

Thermal insulation in pavement as a means of preserving or restoration the historical vertical layout of city streets

A M Simanovskii

Saint Petersburg State University of Architecture and Civil Engineering, 4, Vtoraya Krasnoarmeiskaya str., Saint Petersburg, 190005, Russia

E-mail: alemsi1203@yandex.ru

Abstract. The article is devoted to the problem of street reconstruction in areas with historically valuable buildings using the example of St. Petersburg. Saving the appearance of architectural monuments and street surface elevation points without reconstruction of underground utilities requires a reduction in the thickness of the road pavement. The solution to this contradiction is the use of insulating materials in pavement. The work is devoted to the theoretical study of road structures using thermal insulation made of polystyrene foam. Comparative thermotechnical calculations for traditional structures and structures with thermal insulation on various heaving soils have been performed. It is demonstrated that the use of traditional structures in the reconstruction of road structures leads to an increase in their thickness and frost depth. It is shown that the use of thermal insulation reduces the thickness of the pavement and completely prevents the freezing of soils under it. This allows saving and lowering elevation points of the road surface without reorganizing the underground utilities.

1. Introduction

The work is devoted to a comparative study of the frost depths of traditional pavements and structures with effective thermal insulation. The relevance of the work is determined by the complexity of the reconstruction of road structures in cities with historically valuable buildings. Such cities, as well as St. Petersburg which is taken as an example, for hundreds of years have been changing the coverage on the streets in accordance with changing traffic conditions, the environment, developing building technologies and new pavement materials. Reconstruction of pavements was carried out by a simple and cheap method: by layering new structural layers on old worn ones [1], [2]. Thus, there was an increase in the vertical elevations of the carriageway and sidewalks. Based on these elevations, underground utilities were built under the road, deepened under the level of soil freezing.

Modern approaches to the protection of historical and cultural monuments require that these monuments are open and look as intended by architects. The street facades should be also open. From the point of view of reconstructing the historical appearance of architectural buildings, as well as protecting their structures from moisture from the street pavement, the public and authorities quite reasonably require the preservation or lowering of elevation points of street surface. In addition, the specified characteristic load for the pavements has been recently increased [3], which leads to an increase in the thickness of pavements. These circumstances lead to the fact that street reconstruction using traditional materials lowers the frost level under which services are located. This implies the need for their reorganization, which requires significant resources and significantly increases the time



of work on the street.

Under these conditions, the use of effective thermal insulation in the form of various foams [4-6]) can give a significant economic, environmental and social effect.

2. The study of temperature fields and frost depths

This article presents the results of a comparative study of the frost depths of traditional structures without thermal insulation and their corresponding structures with thermal insulation, and also examines the effect of an increase in the thickness of pavement on the frost depth due to new specified characteristic loads. For the study, traditional structures without thermal insulation were taken in the most heave susceptible type of soil according to the nature of moisture, common in St. Petersburg. Structures for five main groups of heaving soils are analyzed: silty fine sand (group 1), silty clay (group 2), lean clay (group 3), silty loam (group 4), clay (group 5).

The conditions for four categories of city roads are examined: main streets (citywide and district significance); local streets and parking lots. The standard, operating in St. Petersburg, structures without thermal insulation were adopted for the respective categories of streets. The thermophysical characteristics of materials, thermal insulation, and soil were borrowed from regulatory (ODN 218.046-01 Industrial Road Standards), and were also taken according to manufacturers [7]. The characteristics adopted in the calculations are given in Table 1 and 2.

Table 1. Thermotechnical characteristics of PENOPLEX boards

Name of characteristic	Unit	Value
Heat conductivity coefficient at $(25 \pm 5) ^\circ\text{C}$	W/(m·K)	0.030
Estimated coefficient of thermal conductivity under "B" operating conditions (humidity by weight 3%)	W/(m·K)	0.032
Estimated coefficient of thermal conductivity under "A" operating conditions (humidity by weight 2%)	W/(m·K)	0.031
Specific heat capacity	kJ/(kg·K)	1.53
Density	kg/m ³	38 to 47

Table 2. Estimated thermophysical characteristics of soils

Characteristic	Soil group identification number				
	1	2	3	4	5
The coefficient of thermal conductivity, W/(m·K)					
in the thawed state	1.80	1.80	1.62	1.62	1.62
in the frozen state	1.90	2.03	1.97	1.97	1.97
Specific heat capacity, J/(kg·K)					
in the thawed state	1172	1340	1549	1549	1549
in the frozen state	963	1005	1130	1130	1130
Density, kg/m ³	1750	2100	2000	2000	2000
Freezing point °C	-0.1	-0.2	-0.3	-0.3	-0.4
Humidity, decimal quantity	0.13	0.17	0.24	0.31	0.33

Both traditional and proposed structures with thermal insulation were characterized as follows.

Two-layer surfacing; wearing course – dense fine-grained asphalt concrete; the basecourse is dense or porous coarse-grained asphalt concrete.

Base: upper roadbase – porous asphalt concrete or black crushed stone; the lower roadbase is crushed stone-sand mixture or crushed stone.

Sands (fine or medium) are used in an subbase.

Effective thermal insulation in pavements is represented by plates of extruded polystyrene foam with a thickness of 5 cm. The structures are provided with protective layer of sand above the heat-insulating plates, as well as a mounting layer of sand under them.

The proposed structures (with thermal insulation) for comparison and replacement of traditional ones were accepted with the same surfacing and base as the structures without thermal insulation for the corresponding category. Part of the subbase layer was replaced with a protective layer of sand above the thermal insulation, the thickness of which in the study varied from 20 cm to 40 cm.

The schematic diagrams of the structures are given in Tables 3 and 4. The denominator in the tables indicates the total thickness of the pavement structures. All thicknesses are given in cm.

Table 3. Thicknesses of layers of traditional structures without thermal insulation, cm

Layers	Main streets		Local streets, type C-1	Parking places, type AC
	citywide significance, type A-3	district significance, type B-3		
Asphalt concrete, fine-grained, dense type B m. I	5	5	4	4
Coarse-grained porous asphalt concrete m.1	9	8	8	6
Coarse-grained porous asphalt concrete m.1	10	8	-	-
Granite crushed stone	26	24	22	20
Fine sand on the soil of group:				
1	50 / 100	50 / 95	55 / 89	40 / 70
2	40 / 90	40 / 85	45 / 79	35 / 65
3	65 / 115	70 / 115	75 / 109	45 / 75
4	70 / 120	75 / 120	80 / 114	70 / 100
5	64 / 115	70 / 115	75 / 109	45 / 75

Table 4. Structures with thermal insulation for all groups of soil

Layers	Layer thickness options for all soil groups, cm							
	Main streets				Local streets, type C-1		Parking places, type AC	
	citywide significance, type A-3		district significance, type B-3					
Asphalt concrete, fine-grained, dense type B m. I	5		5		4		4	
Coarse-grained porous asphalt concrete m.1	9		8		8		6	
Coarse-grained porous asphalt concrete m.1	10		8		-		-	
Granite crushed stone	26		24		22		20	
Fine sand	20	25	20	25	20	25	20	25
Insulation plate					5			
Mounting layer of fine sand					10			
Total thickness of pavement	85	90	80	85	69	74	65	70

A large number of studies [8], [9] are devoted to questions of freezing soils and roads. Nevertheless, the determination of temperatures in the road structures remains an urgent task, especially in the case of asphalt concrete pavements, due to a significant increase in the standard intermaintenance periods and the establishment of new requirements for the bitumen used [10], [11], [12].

Theoretical studies of temperature fields and frost depths were carried out on the model of the unsteady axisymmetric problem of the theory of heat conduction for a layered half-space. For the numerical solution of problems of this kind, the finite element method is currently used [13], [14], [15]. In this work, we also performed calculations by this method according to our program. The specific feature of the algorithm was to take into account the phenomenon of soil freezing and the corresponding heat release during a phase transition, not simultaneously, but in the temperature spectrum determined by the content of unfrozen water in the soil at different temperatures [16].

Boundary conditions:

- there are calculated temperatures on the surface that vary in a sinusoidal manner during the year:

$$T(t, z = 0) = \sin[f(t)] \quad (1)$$

- at the level of zero annual amplitudes $z = H_0$:

$$T(t, z = H_0) = T_0 \quad (2)$$

Initial condition: constant temperature in depth, equal to the temperature T_0 at the level of zero amplitudes.

Entering the quasistationary regime in 10 years.

3. Research results

The increase in specified characteristic loads in the calculation of pavement leads to an increase in their thickness. Table 5 demonstrates the dependence of the frost depth on the thickness of the pavement without thermal insulation (D-1). The corresponding structure with thermal insulation (T-D-1) is also shown there. Table 5 shows that an increase in the thickness of pavement leads to an increase in the frost depth of the structure.

Table 5. The frost depth of structures depending on the thickness of the pavement

	T-D-1			D-1			
Medium sand h , cm:	20	35	40	50	60	70	80
Total thickness of pavement, cm:	85	85	90	100	110	120	130
Maximum frost depth, cm							
Sandy silt	74.5	161	163	166	169	173	176
Sandy loam	74	137	140	144	150	155	157
Light loam	74	126	129	136	142	147	154
Silty hard loam	73.5	120	124	130	137	142	151
Clay	73.5	123	126	131	138	147	153

Thus, the preservation of elevation points when replacing old pavements with new ones leads to a decrease in the level of freezing into the area of underground utilities, which requires their expensive reconstruction.

The example of loam and clay from Table 5 shows that when the thickness of the pavement is 85 cm, the frost depth is 120-126 cm. With an increase in the thickness of the pavement to 120-130 cm, i.e. the entire depth of freezing, it is not possible to prevent freezing of soils under the pavement: the total frost depth exceeds the initial value by about 30 cm. The same trend is observed in other heaving soils.

Table 6-8 show the maximum frost depths obtained by us for traditional structures and corresponding structures with thermal insulation.

Table 6. The maximum freezing depth of structures of main streets of urban significance Z_p , cm

Soil, # of subtype		T-A-3 (with thermal insulation)		A-3 (without thermal insulation)		
		Thickness of pavement, cm	Z_p	# of pavement subtype	Thickness of pavement, cm	Z_p
Silty fine sand	1	85/90	74.5/79.5	7	100	161
Silty clay	2	85/90	73.5/79	4	90	135
Lean clay	3	85/90	74/79	10	115	140
Silty loam	4	85/90	74/79	13	120	141
Clay	5	85/90	74/79	10	115	140

Table 7. The maximum freezing depth of structures of main streets of regional significance Z_p , cm

Soil, # of subtype		T-B-3 (with thermal insulation)		B-3 (without thermal insulation)		
		Thickness of pavement, cm	Z_p	# of pavement subtype	Thickness of pavement, cm	Z_p
Silty fine sand	1	80/85	69.5/74.5	7	95	160
Silty clay	2	80/85	69/74	4	85	134
Lean clay	3	80/85	69/74	10	115	141
Silty loam	4	80/85	69/74	13	120	142
Clay	5	80/85	69/74	10	115	140

Table 8. The maximum freezing depth of structures of streets of local significance Z_p , cm

Soil, # of subtype		T-C-1 (with thermal insulation)		C (without thermal insulation)		
		Thickness of pavement, cm	Z_p	# of pavement subtype	Thickness of pavement, cm	Z_p
Silty fine sand	1	69/74	58.5/63.5	7	89	166
Silty clay	2	69/74	58/63	4	79	140
Lean clay	3	69/74	58/63	10	109	151
Silty loam	4	69/74	58/63	13	114	150
Clay	5	69/74	58/63	10	109	147

As it can be seen from Tables 6-8, the frost depth of all traditional structures is greater than the thickness of the pavement. At the same time, the structures on sandy soil freeze deeper. Note that this type of soil is used, as a rule, when backfilling trenches when laying underground utilities. The freezing border of structures with thermal insulation does not go beyond the limits of thermal insulation. Soils under pavement remain thawed. Thus, when reconstructing pavement using thermal insulation, there is no risk of freezing for underground utilities. Consequently, there is no need for their reorganization. The difference in the frost depths of traditional road pavement and pavement with thermal insulation, presented in Tables 6-8, allows not only saving vertical elevations of street coverage, but also lowering them. Such a decrease can reach several tens of centimeters, depending on the type of soil.

4. Conclusion

Conclusions from the results of studies of structures without thermal insulation:

1. With an increase in the thickness of the pavement, for example, due to an increase in specified characteristic loads, the total frost depth of the road structure increases.
2. Replacement of the layer of freezing heaving soil under the pavement by increasing the thickness of the latter does not eliminate the freezing of the soil under the pavement.

Conclusions from the results of studies of structures with thermal insulation:

1. For the same thickness of pavement with effective thermal insulation, freezing practically does not depend on the type of soil.
2. Effective thermal insulation from polystyrene foam plates increases the frost resistance of the pavement, which allows reducing its thickness due to the frost protection layer.
3. Using the example of St. Petersburg, it is shown that the use of thermal insulation made of polystyrene foam allows completely eliminating the freezing of soils under pavement with a significant decrease in the thickness of the latter.
4. The use of structures with thermal insulation during street reconstruction can not only preserve, but also lower the vertical elevations of the carriageway and sidewalks by several tens of centimeters.

In conclusion, we should note that the current trend of increasing pavement thickness due to increased calculated loads and calculation methods, presented, for example, in the standard PNST 265-2018 of the Russian Federation, leads to an increase in the frost depth of structures on heaving soils. Meanwhile, the methodology for calculating structures for frost resistance in this standard is the same. Our study shows the need to revise this technique.

References

- [1] McShane C 1979 Transforming the Use of Urban Space: A Look at the Revolution in Street Pavements, 1880-1924 *J. of Urban History* **V** 279
- [2] Williams R B 2016 Neglected Heritage Beneath Our Feet: Documenting Historic Street and Sidewalk Pavement Across America, available at: tclf.org/neglected-heritage-beneath-our-feet-documenting-historic-street-and-sidewalk-pavement-across-america
- [3] Broun S F 1998 Developments in pavement structural design and maintenance *Proc. of the Institution of Civil Engineers Transport* **129** 201-206
- [4] Ruvinsky V I 2000 *Guidebook to Design of Heat-Insulating Layers of Styrofoam Foam on Automobile Roads of Russia* (Moscow: Transport)
- [5] Horvath J S 1999 *Lessons Learned from Failures Involving Geofom in Roads and Embankments*, Manhattan College Research Report No. **CE/GE-99-1** (New York: Manhattan College)
- [6] Ivanov D V, Andrianov K A and Yartsev V P 2010 Evaluation of the thermophysical properties of extruded polystyrene foam used in road construction *Abstr. of the Int. Scientific and Technical Conf. Modern Methods and Means of Research on the Thermophysical Properties of Substances* (St. Petersburg: SPbSUR&FE)
- [7] Roads For professionals PENOPLEX official site: effective thermal insulation, available at: <https://www.penoplex.ru>
- [8] Chisholm R A and Phang W A 1983 Measurement and Prediction of Frost Penetration in 26 Highway In Transportation Research Record: *Journal of Transportation Research Board*, **27 918 28** 1-10
- [9] Baladi G and Pegah R 2015 *Predictive modeling of freezing and thawing of frost-susceptible soils, Final Report RC-1619*, Michigan Department of Transportation, Office of Research Administration, Michigan State University, Department of Civil & Environmental Engineering, available at: www.michigan.gov/documents/mdot/RC1619_500351_7.pdf
- [10] Kiryukhin G N 2013 Temperature conditions of operation of asphalt concrete coatings of automobile roads *J. Roads and bridges* **2 (30)** 309-328

- [11] Read J M and Collop A C 1997 Practical fatigue characterisation of bituminous paving mixtures *Proc. of the Association of Asphalt Paving Technologists* **66** 74-108
- [12] Chapin J, Kjartanson B H and Pernia J 2012 Comparison of two methods for applying 30 spring load restrictions on low volume roads *Canadian Journal of Civil Engineering* **31** **39** **6** 599-609
- [13] Segerlind L J 1976 *Applied Finite Element Analysis* (New York, John Wiley and Sons)
- [14] Sakharov I I 2012 The development of an approach to numerically solving a class of problems related to freezing and thawing of base soils *Mat. Scientific and Technical Conf.* (St. Petersburg, SPbGASU)
- [15] Kudryavtsev S A, Sakharov I I and Paramonov V N 2014 *Freezing and Thawing of Soils. Practical Examples and Finite Element Calculations* (St. Petersburg: Georeconstruction)
- [16] Velly J J, Dokuchaev V I and Fedorov N F 1977 *Guide to Construction on Permafrost Soil* (Leningrad: Stroyizdat)