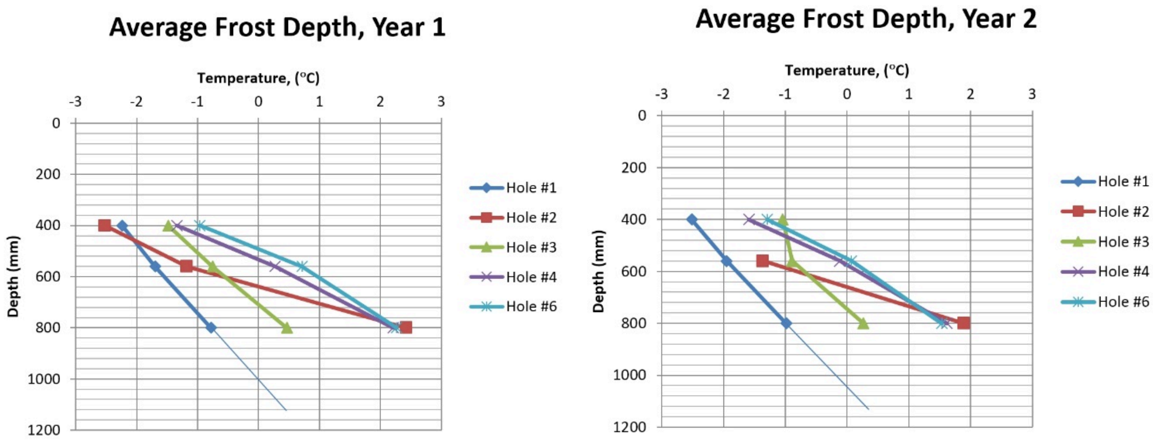

Figure 8. Average thermistor temperatures as a function of depth over the two winters.

Table 1. Average and Maximum Frost Depths

	2011-2012				2012-2013			
	Average Depth		Maximum Depth		Average Depth		Maximum Depth	
	in	mm	in	mm	in	mm	in	mm
Hole #1	39.4	1000	45.6	1158	41.1	1045	45.6	1158
Hole #2	25.2	640	25.6	650	26.0	660	31.2	792
Hole #3	28.3	720	34.2	867	29.5	750	37.8	960
Hole #4	20.9	530	27.0	686	22.4	570	29.4	747
Hole #6	19.7	500	26.4	671	21.7	550	28.8	732

8 PREDICTION OF AVERAGE FROST DEPTH

Several models have been proposed to determine frost penetration (USACE 1988). It appears from the literature that the most commonly used procedure is the Modified Berggren Equation (MBE) as developed by Aldrich and Paynter (1953). A simplified procedure is presented in the Minnesota Department of Transportation's Pavement Design Manual (MNDOT 2007). This model is useful to predict frost depths in multiple pavement or soil/aggregate layers.

The MBE is given by

$$z = \lambda\sqrt{\frac{48k_t nFI}{L}} \qquad [1]$$

where z = the frost depth (in), k_t = thermal conductivity (BTU-in/ft^2-hr.-^{o}F), FI = air freezing index (^{0}F-days), n = ratio of the ground surface freezing index to the air freezing index, λ = function of the initial ground temperature and the thermal capacities of the soil, and L = volumetric heat of latent fusion (BTU/ft^3). The MNDOT procedure is used to predict the depth of frost penetration for design purposes and neglects the λ and the n terms, which are both normally between 0.5 and 1.0. The MNDOT equation is

$$z = \sqrt{\frac{48k_t FI}{L}} \tag{2}$$

The air freezing index is the number of degree-days below 0°C (or 32° F) measured at a height of four feet. It represents an average amount of thermal energy available for freezing materials. Alternatively, for layered systems, FIR_i can represent the amount of energy required to freeze the layer i, which can be determined by

$$FIR_i = \frac{d_i^{\,2} L_i}{48k_{t-i}} \tag{3}$$

where d_i = thickness of layer i. The FIR_i for each layer is subtracted from the FI until the sum of the FIR_i's becomes greater than the original FI. Then, Equation 2 is solved using the remaining FI to determine the frost depth in the last layer.

The thermal conductivity k_t in BTU-in/ft^2-hr-°F can be estimated using the Kirsten equations

$$\begin{aligned} k_{t-Frozen\,Sand} &= 0.076(10)^{0.013\gamma_d} + 0.032w(10)^{0.0146\gamma_d} \\ k_{t-Unfrozen\,Sand} &= (0.7 * \log(w) + 0.4)(10)^{0.01\gamma_d} \\ k_{t-Frozen\,Silt-Clay} &= 0.01(10)^{0.022\gamma_d} + 0.085w(10)^{0.008\gamma_d} \\ k_{t-Unfrozen\,Silt-Clay} &= (0.9 * \log(w) - 0.2)(10)^{0.01\gamma_d} \end{aligned} \tag{4a-d}$$

The conductivity of the frozen subgrade was determined by averaging the frozen sand and frozen silt-clay conductivities. MNDOT recommends using 6.5 BTU-in/ft^2-hr-°F for Portland cement concrete and 10 BTU-in/ft^2-hr-°F for bituminous asphalt pavement. Based on published values and testing, the thermal conductivity of urethane rigid foam is 0.192 BTU-in/^{2}-hr-°F.

The volumetric heat of latent fusion, L, is a function of the amount of water in a volume of soil or aggregate that changes state from liquid to solid. It can be determined by

$$L = 1.43w\gamma_d \tag{5}$$

where w = water content (%) and γ_d = dry unit weight (lb/ft^3). MNDOT recommends using 400 BTU/ft^3 for Portland cement and 0 BTU/ft^3 for bituminous pavement.

While a phase change does not take place during freezing of the polymer, it appears to absorb energy in a similar manner. Using the data determined from the holes having a polymer layer, an equivalent volumetric heat of latent fusion can be determined.

3.1 Hole #1

The air freezing index during the first year was 1206 °F-days (670 °C-days) (Edgar 2014). The road was drilled in April, 2010 and water contents in the profile were determined. Dry unit weights were assumed based on material properties. The frost depth calculation for Hole #1 without any polymer is given in Table 2. The measured frost depth is given in Table 1 as 39.4 inches (1000 mm) while the calculated value is 40.1 inches (1018 mm). Table 3 presents the analysis for the second year when the air freezing index was 1355 °F-days (753 °C-days). The measured depth of frost penetration is 41.1 inches (1045 mm) versus 41.7 inches (1059 mm) calculated. With the largest error being 0.6 inches (14 mm) for the two calculations, the procedure appears to be appropriate and the assumed values are reasonable.

3.2 Holes #4 and #6

The rest of the holes have polymer layers in them, so these holes can be used to estimate the value of the equivalent latent heat of fusion for the polymer. The remaining four holes were set up the same as Tables 2 and 3 with additional lines for the polymer layer and the soil underneath. Estimates of the equivalent latent heat for the polymer were tested in each hole, the computed frost depths were compared to the measured values, the errors were squared and the sum of errors squared was minimized. The equivalent latent heat was determined to be 1625 BTU/ft^3.

Table 2. Frost Depth Calculations for Hole #1 - Year 1

Hole #1						FI =1206°F-days			
Material	γ_d (pcf)	w (%)	L (BTU/ft^3)	d_i (inches)	k_t (BTU/ft^2 hr °F/in)	FIR_i (°F-days)	FI_i (°F-days)	z_i (inches)	Σz_i (inches)
Asphalt	138	0	0	6.5	10	0	1206	6.5	6.5
Base Course	120	3.7	634.9	7.9	9.4	87.4	1118.6	7.9	14.4
Subgrade Silty Sand	105	1.9	285		3.5	1118.6	0	25.7	40.1

Table 3. Frost Depth Calculation for Hole #1 - Year 2

Hole #1		#10-5				FI =1355°F-days			
Material	γ_d (pcf)	w (%)	L (BTU/ft^3)	d_i (inches)	k_t (BTU/ft^2 hr °F/in)	FIR_i (°F-days)	FI_i (°F-days)	z_i (inches)	Σz_i (inches)
Asphalt	138	0	0	6.5	10	0	1355	6.5	6.5
Base Course	120	3.7	634.9	7.9	9.4	87.4	1267.6	7.9	14.4
Subgrade Silty Sand	105	1.9	285		3.5	1267.6	0	27.3	41.7

For example, Holes #4 and #6 have the same physical characteristics so can be compared to the same calculations. Table 4 presents the frost depth analysis for the first year while Table 5 presents the data for the second year. The measured frost depth in Hole #4 was 20.9 inches (530 mm) and the depth in Hole #6 was 19.7 inches (500 mm) during Year 1 compared to the estimated 20.5 inches (520 mm). In Year 2, the air freezing index was 1355 °F-days, which was large enough to allow some of the soil below the polymer to freeze. The measured frost depth in Hole #4 was 22.4 inches (570 mm) and in Hole #6 was 21.7 inches (550 mm) compared to the calculated depth of 21.0 inches (533 mm).

Table 6 presents a summary of the measured and computed frost depths for the five holes over two years. The largest error is 3.3 inches (82 mm) or 11.7% while five of the errors are under 0.7 inches (20 mm). This amount of error is acceptable as a design tool in which the thickness of polymer is determined for a site with known or estimated material properties.

Table 4. Frost Depth Calculation for Holes #4 and #6 - Year 1

Holes #4 and #6						FI =1206°F-days			
Material	γ_d (pcf)	w (%)	L (BTU/ft^3)	d_i (inches)	k_t (BTU/ft^2 hr °F/in)	FIR_i (°F-days)	FI_i (°F-days)	z_i (inches)	Σz_i (inches)
Asphalt	138	0	0	7	10	0	1206	7.0	7.0
Base Course	120	4.4	755	7.4	10.7	80.4	1126	7.4	14.4
Subgrade Silty Sand	105	7	1051	3.6	7.8	36.5	1089	3.6	18.0
Polymer	7		1625		0.192	1089	0	2.5	20.5

Table 5. Frost Depth Calculation for Holes #4 and #6 - Year 2

Holes #4 and #6						FI =1355°F-days			
Material	γ_d (pcf)	w (%)	L (BTU/ft^3)	d_i (inches)	k_t (BTU/ft^2 hr °F/in)	FIR_i (°F-days)	FI_i (°F-days)	z_i (inches)	Σz_i (inches)
Asphalt	138	0	0	7	10	0	1355	7.0	7.0
Base Course	120	4.4	755	7.4	10.7	80.4	1275	7.4	14.4
Subgrade Silty Sand	105	7	1051	3.6	7.8	36.5	1238	3.6	18.0
Polymer	7		1625	3.0	0.192	1238	0	3.0	21.0

Table 6. Comparison of the Measured and Computed Frost Depths

	2011-2012 - *FI* = 1206 °F-day						2012-2013 - *FI* = 1355 °F-day					
Hole #	Measured Depth		Calculated Depth		Difference		Measured Depth		Calculated Depth		Difference	
	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm
1	39.4	1000	40.1	1017	0.7	17	41.1	1045	41.7	1059	0.6	14
2	25.2	640	23.4	594	-1.8	-48	26.0	660	23.6	598	-2.4	-62
3	28.3	720	31.6	802	3.3	82	29.5	750	31.8	808	2.3	58
4	20.9	530	20.5	520	-0.4	-10	22.4	570	21.0	533	-1.4	-37
6	19.7	500	20.5	520	0.8	20	21.7	550	21.0	533	-0.7	-17

9 SUMMARY

A research project is described that used a novel process to inject a rigid structural polymer beneath the subbase to create an insulation layer to reduce heat loss from the subgrade and limit or eliminate frost heave problems. The procedure is faster and inherently safer than traditional methods for frost heave abatement.

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Maintenance and Drainage Issues for Gravel and Snow Road Transitions: Case Study at the Scott Base Transition, Antarctica

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Abstract: The snow roads at McMurdo Station, Antarctica, are the primary transportation corridors for moving personnel and material to and from the airfields servicing intra- and inter-continental air traffic. The majority of the road system is made of snow overlying a snow and ice subsurface. However, at the Scott Base Transition (SBT), the aggregate road leading from Scott Base transitions from the landmass of Ross Island on to the ice shelf and becomes a full depth snow road. Because of the transition between materials, the topography of the area, and extensive use during the austral summer, the SBT is prone to problems unique to that portion of the McMurdo road system and requires specific maintenance activities to remain passable during periods of high temperatures. The SBT area is divided into two subsections. One is the land transition, a soil- or aggregate-surfaced road underlain by permafrost, and the other is the ice transition, a snow-surfaced road underlain by snow and ice. The two sections of the SBT need entirely different construction and maintenance techniques to maintain road surface conditions that will support vehicle traffic. This paper presents some of the issues at the transition area along with maintenance and drainage control measures to alleviate them.

Keywords: Construction; Drainage; Ice; Maintenance; Snow.

1 INTRODUCTION

Ground vehicles at McMurdo Station, Antarctica, use approximately 32 km (20 mi) of snow roads to travel between the station and its airfields. For the past several years, research has been on-going to determine effective ways to improve the snow construction and maintenance activities for the McMurdo Station snow pavement system to lower labor and equipment hour requirements and improve the performance and durability of the snow road surfaces. New manuals were developed to guide maintenance personnel in maintaining the snow-road system to ensure traffic flow through the peak activity periods and the rest of the year (ASC 2014a, ASC 2014b).

The Scott Base Transition (SBT), where the aggregate and soil road leading from Scott Base transitions from the permafrost, soil, and rock subbase of Ross Island onto the ice shelf and becomes a full depth snow road, is a particularly crucial link in the McMurdo snow-road system. Because of the transition between materials, the topography of the area, and extensive use during the summer, the SBT is prone to problems unique to that portion of the McMurdo road system and requires specific maintenance activities to remain passable during periods of warm temperatures. This case study of problems and solutions at the Scott Base Transition is applicable to other locations where gravel roads transition to winter snow or ice road surfaces.

1.1 Scott Base Transition

The SBT as we know it today, Figure 1, was constructed in 1983. The current transition was constructed because the prior transition section was prone to major meltwater issues, cracks, and pressure ridges. The SBT area is divided into two subsections. One is the land transition, a sloped, soil- or aggregate-surfaced road underlain by permafrost, and the other is the ice transition, a level, snow-surfaced road underlain by snow and ice. These two sections of the SBT need entirely different construction and maintenance techniques to maintain road surface conditions to support vehicle traffic.

Figure 1. Scott Base Transition, looking toward McMurdo Station from the ice shelf (left), looking from Ross Island toward the ice shelf (right).

1.2 Seasonal Maintenance

A unique aspect of the work at McMurdo Station, Antarctica, is the seasonal variation in activity level at the station. These changes in personnel levels and vehicle traffic volume affect road construction and maintenance in combination with the seasonal weather changes that affect snow and ice conditions. There are three seasons of work at McMurdo Station with regard to snow-road maintenance and construction:

- Winter—The Antarctic winter season runs from late February through mid-August and is a period of limited science activity. This results in less vehicle traffic on the snow-road system during this time.
- Winter Fly-In (Winfly)—This is a six-week period beginning about 20 August and ending about 1 October. Historically, this is when crews arrive to prepare McMurdo

Station for the influx of scientists over the austral summer. This includes reopening station infrastructure and constructing the ice runway

- Main Body—This period runs from 1 October through late February and is the austral summer season, bringing a mass influx of personnel and the bulk of construction and research activities. The latter half of this period, when temperatures are typically warmer, is the most critical and debilitating to the entire snow-road system but especially to the SBT area.

2 SBT LAND TRANSITION

Vigilance and regular maintenance are critical to providing the SBT the best chance of remaining fully operational through the difficult, warmest periods of the austral summer when temperatures can be above freezing for several days at a time. Year-to-year variances in ambient temperature, cloud cover, winter snow deposition, and melt impact the transition areas greatly. Issues that affect the land transition section are water runoff, subsurface melting, traffic load (vehicle count and weight), and working tidal cracks through the permafrost on the “land” side and the “snow” side of the SBT.

The two main objectives of the maintenance of the SBT land transition are as follows:

- Provide drainage control to keep water off the roads and the ice shelf.
- Keep the ice shelf clean by minimizing dirt transfer from vehicles.

The maintenance and construction descriptions below are grouped according to these objectives. Unless there is major road building or rebuilding, the land transition activities occur solely during Main Body season.

2.1 Drainage Control on the Land Transition

Keeping the road dry alleviates a variety of problems later on; water is diverted from sheeting over or cutting under the land transition road surface. However, this must be done carefully as warm meltwater can undercut the subsurface of the road, causing sinking and erosion on the outer slope of the land transition road section. Many areas of the McMurdo road system, including the SBT, are composed of significant amounts of permafrost. If water is allowed to run across these portions of the road system, large cuts and chasms of ice melt and erosion will result. In addition, water and melting on the land transition results in mud, which invariably ends up on the vehicles and gets transported to the ice shelf; this must be avoided.

Installing and maintaining drainage structures can mitigate this problem by controlling the flow of water. One type of drainage structure is roadside ditches. Adequately sized and bermed ditches (Figure 2) prevent water from flowing onto the roadway.

Further down slope toward the ice shelf requires an Antarctic French Drain (AFD) like the one shown schematically in Figure 3. The AFD is constructed from the base of the rock cliff, across the road to the downslope outflow to allow water to flow from the cliff to the ice without causing erosion or wetting of the road surface. The AFD consists of a ditch approximately 8 ft (2.4 m) wide and 2 ft (0.6 m) deep. After initial excavation, lining the ditch with 3–4 in. (7.6–10.2 cm) of fines seals off the water from penetrating deeper into the road subgrade.

There are varying qualities of fine aggregate material on the McMurdo hillsides. They are carefully excavated and screened to exclude permafrost and ice clumps, which look like dirt or fines when relatively cold; but because of their high ice content, they become unstable and will melt and settle when they warm or contact water. More information on the McMurdo rock and fines can be found in Knuth and Melendy (2012).

Figure 2. Upslope drainage ditches along the land transition of the SBT.

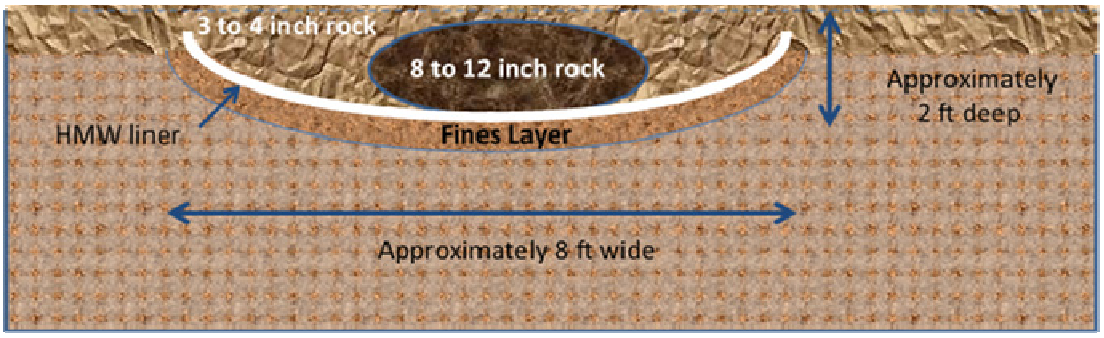

Figure 3. Schematic of the Antarctic French Drain.

Next, 25 ft by 8 ft (7.6 m by 2.4 m) pieces of high molecular weight (HMW) plastic are placed as an impermeable liner on top of the fines layer to further channel the water.

Figure 4 illustrates how laying 8–12 in. (20.3–30.5 cm) rock on the plastic allows for non-erosive water drainage. The larger rock increases the drain's lifespan and flow capacity over the 3–4 in. (7.6–10.2 cm) clean-off rock, which easily plugs with silt. Finally, clean-off rock (3–4 in. [7.6–10.2 cm] rock) is placed to cover the plastic and the larger rock and bring the ditch back to the normal road surface grade.

Figure 5 shows close-up views of the inflow and outflow sides of a completed AFD. The plastic HMW liner extends beyond the land transition road travel lanes on the downslope side to provide erosion protection for the roadside slope at the drain outlet (Figure 5, right). The side slope tends to crack and settle, and water runoff exacerbates the problem. Whether using a culvert or an AFD, the outflow must extend well past the road bed prism or unacceptable erosion and loss of roadway can occur. Large rocks hold down the plastic for the outlet; the plastic does not need to be covered with smaller rock at the outlet as it is not part of the roadway.

Water crossing the road is also a major factor in dirt being tracked out onto the ice. Previously, small drainage ditches were cut across the land transition road. Traffic crossing these small ditches picked up mud. To fix this problem, transverse trenches 6–8 in. (15.2–20.3 cm) deep and 4 ft (1.2 m) wide were cut with a backhoe and then filled with 3–4 in. (7.6–10.2 cm) clean-off rock (Figure 6). Fines and HMW plastic are not needed for these unlined drains because the road subbase is solid, impermeable vesicular basalt with no permafrost, not aggregate and soil over ice as previously discussed with the AFD construction.

Occasionally, plastic is needed on the roadside slope at the unlined drain outlet to provide erosion control (as in Figure 5, right). In this case, the outlet is cut deeper than the road trench, sealed with fines, and then laid over with plastic. The fines help prevent

Figure 4. The fines and plastic are installed and large rock is placed along the center of the drain, 2010 construction.