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Insulated Pavements for Low-Volume Roads

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16. Abstract *An overview of an innovative road construction/reconstruction method that was demonstrated at two Federal land management agency sites to address reducing damage to low-volume pavements due to detrimental effects of frost action. Considerations for design and construction of insulated pavements to reduce road maintenance, as well as performance measures to quantify the effect of the insulating layer, are discussed.*				
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx cd/m^2	lux	0.0929	foot-candles	fc
	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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The Challenge

Federal land management agencies (FLMAs) maintain a vast network of low-volume roads, both paved and unpaved. Many of these low-volume asphalt-surfaced roads in the northern portion of the United States, or at high elevations, are highly susceptible to damage from frost heaving and thaw weakening, because they are neither designed nor constructed to withstand heavy loads during spring thaws. Implementing the practice of spring load restrictions (SLRs), which prohibit or restrict hauling during damage-susceptible spring thaw periods, can limit damage from thaw weakening. However, placing SLRs also adversely impacts industries with livelihoods that depend on trucking to keep products moving (Figure 1).

a. York Pond Road, White Mountain National Forest, New Hampshire.

b. Sawmill in New Hampshire requiring transport of goods.

Figure 1. Low-volume road damage due to springtime trafficking, and company whose livelihood depends on transport of goods on these roads.

Source: All photos provided courtesy of the U.S. Forest Service

Alternately, roads can be constructed to withstand winter and springtime damage. Such springtime damage requires the presence of three factors, in combination:

1. moisture
2. frost-susceptible material
3. freezing temperatures

Removal of any one of these elements will eliminate detrimental effects of frost action. However, these solutions can pose challenges:

1. Constructing drainage systems, such as incorporating an open graded base within the road structure, is not always practical or cost-effective for low-volume roads.
2. Using thick layers of non-frost-susceptible granular material will reduce detrimental effects of frost action. However, such material is not always readily available on site or within a reasonable hauling distance. Hauling in non-frost-susceptible materials to resist frost action can be extremely costly.

The Solution

Incorporating a layer of extruded polystyrene between the subgrade and base course can provide a cost-effective alternative for preventing damage from frost action in situations where utilizing non-frost-susceptible materials for road construction requires long-distance hauling or where constructing a drainage system is impractical. This layer prevents freezing temperatures from penetrating into the subgrade. As a result, the pavement structure will never undergo frost heaving or thaw weakening—with thaw weakening being a major cause of road damage from springtime trafficking, as shown in Figure 1a.

The Journey

Two insulated pavement demonstration sections were constructed during the fall of 2017. Both were in New Hampshire, with two different subgrade underlay materials. One insulated pavement site was constructed at the Hubbard Brook Experimental Forest, on a sandy subgrade in the White Mountain National Forest, New Hampshire, and the other was constructed at Saint-Gaudens National Historical Park, on a silty subgrade in Cornish, New Hampshire.

Both sites were very low-volume pavements and were similarly constructed. The insulated pavement comprised a layer of 2-inch-thick extruded polystyrene atop the natural subgrade (occasionally leveled with sand), on top of which was placed approximately 18 inches of aggregate base course, followed by a 2-inch-thick layer of hot mix asphalt.

a. Example of heave as a result of no insulation.

b. Panel insulation at site.

Figure 2. Transition from non-insulated to insulated road.
Source: All photos provided courtesy of the U.S. Forest Service

For both sites, contractors placed a 16-foot-long section of 1-inch-thick extruded polystyrene panels to transition between insulated pavement and adjacent conventional, non-insulated pavement. This transition section prevents abrupt discontinuities in surface elevation during the winter when non-insulated pavement heaves from frost action.

Note: It is critical that the insulation panels have a minimum cover of 18 inches of aggregate base, which the two sites did have. The U.S. Army, Navy, and Air Force specify this minimum cover, but some other countries specify even thicker cover, such as 21 inches or 24 inches. The purpose of the cover is to reduce differential surface icing. (This is analogous to the widely recognized “bridges freeze first” scenario. However, drivers expect bridges to possibly be icy whereas they do not have any expectation of possible differential freezing on insulated pavements, as they do not have any knowledge of the presence of underlying insulation.)

Saint-Gaudens National Historical Park, Cornish, New Hampshire

Saint-Gaudens National Historical Park, maintained by the National Park Service (NPS), is located just off Rt. 12A in Cornish, New Hampshire. The historic site comprises the home and studios of sculptor Augustus Saint-Gaudens. The complex also includes hiking trails, natural areas, and beautiful gardens. The demonstration site itself comprises a 140-foot segment of a maintenance road, 14 feet wide, accessing some buildings and offices within the historic site.

Construction of the Saint-Gaudens insulated pavement section took place during the fall of 2017. Additionally, a section of conventional, non-insulated pavement was constructed immediately adjacent to the insulated pavement to enable performance measures to be monitored and compared during and after the Coordinated Technology Implementation Program (CTIP) project. The subgrade was a frost-susceptible stony silt.

a. Just a few panels needed to be cut to fit.

b. Panel placement.

c. Placing insulation panels.

d. Compacting base course atop insulation panels.

Figure 3. Saint-Gaudens construction.
Photos: All photos provided courtesy of the U.S. Forest Service.

The demonstration site comprises two adjacent sections—one an insulated pavement, and the other a conventional, non-insulated pavement. The insulated pavement included a wider section of road, for parking, abutting the historic site's archives building. Additionally, the maintenance road was peppered with underground utility lines—waterlines, fiber optics lines, etc. Constructing immediately adjacent to a building and amid a minefield of utilities required extreme care on the part of the construction contractor.

The contractor excavated the subgrade to the desired grade and leveled it. Small quantities of sand were used to fill in localized holes, and a thin layer or sand was placed in areas to level the surface for placement of extruded polystyrene insulation panels. While most insulated pavements don't require special measuring and cutting of panels, the Saint-Gaudens panels did need to be cut to fit in place adjacent to the archives building.

A crew of Forest Service and NPS representatives placed the panels by hand, in a staggered configuration as shown in Figures 2b and 3b.

Although some firms that install insulated pavements pin down the panels or tape panels to each other to prevent panel movement during construction, neither method was used for this demo. This saved a significant amount of time, and, with no wind and careful contractors, panel placement was successful without this extra step.

In addition to working particularly carefully to prevent panel displacement, the contractors used added care in placing and spreading the aggregate base course atop the panels to prevent crushing of the panels, as that would compromise insulating ability. Lifts were placed in the same manner as for standard road construction, except the first lift was slightly thicker to ensure no risk of panel integrity.

Once contractors placed and compacted the gravel base course, they used hot mix asphalt to pave the demo sections of the maintenance road.

In 2019, falling weight deflectometer (FWD) testing, funded separately by USACE-ERDC-CRREL, was conducted during spring thaw and through thaw recovery at Saint-Gaudens. The FWD test point grids comprised eight test points on the insulated pavement (two rows of four test points each—one row per wheel path). The same layout was used for the conventional pavement section.

Surface elevation surveys were periodically conducted during the 2019–2020 winter-spring to monitor frost heaving as a function of time. A similar grid was used for the elevation surveys as for FWD testing, but the elevation grids had an additional row of survey monitoring points along road centerline for each section.

White Mountain National Forest, New Hampshire – Hubbard Brook Experimental Forest, White Mountain National Forest, Thornton, New Hampshire

The Hubbard Brook Experimental Forest is a 7,800-acre northern hardwood forest within the White Mountain National Forest in New Hampshire, in the towns of Thornton and Woodstock, New Hampshire. It is home to the Hubbard Brook Ecosystem Study, "one of the longest running and most comprehensive ecosystem studies in the world. The collaborative, multidisciplinary research efforts include long-term studies of air, water, soils, plants, and animals."

The area is categorized as cold and wet, and freeze-thaw is an issue in the area.

Construction of the Hubbard Brook insulated pavement section also took place during the fall of 2017, shortly after Saint-Gaudens. As with the Saint-Gaudens site, a section of conventional non-insulated pavement was constructed adjacent to the insulated pavement section to enable performance measures to be compared upon conclusion of the construction effort. The Hubbard Brook subgrade was sandy.

a. Extruded polystyrene insulation panels.

b. Spreading gravel base course.

c. Rolling asphalt surface during construction.

Figure 4. Hubbard Brook construction.

Source: All photos provided courtesy of the U.S. Forest Service.

The demonstration site consisted of the reconstruction of a 180-foot section of access road, 12–24 feet wide, running along the outside edge of a gravel parking lot. It included two adjacent sections—one insulated pavement and one conventional non-insulated pavement.

The construction process was almost identical to that at Saint-Gaudens, except no special panel shapes were required. After excavating existing material, a crew of Forest Service representatives placed the panels by hand in the staggered configuration shown in Figure 4a.

The construction contractor used care in placing and spreading the aggregate base course atop the panels to prevent crushing and ensure insulation capacity was uncompromised. Lifts were placed in the same manner as for standard road construction, except the first lift was again a little thicker than is typical to ensure no risk to panel integrity.

Once the contractors placed and compacted the gravel base course, they used hot mix asphalt to pave the sections of roadway.

Modulus – Falling Weight Deflectometer

Low-volume roads in seasonal frost areas are generally not designed to withstand heavy loads during spring thaw. During the winter, freezing occurs from the surface downward, moisture is drawn toward the freezing front, and ice lenses are formed. In the spring, ice lenses, underlain by still-frozen material, melt, and leave the road in an undrained, unconsolidated condition, which is highly susceptible to damage during springtime trafficking. Figure 5 shows the generic relationship among freezing, excess moisture, modulus/stiffness, and damage.

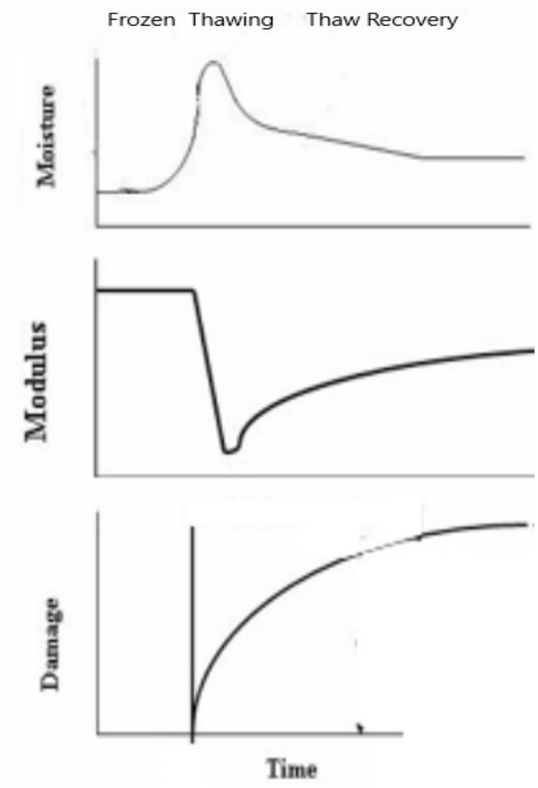


Figure 5. Relationship among freezing, thawing, moisture, modulus, and damage.

The FWD, a sophisticated but commonly used pavement testing device, simulates a moving wheel load and can be used to determine a variety of indices that directly or indirectly quantify pavement modulus or stiffness (Figure 6). For this study, we used an FWD to monitor seasonal variations of pavement stiffness for all test sections and chose to use impulse stiffness modulus (ISM), which is simply the ratio of applied load to maximum deflection under the load place, to measure stiffness in each section over time.

FWD test protocol included the following:

- Approximately three seating drops
- Four drops each from four heights, for a total of 16 drops
- 9,000+/- pound load to be within the approximate center of the load range
- 12-inch load plate
- 1-foot spacing between sensors

a. Van pulling a trailer that contains the falling weight deflectometer on a gravel lot.

b. Close up of the back of the trailer holding the falling weight deflectometer.

Figure 6. Falling weight deflectometer (FWD) (at a non-CTIP site in New Hampshire).

Source: All photos provided courtesy of the U.S. Forest Service.

The Results

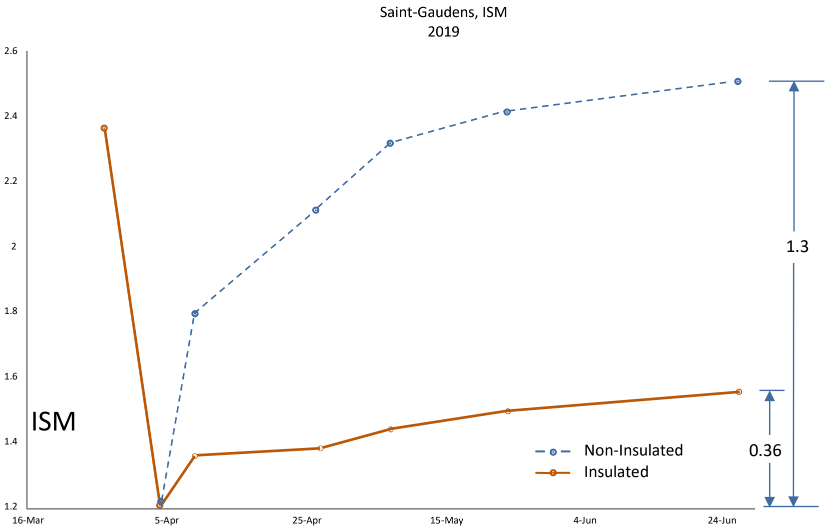
Structural Performance – Seasonal Variations in ISM

As previously noted, FWD tests were conducted periodically throughout the 2019 spring thaw and recovery for the insulated pavement and conventional pavement sections at both demo sites, and ISM, a measure of stiffness, was determined throughout time for all sites. Figure 7 shows an average of ISM values corresponding to the 9,000-pound load level at both Saint-Gaudens and Hubbard Brook.

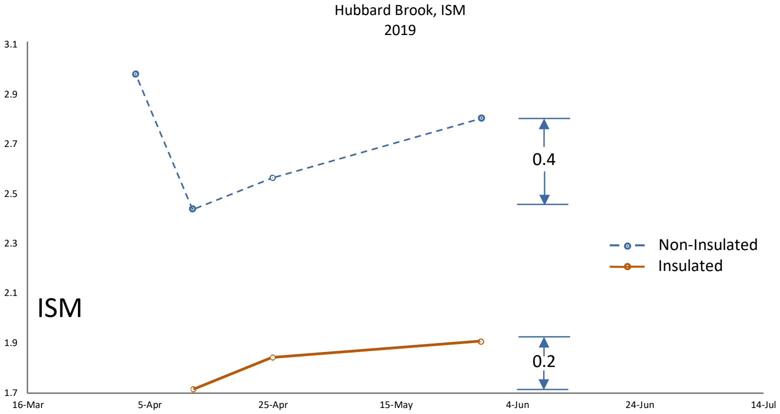
As would be expected, the overall stiffness of the insulated pavement was less than the overall stiffness of the conventional pavement. This is simply because of the presence of the insulating layer, which is structurally weaker than a granular layer would be. However, the purpose of examining this structural performance measure over time was to show that an insulated pavement does not undergo the loss of pavement stiffness during spring thaw (as the loss of stiffness corresponds to a rapid rise in cumulative structural damage as shown in the generic graph in Figure 5). This range in pavement stiffness from the start of spring thaw until thaw-recovery is complete (or is nearly complete) is clear in Figure 7. Note the difference in ISM at Saint-Gaudens (from the weakest point until recovery) is 1.3 for conventional, non-insulated pavement and is only 0.36 for insulated pavement.

Although the difference shown at Hubbard Brook was not as significant, insulated pavement still showed twice as much range, i.e., 0.4 for non-insulated pavement and 0.2 for insulated pavement. It is also clear that the difference will continue to grow as recovery continues (non-insulated pavement had not approached leveling out, as shown in Figure 7), and added FWD tests would need to be conducted into the summer, when full recovery occurs.

The bottom line: The insulated pavement sections did not undergo significant thaw weakening—the critical condition, which occurs each spring, when damage rapidly occurs to conventional pavements.



a. ISM for insulated and non-insulated pavements at Saint-Gaudens.



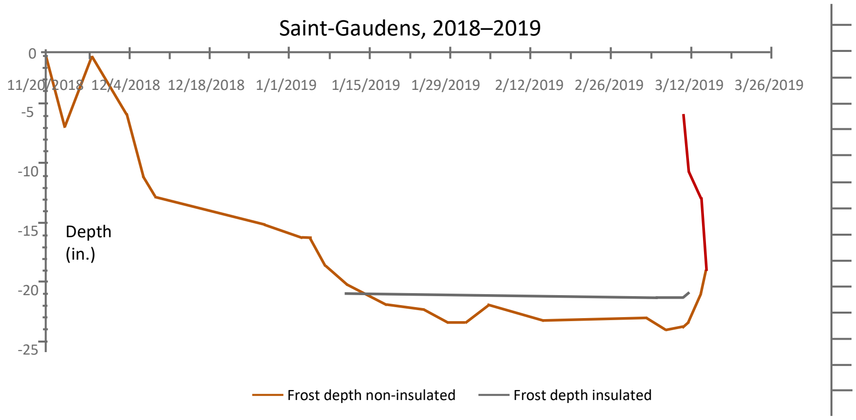
b. ISM for insulated and non-insulated pavements at Hubbard Brook.

Figure 7. Seasonal variations in impulse stiffness modulus.

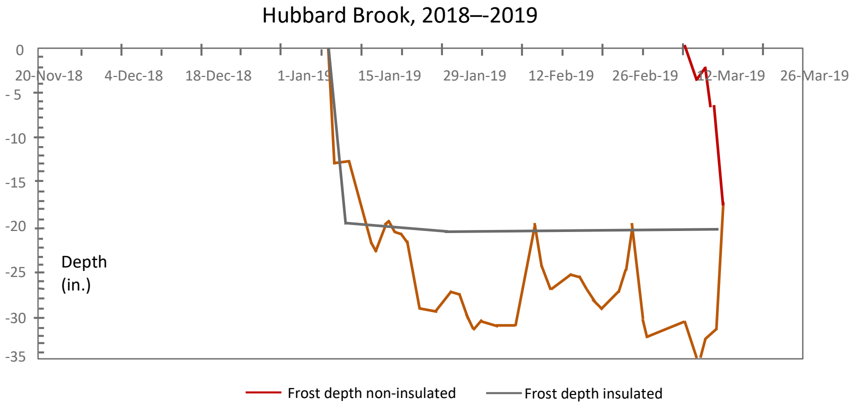
Thermal and Structural Performance – Frost Penetration and Frost Heave

Frost Penetration

While frost penetration may not necessarily be considered a performance measure, it is still a feature that does help demonstrate the benefits of incorporating insulation in a pavement, as reflected by other performance measures (heave and stiffness). Figure 8 shows the effect of a layer of extruded polystyrene on the thermal regime of the pavement structure for the two sites for the 2018–2019 winter. Note the 32-degree isotherm is essentially held back within the insulating layer for the insulated sections whereas frost penetrated to greater depths in the conventional, non-insulated pavement. It just so happens that frost depth was not deep enough at Saint-Gaudens for insulation to have made much of a difference during the winter monitored. However, the effect is more pronounced at Hubbard Brook, a little further north, where the frost depth was somewhat deeper. Nevertheless, in both instances, the insulation prevented the frost from penetrating into the subgrade, which is of course critical because frost in the subgrade is generally the source of freeze-thaw problems.



a. Frost penetration/frozen layer through time at Saint-Gaudens.



b. Frost penetration/frozen layer through time at Hubbard Brook.

Figure 8. Frost depth.

Frost Heave

Elevation surveys were conducted at each of the pavement test sections during the 2019–2020 winter and spring to monitor frost heave, which is considered a performance measure. Table 1 shows the maximum average frost heave measured at each of the pavement sites during the winter of monitoring.

Table 1. Maximum Average[1] Frost Heave

Section Monitored	Saint-Gaudens	Hubbard Brook
Non-insulated pavement: Maximum average frost heave measured (inches)	0.12	0.11
Insulated pavement Maximum average frost heave measured (inches)	0.30	0.02
Date maximum heave was recorded	Jan. 15, 2020	Feb. 25, 2020

[1] *Average of 12–13 survey points measured in each section*

All maximum frost heave values were minimal at most. The maximum average frost heave exhibited by the conventional, non-insulated section at Hubbard Brook was greater than the frost heave exhibited by the insulated pavement, as would be expected. However, the maximum average frost heave for the conventional pavement was not greater at Saint-Gaudens, as should have been the case.

This is most likely attributed to the unfortunate fact that the winter during which frost heave was monitored just happened to be a warmer than a normal winter. We have already seen that at Saint-Gaudens, the frost penetration for the conventional pavement was only slightly deeper than the frost penetration for the insulated pavement during the preceding winter, 2018–2019, which was close to a normal winter. During a warmer than normal winter in this area, freeze-thaw was probably cyclical, and the frost was not deep enough or present long enough to be able to show any reduction in frost heave values for the insulated pavement. Although we believe that this is the most likely cause of the minor overall heave, and non-expected greater heave in the insulated section at Saint-Gaudens, other factors could also have contributed to these results. However, frost heave was so minimal overall, it is likely that all measurements were within a statistically insignificant range already.

It should be noted that other previous non-CTIP studies have shown significant reductions in maximum frost heave by insulated pavements compared to adjacent conventional, non-insulated pavement sections. For instance, a study of an insulated pavement in Jackman, Maine, showed maximum heave of several insulated pavement test sections to be approximately 1/2-inch—a significant reduction from the maximum frost heave of 2 inches exhibited by the nearby conventional, non-insulated pavement (Kestler and Berg 1995). Such frost heave magnitudes are typical.

The Wrap-Up

Traditionally, detrimental effects of frost action have been reduced by one of two methods:

1. placement of thick fills
2. excavation and removal of large quantities of frost-susceptible material and replacement with a thick layer of non-frost-susceptible material

However, incorporating an insulating layer within the pavement structure can often provide a cost-effective alternative for protecting the subgrade from frost penetration, particularly when long hauling distances can be eliminated.

This demonstration project contributes to the evidence that insulated pavement can provide a viable alternative technology for reducing damage from frost action.

Insulation was shown to have prevented frost from penetrating into the subgrade.

- Therefore, frost heave was greater in the non-insulated section than in the insulated section at one demonstration site. Unfortunately, that was not shown to be the case at the other site, but that can likely be attributed to the fact that the frost penetration during the winters of observation was so minimal that it didn’t necessarily get deeper in the non-insulated section than in the insulated section, and freeze-thaw was cyclical. Therefore, frost heave for both the insulated and non-insulated pavement was likewise minimal, making differences insignificant.
- Additionally, structural performance was compared using the FWD (during a normal winter). It was shown that insulated pavement did not undergo the significant thaw weakening that conventional, non-insulated pavement did. This is because the subgrade did not freeze, and therefore the subgrade did not undergo thawing, or thaw weakening.

Insulated pavement would be most beneficial and cost-effective when the use of non-frost-susceptible granular material is not available locally but rather would require a significant haul. It would also be beneficial for small, localized areas prone to frost action problems.

7.0 Q&A

Q: Can any type of insulation be used as an insulating layer?

A: A variety of standard insulation panels (extruded polystyrene, expanded polystyrene, etc.) and less conventional insulating materials (tire chips, tire shreds, chunk wood) can be used to insulate roads. However, this project used extruded polystyrene, which is currently the only type of insulation recommended by the U.S. Army and Air Force.

Q: How is insulation panel thickness determined?

A: Design charts provide design methodology; however, a general rule of thumb is 1/2-inch thickness of extruded polystyrene for each 500 degree Fahrenheit day of the design freezing index.

Q: How much granular cover is required atop the insulation?

A: Different agencies specify different depths for placing insulation, thus different amounts of cover, but most specify a minimum depth such that there are 18 inches of gravel cover atop the insulation. Some countries specify 21 or 24 inches. Thick cover minimizes differential surface icing.

Q: Can one place an insulated pavement directly adjacent to a conventional pavement, or is some type of transition recommended?

A: Transitioning is recommended. If the insulation thickness is 2 inches, a section of two (or three) panel lengths of 1-inch thick insulation is recommended for transitioning. Alternately, 3-inch diameter holes may be drilled in two panels at a spacing of approximately 8 inches on center. Or, insulation panels can be placed on a vertical slope such that it is the same depth as the insulated pavement immediately adjacent to the insulated pavement and reaches a depth of expected frost penetration two panel lengths away from the insulated pavement. The cross section atop the sloped insulation would be the same depth of gravel as in the insulated section immediately adjacent to the insulated pavement and increasing depths of subgrade material between the gravel base and sloped insulation. This will prevent differential frost heaving and completely level out the heaving that will occur over two panel lengths. However, this latter insulation panel configuration is a bit difficult to construct.

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