Energy-Saving, Moisture-Resistant XPS Insulation

ROADWAYS & AIRFIELDS
ENGLISH UNITS

GEOTECHNICAL DESIGN AND INSTALL GUIDE

ROADWAYS AND AIRFIELDS

Frost and Thaw Protection for Roadways and Airfields

Bearing Applications for Roadways and Airfields

DISCLAIMER OF LIABILITY

BACKGROUND AND DESIGN VARIABLES

Introduction

Using FOAMULAR® GEO extruded polystyrene (XPS) to limit seasonal frost penetration in fill embankments has been a long-standing application. Limiting frost penetration during freezing conditions can prevent unwanted ground movement and frost heaving caused by water molecule expansion as it freezes and turns into ice. Furthermore, limiting frost penetration prevents freezing of underlying soils, which allows for better subgrade drainage during spring thaw. Conversely, in permafrost zones, insulation can also be used to control the thaw depth during warm ambient summer conditions, preventing an embankments underlying permafrost subgrade from thawing.

FOAMULAR® GEO can provide long term stability and reliability to roadways and airstrips where subgrades consist of thaw unstable permafrost, especially in Arctic and Subarctic environments. Utilizing insulation in this way can substantially reduce the amount of gravel fill required, reduce the thickness of the embankment, and ensure long-term stability. Where gravel is a scarce commodity or permafrost is very warm (>29°F), using rigid board insulation can substantially reduce construction and maintenance costs.

Determining the amount of insulation required to adequately protect embankments depends on climatic conditions, types of soils present, and soil properties. In areas where the mean annual soil surface temperature (T_{MASST}) is lower than 32°F, permafrost can be expected and the depth of seasonal thaw will control thermal calculations. For areas where T_{MASST} is greater than 32°F, the depth of seasonal freeze will control the thermal calculations.

There are two design philosophies used in the design of insulated embankments, roadways and/or pavements. The first, Complete Protection Method (CPM), maintains the freezing/thawing isotherm within the insulation and prevents freezing/thawing below the insulation layer. The second method is the Limited Protection Method (LPM), which allows a controlled depth of freeze or thaw penetration below the insulation. LPM is often more cost effective, as it requires less insulation. LPM is intended to be used with a subbase material placed beneath the insulation equal to the calculated total depth of frost/thaw penetration, minus the thickness of the pavement, base, and insulation. Figure 1 shows an example of varying active layer depths in an embankment based on the protection method, or lack thereof. An active layer is the soil layer that freezes annually, or in permafrost situations, thaws annually.

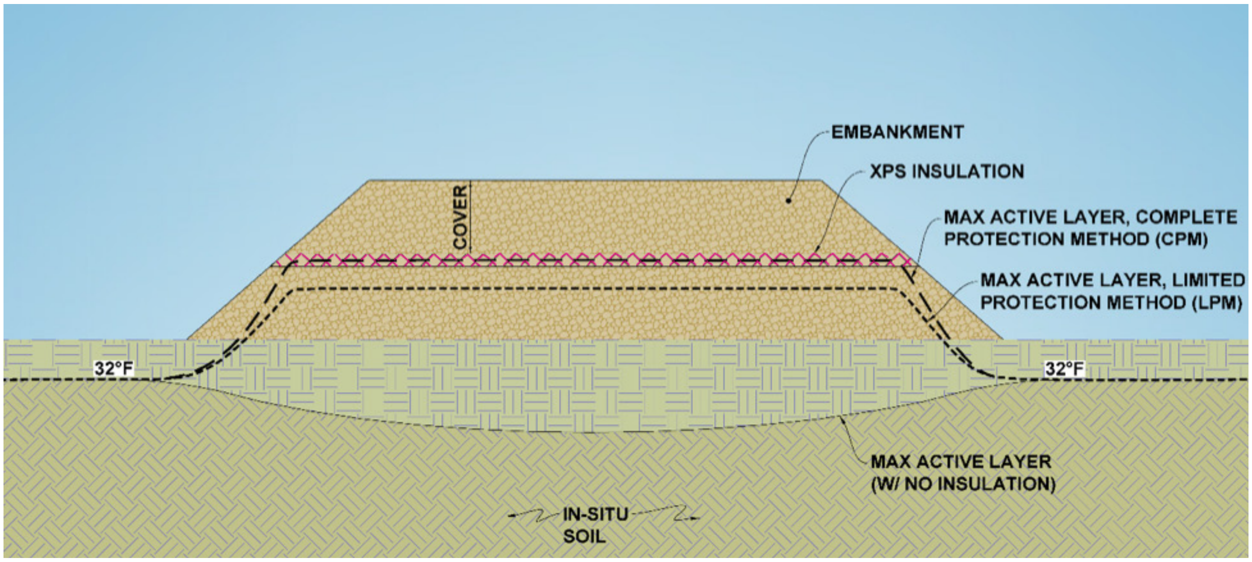


Figure 1: Active Layer Depth in an Insulated Embankment

Regardless of design philosophy, frost/thaw penetration will need to be determined. The most common method for determining frost/thaw penetration is based on the modified Berggren equation. Inputs into the modified Berggren equation include the climate conditions, such as freezing/thawing index, surface conditions, and soil thermal properties.

Freezing Index

The freezing index (FI) is used to evaluate seasonally frozen soils. The freezing index is the summation of temperature differential below freezing (32°F), times the time at that temperature, summed over the course of a freezing season, expressed in degree-days (equation 1).

$$FI = \sum(32^{\circ}F - T_{air}) \cdot t$$

For example, for a given day, if the average air temperature were 20°F for a day, that portion of the freezing index calculation would be given as:

$$FI = (32^{\circ}F - 20^{\circ}F) \cdot 1 \text{ days} = 12^{\circ}F \cdot \text{days}$$

The accumulation of freezing degree days over a given winter is then computed, typically using daily average temperatures between the start of freeze to the start of thaw. Two values for freezing indexes are commonly found: mean and design. The mean represents the average for a particular site's freezing index. The design freezing index is typically taken to be the average of the three coldest winters in the last 30 years for a particular site. Figure 2 below shows the design air freezing index distribution in North America. This figure should be used only as a guide; site specific climatic information should be collected for design. Climate data can be collected from Regional Climate Centers or similar organizations that provide climate monitoring data.

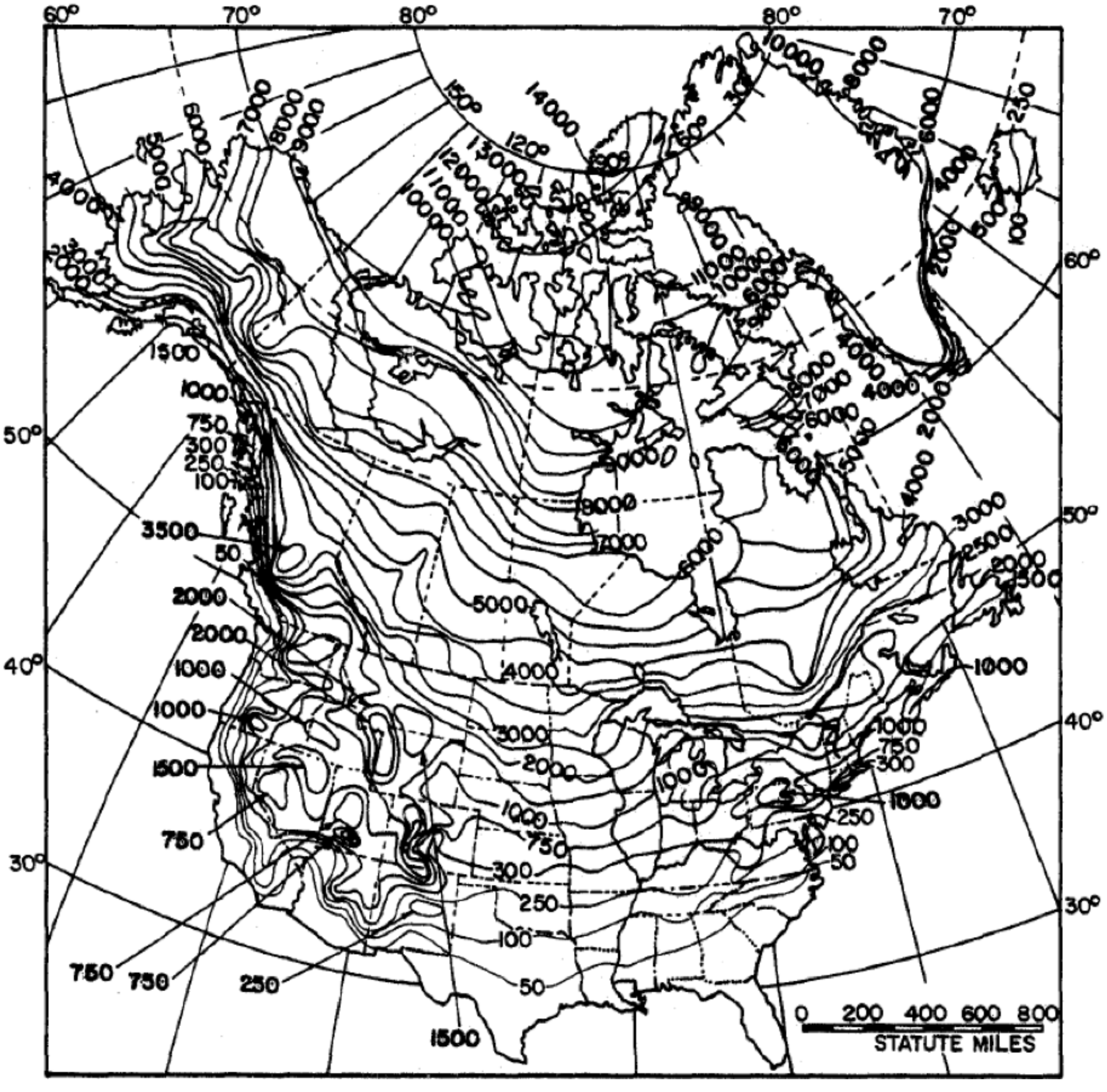


Figure 2: Design Freezing Indexes for North America (from EM 1110-3-138)

Thawing Index

The thawing index (TI) is used to evaluate permafrost soils. The thawing index is defined as the summation of temperature differential above freezing (32°F), times the time at that temperature, summed over the course of a thawing season, expressed in degree-days (equation 2).

$FI = \sum(T_{air} - 32^{o}F) \cdot t$

For example, for a given day, if the average air temperature were 20°F for a day, that portion of the freezing index calculation would be given as:

$FI = (46^{o}F - 32^{o}F) \cdot 1 \text{ day} = 14^{o}F \cdot \text{days}$

Similar to the freezing index, the accumulation of thawing degree days over a given summer is then computed, typically using daily average temperatures between the start of thaw to the start of freeze. Two values for thawing indexes are commonly found: mean and design. The mean represents the average for a particular site's thawing index. The design thawing index is typically taken as the average of the three warmest summers in the last 30 years for a particular site.

Mean Annual Soil Surface Temperature

Following calculation of the freezing index and thawing index, the mean annual soil surface temperature, T_{MASST}, can be calculated as follows:

$$T_{MASST} = 32°\text{F} + \frac{n_t TI - n_f FI}{365\ days}$$

Surface n-factors

Surface conditions have a significant influence on ground temperatures at any given site. Some of the factors affecting ground temperatures include: radiation, vegetation, snow cover, ground thermal properties, surface relief, and surface and subsurface drainage. The difference between ambient air temperature and actual ground temperature is determined with the n-factor. The n-factor modifies the ambient air temperature at a particular time to reflect the actual soil surface temperature. The n-factor can be calculated for a specific site if air and ground surface temperature measurements are available.

Typical n-factors are presented in Table 1 with the subscripts f and t representing frozen and thawed conditions respectively. Selection of a specific value within the range should be based on actual "on the ground" conditions and engineering judgement.

Table 1: Typical Surface n-Factors (Andersland and Ladanyi, 2004)

MATERIAL	n_f	n_t
Snow	1.0	
Sand and Gravel	0.6 to 1.0	1.3 to 2.0
Trees and Brush Cleared Moss Over Peat Soil	0.25	0.73
Asphalt Pavement	0.29 to 1.0	1.4 to 2.3
Concrete Pavement	0.25 to 0.95	1.3 to 2.1

Thermal Properties of Soils

The two most important thermal properties of the soil are the thermal conductivity and volumetric heat capacity. Thermal conductivity is the rate at which heat passes through a material. The volumetric heat capacity is the amount of energy required to raise a unit volume of materials 1 degree in temperature. These thermal parameters vary with temperature, soil type, water and/or ice content, degree of saturation, and soil density.

Generally, granular soils such as gravel and sands have greater freeze and thaw depths than soils with higher moisture contents, such as silts and clays. In some cases, increasing the depth of granular fill to prevent frost/thaw penetration in the native soils is impractical, and board insulation can be used to reduce the amount of fill required for frost/thaw depth control. A rule of thumb for first-order approximations is that 1 inch of insulation can be used to replace 1 foot of sand or gravel. However, this is highly dependent on the soil type, moisture content, and mean annual soil surface temperature and relying solely on this rule of thumb is not recommended.

The most common computation for thermal conductivity uses charts developed by Kersten (1949). These charts were developed for granular and cohesive soils to determine the frozen and unfrozen conductivities at various unit weights and degrees of saturation. The Kersten charts (Figure 3 through Figure 6) and equations 4 through 7 provide frozen and unfrozen conductivities that are reported to give values within ±25% from measured conductivities. This is generally considered sufficient for practical applications, as soil properties in the field are not homogenous. The frozen and unfrozen conductivities can be calculated using the following set of equations:

Unfrozen fine-grained soils:
$k_u = 0.0833(0.9 \log(w) + 0.2) \cdot 10^{0.01\gamma dry}$

Frozen fine-grained soils:
$k_u = 0.0833[0.01(10^{0.022\gamma dry}) + 0.085(10^{0.008\gamma dry})w]$

Unfrozen granular soils:
$k_u = 0.0833(0.7 \log(w) + 0.4) \cdot 10^{0.01\gamma dry}$

Frozen granular soils:
$k_f = 0.0833[0.076(10^{0.013\gamma dry}) + 0.032(10^{0.0146\gamma dry})w]$

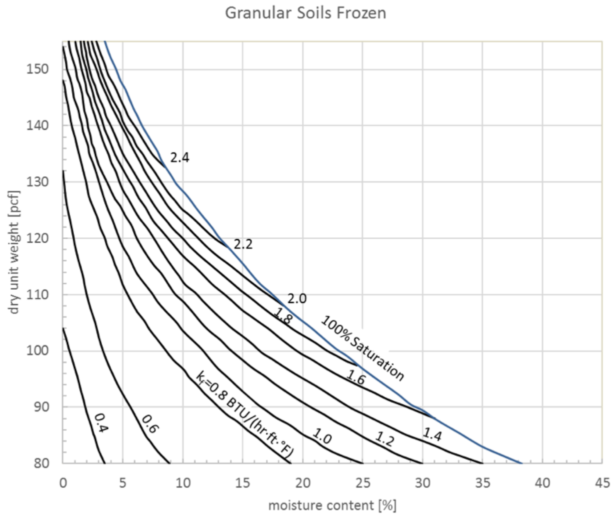


Figure 3: Frozen Conductivity for Granular Soils (from Kersten)

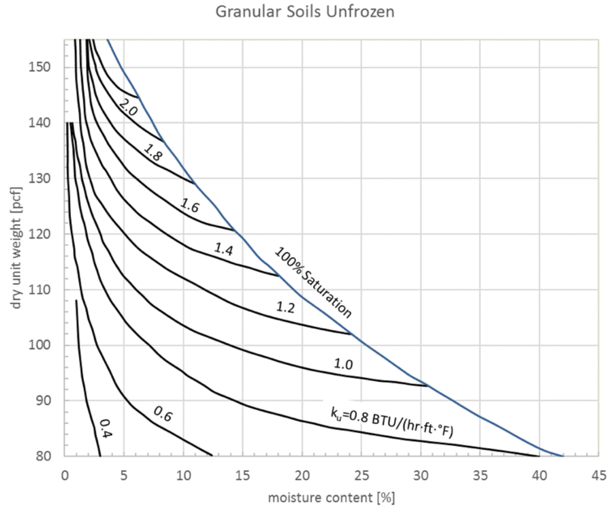


Figure 4: Unfrozen Conductivity for Granular Soils (from Kersten)

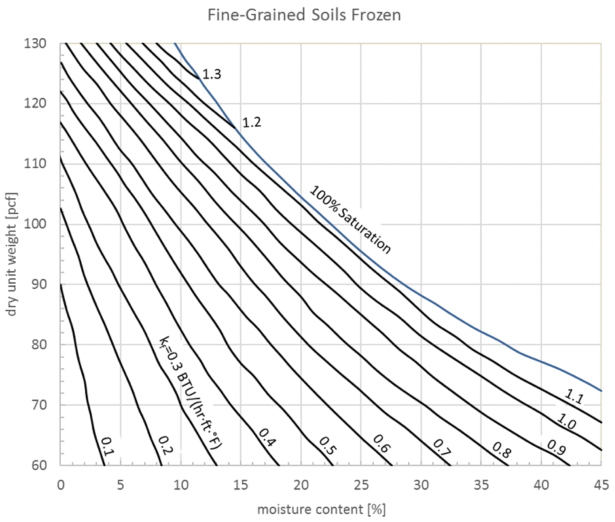


Figure 5: Frozen Conductivity for Fine-Grained Soils (from Kersten)

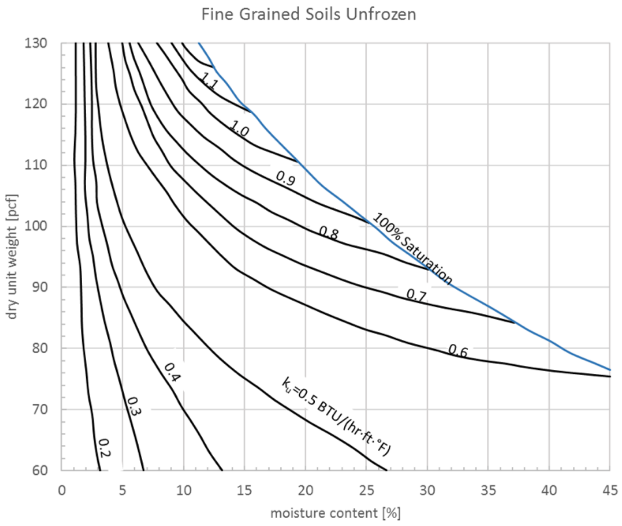


Figure 6: Unfrozen Conductivity for Fine-Grained Soils (from Kersten)

The volumetric heat capacity can be computed for unfrozen soils and frozen soils using equations 8 and 9 respectively and is expressed in BTU/(ft^3 • °F), where w is the water content of the soil in percent. For organic soils, replace the 0.17 with 0.50 in both equations.

$$C_{vu} = \gamma_{dry}\left(0.17 + 1.0 * \frac{w}{100}\right)$$

$$C_{vf} = \gamma_{dry}\left(0.17 + 0.5 * \frac{w}{100}\right)$$

Volumetric latent heat is calculated using equation 10 and is expressed in BTU/ft^3. The volumetric latent heat describes the energy required for the water-ice phase change within the soil.

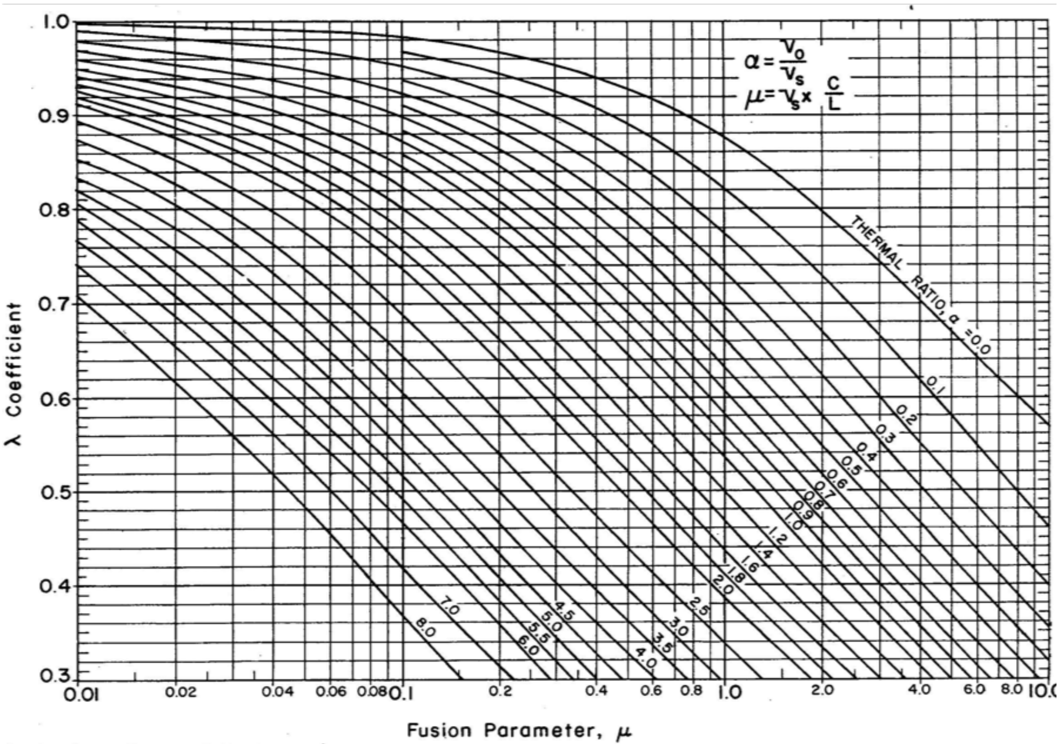
$$L_v = 144 * \gamma_{dry} * \frac{w}{100}$$

In areas with seasonal frost where insulation is used to control frost penetration, the fusion parameter μ is calculated using Equation 11, and the thermal ratio α is calculated using Equation 12.

$$\mu = n_f * \frac{FI}{d_f} * \frac{C_v}{L_v}$$

$$\alpha = \frac{|T_{MASST} - 32°\mathrm{F}|}{n_f * \frac{FI}{d_f}}$$

The fusion parameter and thermal ratio are then used to determine the λ-factor from Figure 7. The λ-factor accounts for the sensible heat due to the phase change of water in non-steady state conditions.



(U.S. Army Corps of Engineers)

Figure 7. Chart for Determination of λ-Factor (U.S. Army Corps of Engineers)

Frost and Thaw Depth

Seasonal Frost Soils (non-permafrost)

The depth of freeze can be calculated using the modified Berggren equation, which uses the average thermal conductivity k_{avg} and the λ-factor to determine the depth of the active layer in a seasonal frost area (Equation 13) (Andersland and Ladanyi, 2004). In areas with seasonal frost, the depth of freezing equals the depth of the active layer. Note that if flowing water is present, the modified Berggren equation is likely to overpredict the depth of freeze. The equation is intended to act as a first-order approximation of active layer depth for a year with the specific freezing/thawing indexes. For long-term, detailed analysis, finite element models are suggested to determine the maximum depth of thaw over the design life of the embankment.

$$x = \lambda \sqrt{\frac{2 k_{avg} n_f FI}{L_v}}$$

For a system with insulation, the equivalent R-value of the soil and insulation is used and the equation becomes a quadratic that can be solved for the thickness of the active layer, x (Equation 14).

$$n_f FI * \frac{\lambda^2}{L_v} = R_{eq}x + \frac{x^2}{2k_{avg}}$$

Permafrost Soils

In permafrost soils, the active layer is defined by the depth of thaw and the previous calculations are adjusted to use thaw parameters. This results in the following modification to the modified Berggren equation:

$$\mu = n_t * \frac{TI}{d_t} * \frac{C_v}{L_v}$$

$$\alpha = \frac{|32°\mathrm{F} - T_{MAAST}|}{n_t * \frac{TI}{d_t}}$$

$$x = \lambda \sqrt{\frac{2k_{avg} n_t TI}{L_v}}$$

Therefore, for an insulated system in a permafrost region, the quadratic equation becomes:

$$n_t TI * \frac{\lambda^2}{L_v} = R_{eq}x + \frac{x^2}{2k_{avg}}$$

It is important to note that in permafrost soils, the modified Berggren equation may under or overestimate the thaw depth if subsurface features such as taliks are present. A talik is an area of unfrozen ground surrounded by permafrost. Similar to seasonal frost soils, finite element models are suggested for long-term, detailed analysis, to determine the maximum depth of thaw over the design life.

Frost Depth Charts

The following chart is provided as a first-order frost depth estimate considering a site's freezing index, soil unit weight, and moisture content using nf=1.0 and λ-factor of 0.77. The chart assumes a dry unit weight of 135 pcf.

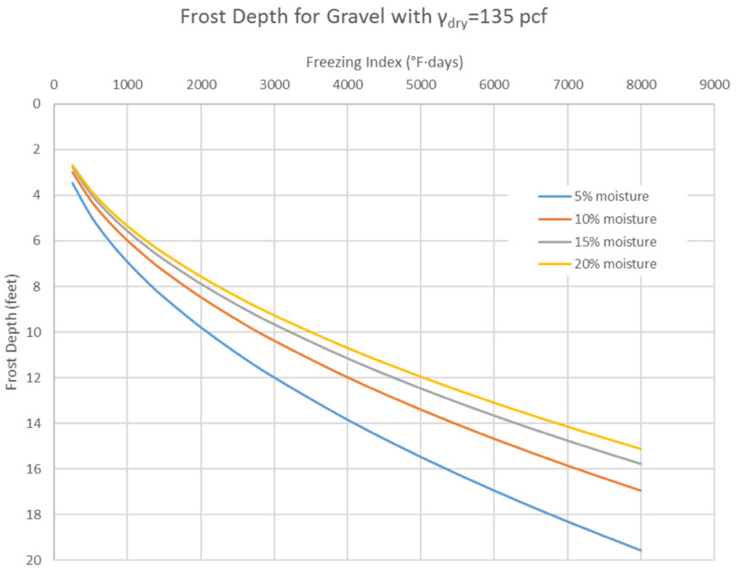


Figure 8: Frost Depth vs. Freezing Index for Gravel

Frost Protection in Roads

Several design tools can be used to approximate insulation requirements. According to the US Department of the Army and Air Force (1985), the minimum amount of XPS insulation required to completely contain frost penetration at different air freezing indexes is given in Figure 9. This figure assumes 4 inches of asphalt pavement and 21 inches of base course below the pavement with soil parameters as shown. The figure was developed using the layered procedure for the modified Berggren equation. The actual thickness of insulation required will depend on material properties and climate conditions. Owens Corning can provide further information on request.

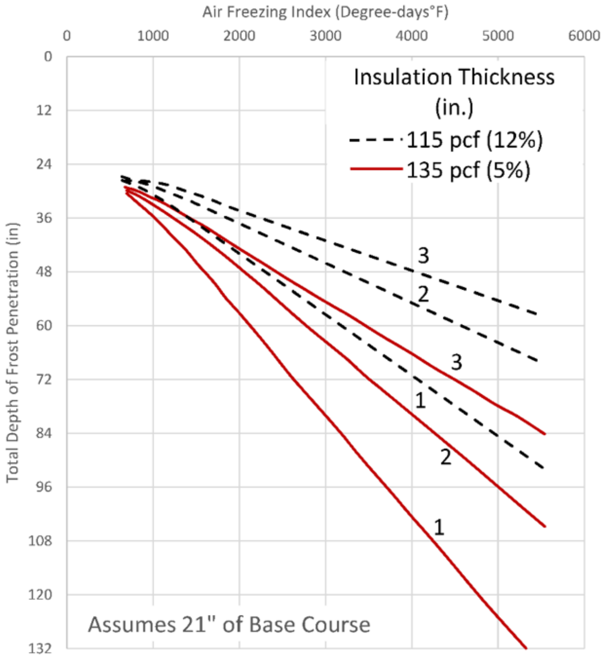


Figure 9: Minimum Insulation Thickness Related to Air Freezing Index (U.S. Department of Army)

Additionally, first-order approximations developed by Owens Corning can be used, which utilize the modified Berggren equation. Table 2 and Table 3 provide the insulation thickness approximations for CPM gravel embankments (for both non-paved and paved) in seasonal frost areas with different cover depths. For Table 2, the embankment material is assumed to be constructed of gravel with a dry unit weight of 135 pcf and a moisture content of 5%. Table 3 assumes the embankment is surfaced with 4 inches of asphalt (0% moisture content for the asphalt) and constructed of gravel with a unit weight of 138 pcf and a moisture content of 5%. The insulation thickness was adjusted so the depth of frost was within 6-inches of the bottom of the insulation. Site specific climate parameters (freezing and thawing indexes) should be used for actual design. Soils with higher moisture contents will require less insulation than soils with lower moisture contents.

Table 2. Insulation Thickness Recommended for CPM Gravel Roads

COVER (FT)	DESIGN FREEZING INDEX (ºF • DAY)*																		
	500				1000					1500					2000				
	MEAN ANNUAL TEMPERATURE (ºF)																		
	32	**35**	**37**	**39**	**32**	**35**	**37**	**39**	**42**	**32**	**35**	**37**	**39**	**42**	**32**	**35**	**37**	**39**	**42**
	MINIMUM INSULATION (IN)				MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)				
1	4	2	1	1	6	4	2.5	2	2	7.5	4.5	3.5	3	2.5	8.5	5.5	4.5	3.5	3
2	3.5	1.5	1		5.5	3.5	2	2	1.5	7	4	3	2.5	2	8	5	4	3	2.5
3	2.5	1			5	3	2	1.5	1	7	4	3	2.5	2	8	5	4	3	2.5
4	1.5				4.5	2.5	1.5	1		6.5	3.5	3	2	1.5	8	5	4	3	2.5
5	1				3.5	1.5	1			6	3	2	1.5	1	7.5	4.5	3.5	2.5	2
6					2.5	1				5	2	1	1		7	3.5	2.5	2	1
7					1					3	1				5.5	2.5	1.5	1	
8										1.5					4	1	1		
9										1					1.5				
10															1				

COVER (FT)	DESIGN FREEZING INDEX (ºF • DAY)*																			
	2500					3000					3500					4000				
	MEAN ANNUAL AIR TEMPERATURE (ºF)																			
	32	**35**	**37**	**39**	**42**	**32**	**35**	**37**	**39**	**42**	**32**	**35**	**37**	**39**	**42**	**32**	**35**	**37**	**39**	**42**
	MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)				
1	9.5	6.5	5	4.5	3.5	10	7	6	5	4	11	8	6.5	5.5	4.5	12	9	7	6	5.5
2	9	6	4.5	4	3	9.5	6.5	5.5	4.5	3.5	10.5	7.5	6	5	4	11.5	8.5	6.5	5.5	5
3	9	6	4.5	4	3	9.5	6.5	5.5	4.5	3.5	10.5	7.5	6	5	4	11	8	6.5	5.5	5
4	9	6	4.5	4	3	9.5	6.5	5.5	4.5	3.5	10.5	7.5	6	5	4	11	8	6.5	5.5	5
5	8.5	5.5	4.5	3.5	2.5	9.5	6.5	5	4	3.5	10.5	7.5	6	5	4	11	8	6.5	5.5	4.5
6	8	5	3.5	3	2	9	6	4.5	3.5	2.5	10	7	5.5	4.5	3.5	10.5	7.5	5	5	4
7	7	4	3	2	1	8	5	4	3	2	9	6	5	4	2.5	10	7	5.5	4.5	3.5
8	5.5	2.5	1.5	1		7	4	2.5	1.5	1	8	5	4	2.5	1.5	9	6	4.5	3.5	2.5
9	4	1	1			5.5	2.5	1	1		6.5	4	2.5	1	1	8	5	3.5	2	1
10	1.5					3.5	1				5	2	1			6	3	1.5	1	

COVER (FT)	DESIGN FREEZING INDEX (°F • DAY)*																	
	4500					5000**					6000**				7000**			
	MEAN ANNUAL AIR TEMPERATURE (°F)																	
	32	**35**	**37**	**39**	**42**	**32**	**35**	**37**	**39**	**42**	**32**	**35**	**37**	**39**	**32**	**35**	**37**	**39**
	MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)				MINIMUM INSULATION (IN)			
1	12	9.5	8	6.5	5.5	12.5	9.5	8	7	6	13	10.5	9	8	14	11.5	10	8.5
2	11.5	9	7.5	6	5	12	9	7.5	6.5	5.5	13	10	8.5	7.5	14	11	9.5	8.5
3	11.5	8.5	7	6	5	12	9	7.5	6.5	5.5	12.5	10	8.5	7.5	13.5	11	9.5	8
4	11.5	8.5	7	6	5	12	9	7.5	6.5	5.5	12.5	10	8.5	7.5	13.5	10.5	9.5	8
5	11.5	8.5	7	6	5	12	9	7.5	6.5	5.5	12.5	10	8.5	7.5	13.5	10.5	9.5	8
6	11	8	7	6	5	11.5	8.5	7.5	6.5	5	12.5	9.5	8.5	7.5	13.5	10.5	9.5	8
7	11	7.5	6.5	5.5	4	11.5	8.5	7	6	5	12.5	9.5	8	7	13	10.5	9	8
8	10	7	5.5	4.5	3	11	7.5	6.5	5	4	12	9	7.5	6.5	12.5	10	8.5	7.5
9	9	5.5	4.5	3	2	10	6.5	5	4	2.5	11	8.5	6.5	5.5	12	9	7.5	6.5
10	7.5	4	3	1.5	1	8.5	5	4	2.5	1	9.5	7	5.5	4	11	8	6.5	5.5

*Insulation thicknesses were determined with physical property values provided on product data sheets.

**Freezing indexes higher than 4500 °F·day are typically associated with permafrost areas. The insulation thicknesses provided in this table are for seasonal frost areas, i.e. controlled by the depth of freezing. The larger freezing indexes will likely require less insulation than indicated by these tables.

Table 3: Insulation Thickness Recommended for CPM Roads with 4" of Asphalt

COVER (FT)	DESIGN FREEZING INDEX (°F • DAY)																		
	500				1000					1500					2000				
	MEAN ANNUAL TEMPERATURE (°F)																		
	32	**35**	**37**	**39**	**32**	**35**	**37**	**39**	**42**	**32**	**35**	**37**	**39**	**42**	**32**	**35**	**37**	**39**	**42**
	MINIMUM INSULATION (IN)				MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)				
1	3.5	1.5	1		5.5	3	2.5	1.5	1	7	4	3.5	3	2.5	8	5	4	3.5	3
2	3	1			5	2.5	2	1		6.5	3.5	3	2.5	2	7.5	4.5	3.5	3	2.5
3	2				4.5	2.5	1.5			6.5	3.5	2.5	2	1.5	7.5	4.5	3.5	3	2
4	1				4	1.5	1			6	3	2.5	1.5	1	7	4.5	3.5	2.5	2
5					3	1				5	2.5	1.5	1		6.5	4	3	2	1
6					1					4	1.5	1			6	3	2	1	
7										2	1				4.5	1.5	1		
8										1					3	1			
9															1				
10																			

COVER (FT)	DESIGN FREEZING INDEX (°F • DAY)																			
	2500					3000					3500					4000				
	MEAN ANNUAL AIR TEMPERATURE (°F)																			
	32	35	37	39	42	32	35	37	39	42	32	35	37	39	42	32	35	37	39	42
	MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)				
1	9	6	5	4	3.5	10	6.5	5.5	4.5	4	10.5	7.5	6	5	4.5	11	8	6.5	5.5	5
2	8.5	5.5	4.5	3.5	3	9.5	6	5	4	3.5	10	7	5.5	4.5	4	10.5	7.5	6	5	4.5
3	8.5	5.5	4.5	3.5	3	9.5	6	5	4	3.5	10	7	5.5	4.5	4	10.5	7.5	6	5	4.5
4	8.5	5.5	4	3.5	2.5	9.5	6	5	4	3	10	7	5.5	4.5	4	10.5	7.5	6	5	4.5
5	8	5	3.5	3	2	9	6	4.5	3.5	2.5	10	6.5	5.5	4.5	3.5	10.5	7.5	6	5	4
6	7.5	4	3	2	1	8.5	5	4	3	2	9.5	6	5	4	3	10	7	5.5	4.5	3.5
7	6	3	2	1		7.5	4	3	1.5	1	8.5	5.5	4	3	2	9.5	6.5	5	4	2.5
8	4.5	1.5	1			6	3	1.5	1		7	4	3	1.5	1	8.5	5	4	2.5	1.5
9	2.5	1				4	1	1			5.5	2.5	1	1		7	3.5	2	1	1
10	1					2					4	1	1			5	1.5	1		

COVER (FT)	DESIGN FREEZING INDEX (°F • DAY)															
	4500					5000*					6000*				7000*	
	MEAN ANNUAL AIR TEMPERATURE (°F)															
	32	35	37	39	42	32	35	37	39	42	32	35	37	39	32	35
	MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)					MINIMUM INSULATION (IN)				MINIMUM INSULATION (IN)	
1	11.5	8.5	7.5	6	5.5	12	9	7.5	6.5	6	12.5	10	8.5	7.5	13.5	10.5
2	11.5	8.5	7.5	6	5	12	9	7.5	6.5	6	12.5	10	8.5	7.5	13.5	10.5
3	11	8	7	5.5	5	11.5	8.5	7	6	5.5	12	9.5	8	7	13	10
4	11	8	7	5.5	5	11.5	8.5	7	6	5.5	12	9.5	8	7	13	10
5	11	8	6.5	5.5	4.5	11.5	8.5	7	6	5	12	9.5	8	7	12.5	10
6	10.5	7.5	6.5	5	4	11	8	7	5.5	4.5	12	9	8	7	12.5	10
7	10	7	5.5	4.5	3.5	10.5	7.5	6.5	5	4	11.5	8.5	7.5	6.5	12.5	9.5
8	9	6	4.5	3.5	2	9.5	6.5	5.5	4	3	11	8	6.5	5.5	12	9
9	7.5	4.5	3	2	1	8.5	5.5	4	3	1.5	10	7	5.5	4	11	8
10	6	3	1.5	1		7	4	2.5	1	1	8.5	5.5	4	2.5	9.5	7

*Insulation thicknesses were determined with physical property values provided on product data sheets.

**Freezing indexes higher than 4500 °F·day are typically associated with permafrost areas. The insulation thicknesses provided in this table are for seasonal frost areas, i.e. controlled by the depth of freezing. The larger freezing indexes will likely require less insulation than indicated by these tables.

Notes on FOAMULAR® GEO In-Situ Long Term Thermal Performance

When determining the actual design, thermal performance at the design life should be taken into account. Research of extruded polystyrene samples, ranging from 1 to 31 years of service in cold region civil projects, has shown that FOAMULAR® GEO will slowly absorb moisture via water vapor. Moisture absorption over time can degrade the insulations thermal resistivity, which progresses slowly over time as moisture absorption increases. Research has determined that FOAMULAR® GEO R-value degrades at a rate of -0.03 (hr • ft^2 • F/BTU) per inch of FOAMULAR® GEO for every year in service. For example, a 1-inch thick layer of insulation in service for 10 years will have a reduced R-value, from 5.0 (initially) to 4.7 (10 years in service).

DESIGN EXAMPLE

List of Variables

- μ – Fusion parameter
- C_v – Volumetric heat capacity [BTU/(ft^3 • °F)]
- d_f – Number of freezing days (days)
- d_t – Number of thawing days (days)
- k_{avg} – Average thermal conductivity [BTU/(hr • ft • °F)]
- k_f – Frozen thermal conductivity [BTU/(hr • ft • °F)]
- k_u – Unfrozen thermal conductivity [BTU/(hr • ft • °F)]
- L_v – Volumetric latent heat (BTU/ft^3)
- n_f – Surface freezing n-factor
- n_t – Surface thawing n-factor
- R_{eq} – Equivalent thermal resistivity [(hr • ft • °F)/BTU]
- FI – Freezing Index (°F • day)
- TI – Thawing index (°F • day)
- T_{MASST} – Mean annual soil surface temperature (°F)
- w – Water content of soil (%)
- α – Thermal ratio
- γ_{dry} – Dry unit weight (lb/ft^3)
- λ – Coefficient for use in modified Berggren equation
- v – Poisson's ratio
- z – Depth below foundation
- B – Width of loading
- C_d – Duration factor
- F_c – FOAMULAR® GEO minimum compressive strength
- F_a – Allowable stress
- F'_a – Allowable design stress
- q_o – Contact pressure
- q_z – Pressure at depth z
- $\Delta\sigma_z$ – Maximum stress change at depth z below load
- σ'_z0 – Vertical effective stress in the soil due to excavation (for insulation = 0)
- L – Length of applied surface load
- P – Applied point load
- I_w – Westergaard influence factor
- R – Horizontal distance from the center of the foundation

Example Calculation
The following example illustrates the calculation for determining the active layer depth using the modified Berggren equation.

Example Problem:
A gravel embankment is being constructed at a site with a freezing index of 6,000°F • days and a thawing index of 3,000°F • days. The dry unit weight of the gravel is 135 pcf and the moisture content is 5%. The number of freezing days is 220 days.

Choose surface n-factors n_t and n_f for the gravel using Table 1. Then, calculate the mean annual soil surface temperature.

$$n_t = 2.0$$
$$n_f = 0.9$$
$$T_{MASST} = 32 + \frac{2.0 * 3000°\text{F} \cdot days - 0.9 * 6000°\text{F} \cdot days}{365 days} = 33.6°\text{F}$$

Because the mean annual soil surface temperature is greater than 32°F, the equations for seasonal frost areas should be used.

Calculate the soil's thermal properties. Gravel is a mineral soil, so use equation 8.

$$C_v = 135pcf\left(0.17 + 0.75 * \frac{5}{100}\right) = 28.01\frac{BTU}{ft^3°\text{F}}$$
$$L_v = 144 * 135pcf * \frac{5}{100} = 972\frac{BTU}{ft^3}$$

Determine the average thermal conductivity using the Kersten Charts

$$k_u = 1.7 \frac{BTU}{hr \cdot ft \cdot {}^\circ\mathrm{F}}$$

$$k_f = 1.6 \frac{BTU}{hr \cdot ft \cdot {}^\circ\mathrm{F}}$$

$$k_{avg} = \frac{1.7 \frac{BTU}{hr \cdot ft \cdot {}^\circ\mathrm{F}} + 1.6 \frac{BTU}{hr \cdot ft \cdot {}^\circ\mathrm{F}}}{2} = 1.65 \frac{BTU}{hr \cdot ft \cdot {}^\circ\mathrm{F}}$$

Calculate the thermal ratio and fusion parameters and determine the λ coefficient.

$$\mu = 2 * \frac{6000{}^\circ\mathrm{F} \cdot day}{220\ days} * \frac{28.01 \frac{BTU}{ft^3 \cdot {}^\circ\mathrm{F}}}{972 \frac{BTU}{ft^3}} = 1.57$$

$$\alpha = \frac{|33.6{}^\circ\mathrm{F} - 32{}^\circ\mathrm{F}|}{0.9 * \frac{6000{}^\circ\mathrm{F} \cdot days}{220\ days}} = 0.065$$

$$\lambda = 0.79$$

Therefore, the depth of freeze is

$$x = 0.79 \sqrt{\frac{2 * 1.65 \frac{BTU}{(hr \cdot ft \cdot {}^\circ\mathrm{F})} * 0.9 * 6000{}^\circ\mathrm{F} \cdot d * \frac{24\ hr}{day}}{972 \frac{BTU}{ft^3}}} = 16.57\ ft$$

DESIGN AND CONSTRUCTION CONSIDERATIONS

Differential Icing

Differential, or surface, icing can occur on bridges and overpasses, shaded areas, locations with extreme wind exposure, or areas where the underlying soils undergo an abrupt change in properties.

Installing FOAMULAR® GEO insulation in an embankment alters the temperature distribution above the insulation layer, which can result in warmer or colder pavement surfaces. The increased temperature differential between adjacent insulated and uninsulated embankments can result in ice formation on one surface and not on the other when exposed to the same ambient conditions. This phenomenon is known as differential icing. Differential icing can be reduced by placing the insulation near the bottom of the embankment, which creates a larger soil mass above the insulation to act as a heat sink. Alternatively, reducing the insulation thickness decreases the temperature differential across the insulation and results in reduced icing. Consideration should be given to locating the insulation in the embankment to maximize thermal benefits (thermally, placing the insulation near the road surface decreases the active layer depth) while minimizing effects of differential icing.

Asphalt pavement surfaces have been shown to be more effective at reducing differential icing effects than a Portland concrete cement surface for pavement surfaces less than 7-inches thick (Arellano, 2007). Increasing the thickness of the base material (between the pavement and the insulation) will reduce the amount of differential icing by increasing the thermal mass.

Research has shown a minimum of 26 inches of cover over insulation is desirable to minimize differential icing (Arellano, 2007). The closer the insulation is to the pavement surface, the greater the possibility of surface icing. Cover requirements may vary by location and jurisdiction and should be confirmed prior to design and installation. For example, the Alaska Department of Transportation and Public Facilities requires a minimum of 36 inches of cover above insulation.

Installation

FOAMULAR® GEO should be installed in one or two layers on a level, prepared subgrade. The subgrade below the insulation should be prepared per project specifications. In practice, a sand layer is often placed on the subgrade to ensure a level surface. This prevents bending and dimpling of the insulation board. Local and state specifications should be consulted to determine gradation, thickness and installation requirements of the sand layer.

The boards should be butted together and secured using a fastener, such as joint tape or dowel, to anchor the insulation in place. Butt-edged boards placed in layers should be overlapped in a staggered configuration to prevent board joints from aligning vertically and inducing thermal short circuits through the insulation. Alternatively, other FOAMULAR® GEO rigid board configurations may be available, including ship-lap and tongue and groove edges, to secure the boards in place. Project specifications should be consulted to determine anchoring methods and requirements.

Transitions

Transitions should be installed at the beginning and end of insulated road segments to prevent an abrupt “bump” in the pavement sections due to differences in frost/thaw penetration. Insulation thickness should be gradually reduced towards the non-insulated road section, generally one 1-inch thick board width at a time. For example, if 3 inches of insulation are being used in a roadway, a 2-inch and 1-inch segment should be installed prior to going into the uninsulated portion of the road. Depending on the construction and thermal resistance of the road, insulation may need to be tapered over a longer distance. The taper length should account for cross-streets, driveways, and frost forces acting on the road. Furthermore, transitions should not occur on curves or locations where users would incur high risk situations with surface ice formation, such as when the road is permanently shaded or near water.

BEARING APPLICATIONS FOR ROADWAYS AND AIRFIELDS
BACKGROUND AND DESIGN

Bearing Design Overview

Rigid foam insulation installed below roadways and airfields must be evaluated for stresses due to applied surface loads. These loads may originate from construction activities, soil overburden, structural foundations, or vehicular traffic. The applied surface loads must be distributed through any medium that the load passes before reaching the surface of the foam layer. This distribution results in a reduced pressure that will be seen at the surface of the insulation. In most cases this medium is soil. If additional components such as bearing plates, mats, cribbing or other means are utilized to help distribute the load, the effect of that component should be considered when determining the stress distribution and required insulation compressive strength.

Boussinesq Method

Since the most common material to be placed on foam insulation is soil, the Boussinesq stress distribution method is recommended for determining the stress applied to the foam. Two common stress distribution charts for continuous (i.e. strip footing) and square (i.e. spread footing or tire pressure) surface loads are shown in Figure 10. This method is appropriate for single tire loading. Where multiple tires are involved, the design needs to consider overlapping pressure distributions.

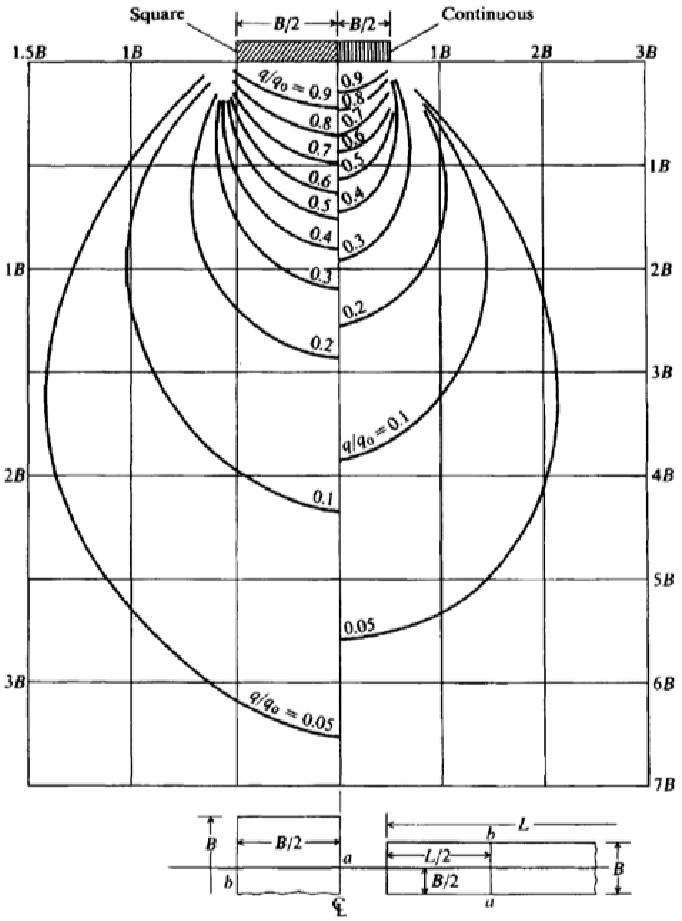


Figure 10. Boussinesq Stress Contours for Infinite and Square Loadings (after Sowers, 1979)

2:1 Method

For simple applications, the 2:1 Method is commonly used as a first order approximation of stress distribution. It is a reasonably accurate method for application in non-layered homogenous soils where $1.5 < z/B < 5$, where z is the depth below the foundation and B is the width of the loading. The 2:1 Method should not be used in the depth zone from z=0 to B (i.e. near the surface) as this method under predicts the stresses in this zone (Bowles, 1996).

PRODUCT PROPERTIES AND DESIGN FACTORS

Compressive Strengths

FOAMULAR® GEO is rated for minimum compressive strength values based on stress-strain curves of the material recorded during testing. The minimum compressive strength should account for safety factors and material variability and modified for load duration to establish the final allowable design stress. For roadway and airstrip applications, cyclic loading is an additional consideration both from a strength and stiffness reduction standpoint, as well as, a permanent deformation (loss of thickness) standpoint.

FOAMULAR® GEO PRODUCT	**FOAMULAR® GEO INSULATION FOUNDATION PROPERTIES**									
	FOUNDATION MODULUS (pci)[1,2,3] THICKNESS (IN)						**ALLOWABLE COMPRESSIVE STRESS (psi)[4]**			
	1"	1.5"	2"	2.5"	3"	4"	Impact[5] Load	Short Term[5] Load	Medium Term[5] Load	Long Term[5] Load
40	1,100	1,000	900	780	680	650	60	30	20	10
60	1,520	1,400	1,275	1,150	1,040	790	90	45	30	15
100			2,600				150	75	50	25

1. Foundation modulus is a measure of deflection at given loads, expressed as inches deflection per inch of thickness or "pci".
2 .For insulation installed in multiple layers, assuming the layers are identical, the foundation modulus for the system equals the foundation modulus for one of the layers divided by the total number of layers.
3. For insulation systems that utilize a variety of thicknesses, the system foundation modulus is determined by adding the reciprocal of the foundation modulus of the individual layers. The total is the reciprocal value for the foundation modulus of the entire system.
4. Allowable compressive stress, Fa, is the minimum compressive stress, Fc, divided by the factor of safety. Values shown include a 2.0 factor of safety.
5. Load duration corrected allowable compressive stresses, i.e. allowable design stresses, are determined by multiplying the allowable compressive stress, Fa, by the loading duration factor, Cd. For each load configuration, utilize the largest duration factor associated with that load configuration when determining the allowable design stress. Cd values are as follows: 3.0 for Impact, 1.5 for Short Term, 1.0 for Medium Term, and 0.5 for Long Term.

Cyclic Loading

For applications involving numerous load cycles such as roadways and airstrips or overloading, cyclic loading and overloading material behavior is an important consideration. Cyclic compressive testing was performed on FOAMULAR® GEO products to determine the effects of cyclic and overloading stess. The effects measured included initial and final material thickness and stiffness of the foam. At loading less than the published minimum compressive strength (loads $< F_c$), a linear relationship (elastic response) was observed and no loss of effective thickness or stiffness was observed.

In general, the initial overload cycle (load $> F_c$), showed an elasto-plastic behavior. Subsequent loading showed a strain hardening behavior. Cumulative deformation occurred between cycles decreasing with each cycle, converging on a multicycle accumulated strain thickness reduction of approximately 30% (70% remaining) of the original section thickness.

Based on the cyclic load tests, FOAMULAR® GEO can exceed the published minimum compressive strength values with no loss of ultimate strength of the material.

When calculating thermal resistance of the material, it is recommended that an effective thickness reduction be taken into consideration where pressures are expected to exceed the published minimum compressive strength of the insulation. This thickness reduction factor should be a minimum of 0.7 (i.e. 30% thickness reduction) for purposes of calculating the effective thermal resistance provided. Where stresses are intended to be less than the published minimum compressive strength, the full thickness of the board can be used.

Loading Duration and Factors

FOAMULAR® GEO allowable strengths are a function of the applied load durations. Live loads (LL) are temporary or transient forces that act on a material or structural element such has vehicles. Longer term loads can produce creep deformations in the material, reducing the effective thermal resistance and allowing larger deformations than may be desirable in design. In cases where load application is relatively continuous, such as dead load (DL), allowable stresses must be reduced to prevent creep of the material. Creep is addressed by use of a duration factor (C_d) that increases inversely with the load duration. For design application, apply the largest duration factor associated with each load configuration. For example, if insulation capacity is being checked for a dead load and an impact load configuration, use the impact load duration factor. When checking the same insulation for a dead load configuration, use the long term load duration factor. The following are recommended duration factors for loads applied to the FOAMULAR® GEO product line. For other product lines consult with Owens Corning technical staff to determine appropriate values.

$$\text{for } DL + LL_{impact} \text{ use } \frac{3.0(Cd)x\ Fc}{2.0(FS)} = F'c$$

$$\text{for } DL + LL_{building} \text{ use } \frac{1.0(Cd)x\ Fc}{2.0(FS)} = F'c$$

Impact Load/Extreme Load: 3.0
Loads less than 10 seconds in duration or extreme load events of very short duration. These include wind loads, seismic loads, oversized vehicle loads (i.e. AASHTO Strength II vehicles) and other extreme events.

Short Term Load: 1.5
Loads less than 10 minutes in duration. These include standard vehicle loads (i.e. AASHTO Strength I vehicles), standard aircraft loads and other typical loads of short duration. This is the standard duration factor for use in roadway and airstrip design.

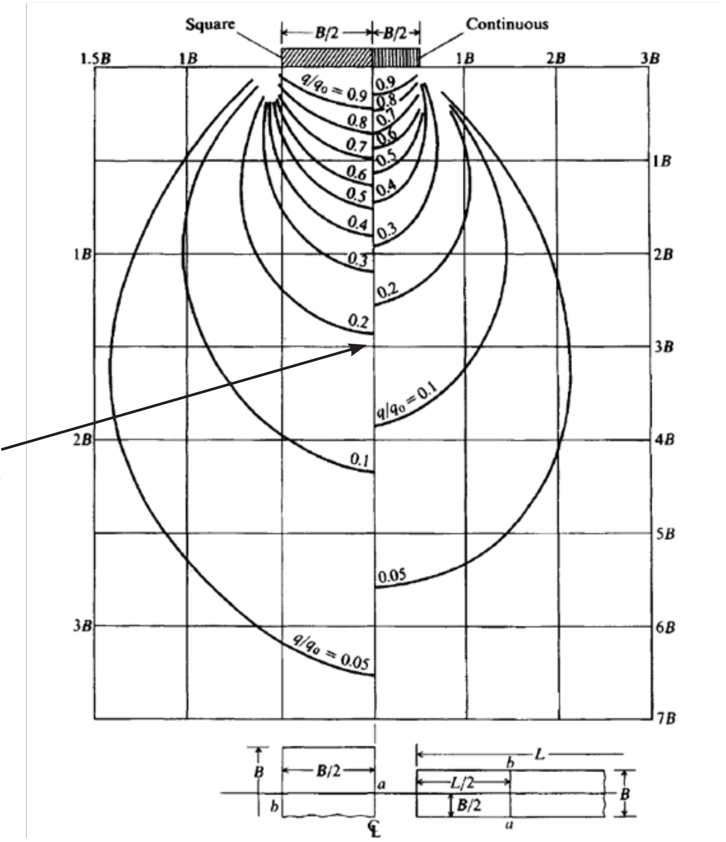
Medium Term Load: 1.0
Loads less than 10 years in duration. These include standard structural live loads (LL) as would be found in building design, wear courses for roadways and similar medium-term loading situations. This is the standard duration factor for building loads.

Long Term Load: 0.5
Permanent loads. This includes dead loads (DL) such as soil overburden, structural self-weight and other very long-term loads. Note: This factor only applies to permanent loads (i.e. DL only) it does not apply to load configurations that may include shorter term elements (i.e. DL+LL).

EXAMPLE APPLICATIONS

The following examples illustrate the calculation method for both applied load and allowable resistance using first the Boussinesq Method and comparing that with the 2:1 Method. As a note, this example is presented at the shallow extreme of the useful range for the 2:1 Method, which serves to illustrate some of its limitations.

Tire Example – Boussinesq Method
Calculate the pressure on a rigid insulation layer placed in a roadway embankment 3 feet below a large tire with a 2-foot square contact area and a tire pressure of 140 psi. Soil unit weight is 130 pcf. Extreme load case.



z = 1.5B
$q_z = 0.2q_o$

Figure 11. Boussinesq Stress Contours for Infinite and Square Loadings (after Sowers, 1979)

Load Calculation
$B = 2$ feet
$q_o = 140$ psi
$z = 3$ feet $= 1.5B$
$q_z = 0.2q_o = 0.2 \cdot 140$ psi $= 28$ psi

$$q_{total} = q_z + z * \gamma = 28\,psi + 3ft * 130\,pcf * \left(\frac{ft^2}{144\,in^2}\right) = 30.7\,psi$$

Use 31 psi for service load design pressure

Allowable Stress Calculation
$F'_a = C_d F_a$

$C_d = 3.0$ (duration factor, 3.0 for 10 second [impact] load application or extreme loading)

$F_a = 0.5F_c = 0.5 \cdot 60$ psi $= 30$ psi for FOAMULAR® GEO 60

$F'_a = 3 \cdot 30$ psi $= 90$ psi

$$\frac{q_{total}}{F'_a} < 1\ OK$$

Tire Example-2:1 Method:
Calculate the pressure on a rigid insulation layer placed in a roadway embankment 3 feet below a large tire with a 2-foot square contact area and a tire pressure of 140 psi. Soil unit weight is 130 pcf. Extreme Load case.

Load Calculation
$B = 2$ feet
$q_o = 140$ psi
$A_0 = 2ft \cdot 2ft = 4\ ft^2$
$A_z = 5ft \cdot 5ft = 25\ ft^2$
$q_z = 4/25 \cdot 140$ psi $= 22.4$ psi
$q_{total} = 22.4$ psi $+ 3 \cdot 130$ pcf $\cdot (ft^2/144in^2) = 25.1$ psi – Note unconservative result
Use Boussinesq Method - 31 psi for service load design pressure

Allowable Stress Calculation
$F'_a = C_d F_a$

$C_d = 3.0$ (duration factor, 3.0 for 10 second [impact] load application or extreme loading)

$F_a = 0.5F_a = 0.5 \cdot 60$ psi $= 30$ psi for FOAMULAR® GEO 60

$F'_a = 3 \cdot 30$ psi $= 90$ psi

$q_{total}/F'_a < 1$ OK

Additional Methods
- Direct Stress Calculation – For direct calculation of the maximum stress at a given depth beneath the center of the applied load, the Boussinesq solution can be simplified to the following set of equations (Coduto, 2001). These equations produce results within 5% of the Boussinesq equations developed by Poulos and Davis (1974).

$$\Delta\sigma_z = \left[1 - \left(\frac{1}{\left(1+\left(\frac{B}{2z}\right)^2\right)^{1.5}}\right)\right](q - \sigma'_{zD}) \qquad \textit{Circular foundation}$$

$$\Delta\sigma_z = \left[1 - \left(\frac{1}{1+\left(\frac{B}{2z}\right)^2}\right)^{1.76}\right](q - \sigma'_{zD}) \qquad \textit{Square foundation}$$

$$\Delta\sigma_z = \left[1 - \left(\frac{1}{1+\left(\frac{B}{2z}\right)^2}\right)^{2.60}\right](q - \sigma'_{zD}) \qquad \textit{Continuous foundation}$$

$$\Delta\sigma_z = \left[1 - \left(\frac{1}{1+\left(\frac{B}{2z}\right)^{1.38+0.62B/L}}\right)^{2.60-0.84B/L}\right](q - \sigma'_{zD}) \qquad \textit{Rectangular foundation}$$

Where:
q = applied surface pressure (i.e. footing bearing pressure)

σ'_{zD} = vertical effective stress in the soil due to any excavation (for insulation = 0)

B = base width of applied surface load

L = length of applied surface load

z = depth below surface

Multiple Soil Layers
Insulation within embankments should be thought of as a layered system. Generally speaking, if the stiffness of the underlying layer is less than the stiffness of the upper layer ($E_{upper} > E_{lower}$), the induced stresses are less than the Boussinesq values. Conversely, if the stiffness of the upper layer is less than the stiffness of the underlying layer ($E_{upper} < E_{lower}$), the induced stresses are greater than the Boussinesq values. Usually, the stiffness of insulation is less than the soil stiffness, so the actual induced stresses below the insulation are smaller than the stresses determined using the Boussinesq charts. Therefore, the use of the Boussinesq values would be a conservative method for establishing design pressures.

The Boussinesq method gives increasingly large errors as the difference between the soil layer stiffness increases (Hazzard, 2007, McCarthy, 1998). The Westergaard Method provides a more accurate stress distribution for calculation of soil stresses in layered systems such as: highways with thicker or more rigid pavements, embankments founded on soft soils or subgrades with distinct layering (i.e. gravel layer on clay or vice versa). The Westergaard solution can be written in terms of an influence factor I_w where P is an applied point load and r is the horizontal distance from the center of the foundation (equation 19).

$$\Delta\sigma_z = \frac{P}{z^2\pi\left[1+2\left(\frac{r}{z}\right)^2\right]^{\frac{3}{2}}} = \frac{P}{z^2} I_w$$

The Westergaard influence factor is a function of Poisson’s ratio. Influence factors for several Poisson’s ratios are given in Table 4.

Table 4. Westergaard Influence Factors

R/Z	**V = 0**	**V = 0.3**	**v = 0.49**
	INFLUENCE FACTOR L_W		
0.0	0.32	0.56	8.04
0.2	0.28	0.46	1.53
0.5	0.17	0.22	0.16
1.0	0.06	0.06	0.02
2.0	0.01	0.01	0.00

Where layered soil conditions and elements of varying stiffness must be considered, a geotechnical engineer with knowledge of the Owens Corning product line should be consulted.

FINAL NOTES

FOAMULAR® GEO can provide long term stability and reliability to roadways and airstrips in remote applications or any environment where heat flow into or out of the ground must be controlled. In many cases where gravel sources are distant or inaccessible or required gravel thickness is excessive, use of an insulation product can be highly beneficial in reducing cost of construction and maintenance. We encourage consultation with Owens Corning technical staff, and/or geotechnical engineers familiar with the products and their applications as the use and benefits of insulation in roadway or airstrip embankment design are considered.

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