Subgrade Temperature and Freezing Cycles in Pervious Pavements

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ABSTRACT

With the construction of four new test cells in 2008, the Minnesota Department of Transportation (Mn/DOT) now has six unique pervious pavement test sections at the MnROAD test facility. Recorded temperatures in the pervious pavements and subgrades were compared to impervious Portland Cement Concrete (PCC) test sections over the same time interval. It was found that the subgrade in pervious PCC and Hot Mix Asphalt (HMA) was up to 4 °C warmer in the winter than impervious PCC pavements. The frost depth in an impervious PCC pavement was found to be 45.7 cm deeper than in a pervious PCC pavement of similar thickness. One pervious pavement test cell experienced 60% less freezing cycles over a three year interval than impervious PCC pavements of similar thickness. The air trapped in the pavement voids was suspected to be the main reason for the reduced number of freeze-thaw cycles by creating an insulating effect. In another pervious pavement, entrapped air within the base material may also insulate the pavement from the subgrade.

INTRODUCTION

In a high moisture, hard freeze environment such as Minnesota’s, freeze-thaw durability is of great concern in any pavement, but even more so in potentially lower strength pervious pavements. While laboratory tests have shown that pervious pavements can have adequate freeze-thaw durability (Schaefer 2006) compared to impervious pavements, long term field performance is still unproven. The Minnesota Department of Transportation (Mn/DOT) has constructed six pervious test cells at the MnROAD test facility since 2005. Heavily instrumented, the data from thermocouples, pressure gauges, moisture sensors, and stain gauges is recorded every fifteen minutes. In addition, changes in pavement distress, infiltration, sound absorption, surface texture, and warp and curl are monitored seasonally. This information, along with data from typical impervious pavements at MnROAD, will
greatly expand our knowledge of pervious pavement performance in a moist, cold weather region.

**MnROAD Facility**

MnROAD is a pavement research facility located along Interstate 94 in Albertville Minnesota, forty miles northwest of Minneapolis/St. Paul. Initially constructed by Mn/DOT between 1990 and 1994, MnROAD consists of two primary roadway test segments, Mainline and Low Volume Road (LVR), containing several dozen distinct test cells. Subgrade, aggregate base, roadbed structure, drainage methods, and materials vary from cell to cell. Automated sensors are configured to record data continuously to the MnROAD database. All historical sensor, sampling, testing, and construction data can be found in the MnROAD database and in various publications (Tompkins, Khazanovich, and Johnson 2008).

The mainline test section consists of a 5.6 km, two lane interstate roadway carrying “live” traffic diverted from Westbound I94. The Low Volume Road (LVR) is adjacent to Interstate 94 and the Mainline test sections. The LVR is a two lane, 4 km closed loop that contains over 30 test cells. Controlled loading on the LVR is applied by a 36.3 tonne, 18 wheel, five axle tractor/trailer. The tractor/trailer travels 80 laps daily on the inside lane of the LVR loop. The outside lane, monitored for environmental effects, remains unloaded except for lightweight test vehicles (Worel et al. 2007). Additional isolated test sections have been installed and monitored at the MnROAD test site and throughout the state of Minnesota. These include small scale driveway and walkway test sections.

**Pervious Pavements at MnROAD**

The first pervious pavement constructed at the MnROAD research facility was a pervious Portland Cement Concrete (PCC) driveway in September 2005 (Eller and Izevbekhai 2007). This test cell (Cell 64) served not only as a study of the durability of pervious concrete in Minnesota’s climate, but as a demonstration of pervious concrete construction and curing methods. Three different mix designs were used in this test cell with the primary difference between mixes being aggregate size (12.5 or 9.5 mm) and type (quarried dolomite or rounded gravel). Cell 64 consisted of a 17.8 cm thick pervious PCC pavement and 30.5 cm drainable base layer (4.75 mm single sized) above a clay subgrade (Figure 1). The test cell is subjected to twice daily loading by the 36.3 tonne tractor/trailer en route to the daily loading of the MnROAD low volume loop (LVR).

The second pervious PCC test cell, a pervious walkway was constructed in 2006 at the MnROAD test facility. This test cell (Cell 74) consisted of a 10.2 cm thick pervious concrete with a 15.3 cm washed stone base above a clay subgrade. The purpose of this test cell was to evaluate the performance of different pervious mixes incorporating sand and fibers (Worel, Frentress, and Clendenen 2007).

In October 2008, four more pervious test cells were constructed on the MnROAD LVR. Test Cells 85 and 86 are pervious PCC and Hot Mix Asphalt (HMA), respectively, on a sand subgrade. Test Cells 89 and 88 are PCC and HMA, respectively, on a clay subgrade (Figure 1). Each test cell has concrete curbing on the edges, and surrounded by a 1.2 m deep vertical plastic barrier to contain the
infiltration of water through the pavement. Below the 17.8 cm PCC or 12.7 cm HMA pervious pavements, is a 10.2 cm thick crushed stone (railroad ballast) base layer. This layer was provided to increase the rate of infiltration and as a sturdy platform for construction. Below this layer is a drainable base layer (4.75 mm single sized) above a sand (Cells 85/86) or clay (Cells 88/89) subgrade.

Figure 1. Pervious pavement cross sections.
To monitor environmental and water quality effects in the pervious pavement systems, the groundwater in the pervious test cells will be monitored for pH, suspended solids, chlorides, Nitrogen, Phosphorous, cadmium, chromium, copper, iron, lead mercury, nickel, and zinc. For comparison, an adjacent impermeable pavement test section (Cell 87) has the same water testing plan. This test cell is an impervious HMA pavement with similar layer thicknesses as Cells 86/88. In addition to ground water monitoring, the test cells were instrumented with thermocouples, pressure gauges, and strain gauges. The thermocouples were arranged on a vertical “tree” so that discrete temperatures can be monitored at various depths in the pavement, base, and subgrade.

**SUBGRADE TEMPERATURE**

The subgrade temperature from October 2008 to March 2009 at 91.4 cm below the top pavement surface is shown in Figure 2 for pervious PCC and HMA and two impervious pavements; 16.5 cm and 30.5 cm thick PCC pavements. As shown in the figure, the subgrade temperatures for the pervious PCC and HMA test sections were similar and both were up to 4 °C warmer than the impervious sections. The subgrade temperatures under the pervious test sections remained more stable than the subgrade temperatures under the impervious PCC test sections and fluctuated less with changing air temperatures (Figure 3).

Backstrom (2000) attributed elevated subgrade temperature to increased subgrade moisture content and an insulating effect from air trapped in the pervious pavement and base voids. While the test cells did not have the required sensors to accurately monitor subgrade moisture content, Figure 2 shows that the subgrade was warmer during the winter than the impervious concrete pavements. Increased subgrade moisture content could be contributing to this phenomenon.

The subgrade in pervious PCC test Cell 64 was warmer in the winter and cooler in the summer than impervious pavements at MnROAD. This could have several benefits. The relatively cooler temperatures in the summer could decrease the temperature of water runoff. This is particularly important in environmentally sensitive areas where warm water runoff can hurt fish and wildlife populations. The relatively warmer subgrade temperatures in the winter can reduce frost depth. The frost depth for pervious PCC Cell 85 and an impervious PCC pavement of similar thickness is shown in Figure 4 for the winter of 2008/09. In the pervious pavement, the maximum frost depth was 45.7 cm shallower than in the impervious pavement.
Figure 2. Subgrade temperatures at 91.4 cm below pervious PCC, pervious HMA, and impervious PCC test sections.

Figure 3. Average daily air temperature at MnROAD.

Figure 4. Frost depth in pervious and impervious PCC pavements.
FREEZE-THAW DURABILITY

The number of freezing cycles measured using thermocouple data is shown in Figure 5 at various vertical depths below the pavement surface for the winters of 2005/06, 2007/08, and 2008/09 through March 1. Temperature data was not collected in the pervious PCC driveway, Cell 64, during the winter of 2006/07. One freezing cycle was defined as a fall and rise above 0 °C. While this is a very simple definition, and may not represent the true number of freeze-thaw cycles, this method can be used as an effective comparison between different pavements.

The data from two different thermocouple trees in the 19 cm thick pervious PCC test Cell 64 is shown in the figure; a north (Cell 64:PPCC-D/WN) and south tree (Cell 64:PPCC-D/WS). Three other impervious PCC pavements of similar thickness are also shown, two 16.5 cm thick and one 19 cm thick pavement. Pervious Cell 64 experienced 130 freezing cycles at 2.5 cm below the top pavement surface. The two 16.5 cm thick pavements experienced 205 (58% increase) and the 19 cm thick pavement experienced 222 (72% increase) freezing cycles at 2.5 and 3.5 cm, respectively, below the top pavement surface. At pavement mid depth, the pervious pavement experienced 77 freezing cycles compared to 177 (130% more) in the two 16.5 cm thick and 196 (150% more) in the 19 cm thick PCC pavements.

This reduction in freezing cycles experienced by pervious PCC Cell 64 may indicate that even with decreased laboratory-measured freeze-thaw durability of the pavement materials (ASTM C 666), field (actual) freeze-thaw durability of the roadway may be comparable to impervious roadways due to fewer experienced pavement freeze-thaw cycles.

Rate of Temperature Change

The insulating effect of the air trapped in the pervious concrete voids can be observed from the rate of temperature change in the pavement in comparison to changes in ambient air temperature. A lower rate of relative temperature change indicates that the pavement has a greater insulating effect than a pavement with a higher relative rate of temperature change. Figure 6 shows the temperature at mid pavement depth for pervious pavement Cell 64 and an impervious PCC pavement of similar thickness. This figure indicates that the temperature in pervious Cell 64 was more consistent and had less extreme changes than the impervious PCC pavement. The more stable pavement temperature could be the reason that pervious Cell 64 experienced significantly less freezing cycles than impervious PCC test cells at MnROAD.

Comparison between Old and New Pervious MnROAD Test Cells

While pervious test Cell 64 experienced less freezing cycles than impervious PCC pavements of similar thickness, the new pervious PCC test Cells 85 and 89 did not. Both pervious PCC test cells (85 and 89) as well as both pervious HMA test cells (86 and 88) had elevated subgrade temperatures similar to test Cell 64. Pervious HMA test cells 86 and 88 did not have thermocouples installed in the pavement itself so they can not be compared, but pervious PCC test Cells 85 and 89 both had decreased temperature variability similar to test Cell 64.
The main difference between Cell 64 and Cells 85/89 is the 10.2 cm thick layer of 7.6 cm single sizes aggregate directly beneath the pavement installed as a construction platform. This layer had apparently higher voids content which insulated the pavement from the base layers, resulting in a lower pavement temperature than in Cell 64. Figure 7 shows the difference in temperature between 15.2 and 30.5 cm below the top pavement surface for Cells 85 and 64. These depths are right above and below the 7.6 cm single sized aggregate layer in Cell 85. Negative temperatures indicate that the top of this layer is colder than the bottom.

The difference in temperature between the top and bottom of the railroad ballast layer was much greater (Figure 7) than between the same two depths in Cell 64, which does not have this layer (Figure 1). The pavement is apparently insulated more from the higher void base material in Cell 85 than in Cell 64, which can explain the difference in number of pavement freezing cycles counted.
CONCLUSION

While pervious PCC material samples may have poor laboratory measured freeze-thaw durability (ASTM C 666), both pervious PCC and HMA pavements could demonstrate better durability in the field due to fewer freeze-thaw cycles. The primary reason for the reduction in freeze-thaw cycles is believed to be the insulating effect of the air and possible moisture trapped in the voids of the pervious pavement and base materials. Sixty percent fewer freezing cycles were observed over a three year period for a pervious pavement test section compared to impervious PCC pavements of similar thickness at MnROAD.

Pervious pavements remain at a more stable temperature and do not fluctuate with ambient air temperature extremes as much as typical PCC pavements. Therefore reduced internal temperature variations and extremes are observed in the pervious pavements compared to similar impervious PCC pavements. The pervious test sections also had elevated winter subgrade temperature of up to 4 °C at similar depths compared to impervious pavements. The relatively warmer subgrade resulted in a maximum frost depth 45.7 cm shallower than in a comparable impervious pavement.

REFERENCES


