R-square).

ANOVA has the ability to be used on both continuous [numerical] and categorical [non-numerical] variables where a hypothesis testing is typically only use on continuous variable. If a clever scheme is developed using a more binomial approach, categorical variables can be used in hypothesis testing by “turning on and off” specific regression terms developed for the differences in categories where continuous numbers can not be used.

The main purpose of this regression fit is to get an overall idea about the frost heave trend and relative contribution of different design features. These regression equations were not and are not intended for prediction models.
1) Mainline HMA Cells

The critical design factors identified in the bivariate analysis were total thickness, design life, and drainage layers. Equation 1 gives the YRCE model used for the Mainline HMA cells. The drainage layer, base material and design life are taken as categorical variables. The binomial scheme used for the drainage and base material variables the $D_i$ terms. Three different outcomes are possible. When $D_1$ equals 1 and $D_2$ equals 0, a class 6 aggregate base is used for a drainage layer. When $D_2$ equals 1 and $D_1$ equals 0, a permeable aggregate base is used. When 0 is used for both, no drainage layer is used. A binomial scheme was also used for design life. When $t_{\text{design}}$ is 0, a 5-year life is used. When $t_{\text{design}}$ is 1, a 10-year life is used.

\[
YRC_{E_{\text{HMA-ML}}} = \beta_0 + \beta_1 h_{\text{total}} + \beta_2 t_{\text{design}} + \beta_3 D_1 + \beta_4 D_2
\]  

(1)

The high p-value ($p = 0.1458$) for $D_1$ shows that this term is not significant. Therefore, this base type parameter is considered insignificant. The design life term is also insignificant in the YRCE model ($p = 0.088$). Although this contradicts earlier findings from the bivariate analysis, this is no surprise. Pavements designed for a longer life are generally built more conservatively to achieve the additional design life. This is typically done by increasing total thickness, upgrading on construction materials or better coping for applied traffic and environmental loads. There is most likely a confounding effect from any one or more of these explanations.

The analysis was repeated with the results from above using the updated model shown in equation 2. The design life term was removed and the binomial scheme to $D_1 = 0$ means no drainage or a drainage structure with a class 6 base or $D_1 = 1$ means a permeable aggregate base is used.

\[
YRC_{E_{\text{HMA-ML}}} = \beta_0 + \beta_1 h_{\text{total}} + \beta_2 t_{\text{design}} + \beta_3 D_1 + \beta_4 D_2 \rightarrow \beta_0 + \beta_1 h_{\text{total}} + \beta_2 D_1
\]  

(2)

Equation 3 gives the complete regression model for mainline HMA cells. It suggests that the frost heave decreases with increasing total thickness and with the presence of a PSAB base drainage layer. From the model, a one inch increase in total thickness decreases frost heave by 0.007 inch and the presence of PSAB drainage layer decrease frost heave by 0.144 inch. These results are consistent with the conclusions drawn from hypothesis testing. The $R^2$ value may decrease by using less terms, but the change is less than 2 percent and insignificant.

\[
YRC_{E_{\text{HMA-ML}}} = \beta_0 + \beta_1 h_{\text{total}} + \beta_2 D_1 \rightarrow 0.8590 - 0.0083 h_{\text{total}} - 0.01511 D_1
\]  

(3)

Confounding effects, due to the lack of control between the two cells, may change the outcome of the results. Cell 18 has a conventional design that includes the use of higher quality base materials [class 6 base on a class 3 subbase] that have a low percentage of fines and is rather thick [31 inches] compared to cell 23 [PSAB on a class 4 subbase and 16 inches]. Too many design parameters are compared between these cells and the differences between the selected cells may be too great to interpret the results correctly.
2) HMA LVR Cells

The bivariate analysis showed that total thickness and subgrade type were the important design factors for frost heave in HMA LVR cells. Equation 4 gives the model used for this analysis. The subgrade type binomial scheme used for the regression is 0 for sand and 1 for clay.

\[ YRCE_{HMA-LVR} = \beta_0 + \beta_1 h_{total} + \beta_2 S_{type} \]  

(4)

The high p-value (p = 0.988) for total thickness suggests that the variable is not a significant parameter. This is expected from the results of the subgrade type bivariate analysis. The sand data was fairly tight around the median as compared to the clay values that showed much more variation. The amount of variation seen would justify the subgrade term dominating the equation. The analysis was repeated without the pavement thickness term as shown in equation 5.

\[ YRCE_{HMA-LVR} = \beta_0 + \beta_1 h_{total} + \beta_2 S_{type} \rightarrow \beta_0 + \beta_1 S_{type} \]  

(5)

Equation 6 is the complete model for the HMA LVR cells. The final model still shows a strong effect for subgrade type on heaving. When a sand subgrade is used, a 0.590 inch decrease in frost heaving is seen as compared to clay. This finding is consistent with the results obtained from the bivariate analysis.

\[ YRCE_{HMA-LVR} = \beta_0 + \beta_1 S_{type} \rightarrow 0.213 + 0.590S_{type} \]  

(6)

3) Mainline PCC Cells

Earlier findings from the hypothesis test suggest that total thickness, joint spacing and drainage are major factors for frost heave on mainline PCC cells. Therefore YRCE model was fitted with these parameters as shown in equation 7. A binomial scheme was used for the drainage variable. When D1 equals 1 and D2 equals 0, a drainage structure [edge drain] is used. When D2 equals 1 and D1 equals 0, a permeable aggregate base is used. When 0 is used for both, no drainage feature is used.

\[ YRCE_{PCC-ML} = \beta_0 + \beta_1 h_{total} + \beta_2 J_{space} + \beta_3 D_1 + \beta_4 D_2 \]  

(7)

The high p-value (p = 0.504) for total thickness suggests the term is not significant for mainline PCC sections. Regression analysis was performed again without this variable following equation 8.

\[ YRCE_{PCC-ML} = \beta_0 + \beta_1 J_{space} + \beta_2 D_1 + \beta_3 D_2 \]  

(8)

The model shows some correlation with YRCE. The difference in the \( R^2 \) values from the first and second ANOVA analysis is very small. The updated linear fit is expressed by equation 9. All terms decrease the YRCE values. The use of a PASB drainage layer has the greatest effect on the YRCE value. This follows the visual and bivariate analysis. However, the use of less or not permeable drainage layer also decreases the amount of frost heave. This contradicts the
previous analysis as well as the visual and bivariate analysis. The joint spacing term does not have a very large coefficient. Its effect on YRCE is small compared to the drainage terms, as expected.

\[
YRCE_{PCC-ML} = \beta_0 + \beta_1 J_{space} + \beta_2 D_1 + \beta_3 D_2 \\
\rightarrow 1.196 - 0.011 J_{space} - 0.170 D_2 - 0.248 D_3
\]  

(9)

CONCLUSION

Differential frost heaving is a major source of pavement deterioration in cold climates. A recent study sponsored by the MnDOT examined frost heave as it relates to different pavement design parameters by analyzing over 33,700 MnROAD frost pin elevation data points. The results show that frost action can produce 1 inch of elevation change on interstate and low volume. This elevation change shown occurs in both HMA and PCC pavements. A continuation of the MNDOT study reported pavement distresses in HMA sections, but not PCC during the recorded four year period.

The results of the visual, bivariate and multivariate analyses show that subgrade and base type, pavement thickness and drainage capabilities are the major design factors that have the greatest effect on pavement frost heave separately and in combination. Sand subgrades heave less than clay. Thicker pavements heave less than thin. Pavements with drainage capabilities heave less than those without. Permeable base drainage layers perform better than drainage structures. Less fines in base materials yield less heaving.

ACKNOWLEDGEMENTS

This research was sponsored by the Minnesota Department of Transportation and Local Road Research Board. Furthermore, the work and final report is particularly indebted to Erland Lukanen, Bernard Izevbekhai, Tom Burnham, Cory Johnson of Mn/DOT and Jill Thomas of Minnesota Asphalt Pavement Association for their reviews of early drafts and/or provision of materials for research.
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