CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2024; 34 (3): 0071-0084
DOI: 10.59440/ceer/186492
Original Research Article

SELECTED ASPECTS OF FROST PROTECTION USING EXTRUDED POLYSTYRENE FOR THE DESIGNED ROAD SURFACE

Jacek PARTYKA[1], Andrzej WYSOCZAŃSKI
Military Institute of Engineer Technology, Wroclaw, Poland

Abstract

The present article delves into the consequences of subzero temperatures on the integrity of road elements, specifically scrutinizing their load-bearing capabilities and structural resilience. Central to the discourse is the elucidation of frost heave mechanisms, alongside an exposition of the overarching principles underpinning frost protection strategies within the framework of Polish engineering protocols. Attention is directed towards the deployment of extruded polystyrene as a pivotal component in fortifying road structures against frost-induced degradation. Moreover, the article encompass the preliminary conjectures on the adoption of insulating materials, prevalent in Anglo-Saxon jurisdictions, which offer promising prospects for enhancing frost protection measures in Polish road design, particularly within the context of bespoke structural configurations.

Furthermore, a comprehensive exploration into the soil characteristics endemic to specific geographical locales, delineating methodologies for ascertaining parameters germane to fortifying road structures against frost-induced stresses. Of particular significance is the delineation of computational methodologies aimed at determining the depth of the subterranean frost zone, with a view towards pragmatic application in real-world scenarios.

The article culminates in a succinct synthesis of findings, underscoring the efficacy of the proposed design paradigm in bolstering the resilience of road infrastructures against the deleterious effects of frost-induced phenomena.

Keywords: frost protection, extruded polystyrene, frost index

1. INTRODUCTION

Climatic conditions have a significant impact on the load-bearing capacity and durability of the road surface of streets and sidewalks. At work [1], the authors point out that a significant reduction in the bearing capacity of the subgrade and damage to the surface of road elements is observed, especially in regions with a moderate climate during the spring thaw period.

---

[1] Corresponding author: Jacek PARTYKA, Military Institute of Engineer Technlogy, Obornicka 136, 50-961 Wrocław, Poland, partyka@witi.wroc.pl

This mainly applies to surfaces made of covered soil containing clay or dust, which are particularly sensitive to frost. Based on the studies performed at work [2], it can be concluded that the main factors contributing to the freezing of road structure elements is air temperature, sunlight, radiation, wind and precipitation.

Frost penetration deep into the surface and subsoil results in a high level of moisture in the subgrade soil to remain high and the resulting load-bearing capacity in soils containing fine aggregate fractions, during the thawing period to be low. Therefore, frost heave is formed, which is pointed out in works [3, 4]. Not only is frost heave an undesirable phenomenon but it poses a threat to road users, and increases the costs associated with the ongoing road maintenance.

The presented phenomena occur in regions known for extreme temperatures, but also in Poland, as in Polish conditions the road surfaces can reach temperatures t_{min} = -30°C in winter. Due to the high financial costs of the so-called winter road maintenance, the negative impact of frost on road elements should be limited by using methods to counteract frost processes, as described in works [5-9] One of these methods is the use of a frost protection solution that limits the thickness of frost-protective layers using extruded polystyrene. These issues were presented in [10], which shows examples of the long-term use of polystyrene in road construction in Sweden.

In road frost protection, the particular advantages of extruded polystyrene are used, namely low value of the thermal conductivity coefficient $\lambda = 0.30 \div 0.65$ W/m·K and high resistance to factors aggravating the road surface. As the author of [11] points out, the main advantage of using extruded polystyrene frost protection of the road involves limiting the penetration of the seasonal freezing zone deep into the road embankment in order to ensure better drainage of the ground during spring thaws. In addition, extruded polystyrene board insulation can also be used to control the depth of thaw in warm summer ambient conditions, preventing thawing of underlying embankments in areas with the so-called permafrost. Other advantages of extruded polystyrene used in road construction include the low volumetric weight of extruded polystyrene (approximately 30/45 kg/m^3) and ease of processing, thanks to which a high work rate is achieved in construction works [12,13]. The needs related to shortening the implementation time while maintaining the quality of construction and road works determine the introduction of new, diversified technologies, as the authors point out in [14]. Recently, frost protection solutions limiting the thickness of frost protection layers have been used in Poland. These are insulating materials with low thermal conductivity coefficient $\lambda = 0.25 \div 0.65$ W/m·K. These include, for example, foam concrete, which is also used to strengthen weak-bearing subsoils and even to construct road bases [11].

As a result of using insulating materials, it is possible to reduce the thickness of the structure but this requires the use of a separate methodology and individual calculations, the main assumptions of which are presented in this study.

2. FROST PROTECTION OF ROAD SURFACES IN POLISH DESIGN PRACTICE – GENERAL INFORMATION

At work [1] noted that it is known that in Poland frost protection of road surface subgrades involves the construction of structures of appropriate thickness.

According to the Polish technical regulations, the required thickness of the surface together with the improved subfloor or frost protection layer, due to frost resistance, should be $H = (0.4 \div 0.85) \cdot hz$, where hz is the depth of soil frost in Poland, assumed to be in the range of 0.8÷1.4 m according to PN-81/B-03020 standard. The value of the adopted coefficients (0.4÷0.85) depends on the subgrade load-bearing group (Gi) and the traffic load category. This means that the ground under the road structure may freeze but the thickness of the frozen ground layer is greater in the case of low traffic loads and smaller in the case of heavy traffic.

The parameter occurring in the presented dependency, aimed at determining the thickness of the pavement and the depth of ground frost penetration, can be calculated according to the formula [14]:

$$x = a\sqrt{0.9AFI}\ , \tag{2.1}$$

where:

$a -$ soil-type dependent coefficient;

$AFI -$ air-freezing index.

To determine the average depth of frost penetration under Polish conditions, the data from reference [14] was employed, where: AFI = 989 degree days; and a = 0.058. Utilizing this information, the average frost penetration depth can be calculated as follows:

$$x = a\sqrt{0.9AFI} = 1.73\ \text{m} \tag{2.2}$$

It should be emphasized that the simple formula (2.1), applied in the Polish design practice, pertains to conditions where areas of so-called permafrost are absent. Permafrost is characterized by a significantly deeper zone of low ground temperatures than are noted in Poland. Such a scenario is further elaborated upon in the subsequent sections of this paper. This formula takes into account parameters related to soil characteristics, such as moisture content, degree of soil saturation, thermal conductivity, and heat capacity. However, a limitation of this method for determining frost penetration depth is its applicability to conditions of permafrost, which are practically non-existent in Poland.

The limited frost protection means that the road surface structure is designed taking into account the freezing of the ground and the possibility of frost heave formation, and this may be counteracted by the weight of the layers of the pavement structure. However, the heave will only be partially eliminated. The phenomenon of road surface freezing concerns roads with traffic categories (KR1 and KR2) in particular, as these are exposed to damage due to poorer protection of the surface against freezing. Pavement structures carrying heavy traffic (KR3÷KR7) provide more effective protection against frost due to their load-bearing capacity and adequate strength.

At work [1] elucidate the prevailing stance in Poland, wherein it is posited that both the surface and subsoil ought to be safeguarded against frost to a depth shallower than the actual frost depth. Consequently, the road surface configuration is tailored under the presumption of ground freezing, a notion that entails a potential risk of ground heaving during road operation.

Drawing upon the methodology presented in this study which advocates for the incorporation of an insulating layer beneath the structural strata of the road surface for frost protection, it is suggested that this approach finds applicability, as evidenced in select English-speaking nations.

3. APPLICATION OF CPM AND LPM METHODS IN DESIGNING ROAD SURFACE STRUCTURES USING INSULATING MATERIAL – GENERAL INFORMATION

Using only aggregates for road construction layers involves increasing their thickness, which is not beneficial from an economic point of view. For this reason, it is preferable to use insulating materials to reduce the total required thickness of the pavement, which consists of aggregates of different grain sizes. Moreover, as the author points out in [11], the use of insulation in this way can significantly reduce the amount of gravel fill required, the height of the fill and ensure its long-term stability. In areas where gravel is a scarce commodity and its acquisition for road construction is difficult, the use of insulation made of a rigid extruded polystyrene board is advisable. Determination of required insulation parameters for adequate frost protection of the road surface depends on climatic conditions, the type of soil and their properties.

In English-speaking countries, two distinct methodologies are employed for designing insulated embankments, roadways, and sidewalks. The first, known as the complete protection method (CPM), entails maintaining the freeze/thaw isotherm within the insulation layer, thereby preventing freezing/thawing beneath this insulation layer. Conversely, the second approach, termed limited protection method (LPM), allows for the regulation of frost penetration depth or defrosting beneath the insulation. The LPM method is more prevalent due to its enhanced cost-effectiveness, as it necessitates insulation within a narrower range of parameters concerning thickness and the area occupied within the structural layer of the road surface.

The latter method is designed to incorporate an underlayment material positioned beneath the insulation, equivalent to the calculated total frost/thaw penetration depth, minus the combined thickness of the pavement, underlayment, and insulation layers.

Figure 1 illustrates varying depths of the active layer in the embankment, contingent upon the employed frost protection method or its absence. The active layer denotes the stratum of soil that undergoes annual freezing and thawing, or, in the case of permafrost, seasonal thawing.

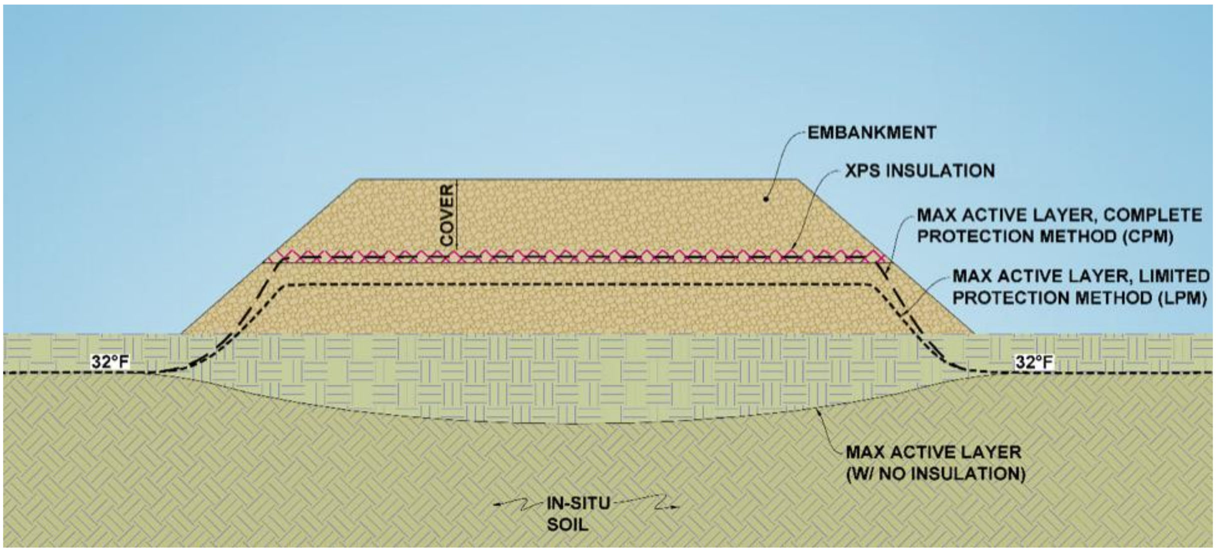


Fig. 1. Depth of the active layer in an insulated embankment [11]

Regardless of the design method adopted, when developing technical documentation, the depth of frost/thaw penetration should be determined. The most popular method for determining frost/thaw penetration is based on the modified Berggren equation. Inputs to the modified Berggren equation include climatic conditions such as frost rates, surface conditions, and soil thermal properties.

4. FROST AND THAWING INDEX FOR ROAD SURFACES IN DESIGN IN ANGLO-SAXON COUNTRIES

In the road surface design process, significant emphasis is placed on ensuring adequate drainage within the road surface structure, thereby mitigating the detrimental effects of frost. It is advised to design road surface structures with a thickness of at least half the determined frost depth based on the Freezing Index (FI).

The FI typically represents the cumulative sum of negative average daily temperatures experienced over a specified period, often the winter season [1, 11]. The FI is expressed in degree days and is calculated using the following formula:

$$FI = \sum(32°F - T_{air})t \tag{4.1}$$

where:
T_{air} – average daily temperature, $°F$;
t – number of days,

The design freeze index is typically taken as the average of the three coldest winters over the past 30 years for a given road location. For design purposes, climatic information is collected and can be obtained from the relevant national meteorological services [11]. Another parameter used to assess the land located in a given area is the Thawing Index marked TI. It is defined as the sum of the temperature difference above freezing (32°F) and the time at that temperature during the thaw period. The TI index is expressed in degree days and can be calculated from the following formula [11]:

$$TI = \sum(T_{air} - 32°F) \cdot t. \tag{4.2}$$

Symbols T_{air} and t as in equation (2).

In the case of the TI index, similarly to the FI, the accumulation of freezing days during a given frost period is determined by taking the average daily temperatures between the beginning of thawing and the beginning of the thaw. The TI values, both the average- and the design one, are adopted in a similar way as for the FI. The calculated values of the frost- and thaw indexes are necessary to determine the average annual ground temperature (T_{MASST}), which can be calculated as follows:

$$T_{MASST} = 32°F + \frac{n_t TI - n_f FI}{365} \tag{4.3}$$

The coefficients n_t and n_f appearing in equation (4.3) have a large impact on determining the ground temperature in a given area, as they depend on the type of surface in the analysed and designed area. Table 1 illustrates the values of the n_t and n_f coefficients for various types of surfaces [11, 16].

Table 1. Values of the n_t and n_f coefficients for various types of surfaces

Type of road surface	**Factor**	
	$\boldsymbol{n_t}$, [−]	$\boldsymbol{n_f}$, [−]
a layer of snow covering the road surface	1.0	-
sand and gravel surface	0.6-1.0	1.3 – 2.0
peat substrate	0.25	0.73
bituminous	0.29-1.0	1.4 – 2.3
concrete	0.25-0.95	1.3 – 2.1

5. THERMAL PROPERTIES OF SOIL

The two most important thermal properties of soils are related to conductivity and heat capacity. These thermal parameters may vary depending on temperature, type of soil, water and/or ice content, degree of soil saturation and density. The graphs presented to calculate thermal conductivity were taken from [11]. These graphs were developed for granular and cohesive soils to determine the conductivity of frozen and unfrozen soil, at various unit masses and degrees of saturation. Thermal conductivity values of soils based on Kersten plots are considered sufficient for practical applications.

Thermal conductivity coefficients marked k_u for frozen soil and k_f for the unfrozen one, can be calculated using the following set of equations:

– for unfrozen fine-grained soil:

$$k_u = 0{,}0833(0{,}9\log(w) + 0{,}2) \cdot 10^{0{,}01\gamma dry}, \tag{5.1}$$

– for frozen fine-grained soil:

$$k_u = 0{,}0833\left[0{,}01\left(10^{0{,}022\gamma dry}\right) + 0{,}085\left(10^{0{,}008\gamma dry}\right)w\right], \tag{5.2}$$

– for unfrozen granular soil:

$$k_f = 0{,}0833(0{,}7\log(w) + 0{,}4) \cdot 10^{0{,}01\gamma dry}, \tag{5.3}$$

– for frozen granular soil:

$$k_f = 0{,}0833\left[0{,}076\left(10^{0{,}013\gamma dry}\right) + 0{,}032\left(10^{0{,}0146\gamma dry}\right)w\right], \tag{5.4}$$

where:
w – water content in the ground, [%];
γdry – dry unit weight, $\left[\frac{lb}{ft^3}\right]$.

Another parameter characterizing the thermal properties of soil is the volumetric heat capacity. It can be calculated for unfrozen and frozen soil using equations (5.3) and (5.4), respectively, and expressed in units of applied energy in the UK and US, BTU/(ft^3 ·°F) as shown below:

$$C_{vu} = \gamma_{dry}(0{,}17 + 1{,}0 \cdot \frac{w}{100}) \tag{5.5}$$

$$C_{vf} = \gamma_{dry}(0{,}17 + 0{,}75 \cdot \frac{w}{100}) \tag{5.6}$$

Volumetric latent heat is calculated using the following equation and is expressed in BTU/ft^3. The volumetric latent heat describes the energy needed for the phase transformation of water in the ground.

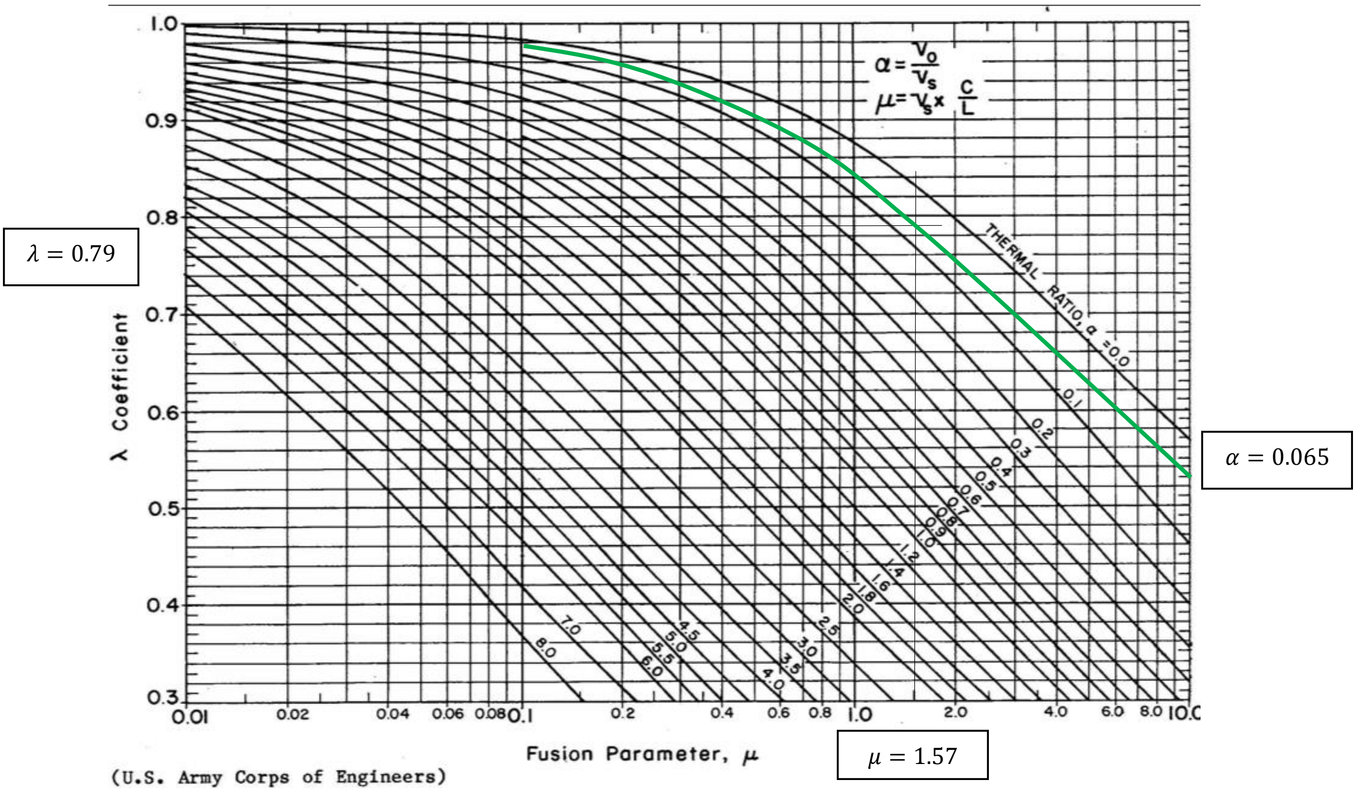
$$L_v = 144 \cdot \gamma_{dry} \cdot \frac{w}{100} \tag{5.7}$$

In areas with seasonal frost, thermal insulation is used to prevent frost from penetrating deep into the structural layers of the road surface, the coefficient μ is calculated from equation (5.8), while the fusion parameter μ is calculated from equation (5.9).

$$\mu = n_f \cdot \frac{FI}{d_f} \cdot \frac{C_v}{L_v} \quad , \tag{5.8}$$

$$\alpha = \frac{|T_{MASST} - 32°F|}{n_f \cdot \frac{FI}{d_f}} \tag{5.9}$$

The values of the parameters μ and α are taken based on the graph (Fig. 2) in order to determine the heat conduction coefficient λ.



$\lambda = 0.79$

$\alpha = 0.065$

$\mu = 1.57$

(U.S. Army Corps of Engineers)

Fig. 2. Graph used to determine the heat conduction coefficient λ [7]

6. DEPTH OF THE FROST AND THAW ZONE

There are many methods and ways of determining the frost depth, based on empirical formulas based on meteorological data, as well as formulas derived from heat conduction equations. This work presents the freezing depth determined using the modified Berggren equation, which uses the average thermal conductivity k_{avg} of the material and the λ coefficient to determine the depth of the frost zone in the area of seasonal frost, expressed on the basis of the works [11, 16], with the following formula:

$$x = \lambda \sqrt{\frac{2k_{avg} n_f FI}{L_v}} \tag{6.1}$$

Equation (6.1) is intended to serve as a first-order approximation of the depth of the active layer per year at specific freeze/thaw rates. If applicable in the construction of a road surface system with thermal insulation, the equivalent value of thermal resistance R of the soil and insulation is used, and equation (6.1) which can be solved for the thickness of the active layer x, denoting the frost zone, takes the following form:

$$n_f FI \cdot \frac{\lambda^2}{L_v} = R_{eq} x + \frac{x^2}{2k_{avg}} \tag{6.2}$$

For road surface design, if the influence of frost on the road structure is to be considered, pertinent parameters for calculations can be derived from the provided chart (Fig. 3). This graph illustrates the correlation between ground frost depth and the FI across different soil moisture levels, specifically focusing on gravel in our context.

Fig. 3. Relationship between the freezing depth and the freezing index for gravel [11]

7. FROST PROTECTION OF ROAD SURFACE STRUCTURES USUNG XPS – CALCULATION EXAMPLE

According to the study [11], several design tools can be used to determine the requirements for the use of thermal insulation in the form of extruded polystyrene (XPS) boards. According to the United States Department of the Army and Air Force (1985), the minimum amount of XPS insulation required to completely prevent frost penetration at various air freeze rates is 4 inches (approximately 10 cm) of bitumen pavement per 21 inches (approximately 53 cm) of base thickness beneath the road surface, with the soil parameters shown in Figure 3. The drawing was developed based on the modified Berggren equation. The actual thickness of insulation required will depend on the properties of the material and climatic conditions.

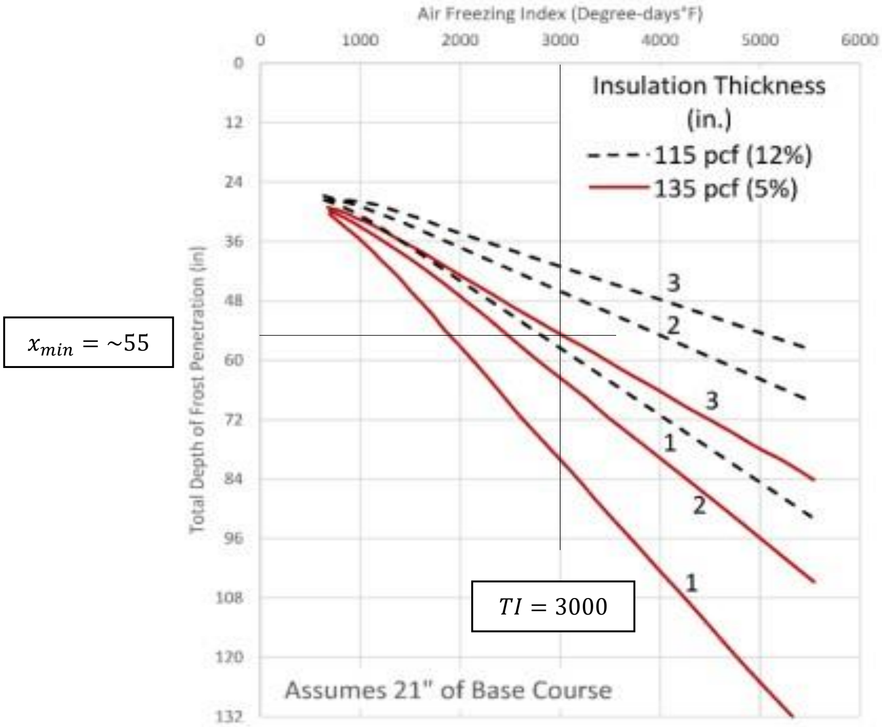


Fig. 4. Minimum insulation thickness related to the freezing index (U.S. Department of the Army) [11]

In actual operating conditions, the thermal conductivity coefficient of the material being utilized must be duly considered.

As per [11], it has been inferred that over approximately 30 years of testing XPS samples employed for frost protection in cold regions, there was a progressive absorption of moisture via water vapour. Over time, this moisture absorption can potentially compromise the thermal insulation properties of the material. Research indicates that a one-inch thick insulation layer of a thermal insulation board may experience a reduction in thermal resistance by around 6% over a decade of use. The provided example elucidates the calculation process for determining the depth of the active layer, denoting the ground frost zone, utilizing the modified Berggren equation, concerning the data delineated in the table:

Table 2. Data for calculations:

Object name	***FI*** $[°F \cdot days]$	***TI*** $[°F \cdot days]$	***Dry unit weight of gravel pcf***	***Humidity gravel%***	***Number of days of freezing*** d_f ***[-]***	n_f ***[-]***	n_t ***[-]***
A section of road on a gravel embankment	*6000*[1]	*3000*[2]	*135.0*[3]	*5.0*	*120*	*0.9*[4]	*2.0*[5]

[1,2,3] adopted on the basis of [11];

[4,5] adopted based on the Table 1.

Table 3. Calculations and results

Parameter	***Pattern used***	***Calculation results***					
		jm					
		$[°F]$	$[\frac{BTU}{ft^{3°}_F}]$	$[\frac{BTU}{ft^3}]$	$[\frac{BTU}{hrft°_F}]$	*[-]*	*[ft]*
T_{MASST}	*(5)*	*33.6*					
C_v	*(10)*		*28.01*				
L_v	*(12)*			*972.0*			
k_u	*Kersten chart, [11]*				*1.7*		
k_f	*Kersten chart, [11]*				*1.6*		
k_{avg}	$\frac{k_u + k_f}{2}$				*1.65*		
μ	*(13)*					*1.57*	
α	*(14)*					*0.065*	
λ	*Reading from Fig. 2*					*0.79*	
x	*(15)*						***16.57***
x_{min}	*Reading from Fig.4*						***4.58***

8. APPLICATION

The calculated average value of the frost zone depth for the assumed conditions is **16.57 ft (approximately 505 cm)**, which indicates a significant depth of the frost zone and results from climatic conditions typical of the Central Canadian region. The calculated depth of the frost zone also indicates that the so-called permafrost.

The approach delineated for identifying the frost zone and associated parameters, coupled with frost protection, could potentially serve as a recommendation for adoption within Polish design practices. Primarily owing to the straightforward methodologies employed during the computations, the phenomenon of ground freezing has been adequately described, promising practical advantages.

9. COMMENTS AND GUIDELINES FOR DESIGN – PROPOSALS

As a result of the cooling of water particles (fog) under the influence of low temperature, we have dealing with icing that may occur on the surfaces of roads and bridges. The work [17] indicates a phenomenon that may also occur in shaded areas and in areas with extreme wind exposure or in areas where the soil properties change suddenly. In this case, the advantage of using insulating material in the form of extruded polystyrene boards in the designed structure of a road embankment is a change in the temperature distribution above the insulation layer, which may result in warmer or colder surfaces of the road element. The increased temperature difference between adjacent insulated and uninsulated layers of road embankments can cause ice to form on one surface rather than the other when exposed to the same environmental conditions. Elimination of the negative effects of icing can be attempted by designing structures in such a way that the optimal location of insulation maximizes thermal benefits, reducing the depth of the frost zone while minimizing the effects of icing. Interesting guidelines for the design and practical use of thermal insulation in the construction of various types of road surfaces are presented in the works [16-19]. It particular they concluded that bituminous pavements are more effective at reducing icing than concrete pavements for pavements less than 7 inches (approximately 18 cm) thick. Increasing the thickness of the substrate material (between the surface and the insulation) will reduce icing by increasing the insulation in this impact zone. It follows that in the frost protection system and the reduction of frost heaving, the arrangement of the thermal insulation material in the structure of the structural layers of the road section has a significant impact on the occurrence of heaving. The closer the thermal insulation to the road surface, the greater the risk of frost heaving and road damage. Hence, during the design process, it is recommended to place the thermal insulation layer in the lower structural layers of the road.

When designing thermal insulation for frost protection of road structures, the method of connecting the thermally insulated road section with the uninsulated section plays a crucial role. In such scenarios, it's essential to consider a gradual reduction in the insulation thickness towards the uninsulated road section. Thermal insulation of the road structure should also be implemented where a road segment intersects with other sections, such as intersections, and along road curves.

The selection and arrangement of insulating materials within the road structure should adhere to specific requirements tailored to each case, considering relevant regulations and standards. Intriguing design approaches for the frost layer employing insulating materials, like extruded polystyrene, are discussed in [20]. The authors suggest that polystyrene can be combined with granular material to create a layer that promotes heat accumulation and prevents deep penetration of frost into the substrate.

Additionally, an important aspect to address in the design process is the consideration of insulating material requirements concerning stresses induced by surface loads from overlying soil or vehicular traffic. Whenever issues important for the proper construction of a road are considered, there is a need to develop unified guidelines for the design and construction of engineering facilities in the communication infrastructure, as the author draws attention to in work [21].

10. SUMMARY

The article delves into issues concerning frost heave, frost protection, and the utilization of extruded polystyrene as insulating material in the design and construction of road structures. By leveraging the parameters elucidated in the study and the data characterizing the subgrade and road structural elements, the depth of the ground frost zone has been determined. The resultant calculation outcome signifies the actual depth of ground frost in the given conditions and underscores the feasibility of employing the presented approach in designing road surface structures.

A notable advantage of this method lies in its universal applicability across various regions and climatic zones, owing to its consideration of specific environmental conditions. The inclusion of climate indices, such as average daily temperatures recorded across different seasons and regions, as well as factors like soil conductivity and thermal volume, enhances the accuracy of frost zone calculations. By integrating such detailed data, the method facilitates the generation of reliable calculation results, serving as a robust foundation for accurately delineating the depth of the ground frost zone.

Furthermore, this algorithm supplements the current design procedures, particularly in regions like Poland where frost protection measures are limited. The prevailing approach assumes ground freezing and potential frost formation, with frost lining being mitigated partially by the weight of pavement construction layers. However, the utilization of construction techniques incorporating thermal insulation materials like extruded polystyrene offers a more effective means of frost protection. This is especially pertinent given the high compressive strength of extruded polystyrene, as evidenced by tests described in [22], which ensures favourable distribution of traffic and structural loads on the ground.

REFERENCES:

1. Rafalski, L, Wilczek, J and Kraszewski, C 2014. Ochrona przeciwmrozowa nawierzchni drogowych na przykładzie wybranych krajów. *Drogownictwo*, **2**, 39-45.
2. Øiseth, E, Aabøe and Hoff, R 2012. Field test comparing frost insulation materials in road construction, Current Practices in Cold Regions Engineering, 1-10. https://doi.org/10.1061/40836(210)62
3. Ickiewicz, I 2009. Analiza zjawiska wysadziny zmarzlinowej dla celów inżynierskich, *Czasopismo Techniczne, Budownictwo, Wydawnictwo Politechniki Krakowskiej*, Zeszyt **5**, Issue **5**, 63-70.
4. Dettenborn, T, Hartikainen A, Koivisto, K, Nykänen, H and Ylönen, S 2021. *Frost monitoring of the Finnish road network*, 18th Nordic Geotechnical Meeting, OP Conf. Series: Earth and Environmental Science **710** (2021) 012045, 1-9. https://iopscience.iop.org/article/10.1088/1755-1315/710/1/012045/pdf
5. Vaitkus, A, Gražulyte, J, Skrodenis, E and Kravcovas, I 2016. Design of Frost Resistant Pavement Structure Based on Road Weather Stations (RWSs) Data, *Sustainable Engineering and Science,* **8**, 1328, 1-13. https://www.mdpi.com/2071-1050/8/12/1328#
6. Kuznetsova, E, Hoff, I and Danielsen, SW 2016. FROST – Frost Protection of Roads and Railways, *Mineralproduksjon*, **7**, 1-8. http://mineralproduksjon.no/wp-content/uploads/2017/03/MP7-FN-Kuznetsova-et-al.-PRINT.pdf
7. Roustaei, M and Thomson, MH 2023. Frost Action in Canadian Railways: A Review of Assessment and Treatment Methods, *Journal of Cold Regions Engineering*, Volume **37**, Issue 4. https://doi.org/10.1061/JCRGEI.CRENG-668
8. Galkin, A and Pankov, V, Yu 2022. Thermal protection of roads in the permafrost zone. J *Appl Eng Sci* **20** (2), 395–399. https://doi.org/10.5937/jaes0-34379
9. Amin, S and Heweidak, M 2022. Chapter 20 in *Phenolic Foams: The Insulating Materials to Reduce the Frost Penetration*, Skidding, and Flooding Risk of Road and Airfield Pavements, Singapore, Springer, 359–369.
10. Gandhal, R 1988. Polystyrene Foam as a Frost Protection Measure on National Roads ín Sweden, Swedish Road and Trafûc Research Institute, 5-581 01 Linköping Sweden, *Transportation Research Board*, **1146**, 1-9.
11. Owens Corning Foam Insulation 2019. *LLC Roadways & Airfields English Units Geotechnical Design and Instal Guide*, United States of America, 1-24.
12. Nicholson, PG 2015. *Soil improvement and ground modification methods,* Coursebook, UK, Oxford: Elsevier, 441. https://www.afzir.com/knowledge/wp-content/uploads/2018/07/Soil-improvement-and-ground-modification-methods.pdf
13. Moghaddas Tafreshi, SN, Amin Ghotbi Siabil , SM and Dawson, AR 2020. Expanded polystyrene geofoam, *New Materials in Civil Engineering*, Book, 117-153. https://doi.org/10.1016/B978-0-12-818961-0.00004-1
14. Gontaszewska, A 2010. *Własności termofizyczne gruntów w aspekcie przemarzania*, Podręcznik, Oficyna Wydawnicza Uniwersytetu Zielonogórskiego.
15. Juszczyk, A and Wysokowski, A 2016. Stalowe ruszty jako innowacyjne nawierzchnie dróg tymczasowych, *Budownictwo i Architektura* **15**(1), 105-114.
16. Andersland, OB and Ladanyi, B 2004. *Frozen Ground Engineering - 2nd Edition*. New Jersey: John Wiley & Sons, Inc., Hoboken, New Jersey, Coursebook, 384.

17. Kersten, MS 1949. Laboratory Research for the Determination of the Thermal Properties of Soils. *ACFEL Technical Report*, **23**, AD71256.
18. Arellano, D 2007. Consideration of Differential Icing Conditions in the Design of Road structure Systems Overlying Geofoam Lightweight Fills. *Transportation Research Record*, **07-1103**,1-19. https://www.researchgate.net/publication/242552898_CONSIDERATION_OF_DIFFERENTIAL_ICING_CONDITIONS_IN_THE_DESIGN_OF_PAVEMENT_SYSTEMS_OVERLYING_GEOFOAM_LIGHTWEIGHT_FILLS
19. Quentin, FA, Segui, P, Côté, J, Bilodeau, JP and Doré, G 2024. Thermal insulation of flexible pavements utilizing foam glass aggregates to mitigate frost action in cold regions — Development of design tools, *Construction and Building Materials*, **414** (2024) 134841, -13. https://doi.org/10.1016/j.conbuildmat.2023.134841
20. Grimstad, G, Amiri, S, A,G, Hoff, I and Watn, A 2018. Frost protection in roads using insulation materials, *AIC Transportation Engineering Infrastructure in Cold Regions*, 43-44. https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2676886/Mine.pdf?sequence=2
21. Wysokowski, A and Howis, J 2018. Propozycja wytycznych dotyczących projektowania i budowy obiektów inżynierskich w technologiach bezwykopowych w infrastrukturze komunikacyjnej, *Materiały Budowlane*, nr **11**, 63-65. http://dx.doi.org/10.15199/33.2018.11.17
22. Han, L, Wei, H, Zhang, Y, Zhang, J and Wang, F 2020. Study on Cold Resistance Performance of Composite Subgrade Structure in Seasonal Frozen Regions, *MDPI, Applied Sciences*, **10** (13), 4681. https://doi.org/10.3390/app10134681