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Granulated foam-glass ceramics for ground protection against freezing

Гранулированная пеностеклокерамика для защиты грунтов от сезонного промерзания и морозного пучения

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Ключевые слова: гранулированная пеностеклокерамика; морозное пучение; сезонное промерзание; теплозащита грунтов

Abstract. The problem of seasonal freezing and frost heaving of soils of the engineering structures foundations is considered. For the purpose of thermal protection of soils, a granular inorganic closed-porous material, named granulated foam-glass ceramic is proposed. In the laboratory modeling of seasonal freezing, the dynamics of temperature and deformation, as well as the distribution of moisture over the depth of the soil, were studied in three cases: a soil without thermal insulation, a soil with a layer of granulated foam glass ceramics and a soil with an extruded polystyrene layer. Simulation was carried out with ensuring the flow of water to the freezing front. Heat-insulating layers allow to reduce frost heaving of models to the same extent (in comparison with soil without insulation) due to the decreasing of the depth of soil freezing. As a result, the relationship of soil deformations with the distribution of temperature and humidity over the depth of the soil was established. The increased frost heaving deformation of the soil without a heat-insulating layer is explained by the significant migration of capillary water to the upper layer of soil at freezing. The data of the annual monitoring of the experimental road section with the thermal insulation layer of granular foam-glass ceramics placed in embankment is given. The suggested constructive measure was made it possible to substantially reduce the depth of seasonal freezing of the soil compared with the typical road section.

Аннотация. Рассмотрена проблема сезонного промерзания и морозного пучения грунтов оснований инженерных сооружений. С целью теплозащиты грунтов предложен зернистый неорганический закрыто-пористый материал – пеностеклокерамика в виде гранул. При лабораторном моделировании сезонного промерзания, исследованы динамика температуры и деформаций, а также распределение влажности по глубине грунта в трёх случаях: грунт без теплоизоляции, грунт с покрытием из гранулированной пеностеклокерамики и грунт с покрытием из экструзионного пенополистирола. Моделирование проводилось с обеспечением подтока воды к фронту промерзания. Теплоизоляционные слои позволяют в одинаковой мере уменьшить морозное пучение моделей (в сравнении с грунтом без изоляции) за счёт снижения глубины промерзания грунта. В результате была установлена взаимосвязь деформаций грунта с распределением температуры и влажности по глубине грунта. Повышенное морозное пучение грунта без теплоизоляционного слоя объясняется существенным потоком воды к верхнему слою при его промерзании. Приведены данные годичного мониторинга опытного участка автомобильной дороги с устройством в теле насыпи теплоизоляционного слоя из гранулированной пеностеклокерамики, в сравнении с типовым участком. Предложенная конструктивная мера позволяет существенно сократить глубину сезонного промерзания грунта.

1. Introduction

At construction of engineering structures in areas with seasonal freezing special measures to reduce the freezing depth of soils are required. As it known, one of such measures is the heat protection of soils, i.e. the creation of heat-insulation (frost-proof) layers at building of the foundations, pavements and embankments. The boards of extruded polystyrene (EPS) and crushed foamed glass are mainly used for this purpose in practice [1–5]. Due to these layers, the freezing depth of soil is reduced, which is

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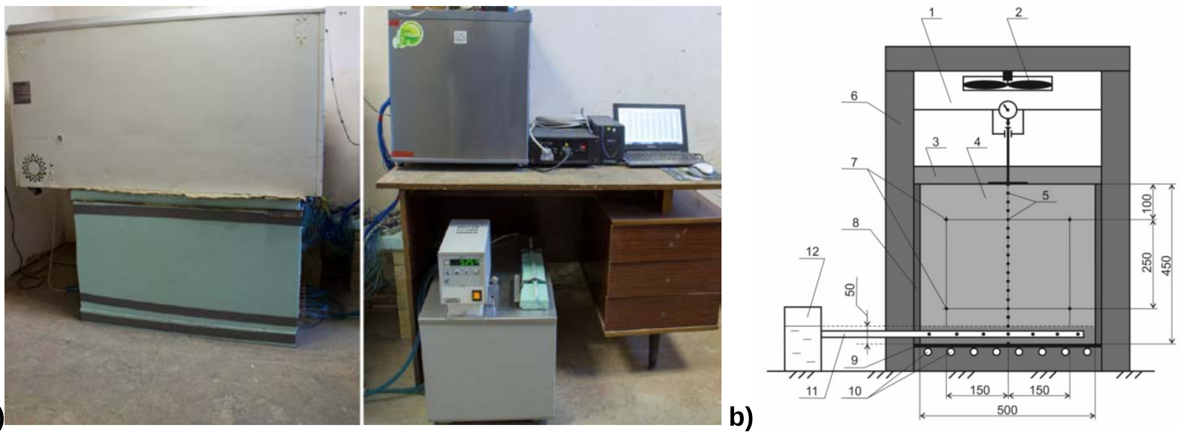
especially important at the construction on highly frost-heaving soils and watered soils. In the latter case, the water migration from the warm subsoil to the freezing front can substantially increase the frost heaving deformation the by the formation of ice lenses [6–9]. According to the evaluation of the Swedish Road Administration, the costs associated with the annual elimination of the effects of frost heaving of the roadbed are 25 % of the organization's budget [1]. The aforesaid can be attributed to the railways. Studies on the reducing of deformations of frost heave process on the railways of the USSR were carried out back in the early 1930s. The heat-insulation in the form of slag layers was recognized as one of the effective methods of reducing frost heaving deformations of the railway embankment at that time [10].

The experience with the application of EPS and crushed foam glass to protect the soil from frost heaving testifies to the essential effectiveness of these measures [2–5, 11–14]. However, there are difficulties in organizing the mechanized stacking of ESP boards in the roads and railways construction. Foam glass crushed stone is made from waste glass, which creates difficulties in their collection and transportation while ensuring the production of raw materials.

The thermal protection of soils is important technical task, therefore the appearance of new heat insulation materials is of practical interest. For example, granular foam-glass ceramic known as an inorganic heat insulation material, which is pelletized granules, whose thermal conductivity lies in the range 0.08–0.01 W/(m·K), can find use in thermal insulation of soils in addition to EPS and crushed foam glass [15]. The granular structure of the material creates the possibility of laying heat-insulating layers with the use of mechanized means, which is especially important in the construction of long engineering facilities (roads, railways, pipelines, etc.) [16–19]. In this connection, the aim of the work was to study the temperature and deformation changes in the soil with the use of a heat-insulating layer of granulated foam-glass ceramics (GC), under the conditions of laboratory modeling of seasonal freezing and under the conditions of a field test as well. The present work was supported by the Basic Research Program of RAS No. IX.135.2.3, project No. 77.2.5.

2. Methods

The freezing simulation was carried out in an experimental setup representing a thermally insulated cubic tray with soil, having the possibility to create a vertical temperature gradient and free the water migration from the bottom of the tray to the freezing front**,** Fig. 1a and 1b. The latter is due to the fact that frost heave process is understood as the deformation of soil not only due to the crystallization of pore water, but also due to capillary water migrating to the freezing front [7, 11, 12].



a) b) .

Figure 1. Experimental setup: a – General view and measuring system; b – Schematic view (dimensions given in mm): 1 – freezing chamber; 2 – fan; 3 – layer of heat-insulating material; 4 – soil; 5 – thermocouples; 6 – walls with thermal insulation; 7 – auxiliary thermocouples; 8 – plywood tray; 9 – steel sheet (3 mm thick); 10 – copper tubes of the system for maintaining the set temperature at the bottom of the tray; 11 – perforated tube; 12 – water tank

On the surface of the soil, a layer of the insulating material being inspected can be placed. A temperature gradient inside the tray, which promotes the freezing of soil, is created by setting the temperatures at the top and bottom of the tray, respectively, equal to -9±0.2 and +0.5±0.1 °C. Perforated tube is mounted at the bottom of the tray and connected to a reservoir in which a constant water level of 5 cm is maintained. The perforated tube is laid in a layer of coarse sand of 5 cm thick (Figure 1b), which creates a natural migrating of capillary water upward to the freezing front.

With an interval of 2.5 cm along the vertical axis, temperature sensors are placed: type T (copper-constantan) thermocouples. On both sides of the axis auxiliary thermocouples are placed, which are designed to measure the lateral temperature gradient. The deformations of the soil are measured with using a dial indicator at ±0.01 mm accuracy (shown in Figure 1b). The dial indicator is fixed to the walls of the freezing chamber. The rod of the dial indicator touches the steel rod, which, having free vertical movement, transfers the deformations of the soil through the layer of thermal insulation, leaning on the plate.

The soil was represented by light loam, with the following physical characteristics: moisture content 15 %, soil density 1.69 g/cm^3, plasticity index 8.4, soil salinity degree 0.4 % (with predominance of chloride sulfate salinity). According to X-ray phase analysis, the mineralogical composition of loam is represented by quartz (82 %), montmorillonite and illite (12 %) and albite (6 %). The soil which was stacked into the tray with layers 2.5 cm thick, with a compaction factor of 0.95 ± 0.01. A heat-insulating layer was laid over the soil (Figure 1). The temperature was measured using an analog-to-digital converter. The error in measuring the temperature was ± 0.1 °C. The end of the measurements was corresponded to the formation of a stationary temperature field in the tray with the soil. In view of the fact that the difference in the readings between the main and auxiliary thermocouples at one depth did not exceed ± 0.2 °C, one can judge about the practically one-dimensional heat flux in the tray.

At the end of each experiment, the water content at a different depth of the soil was determined using a standard procedure. The initial water content of the soil when stacked in the tray was 15%. Before starting the freezing chamber of the experimental setup, the soil mass was held to stabilize the temperature within 20 ± 0.2 °C.

Thermal insulation layers made of EPS boards of 3 cm thick, with an average density of 35 kg/m^3, and a layer of fraction 5–10 mm from GC with a bulk density of 300 kg/m^3 were used in the studies. The values of the thermal conductivity of the EPS and GC were established equal to 0.035 and 0.086 W/(m · K), respectively. Due to the fact that the thermal conductivity of the GC layer is almost twice high as the ESP boards, the thickness of the thermal insulation layer in the experiments was taken to be 6 and 3 cm for the GC and ESP, respectively. This provides approximately equal thermal resistance. Depending on the type of thermal insulation, laboratory experiments had the following marking: soil without thermal insulation – C, soil with ESP – E and soil with GC – G.

A field test of the GC layer to protect the foundation from seasonal freezing was carried out on the experimental section of the Beskozobovo-Evsino-Lamensky road (Golyshmanovsky district, Tyumen region, Russia). The experimental and typical sections of the road were carried out during the repair work from 5.10 to 16.10.2016, km 47+540 – km 47+690. The GC of 5–10 mm fraction was laid in the experimental section as a heat-insulation layer, and the layer of sand instead of GC was laid in the typical section. Both sections had the following layers (from top to bottom): surface course – 12 cm, base course (gravel mixture for pavements) – 30 cm, geotextile, heat-insulation layer of GC or sand (in the first and the second section respectively) – 25 cm, geotextile, natural soil. The roadway and heat-insulation layer were 7.3 and 8.3 m width, respectively, the length of each section was 50 m.

The temperature sensors were placed into vertical wells located on the axis of the corresponding sections of the road (depth up to 3.5 m). Temperature monitoring was carried out from October 18, 2016 to October 27, 2017. The temperature of the ground was measured twice a day with a digital data logger (accuracy of ± 0.1 °C).

3. Results and Discussion

The process of the freezing of soil without the use of thermal insulation was investigated in the first stage. A fragment of the temperature dynamics at depths from 2.5 to 25 cm is shown on Figure 2a. After 90 hours all the temperature curves are aligned along the horizontal axis of the graph, which indicates the formation of a stationary temperature field in the soil. A sharp bend of the curve at a depth of 2.5 cm characterizes the heat release of the underlying layers of the soil during the water-ice phase transition and indicates that the soil freezing point is in the range from -0.2 to -0.4 °C. At depths of 7.5 to 20 cm, a more smooth and prolonged inflection is observed, corresponding to a slowing down of the freezing rate and transition to a stationary state. Extrapolating the data of Figure 2a near 0 °C, the freezing depth of 23 cm after 90 hours was established.

Dynamics of deformation of soil in experiment C is shown in Figure 3 (curve C). Up to 25 hours the shrinkage deformation of soil (up to -1.5 mm) is observed, despite the fact that by this time the soil was frozen to a depth of 5–6 cm (according to Figure 2a). Apparently, the deformation of the frost heave process and the shrinkage deformation are developed simultaneously as a result of the capillary water migration and the compaction of soil particles. Similar shrinkage deformations were observed when the loam was frozen from above, under conditions of capillary water moving upward to the freezing front [20].

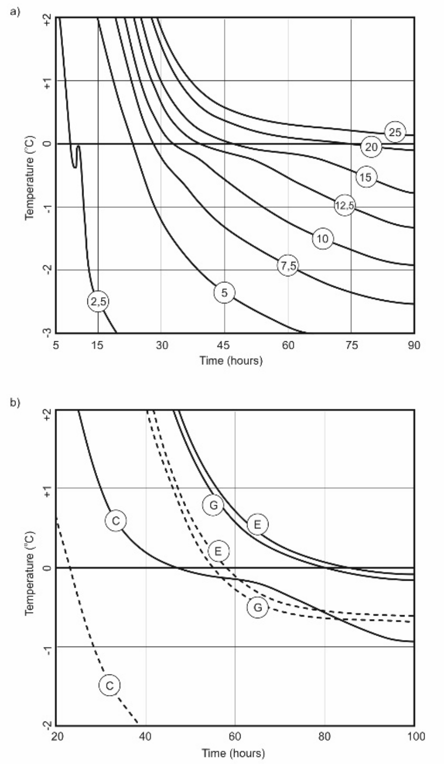


Figure 2. Temperature dynamics: a – experiment C (the numbers in the circles correspond to the depths, cm); b – experiments E and G compared to C (the dashed curves correspond to a depth of 5 cm, solid curves – 15 cm)

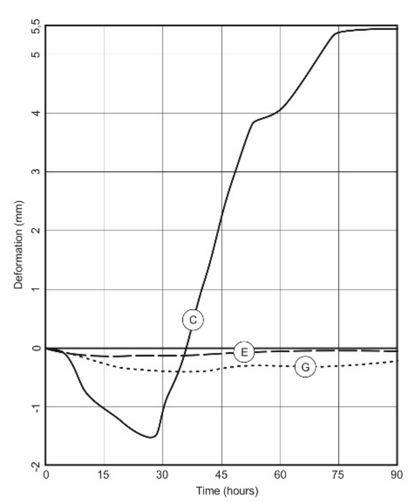


Figure 3. Deformation dynamics of soil

During the period from 25 to 37 hours the initial position of the soil level was reached due to the increase of development of frost heave process, which lasts up to 75 hours and practically stops to 90 hours, reaching a value of 5.45 mm. From the graphs in Figure 3 it is seen that the most intensive growth of deformations was occurred from 25 to 52 hours, corresponding to the freezing of the soil from 6 to 17.5 cm (Figure 2a). Corresponding value of deformation of the soil of 3.8 mm was reached. Freezing from 17.5 to 20 cm took place from 52 to 75 hours and corresponded to an increase in the deformation of the soil by 1.65 mm: from 3.8 to 5.45 mm. The inflection of curve C in the interval 45–60 hours is associated with a significant slowdown in the freezing rate of the soil (Figure 3). Thus, the freezing time of soil from 10 to 15 cm was about 15 hours, and from 15 to 20 cm – 28 hours (according to Figure 2a). During this period, the processes of shrinkage of the unfrozen part of the soil under the rising capillary water could begin to develop again.

The significant water content at the upper layers of soil is established according to the graph of water content distribution along the depth for experiment C, Figure 4 (dotted curve). With increasing the depth, a continuous increase in the water content of soil from 15 to 45 % is noted. Water content of a part of the soil at a depth from 10 to 20 cm, corresponding to the most intensive frost heave deformations in period from 37 to 75 hours (Figure 2a) is 26–28 %.

Subsequently, the soil was freezed using heat-insulating layers. The dynamics of soil freezing in experiments E and G is similar, as can be seen from the graphs in Figure 2b. In comparison with soil without insulation (curves C), cases E and G are characterized by a much later start of the freezing of the upper layer at a depth of 5 cm: 55–57 hours against 24 hours for the case C. The depth of freezing of 15 cm is reached through 83 (for E and G) and 47 hours (for C). Thus, the cooling rate of the soil is reduced by about half.

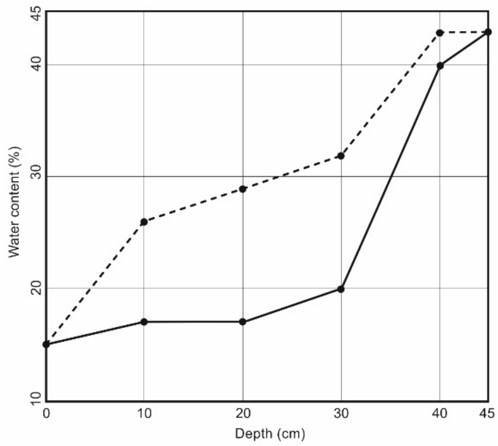


Figure 4. Distribution of water content over the depth of the soil (the dotted curve corresponds to experiment C, solid – E and G)

Extrapolating the E and G graphs at a depth of 15 cm (Figure 2b) and taking into account the error in measuring the soil temperature, it was established that the freezing depth in the cases E and G can be taken to be 16 ± 1 cm. However, in spite of this, frost heaving deformations of the soil, characteristic for the case of C, are absent. A slight shrinkage of the soil during freezing is proved by curves E and G in Figure 3. The peak of shrinkage deformation, characteristic for curve C, is smoothed, due to the later freezing of the upper layers in cases E and G (Figure 2b). After 40 hours, the deformations of the soil are close to the initial position, but their values are negative (Figure 3, curves E and G).

The water content distribution along the depth of the soil in Figure 4 for the cases E and G is presented on the same graph (solid curve), in view of the insignificant discrepancies in the measurements. As it is seen on Figure 4, the soil layer up to a depth of 20 cm has water content in the range of 15–17 %, which is almost twice less than in the case of C and close to initial water content. Consequently, the smoothing of the soil shrinkage and frost heaving deformations in cases E and G can be explained by an insignificant raise of capillary water to the freezing layer. Thus, due to the application of ESP and GC, a water-thermal regime in the soil is formed, therefore the development of shrinkage and frost heaving deformations are substantially reduced, despite the freezing of a part of the soil.

Decrease in the depth of seasonal freezing of soil with the use of GC is observed in the field test. The pattern of temperature distribution in the soil on the experimental section of the road is presented in Figure 5. Three types of the temperature distribution of the soil are shown on the graphs: the initial temperature distribution on 18.10.2016 (curves G1 and S1), the distribution corresponding to the maximum freezing depth of the soil in the sections by 24.03.2017 (curves G2 and S2) and the distribution at the maximum temperature at a depth of 0 cm in summer 03.08.2017 (curves G3 and S3). Construction of the experimental section with GC in October 2016 is shown on Figures 6a and 6b.

The graphs labeled G1 and S1 corresponding to the initial temperature distribution (section with GC and typical section, respectively) are shifted to the left as the ground cools in autumn and winter, after which they pass to curves G2 and S2 – when a maximum value of the depth of freezing is reached. The soil temperature at a depth of 0 cm at this moment is -3.8 and -6.1 °C, and the depth of freezing is 100 and 162 cm, respectively for section with GC and typical section (curves G2 and S2 on Figure 5).

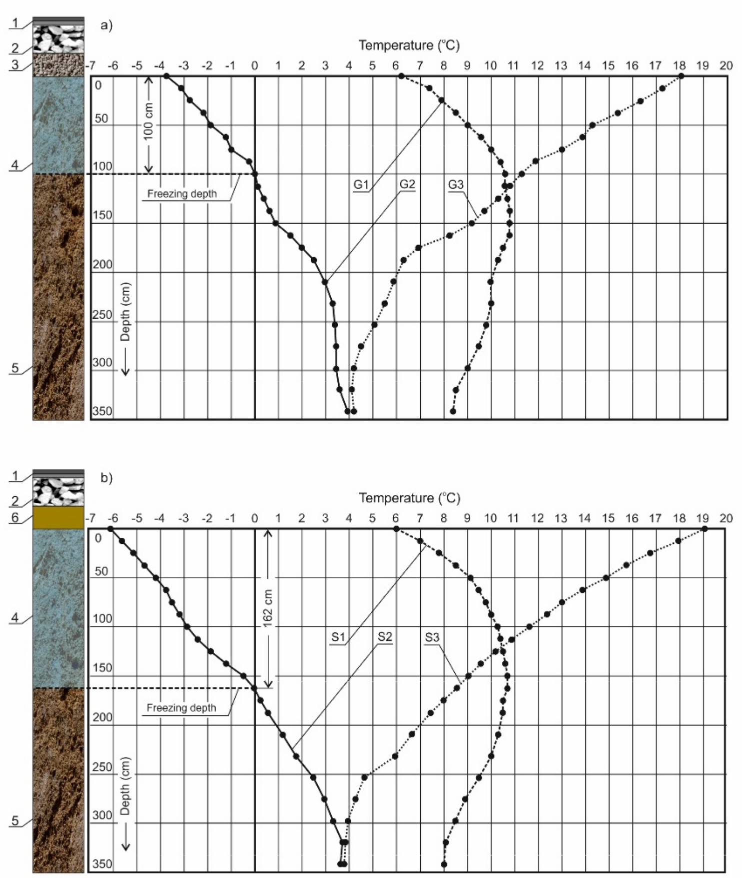


Figure 5. Distribution of temperature in the soil: a – road section with GC; b – typical road section. 1 – surface course 12 cm thick; 2 – base course 30 cm thick; 3 – GC 25 cm thick; 4 – frozen soil; 5 – soil with a positive temperature; 6 – layer of fine sand

Figure 6. Construction of the experimental section with GC: a – GC compaction by roller; b – geotextile laying above GC

The obtained results can be compared with the data of the authors who monitored the experimental section of the road with a heat-insulating layer of crushed foam glass stone of 35 cm thick (Norway) [2, 5]. After the first winter the authors observed a reduction of the freezing depth in the experimental section from 35 to 0 cm (in comparison with the typical section where granite crushed stone was used instead of crushed foam glass).

As the air temperature during the spring and summer is raised, the curves G2 and S2 are shifted to the right and took the form of G3 and S3 (Figure 5). At this point, the soil under the layer of GC at a depth of 0 cm has a temperature of 1 °C lower than the typical section: 18 and 19 °C correspondingly. In the future, the annual cycle of soil temperature change is repeated, beginning with the temperature distribution near the curves G1 and S1.

4. Conclusions

1. Frost heaving deformation of the soil without insulation equal to 5.45 mm was established, while in experiments with ESP and GC the shrinkage deformation of soil was observed. In the first case, a significant rise of capillary water to the upper layers is established, because the water content of the soil at a depth of 20 cm was changed from 15 to 28 %, and in the experiments with ESP and GC – up to 17 %.

2. The freezing depth of soil with the use of heat-insulating layers of ESP and GC with equal thermal resistance is approximately 16 cm, whereas without usage of thermal insulation the freezing depth of the soil is 23 cm. In the field test for the first year of operation of the experimental section of the motorway with heat insulating layer of GC the freezing depth of soil was decreased from 162 to 100 cm. According to the data of Swedish Road Administration, the elimination of the frost heaving due to the use of thermal insulation can save up to a quarter of the organization's budget spent on road repair [1, 5].

3. Apparently, the frost heaving deformations in experiments with ESP and GC are summarized with shrinkage deformations of the soil due to high water content at a depth below 20 cm (where a positive temperature persists), which explains the slight shrinkage.

4. Experiments clearly demonstrate not only the effectiveness of the application of GC and ESP to reduce the freezing depth, but also the importance of taking into account the interrelationship of the water-heat regime arising in this case with the nature of soil deformations.

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