Resistance of Extruded Polyethylene Foam to Temperature and Humidity Effects

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Abstract. The article describes an approach to the optimal design for materials intended for the construction of roads. Insufficient strength and deformability of materials used in road construction, which are affected by frost heaving of soil and frost fractures during operation, temperature drops with repeated transitions through freezing and thawing points of water and other negative processes lead to significant damage of the roadway.

1. Introduction
At present, polystyrene foam plates and blocks are used in road constructions as a temperature barrier between the roadway and heaving soils [1-4]. However, there is a tendency to expand the use of new heat insulation materials, which include products from foamed polyethylene of different density. Non-laminated foam (extruded) polyethylene is most widely used as an insulating and compensating material for protecting foundations of structures, constructions and their elements from environmental influences – the temperature and moisture. Nevertheless, due to the unique properties (low thermal conductivity and water absorption) of the closed-pore structure and the unique mechanical properties [5, 6], polyethylene foam can also be used in road construction, especially in difficult soil and climatic conditions of the Republic of Sakha (Yakutia).

Laying heat-insulating materials in the foundations of motor roads allows stabilizing the temperature of frozen soil and eliminating subsidence of the roadbed and these, therefore, improve the performance properties of road structures [7, 8]. Despite the fact that the present energy-efficient polymeric materials, including those made of polyethylene foam, have no analogues for their heat-shielding properties, there are no studies of their resistance to temperature and humidity effects, the results of which will allow to evaluate their performance and guaranteed service life in road structures.

2. Research methodology
For the studies, samples of extruded polyethylene foams of Ethafoam-220 (32 kg/m³ density) and Arctic-R- plank™ HD (density is 37 kg/m³) grades were selected to determine the physical and mechanical properties, including low-temperature; Arctic-R- plank™ HD (65 kg/m³ density) and Arctic-R- plank™ UHD (density is 100 kg/m³) grades were chosen to determine changes in the basic physical and mechanical properties after thermal cycling. Extruded polyethylene foams were provided by ZAO Gemma Graphics (authorized distributor in Russia and the countries of the Customs Union - Sealed Air Corporation) [9].

Compression tests at 10%, 25%, 50% and 70% deformations were performed in the direction, in which the finished product will be in a stressed state during its operation. The samples of polyethylene
foam, which axis was located both in the direction of extrusion and perpendicular to the direction of extrusion, were tested on low-temperature properties.

Samples of polystyrene foam of Technopplex 45-500 grade were also examined to compare the characteristics.

The studies included the assessment of physical and mechanical properties: compressive strength at 10% deformation (GOST EN 826-2011), stress-strain under compression and compressive stress (GOST 26605-93, ISO 3386-1-86), compression set (GOST 29089-91, ISO 1856-80), nominal tensile stress and relative elongation at break (GOST 29088-91 ISO 1798-83), apparent density (GOST 409-77), frost resistance coefficient (GOST 22346-77), water absorption (GOST 15588-2014), thermal conductivity (GOST 7076-99).

The method of thermal cycling of foam samples determines the amount of water absorption and indicators of changes in thermal conductivity and the number of open pores during temperature cycling of samples immersed into an enclosed volume of water. Single research cycle lasts 48 hours and includes the following steps (Fig. 1):

1) Cooling samples in a metal container with water to a temperature of minus 20 °C for 4 hours.
2) Freezing of samples placed in a metal container with water at a temperature of minus 20°C for 20 hours.
3) Defrosting samples placed in a metal container with water to a temperature of 20 °C for 4 hours.
4) Curing of samples placed in a metal container with water at a temperature of 20 °C for 20 hours.

50 cycles of alternate freezing and thawing were accomplished. A visual inspection of the samples was performed after every 10 cycles and the water absorption values were recorded. The thermal conductivity of the water-saturated and dried samples and their open porosity were determined after 50 cycles.

3. Results and discussion

As a result of studies conducted in the temperature range from 20 °C to minus 60 °C, the physical-mechanical properties of extruded non-laminated polyethylene foam of Ethafoam 220 and Nopaplak (Arctic R-plank) grades were determined by standardized methods. It has been established that the obtained temperature dependences of the properties correspond to the known laws [10-15], no abnormal effects have been identified (Tables 1, 2, 3).
Table 1. Compression characteristics of foamed polyethylene of Nopaplank (Arctic R-plank) and Ethafoam - 220 grades.

| Characteristics | Nopaplank (Arctic R-plank) | Ethafoam 220 |
|-----------------|---------------------------|--------------|
| Strength at 10% deformation, kPa, at temperatures °C: | | |
| 20              | 32                        | 45           |
| 0               | 38                        | 58           |
| -20             | 60                        | 82           |
| -40             | 90                        | 118          |
| -60             | 115                       | 142          |
| Compression set, % at temperatures °C: | | |
| 20              | 23,0                      | 30,0         |
| 0               | 7,1                       | 8,9          |
| -20             | 2,8                       | 3,4          |
| -40             | 4,0                       | 3,2          |
| -60             | 5,0                       | 5,6          |
| Resistance to compression (4th cycle), kPa 25/50/70 % compression, at temperatures, °C: | | |
| 20              | 58/117/244                | 80/127/237   |
| 0               | 70/130/258                | 99/149/268   |
| -20             | 88/152/293                | 132/187/321  |
| -40             | 129/189/278               | 198/232/331  |
| -60             | 156/201/299               | 243/252/356  |

However, the strength of polyethylene foam samples of both grades at 10% deformation and compressive strength at 25, 50 and 75% compression increase as the test temperature drops to minus 60°C. The nominal tensile strength of samples depends not only on the test temperature, but also on the direction of the axis of the manufactured sample, and it is higher for samples manufactured along the axis in the extrusion direction and tested at lower temperatures.

Table 2. Elongation characteristics of foamed polyethylene of Nopaplank (Arctic R-plank) and Ethafoam 220 grades.

| Characteristics | Nopaplank (Arctic R-plank) | Ethafoam 220 |
|-----------------|---------------------------|--------------|
| Specific tensile stress, MPa (md/transverse direction) at temperatures, °C: | | |
| 20              | 0,255/0,208               | 0,182/0,173  |
| -20             | 0,340/0,286               | 0,238/0,224  |
| -40             | 0,430/0,348               | 0,321/0,241  |
| -60             | 0,530/0,445               | 0,388/0,315  |
|                 | 0,486/0,301               | 0,399/0,333  |
| Breaking elongation, % (MD/transverse direction) at temperatures, °C: | | |
| 20              | 26/39                     | 27/57        |
| 0               | 22/37                     | 21/49        |
| -20             | 18/24                     | 17/41        |
| -40             | 9/16                      | 8/38         |
| -60             | 4/3                       | 7/24         |
The apparent density of polyethylene foam of Ethafoam 220 and Nopaplank (Arctic R-plank) grades corresponds to the data [9].

Samples of polyethylene foam have low water absorption. It is explained both by the closed cell structure of the materials and the specificity of the chemical structure of the initial non-polar polymer, that is polyethylene with high hydrophobic properties (Table 3) [10, 16].

| Characteristics                        | Nopaplank (Arctic R-plank) | Ethafoam 220 |
|-----------------------------------------|-----------------------------|--------------|
| Apparent density, kg/m³                 | 35                          | 32           |
| Water absorption, % by volume in 24 hours | 0,2                         | 0,5          |
| Frost resistance coefficient for deformation at temperatures, °C: 60% | 1,44                        | 1,40         |
| -40                                      | 1,90                        | 1,90         |
| Frost resistance coefficient for load at temperatures, °C: 20% | 2,52                        | 3,05         |
| -40                                      | 3,45                        | 3,26         |
| Thermal conductivity, W/(m °C)           | 0,057                       | 0,057        |

According to GOST 22346, the frost resistance temperature of the material is considered as extreme when the frost resistance coefficient for the load is about 5. Samples of Ethafoam 220 and Nopaplak (Arctic R-plank) materials have frost resistance coefficients for the load at a temperature of minus 60°C equal to 3.26 and 3.45, respectively. Therefore, it can be concluded that these materials can be used at temperatures below minus 60 °C. Thus, testing the samples of foamed polyethylene of Ethafoam 220 and Nopaplak (Arctic R-plank) grades, including testing at low negative temperatures, showed high hydrophobic and strength properties, as well as high frost resistance at external temperatures down to minus 60 ºС.

However, the stability of the physical-mechanical properties, and, in particular, thermal conductivity, water absorption and strength to a large extent depend on the operational factors that accelerate the natural process of destruction of polyethylene foam [17-19]. Some experts [18, 19] use the frost resistance criterion by analogy with brick and concrete. Thus, [19], when predicting the service life of foam plates, 1-3 cycles of alternating thermal cycling equate to one year of operation of the structure. In this case, dry or moisture-saturated samples are subjected to freezing and further thawing in the water at t = 20 ° C or in a steam-air medium at t = 60 °C and air humidity equal to 97%. Tests based on temperature and humidity cycling do not fully reflect all factors affecting ageing, and the processes of sample thawing in the water at 20 °C and steam-air medium at 60°C do not correspond to the humidity and temperature conditions of road construction. The destruction of the pore structure of the samples, or rather their thin walls, in this case, is more influenced by the drying process at t = 60 °C. The considered freezing-thawing impact criteria do not reflect the processes occurring in thermal insulation materials used in road construction. Therefore, it is rather difficult to characterize the durability of structures by the results of tests on frost resistance of heat insulating materials.

According to the method described above, studies have been held on the variability of water absorption, thermal conductivity and the number of open pores as a result of the destruction of the closed-pore structure of the composite after repeated freezing-thawing in water in an enclosed volume.

The primary water absorption of the foam samples was determined before thermal cycling: 0, 62% is for Arctic-R- plank™ HD samples, 1, 38% is for Arctic-R- plank™ UTD samples, and 0,07% is for Technoplex 45-500 samples. After 5 cycles of thermal cycling, the samples of extruded polystyrene foam Technoplex 45-500 have the lowest water absorption value. However, after 50 cycles of alternate
freezing-thawing, the water absorption of the samples increases up to 20 times and more than 960 times compared to the primary water absorption and this indicates significant destruction of the closed-pore structure of the material.

![Figure 2. Water absorption of samples after thermal cycling.](image)

After 50 cycles of thermal cycling, water absorption of polyethylene foam samples of Arctic-R-plank™ HD and Arctic-R-plank™ UHD grades increases by 3 and 5 times, respectively, relative to water absorption of samples after 5 cycles and up to 50 and 20 times compared to the initial water absorption. At the same time, after 50 cycles of thermal cycling water absorption of extruded polystyrene foam samples is up to 2.5 times higher than water absorption of polyethylene foam samples after similar tests (Fig. 2).

The obtained data on the water absorption of the samples correlate with the results on the number of open pores in the foam samples. Thus, the number of open pores in samples of extruded polyethylene foam grades increases by 1.8 and 1.6 times, respectively, after 50 cycles of thermal cycling, whereas for samples of foamed polystyrene Technoplex 45-500 it increases up to 10 times.

Since the main purpose of the frost-protecting (heat-insulating) layer of foam plastics is to reduce or completely prevent the roadbed from freezing, it is necessary to pay special attention to the thermal-physical properties as determining its role in the design of pavement [20]. In the present paper, the change in the coefficient of thermal conductivity of materials during temperature and humidity effects after 50 cycles of thermal cycling in water-saturated and dry states was tracked.

| №№   | Substance                                | Thermal conductivity, W/mK |
|-------|------------------------------------------|----------------------------|
|       |                                          | Dry | Water-saturated |
| 1     | Arctic-R-plank™ HD primary               | 0,042 | 0,044 |
| 2     | Arctic-R-plank™ HD after 50 cycles of thermal cycling | 0,044 | 0,044 |
| 3     | Arctic-R-plank™ UHD primary              | 0,047 | 0,043 |
| 4     | Arctic-R-plank™ UHD after 50 cycles of thermal cycling | 0,054 | 0,056 |
| 5     | Technoplex 45-500 primary                | 0,036 | 0,037 |
| 6     | Technoplex 45-500 after 50 cycles of thermal cycling | 0,037 | 0,041 |
It has been established that after 50 cycles of thermal cycling of samples, the thermal conductivity of foams of all grades varies slightly (Table 4), besides, regardless of the state of the samples, whether dry or water-saturated.

![Technoplex 45-500](image1)
![Arctic-R-plank™ HD and Arctic-R-plank™ UHD](image2)

**Figure 3.** The appearance of the samples after 50 cycles of freezing and thawing in water in an enclosed volume.

A visual inspection of the samples after 50 cycles of thermal cycling showed high resistance of foams of all grades to alternate freezing and thawing. There are no visible changes in the shape of the samples, the sizes are at the initial level (Fig. 3).

The obtained experimental results and comparative studies of the properties of extruded polyethylene foam and Technoplex 45-500 polystyrene foam, which is widely used in road construction, led to the following conclusions:

1. The basic low-temperature physical-mechanical properties of polyethylene foams of various densities were investigated. A method was proposed for evaluating their resistance to temperature and humidity effects by changes in water absorption, porosity and thermal conductivity of samples of materials when they were destroyed in water in an enclosed volume during thermal cycling.

2. It has been established that the extruded polyethylene foams of the Arctic-R-plank™ HD and Arctic-R-plank™ UHD grades are not inferior, and in some positions are ahead of the expanded polystyrene, which is widely used in road construction. In view of this, they can be used in severe soil and climatic conditions.

3. The use of extruded polyethylene foam with high resistance to temperature and humidity effects in road construction will stabilize the temperature of the frozen soil and eliminate subsidence of the roadbed, hence, it will improve the performance properties of road construction, increase the time between repairs, reduce the cost of their performance and improve the quality of passenger and truck transport.

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