Table 2. Summary of thermal conditions

Load, kN	Frozen length, m		Average temperature over frozen part, °C	
	at start	at end	at start	at end
Spiral Leg 1				
222	2.29	2.44	-2	-2
444	2.44	3.66	-2	-2
667	3.66	4.27	-2	-2
Spiral Leg 2				
444	3.35	4.27	-2	-2.5
667	4.27	4.27	-2.5	-3

Data Analysis

Theoretical displacement for the legs was evaluated using Equation 1, which predicts pile velocity for a smooth pile in polycrystalline ice at temperatures below -1°C assuming constant load (Morgenstern et al., 1980). The theoretical displacements together with the observed values are given in Table 3 and in Figure 9. The observed values are larger than the theoretical values and don't follow the anticipated pattern. The difference is assumed to be a result of the varying conditions in the field, including changing stress with changing temperature and heterogeneous soil strata. The large displacement rate may also be due to possible air gaps beneath the spirals.

$$\dot{u} = \frac{9}{2} aB\tau^3 \qquad (1)$$

Where: $\dot{u}$ = pile velocity (mm/yr), a = pile radius (mm), τ = constant shear stress (kPa), B = 1.2E-7/(1-T)^2 for -2 < T ≤ -1°C and B = 6E-8/(1-T)^2 ≤ -2° (kPa-3/yr), and T = temperature (°C).

Table 3. Theoretical displacement calculations of smooth pile - polycrystalline ice

	Spiral Leg 1			Spiral Leg 2	
Load, kN	222	444	667	444	667
Effective pile length, m	2.29	2.44	3.66	3.81	4.27
Upper pile radius, m	0.17	0.17	0.17	0.17	0.17
Lower pile radius, m	0.11	0.11	0.11	0.11	0.11
Average Temperature, °C	-2	-2	-2	-2.5	-2.7
Area, m^2	1.87	2.03	3.33	3.49	3.98
Stress, kPa	118.93	219.05	200.30	127.21	167.52
B in Equation 1(kPa^{-3}/yr)	2E-08	2E-08	2E-08	1.71E-08	1.62E-08
Eq 1: Displacement Rate, mm/h	0.0029	0.0183	0.0140	0.0031	0.0067
Observed Displacement Rate, mm/h	0.0230	0.0260	0.0270	0.0240	0.0200

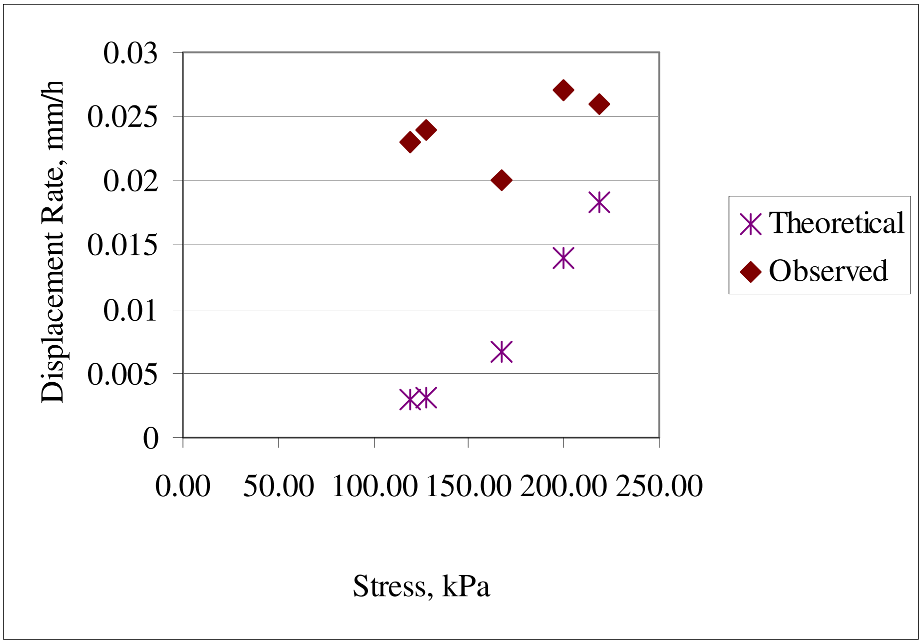

Figure 9. Theoretical and observed displacement rates with stress

Pile installation and removal

The pile installation proceeded without any difficulties and did not differ from installation of smooth piles. The slurry was not vibrated when it was dropped to the oversized hole around the piles, which may have resulted in gaps directly below the helixes. Because of the tight schedule, the pile testing was started while the ground temperatures were still changing due to the freeze back of the warm slurry around the piles. The removal of piles was conducted with a learning curve, but progressed mostly without difficulties. The removal time per pile was from 30 to 45 minutes and was estimated to be even less during production, as three to four piles can be hooked up to the steam plant at the same time. A more comprehensive description of the pile removal can be found at Zubeck et al. (2003).

Conclusions and recommendations

The testing period represented the warmest permafrost temperatures, which is the worst case scenario for pile bearing capacity considerations and pile installation, and the best case scenario for pile removal. The following conclusions apply for the ice rich silty soil and pure ice found at the test site at the average temperature of –2°C:

- The Spiral Legs met the requirement for the 667 kN load in regards of instantaneous failure. However, the required pile displacement rate was not met. Vibration of the slurry during installation may have reduced the settlement rate.

- The observed pile settlement rate was greater than theoretical rate for polycrystalline ice, and was not affected significantly with the magnitude of the stress. Varying field conditions affected the displacement rate.
- The Spiral Legs were installed with the same effort as smooth adfreeze piles. The spiral design aided in the removal of the Legs. Three to four Spiral Legs can be removed in about 40 minutes.
- The test frame and the potentiometer functioned well for the given test period the air temperature being warmer than –23°C. The dial gages and surveyor's level worked well, too, and were handy in verifying the potentiometer readings. The wire, scale and mirror displacement measuring system was hard to use.
- The following was recommended for possible future Spiral Leg testing in the field: a larger capacity test frame (1334 to 1780 kN), a system that works down to –40°C, and a flexible schedule that assures that the slurry around the pile is properly frozen. The slurry need to be vibrated around the piles.

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References

American Society for Testing and Materials, (1995). Designation: D 5780 Standard Test Method for Individual Piles in Permafrost Under Static Axial Compressive Load, West Conshohocken, PA.

Morgenstern, N.R., W.D. Roggensack, and J.S. Weaver, (1980), "The behavior of friction piles in ice and ice-rich soils," *Canadian Geotechnical J.*, Vol. 17(3), pp. 405-415, 1980.

Zubeck, H., Porhola, S. and Aleshire, L., (2003), "Tundra Platform Leg Test," prepared for Anadarko Petroleum Corporation, accessed January 6, 2006. at http://www.maurertechnology.com/Engr/RDprojects/Hydrates/TopRepUAAFoundations.pdf.

Low Temperature Cracking Performance at MnROAD

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Abstract

The Minnesota Road Research Project (MnROAD) was constructed in 1990-1993 as a full-scale pavement testing facility. Several different cells were built with various materials, mix designs, and structural designs. Two different asphalt binders were used during the original construction: PG 58-28 and PG 64-22. The sections have all shown various degrees of low temperature cracking. In general the cells with stiffer binder (PG 64-22) experienced a higher number and greater severity of thermal cracks than those with the softer binder. The ride quality of the pavements has been adversely affected by the deterioration of the low temperature cracks.

In 1999 three cells were reconstructed on the Low Volume Road as a study specifically examining low temperature cracking. These sections were designed using the exact same Superpave mix design except for the asphalt binder type, which differed at the low temperature performance grade. The performance grades for Cells 33, 34, and 35 were PG 58-28, 58-34, and 58-40 respectively. After several years in service these sections have begun to show marked differences in performance. Cell 35 has shown the most cracking, even though it has the softest grade at -40. The cracks on Cell 35 do not look like typical thermal cracks, while Cell 33 exhibits the expected typical thermal cracks. Cell 34 had virtually no distress after six years.

Introduction

The Minnesota Road Research Project (MnROAD) was constructed in 1990-1993 as a full-scale pavement testing facility, with traffic opening in 1994. Located near Albertville, Minnesota (40 miles northwest of Minneapolis-St. Paul), MnROAD is one of the most sophisticated, independently operated pavement test facilities of its type in the world. Its design incorporates thousands of electronic sensors and an extensive data collection system that provide opportunities to study how heavy commercial truck traffic and environmental conditions affect pavement materials and performance. MnROAD consists of two unique road segments located parallel to Interstate 94:

Figure 1. MnROAD Aerial View

- A 3.5-mile mainline interstate roadway carrying "live" traffic averaging 28,500 vehicles per day with 12.4 % trucks.
- A 2.5-mile closed-loop low-volume roadway carrying a controlled 5-axle tractor-semi-trailer to simulate the conditions of rural roads. Traffic on the LVR is restricted to a MnROAD-operated 18-wheel, 5-axle tractor/trailer with two different loading configurations of 102 kips and 80 kips.

Mainline Thermal Cracking Performance

The 14 original mainline hot mix asphalt cells were constructed with various materials, mix designs, and structural designs. Please refer to the cell maps at the end of the paper for the layout of each test section. Two different unmodified asphalt binders were used for these sections: PG 58-28 (Pen 120/150) and PG 64-22 (AC 20). The cells can be organized into three groups:

- 5-year test cells using PG 58-28 (Cells 1-4)
- 10-year test cells using PG 58-28 (Cells 14, 20-23)
- 10-year test cells using PG 64-22 (Cells 15-19)

Cells 4, 14, and 15 are full-depth HMA cells on a clay subgrade; the others are built over various granular base layers. The test sections have shown various degrees of low temperature cracking over the years. The analysis for the mainline continued through 2003. That year most of the sections received microsurfacing treatments to fill in ruts that were becoming problematic. Cells 20 and 23 also received microsurfacing treatments in 1999, although most of the cracks reflected through over the first winter. A detailed description of the performance of the test cells can be found in (Palmquist et al., 2002).

Figure 2 shows the progression of thermal cracking over time for the driving lane. Four of the PG 64-22 cells cracked over the first winter before the mainline was open to traffic. A cold snap in February 1996 caused all the pavements to crack over a four-month period, and the sections have remained relatively constant since then.

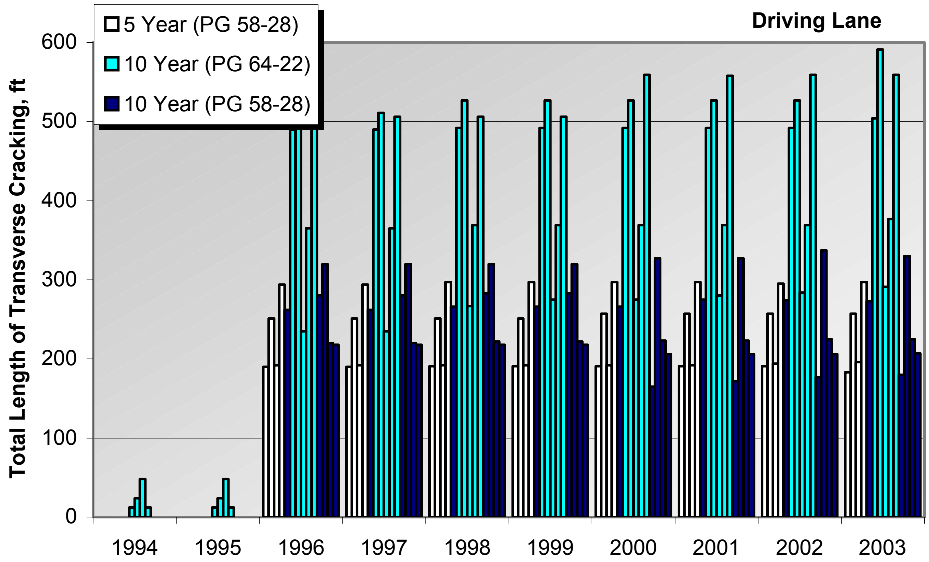

Figure 2. Mainline Thermal Cracking History (Driving Lane)

Figure 3 shows the total length of cracking for each cell in 2003. Several trends can be observed. For most cells the driving lane had more cracking than the passing lane. Increased traffic loading has contributed to an increased amount of thermal cracking. The PG 64-22 cells cracked more than the PG 58-28 cells, indicating that a stiffer binder leads to more thermal cracking, as expected. Finally the 5- and 10-year cells (PG 58-28) showed similar cracking patterns, indicating that pavement thickness has little effect on thermal cracking.

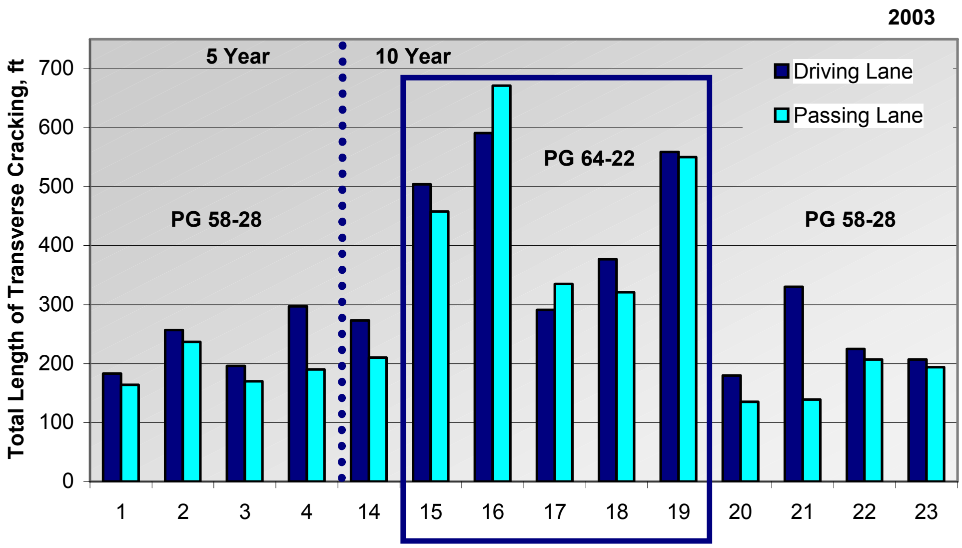

Figure 3. Mainline Thermal Cracking by Cell (2003)

Several other observations can be made concerning low temperature cracking on the Mainline cells at MnROAD:

- The cells with PG 58-28 binder tended to crack in a typical transverse pattern with 30-50 foot spacing between adjacent cracks. The PG 64-22 cells displayed multiple short cracks with a random "shattered" appearance (see Figure 4 for examples).
- The mean distance between thermal cracks is much smaller in the PG 64-22 cells than in the PG 58-28 cells.
- The PG 64-22 cells and the full depth cells had more medium severity thermal cracks than the other cells.
- The leaner (lower AC content) 75-blow Marshall mixes and Gyratory mixes have more medium severity transverse cracks than those with more binder.
- The PG 64-22 cells have more cupping along the transverse cracks than the PG 58-28 cells. In addition, the full depth cells have more cupping on average than the 5- and 10-year cells. Cupping and degradation along the crack face have lead to rougher ride numbers, as measured by IRI.
- Test cells with Class 6 base (very coarse, crushed granite) cracked sooner than cells with other base materials. This may be the result of increased friction between the base and the HMA layer, leading to an increase in thermal tensile stresses. The Class 6 base also is dryer (less water content) than other base materials. As of yet it is not well understood what effect the base material properties have on thermal cracking, but Marasteanu et al. (2004) made significant progress in this area by developing a crack spacing model that takes several base and HMA material properties into account.

Figure 4. Typical Cracking Patterns on PG 58-28 (left) and 64-22 (right) Cells

Table 1 provides a summary of the performance data from 2003.

Table 1. Mainline Performance Data Summary (2003)

	Transverse Cracking (ft)			Cupping	IRI (m/km)		
Cell	Passing Lane	Driving Lane	Total	Average Wheel Path	Passing Lane	Driving Lane	Average
1	164	203	367	0.33	1.53	1.26	1.40
2	237	263	500	0.31	1.77	2.26	2.02
3	180	206	386	0.34	1.64	1.63	1.64
4	326	474	800	0.56	2.30	2.48	2.39
14	414	512	926	0.46	1.96	2.35	2.16
15	582	860	1442	0.70	2.08	2.43	2.26
16	679	656	1335	0.57	2.67	2.83	2.75
17	487	537	1024	0.32	2.48	2.48	2.48
18	291	369	660	0.37	2.57	2.94	2.76
19	526	643	1169	0.50	3.17	3.27	3.22
20	110	182	292	0.21	1.15	1.10	1.13
21	141	321	462	0.11	1.04	0.99	1.02
22	187	232	419	0.34	1.66	1.53	1.60
23	172	197	369	0.23	1.47	1.74	1.61

Low Volume Road Thermal Cracking Performance

The thermal cracking performance on the Low Volume Road is rather difficult to analyze, as several cells have been reconstructed over the years. Each group of cells warrants a separate analysis, which will follow.

- The original Low Volume Road test sections (Cells 24-31) were built in 1993. All contained PG 58-28 asphalt binder, but they were constructed at different thicknesses and over different base and subgrade types. These sections contained different asphalt contents based on different mix designs, which is an added variable in the experiment. Four of the original eight cells are still in service.
- Three Superpave test sections (Cells 33-35) were constructed in 1999. These cells contained the same structural and mix designs except for the asphalt binder type, which differed at the low temperature performance grade. The performance grades for Cells 33, 34, and 35 were PG 58-28, 58-34, and 58-40 respectively.
- Three Oil Gravel test sections (Cells 26-28) were built in 1999 and 2000. Oil gravel is a pavement technology imported from Scandinavia in the mid-1990s that consists of a soft asphalt emulsion surface over a strong, stable, and often large stone base. Oil gravel technology has evolved over time at MnROAD. It began with a cold paving process by the Finnish Road Administration on a county road adjacent to MnROAD in 1994, and became “Americanized” with a warm plant mix in later applications.
- Cells 26 and 31 were reconstructed in 2004. These new sections will not be considered further in this report.

Original Low Volume Road Cells

Figure 5 shows the progression of low temperature cracking over time in the 80K lane. The 102K lane shows similar results. It can be seen that most of the pavements cracked during the cold snap in 1996 and remained relatively constant since then.

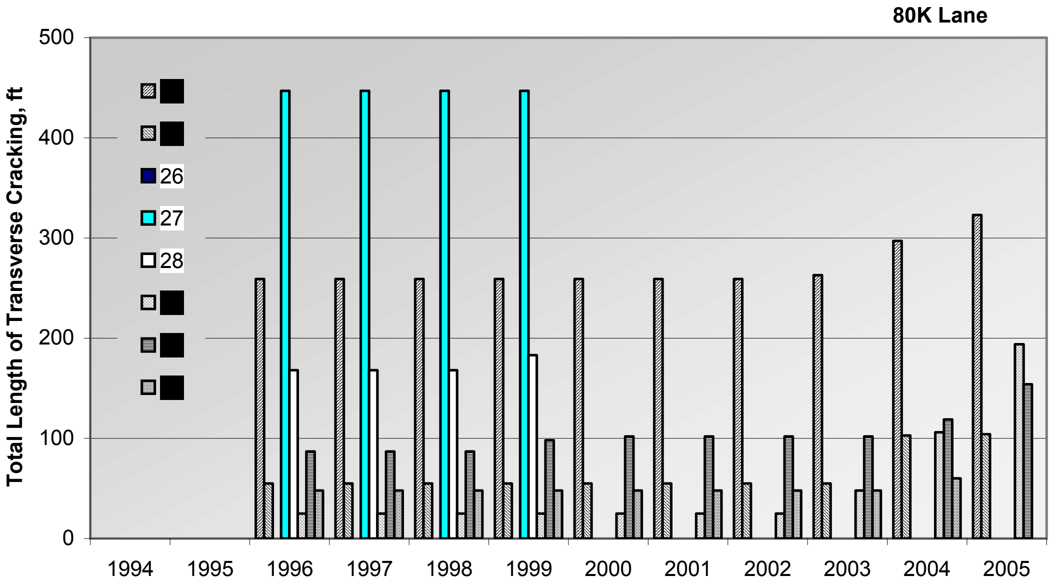

Figure 5. Thermal Cracking Progression Over Time on Original LVR Cells

Each original cell on the Low Volume Road tells an interesting story. Cells 24 and 25 are similar in that they were built over a sand subgrade. Cell 24 has a thinner HMA surface with a 4-inch Class 6 (very coarse, crushed granite), while Cell 25 is a full depth pavement. Cell 24 has significantly more thermal cracking, which seems to indicate that the added friction between the asphalt layer and the Class 6 base led to an increase in low temperature cracking. Cell 26 did not experience any thermal cracking in the 80K lane, and the cracking in the 102K lane totaled only 40 ft. The softer and wetter clay subgrade allowed the pavement to slide without building up large tensile stresses, in comparison to Cell 25, which was a full depth pavement on sand. Cell 27 had the most low temperature cracking of any cell on the Low Volume Road, which again illustrates that the added friction from the Class 6 base leads to more thermal cracking. Cell 28 had less than half the amount of thermal cracking as on Cell 27. The Class 5 gravel base on Cell 28 induced less friction and therefore less cracking. Until recently Cell 29 (Class 4 base) has had less thermal cracking than Cell 30 (lower quality Class 3 base), and they have both shown less thermal cracking than Cells 27 and 28. It is difficult to compare these four cells because of different HMA thicknesses, base types, and HMA mix designs. Cell 31 has shown much less thermal cracking than Cells 28 and 30. Cell 31 has a thin HMA surface like Cell 28, but it includes 4 inches of Class 5 base over 12 inches of Class 3. The combination of different materials and thicknesses has lead to a reduction in thermal cracking.

While several different variables are in play with the original Low Volume Road cells, some reasonable observations about low temperature cracking can be made.

- Once a critical HMA thickness threshold is met, additional thickness seems to have little effect on the amount of thermal cracking observed. However, the thermal cracking performance of thin pavements may be affected by other variables such as base stiffness and moisture properties.
- Base type has a big effect on thermal cracking. The more coarse and angular a base material is, the more thermal cracking it induces because of increased friction with the HMA layer.
- The effect of asphalt binder content on thermal cracking is inconclusive. Other variables contributed to the amount of thermal cracking, so it is difficult to separate the contribution of the binder itself.

Superpave Test Cells

Three Superpave test cells were built in 1999 to validate the current low temperature performance grading (PG) system currently being used by the Minnesota Department of Transportation (Mn/DOT) and many other agencies. The sections contained the same structural and HMA mix designs except for the PG binder used in each cell. Cell 33 used an unmodified PG 58-28 binder, while Cells 34 and 35 used SBS polymer modified PG 58-34 and PG 58-40, respectively. More information on these test sections is available elsewhere (Worel et al, 2003).

These three test sections have shown a marked difference in their performance over the last six years, as shown in Table 2. Cell 33 shows the expected pattern of evenly spaced thermal cracks straight across the pavement. Cell 34 has only two small cracks over the entire 500-ft section. Cell 35 has a shattered appearance of numerous small cracks spaced close together. These cracks appear to be more fatigue in nature, as there are few if any cracks that go straight across the 12-ft pavement lane. There appears to be a substantial increase in low temperature cracking performance with PG 58-34 polymer modified binder over neat PG 58-28. Other issues (i.e., fatigue, rutting because of a very soft binder) may play a role with the field performance of PG 58-40 binder, and these need to be considered further.

Table 2. Total Length of Transverse Cracks (2005)

Cell	80K Lane	102K Lane	Total
33	114	60	174
34	8	0	8
35	663	703	1366

Oil Gravel Test Cells

Three oil gravel test sections have been built at MnROAD in recent years. Oil gravel is a technology developed in Sweden and Finland in the 1950s. It uses soft high float emulsion asphalt with a lower viscosity and higher penetration than conventional hot mix asphalt. HMA paved surfaces are typically designed to distribute and carry much