GeoAmericas2020
4th PAN AMERICAN CONFERENCE ON GEOSYNTHETICS
26-29 APRIL 2020 • RIO DE JANEIRO • BRAZIL

Development and application of an engineered drainage geocomposite for the control of the frost heave in road structures in arctic regions

P. Rimoldi, Consultant, Milano, Italy
P. Pezzano, Officine Maccaferri, Bologna, Italy
L. Martino, Maccaferri Gabions CIS**,** Moscow, Russia
M. Scotto, Officine Maccaferri, Bologna, Italy

ABSTRACT
The design of road structures in arctic regions has often to face the problem of cohesive subgrade in areas with high water table. In such areas the temperature in the winter season goes down even to -50°C and, due to saturation of the road embankment by the capillary rise of the ground water, the road structure completely freezes. In the summer season, when the temperature increases, the ice melts and becomes water again, producing high water flow that percolates into the foundation layers, producing the loss of bearing capacity and causing huge settlements and distresses in the road structure. This phenomena could occur in a single winter. The only way to avoid such problems is to prevent the frost heave phenomena. The paper aims to present an innovative drainage geocomposite, purposely engineered to create a capillary break for preventing the rise of groundwater into the road embankment. The capillary break is afforded by a hydrophobic nonwoven geotextile at the bottom face of the geocomposite; while at the top a standard nonwoven geotextile allows the water percolating through the granular layers of the road embankment to reach the draining core of the geocomposite, which has high thickness for both providing the required flow rate to carry all the incoming water and for avoiding that the top and bottom geotextiles get in touch, which would impair the capillary break. The performances of this innovative product has been evaluated through an extensive testing program, results of which are presented. Indications for specifications and installation are provided.

1. INTRODUCTION

The effects of climate and water on roadway design, construction, and performance shall always be considered. In cold regions the frost action beneath the roadway surface is a major concern since it contributes to accelerated pavement damage resulting from freezing and thawing process combined with heavy truck traffic.

Frost heave results from the freezing of water in a fine grained soil above the frost line. Keeping low the degree of saturation of the soil in the zone that is liable to freeze, can significantly reduce the magnitude of frost heave. Water can enter the soil mass above the frost line in two ways, capillary rise from the water table or infiltration downward or laterally under the roadway. Both sources of water can be successfully controlled by the introduction of a capillary break constructed out of drainage stone or a geocomposite. The capillary break if correctly installed will prevent the capillary rise of water and provide drainage for infiltration water above the capillary break to leave the soil mass. An impermeable material located above the water table would also prevent capillary rise but it will not drain the soil and could result in ponding of water or the creation of a perched water table above the frost line or the buildup of a pore pressure under the embankment if the ground water conditions change. Both these circumstances could lead to a loss of function of the road.

Frost heave in frost susceptible soils is perhaps the most common cause of failure in pavements within cold climates. The freezing of the ground and the growth of ice lenses in the soil causes the ground surface to heave. As a result the pavements are lifted, cracked and damaged.

During the Spring thaw the foundation soil is softened as the ice melts thus greatly weakening the structural support for the pavement. Trafficking at this time causes major damage to pavements due to the combination of soft foundation soil, cracked weakened pavements and loading. It is common in such conditions for pavements to require major repairs and even rebuilding on an annual basis.

Maccaferri has developed the geocomposite MacDrain Arctic Blanket (“AB”), which is designed to eliminate or drastically reduce the frost heave, thus preventing the damage to pavements, thanks to:
- capillary break action;
- fast lateral drainage of rainfall and thawing water;

- high resistance to construction damage and to compressive creep due to the overburden load of the road embankment. It is worth to be noted that AB can be purchased and installed at a fraction of the total pavement cost.

2. THE PROCESS OF FROST HEAVE

There are various definitions of frost susceptible soils. In the US, the Corps of Engineers criterion stipulates that there should be no more than 3% of particles smaller than 0.02 mm. To make it more practical to implement, the Corps also recommended a criterion of no more than 2 % of particles passing the #200 sieve (0.075 mm), since it is usually the smallest sieve used in the grain size analysis. It has been discovered than this criterion can be overly conservative in some cases. The use of the 0.075 mm grain size alone as an indicator of frost susceptibility was not found to be justified by others.

In Norway, the grain size criteria for frost susceptibility involve 0.002 mm, 0.02 mm, and 0.2 mm sizes (Knutson, 1993). Soils are categorized into four groups, ranging from T1 (no frost susceptibility) to T4 (high frost susceptibility), as shown in Figure 1. Highly frost-susceptible soils are typically coarse silts with less than 40 % of particles smaller than 0.002 mm, more than 12 % of particles smaller than 0.02 mm and more than 50 % of particles smaller than 0.2 mm.

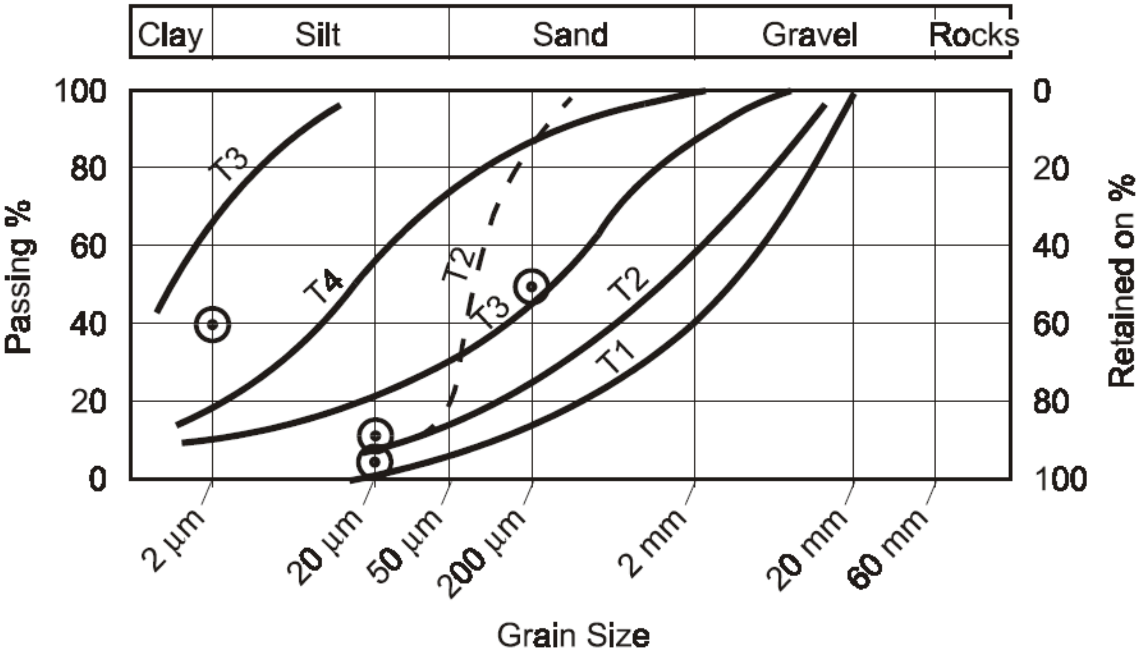

Figure 1. Norwegian frost susceptibility criteria

Frost heave results from the water in fine grained soils, such as silts and clays, expanding when frozen. Frost heave under a roadway leads to loss of function, resulting in high maintenance costs.

Three conditions are necessary for frost heave to occur (Henry & Holtz, 2001):
1. Freezing conditions,
2. Frost susceptible soil,
3. Water supply at the freezing front.

In the absence of any of these conditions frost heave does not take place. Thus, efforts need to be made to mitigate at least one of them in roadway constructions in cold regions.

In regions where frost penetrates a significant depth into the ground, roadways are often constructed on low embankments that provide an added degree of insulation to the soil. Considerable economic savings can be achieved by using locally available material in the construction of these embankments, since in many regions the granular materials, which are not affected by frost heave, are not available at short distance and/or are very expensive. Therefore many embankments are constructed up to the road structure using locally won frost susceptible cohesive materials.

Where frost susceptible soils are used in freezing conditions it is therefore necessary to control the water content of these soils to prevent frost heave. Water can enter the embankment in two ways:

- Capillary rise of ground water above the level of the water table,
- Downward and lateral infiltration of water into or immediately below the road embankment.

Capillary rise above the water table can be controlled in two ways:
1. The introduction of a capillary break, which prevents the upward migration of water but allows downward movement of water towards the water table.
2. The installation of an impermeable barrier, preventing both the upward and downward movement of water in the soil mass.

Capillary breaks have been successfully used to control capillary rise above the water table (Casagrande, 1938, Rengmark, 1963). Traditional capillary breaks were constructed from granular, single sized or gap graded stone laid in a layer up to 0.5 m thick and located above the highest water table level. This type of construction prevents capillary rise and thus reduces the height of the capillary zone and reduces the frost heave. Provided the capillary break is installed at the correct level, below the frost line and above the highest water table, then the magnitude of the frost heave will be considerably reduced.

More recently, capillary drains have been constructed from geocomposites consisting of a geomat core sandwiched between two layers of geotextile. Geocomposites of this type (Fig. 2) have been successfully used as frost heave blankets (Henry and Holtz, 2001). Where the geocomposite is laid with a lateral slope, the geomat core also facilitates lateral drainage, thus preventing water ponding in the soil mass above the geocomposite.

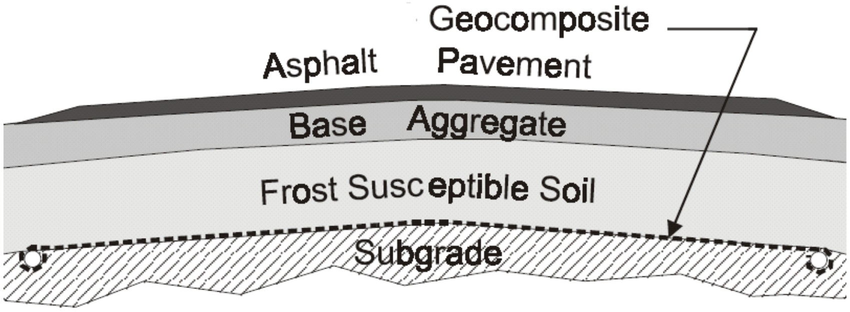

Fig. 2. Geocomposites used as capillary break

According to Henry and Holtz (2001), an alternative to a capillary break is to use an impermeable material above the highest water table. The impermeable material will prevent upward capillary rise, however, it will also prevent downward movement thus causing infiltration water to pond unless a suitable drainage medium is provided above the impermeable layer. Installation of the impermeable material at an inappropriate level in the soil could lead to the generation of an upward pore pressure under the embankment if the water table rose and insufficient drainage was provided under the impermeable material. The downward infiltration is prevented resulting in a possible creation of a perched water table causing an increase in the degree of saturation of the soil mass in the frost zone. Where water ponds above the impermeable material frost heave could result. Water can infiltrate into the soil above the capillary break or impermeable material directly through unpaved roadways or cracks in paved roads. Lateral infiltration can also occur where the hydraulic conditions are favorable. When the water table is confined beneath an impermeable layer or in the case where the water table rises above the impermeable layer, the difference in height between the bottom of the impermeable layer and the free water surface represents an uplift pressure on the impermeable layer. Two possible situations can develop: the uplift pore pressure is such that a blow-in failure occurs, or the upward pore pressure results in upward heave (in the absence of frost) of the embankment.

The pore pressure under the impermeable layer significantly increases the hydraulic gradient across the impermeable layer, thus increasing the likelihood of flow channels developing locally through the impermeable layer. Flow channels are most likely to develop in poorly constructed impermeable layers.

The upward pore pressure resulting in heave can be overcome by placing sufficient weight of material over the impermeable layer, such that there is a resultant down force on the impermeable layer. Where the resultant vertical force is upwards heave will occur. The height of embankment required to prevent heave can be determined from equilibrium calculations of the vertical forces at the level of the impermeable layer.
In order to reduce the hydraulic gradient across the impermeable layer a drainage medium is required under the full width of the impermeable layer. Alternatively, the thickness of the impermeable layer can be increased and with regular quality control testing and inspection the likelihood of localized flow channel development can be significantly reduced.

Henry & Holtz (2001) have shown, for a fine grained soil located in the frost zone with a degree of saturation above 71 %, that the benefit of a capillary break or impermeable material is removed and frost heave will result.
It is therefore essential that the degree of saturation of the soil above the capillary break is kept low by the inclusion of a suitable drainage system, which allows water to move naturally towards the water table or the drainage layer.

Geocomposite capillary breaks such as the AB, tested in accordance with GOST 28622-2012 test standard, have been shown to reduce frost heave almost to zero. GOST 28622-2012 is designed to measure the frost heave in a fine grain soil resulting from capillary rise of water into the soil.

Frost heave results from the following mechanisms: ground water in frost susceptible soils is drawn up into the soil above by capillary action. This soil in the capillary zone is typically unsaturated. As shown in Fig. 3, when the moisture in the capillary zone freeze, water becomes solid ice, the capillary forces are no longer in balance and more water is drawn up from the water table. In this way the process of capillary rise and freezing of ground water becomes continuous throughout the freeze period.

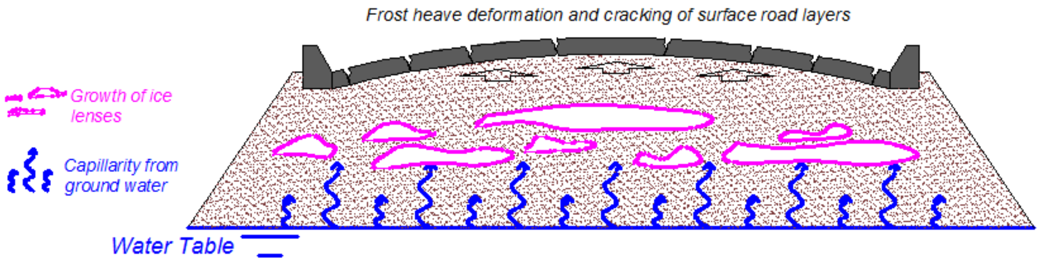

Figure 3. The process of frost heave from raise of capillary water

The amount of water held in a frozen condition in the capillary zone can be many times more than the non-frozen saturation level for the soil. Thus the ground is caused to heave. The amount of heave is dependent upon the nature of the soil and the duration of the freeze period.

Soils most prone to heave are those containing a significant proportion of silt and fine sand sized particles. The pore sizes in such soils are small enough for capillary forces to be strong and yet large enough to allow significant upward flow of water to feed ice growth.

This frost heave can lift the road pavement and thus causes some initial cracking and damage (Fig. 3). The major structural damage to the pavement often occurs during the following Spring thaw. As the air temperature rises above freezing, the ground begins to thaw from the surface downwards releasing the melt water into the soil. This water cannot readily drain back down to the water table because the ground below remains frozen for a time. The water content of the thawed soil with the melt water can be many times the saturation capacity of the soil and therefore causes it to be extremely soft, or even to become a slurry with virtually no strength. The road pavement has therefore very little foundation support. Trafficking of the already cracked and weakened pavement at this time causes severe damage to the pavement (Fig. 4).

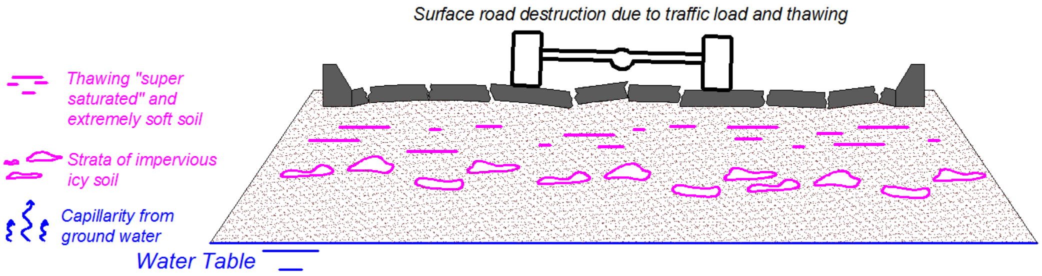

Figure 4. Deterioration of pavement during thaw

3. THE ARCTIC BLANKET

The AB prevents frost heave by acting as a capillary break above the water table and by providing fast lateral drainage of rainfall and thawing water.

The AB (Fig. 5) comprises 3 layers, each with a specific function:

- The top layer is a nonwoven geotextile, which acts as a filter allowing water percolating from the soil above to enter the drainage core.
- The central layer is a drainage core, made up by a geomat with W shaped profile which affords high resistance to compressive loads (thus minimizing compressive creep) and high flow rate, which allows water entering from top and bottom to drain away laterally to side drains.
- The bottom layer is a special nonwoven geotextile with hydrophobic polymer enhancement designed to repel water thereby resisting the capillary rise of ground water from beneath.

With the AB the capillary raise is totally stopped by the empty thickness of the drainage core: in fact the surface tension of water is not strong enough to overpass a void of 9 - 10 mm (Fig. 6). Moreover the bottom surface of the nonwoven geotextile is hydrophobic, and it requires a minimum water head of 100 mm to allow water to pass through; since the capillary action can never produce such water head, the capillary water is prevented from entering the drainage core.
Hence the hydrophobic geotextile resists upward flow of water, while it remains permeable to downward flow. The overall effect of this geotextile is therefore like a one way valve.

Figure 5. Picture showing the structure of AB

The hydrophobic geotextile placed at the bottom is fundamental for preventing the drainage core to be clogged by ice due to capillary raise during Winter: in fact if capillary water would enter the drainage core during Winter, the water would freeze and the full thickness of the drainage core would become full of ice; then ice would connect the top and bottom geotextiles, the void space would be suppressed and the capillary raise would continue upward thus producing ice lenses in the embankment.

The possibility for the top and bottom geotextiles to come in contact is also prevented by the high relative thickness (9 – 10 mm) of the AB core, while a geocomposite with a low thickness core (4 – 5 mm) would not prevent the top and bottom geotextiles to get in touch, which would impair the capillary break.

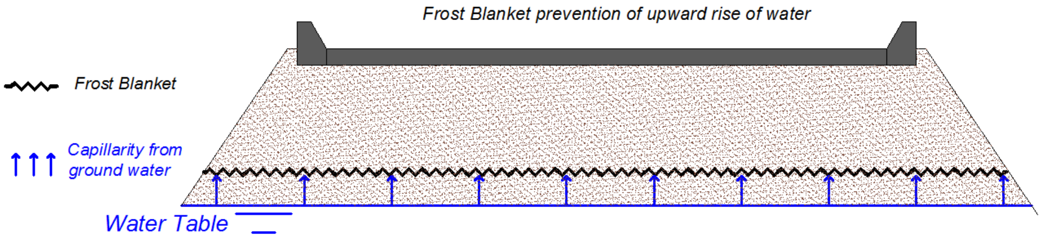

Figure 6. Function of AB

During non-freezing conditions the bottom geotextile acts as a filter allowing the free movement of water essential for effective drainage: if the central drainage layer becomes ineffective for any reason (e.g. poor construction with inadequate lateral slope) then the water will be still be able to drain downwards.

A very important feature of the AB is that the geotextiles are composed of Polypropylene, which has lower affinity for water than polyethylene, and much lower affinity for water when compared to polyester, which is hydrophilic: in fact, if a geotextile has a lower affinity for water than the soil particles, its ability to act as capillary break is highly enhanced (Henry, 1990).

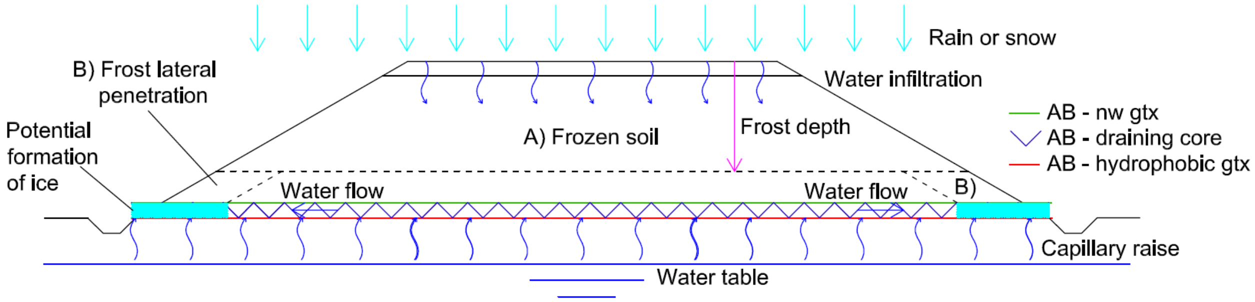

Figure 7. Potential conditions of the embankment in the freezing period

With reference to Fig. 7, if layer A) is saturated or partially saturated, in winter it will freeze and all the water inside will become ice, thus increasing its volume of approx. 9 %. If the frozen soil is not able to accommodate the 9 % volume increase, the all layer A) will heave.

Even the lateral zones B) will freeze, hence the water flow carried by the AB can freeze as well, thus impairing the outlet of further drained water. But the water above the AB is frozen (even in the B) zones), hence in winter the water can enter the AB only from below, due to capillary raise from the water table. But the bottom geotextile of the AB is hydrophobic, hence it prevents the capillary raise to enter into the draining core. In this way the AB prevents both the formation of ice lenses due to capillary raise and the formation of ice in the draining core at the outlets during winter.

When the thaw period starts, thawing will proceed from top to bottom and from lateral surfaces towards inside: hence the AB will start to collect the thawing water below the B) zones, and progressively will collect water from all the top surface while thawing progresses. In this way the thawing water is immediately removed from the embankment body, thus preventing the formation of ponding water and the over-saturation of soil.

It is evident that, due to rational behind the engineering of the AB, the geocomposite must be placed with the hydrophobic geotextile at the bottom; while placing it upside down would totally impair the functionally of the product.

4. INDEPENDENT TESTING OF THE AB

The AB was tested under controlled laboratory conditions by Petromodelling Lab, Moscow, Russia, using the Frost Heave test according to GOST 28622-2012 standard. Note that the same test can be performed also according to ASTM D5918: 2013 or BS 812-124:2009.

The test apparatus (Fig. 8) exposes test specimens to a surface air temperature of -4ºC. The lower end of the samples are allowed access to water maintained at +2ºC. Capillary rise of the water in the frost susceptible test soil causes water to be drawn up into the freezing zone. Ice lenses form within the samples which lead to an increase in height of the specimens, which is measured at intervals over a period of 96 hours. The maximum recorded increase in height is defined as the frost heave of the sample.

The test on the AB was carried out using two frost susceptible soils, known to give a large frost heave. The soil-grading curves are shown in Fig. 9.

The AB has been placed in two positions inside the testing cell, at 50 mm and 100 mm from the top respectively. Test have been performed both with optimum humidity for compaction and with higher humidity.

Results from test certificates are reported in Tables 1 and 2. The specimens after testing are shown in Fig. 10.

From the test results it can be concluded that the AB suppressed the frost heave almost entirely. Anyway the height of frost heave in Tab. 2, with higher moisture content than optimum, is higher than in Tab. 1, with moisture content than optimum, both without AB and with AB: this result show the importance of the proper installation procedure, where the moisture content should always be controlled to be at optimum or close to optimum on the dry side.

Results also show that placing the AB at 100 mm from the top (that is closer to the capillary raise source) is more effective in reducing the frost heave.

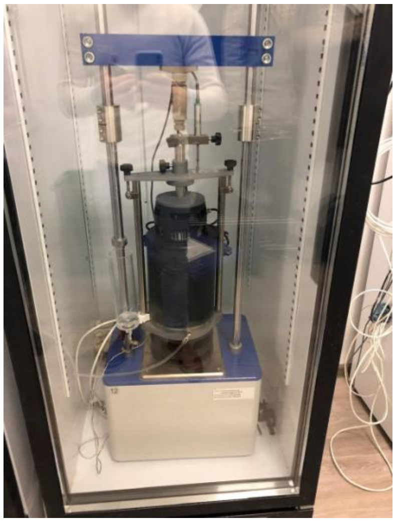

Fig. 8. Test apparatus according to GOST 28622-2012 standard

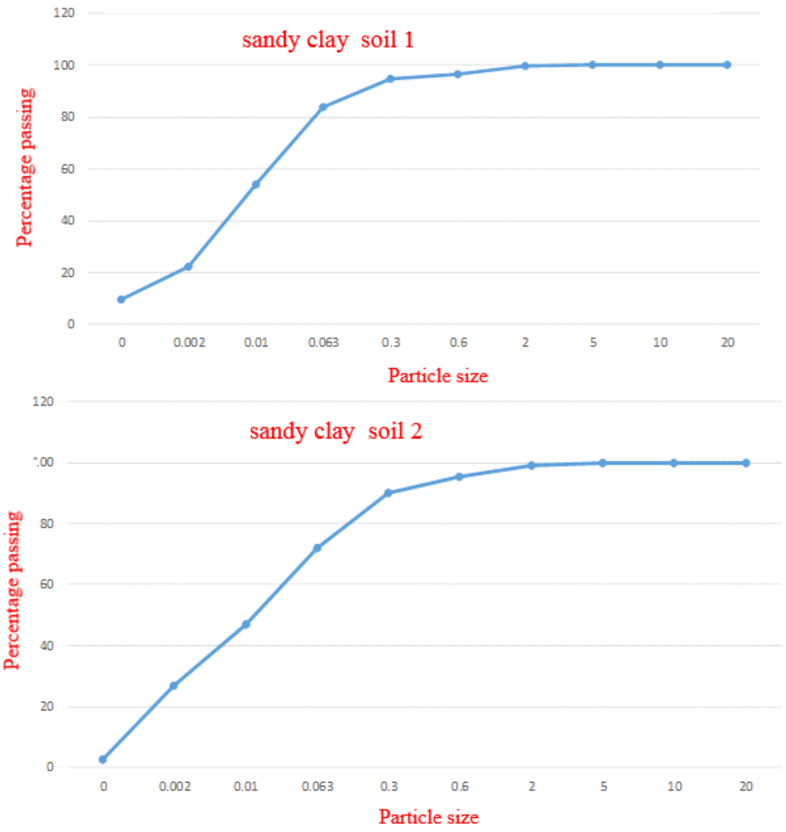

Figure 9. Particle distribution curve for frost susceptible soils used in testing

Table 1. Results of tests with soil at optimum moisture

Frost heave deformation after 96 hours	Without AB (mm)	With AB (at 100 mm), (mm)	With AB (at 50 mm), (mm)
№ 1 Firm loam	7,38	0,23	1,74
№ 2 Soft loam	7,42	0,31	-

Table 2. Results of tests with soil at moisture > optimum

Frost heave deformation after 96 hours	Soil Density (kN/m^3)	Soil moisture W, (%)	Without AB, (mm)	With AB (at 100 mm), (mm)
№ 1 Firm loam	15,8	25,9	9,47	2,12
№ 2 Soft loam	17,1	23,1	8,54	-

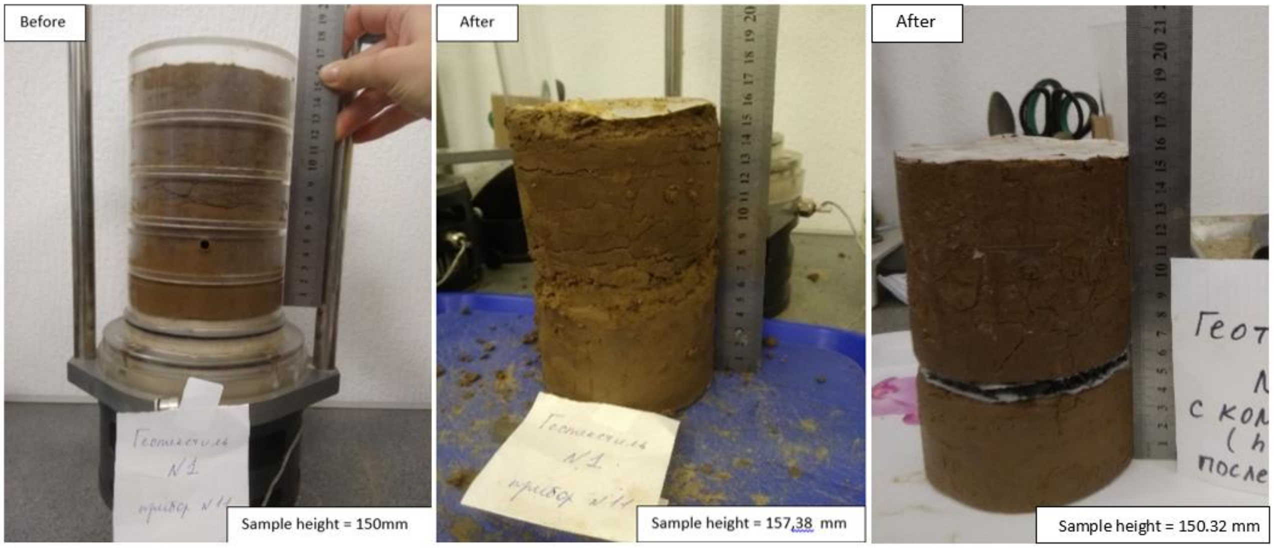

Figure 10. Frozen soil samples showing frost heave without and with the AB

5. COST COMPARISON

The protection against frost heave using natural aggregate would require laying 300 - 500 mm of clean granular soil.
In Russia the cost of sourcing, transporting, laying, compacting just 300mm of clean granular soil would be ~10 € per square metre of embankment. If this layer becomes clogged with fine particles, periodical maintenance will be required.
By comparison the cost of sourcing, transporting, laying the AB is ~6 € per square metre of embankment. The AB, if properly laid, is practically maintenance free.
It is evident that the AB affords very high savings, while ensuring a much more effective protection against frost heave, when compared to the use of granular soil layers.

6. DESIGN AND INSTALLATION OF THE AB

Beside the frost heave protection provided by its engineered structure, the design of the AB as drainage layer have to be carried out, based on the flow rate charts obtained from ISO 12958 flow rate testing (Fig. 11), according to ISO/TR 18228-4.

From Fig. 11 it results that the AB can replace a 300 mm thick granular layer placed below embankments of different heights, up to 10 m high embankments and even more..

The AB performs a function of eliminating the capillary rise of ground water in frost susceptible soils during periods of frost, thus preventing damage to road pavements caused by frost heave.

As shown in Fig. 12, to perform its function the AB should be placed at a level below the frost penetration depth but above the winter water table level.

The moisture content of the soil should always be controlled to be at optimum or close to optimum on the dry side.

The AB should be installed in the same manner as a standard geotextile with the following additional recommendations:
- The AB shall be placed with the hydrophobic geotextile faced down.
- The outer edge of the AB should be exposed at the embankment face, in order to provide free outward drainage of any water entering the core of the AB.
- For positive lateral drainage the AB should be laid with a lateral slope of 2 – 3 % to a free-draining edge at the side of the embankment.

For getting the best performance, specs of the AB should include:
- The water penetration resistance of the hydrophobic geotextile, measured according to ISO 811:2007;
- positive results of the frost heave test with and without the AB, according to ASTM D5918: 2013 or BS 812-124:2009 or GOST 28622-2012;
- flow rate, measured according to ISO 12958 at hydraulic gradient $i = 0.03 – 0.10$, with applied pressure of 200 kPa:
    with Soft – Soft boundaries: $Q_{SS} \geq 0.20$ l/s/m;
    with Rigid – Rigid boundaries: $Q_{RR} \geq 0.30$ l/s/m;
- moreover, since the ratio Q_{SS} / Q_{RR} is indicative of geotextile intrusion, it should be: $Q_{SS} / Q_{RR} \geq 0.70$.

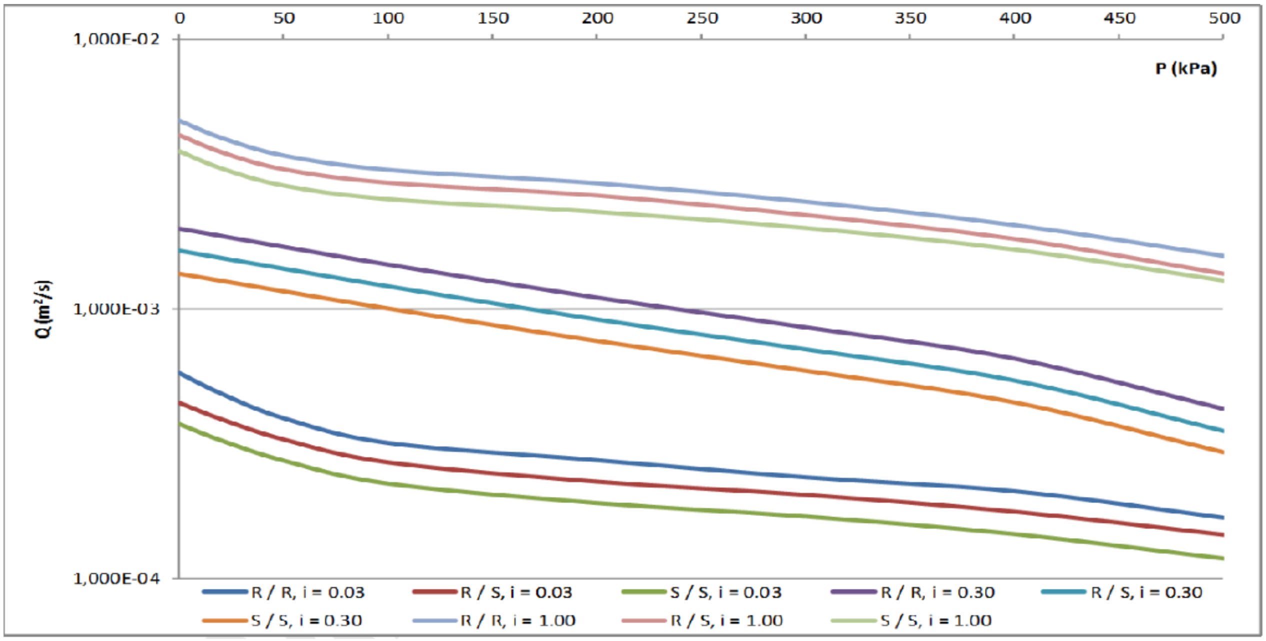

Figure 11. Flow rate chart for the AB

7. CONCLUSIONS

The AB is a geocomposite specifically engineered to provide a cost effective solution to the problem of frost heave.
Laboratory tests have been performed according to the Frost Heave test GOST 28622-2012: the results confirmed that the AB suppressed the frost heave completely.
Design and installations suggestions have been provided for ensuring the best performance of the AB.
Research is ongoing for testing existing geocomposite products in current market for the control of the frost heave; results will be published as soon as available.

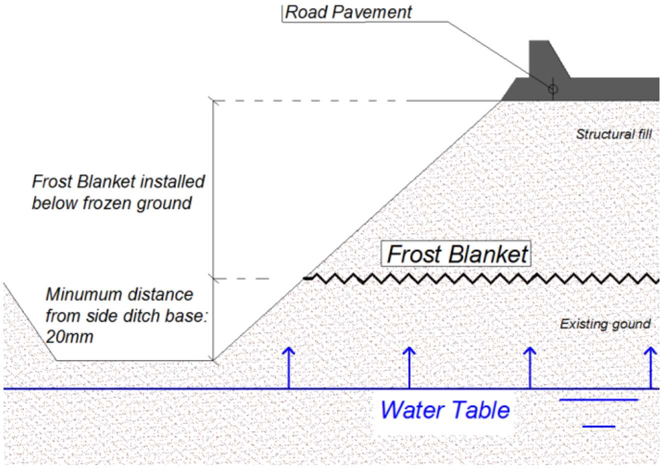

Figure 12. Installation of AB

REFERENCES

ASTM D5918 - Standard Test Methods for Frost Heave and Thaw Weakening Susceptibility of Soils (2013). *ASTM International*, West Conshohocken, PA, USA.

BS 812-124:2009 Testing aggregates. Method for determination of frost heave. *British Standards Institution*, London, UK

GOST 28622-2012, Soils, Method for laboratory procedure for determination of frost heave deformation; *Interstate Council for Standardization, Metrology and Certification*, Moscow, Russia.

Casagrande, L. 1938. Examination of the sub soil of roads. *Proceedings of the 8th International Road Congress*, The Hague, pp 1- 27.

Henry, , K.S (1990). Laboratory Investigation of the Use of Geotextiles to Mitigate Frost Heave, CRREL Report 90-6,*U.S. Army Corps of Engineers*, August 1990.

Henry, K.S and Holtz, R.D. (2001). Geocomposite capillary barriers to reduce frost heave in soils. *Canadian Geotechnical Journal*, Vol. 38 pp 678 - 694.

Knutson, A. (1993). Frost action in soils. *Norwegian Road Research Laboratory*, Oslo, Norway.

ISO 811 (2018). Textiles -- Determination of resistance to water penetration -- Hydrostatic pressure test. *ISO*, Geneve, Switzerland

ISO 12958, Geotextiles and geotextile-related products - Determination of water flow capacity in their plane. *ISO*, Geneve, Switzerland

ISO/TR 18228-4. Design using geosynthetics – Part 4: Drainage. *ISO*, Geneve, Switzerland.

Rengmark, F. (1963). Highway pavement design in frost areas in Sweden. *Highway Research Record* 33, Pavement design in Frost areas II. Design considerations, pp 137 - 157.