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WATERTIGHT ICE AND CRYOGEL-SOIL COMPOSITE MEMBRANCES IN UPPER PARTS OF DAMS CONSTRUCTED IN COLD REGIONS

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ABSTRACT

The paper describes the work carried out to develop the methods of ice and soil reinforcement using cryotropic gel formation. It deals with the solving of a number of serious problems concerning both building and repairing the upper parts of dam cores constructed in cold regions by means of using the ice- and cryogel-soil composites generated by the method of cryotropic gel formation. Some problems are connected with difficulties in finding soils with necessary properties for building dam cores and also technological obstacles arising in winter time when trying to put the soils in the body of the dam. Another group of problems deals with cracks appearing in the upper parts of dams because of the core freezing to the banks when leakage along the cracks threatens to destroy the dam. It concerns not only dams of the thaw type but also of the frozen one when freezing columns break down. One more problem is connected with the process of erosion at the bottom of the core which may happen through fissures in the rock foundation of the dam. In addition, a number of problems may arise during earthquakes.

The ice- and cryogel-soil composites are proposed to be used to create water tight elements in dams and marine structures in cold regions.

INTRODUCTION

In recent years a great deal of attention has been focused on the study of cryogels obtained by the methods of cryotropic gel formation (CGF) (Lozinsky, 2002; Altunina et al., 2006; Vasiliev et al., 2012). Cryogels are considered as potential materials for solving practical problems. Especially it concerns cryogels with a polyvinyl alcohol base (PVA). The range of application for cryogels is increasing (Lozinsky, 2002). An example of cryogel application is the creation of reliable materials for building dams and other hydro engineering constructions. The material created by using the method of CGF has low permeability and can be used in a wide range of temperatures including positive ones. An example of such application is a full-scale experiment of manufacturing moisture-proof coating for the bottom of the ash disposal heat and power plant in Magadan. The method of CGF consists in the formation of strong hydrogels from polymer aqueous solution such as PVA and some others by means of a freezing and thawing process. Briefly speaking, PVA solutions are frozen at -5 to -20 °C. Then they are allowed to thaw to positive temperature. PVA is a polymer with exceptional properties such as water solubility, biocompatibility, it is non – toxic and not carcinogenic and has the capacity to form hydrogels by chemical or physical methods. PVA is a reasonably priced and versatile polymer, adaptable to various needs with minor modifications for synthetic procedures. PVA has been applied to railway constructions on the Zabaikal Railroad Way, Siberia, for strengthening soils and to prevent soil erosion (Eliseev and Cheverev, 2008). Water is the only practically available solvent for PVA. PVA is a crystalline polymer obtained by hydrolysis of polyvinyl acetate. The molecular mass of the polymer is 10,000 – 1,000,000. More than 10 types of PVA with different molecular mass are available on the market. Water resistance of PVA is obtained by adding such substances as boron (tincalconite or boric acid) to the solution (Fig.1).

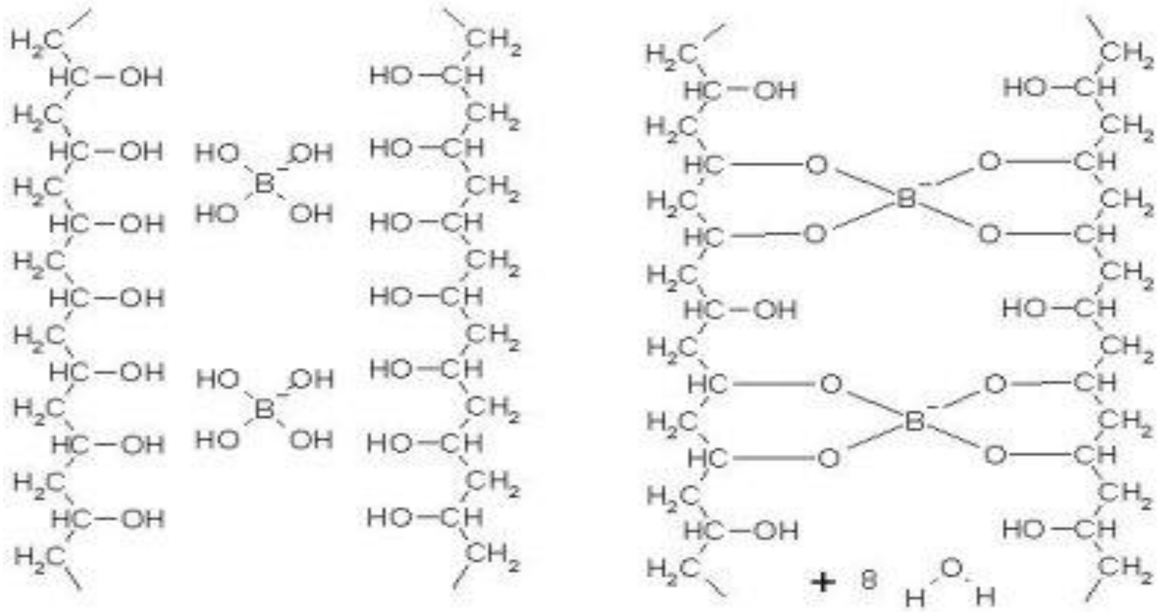

Figure 1: The reaction that creates PVA water resistance. The borax cross-links the PVA.

PVA has some foam stabilizing properties. It is also capable of strengthening ice which is one of the components of frozen soils.

The experiment which confirmed the advantages of the method was carried out at the beginning of the 1990s. Local ash covered with a cryogel coating was used as a dispersed material (for one m^2 of the surface of the coating 0.3 kg of PVA was required). This polymer was the basic and most expensive component of the frozen soil coating. At present more than ten different brands of this polymer are sold at quite low prices. These brands vary according to the levels of solubility in water and their viscosity. Lower degree of hydrolysis contributes to lower solubility of the polymer and higher molecular weight - to higher viscosity of the solution of the polymer. In 2003–2004 the cryotropic gels were successfully used during the pilot tests. These tests were aimed at sealing a leaking interval at the base of the dam at the Irelyakh hydro system (Altunina, 2006).

The unique structure of cryogels appears to be useful in many spheres and the application of this method is very promising in various structures: foundations of roads, docks, quays, dams, cells to control waste etc.

The paper is concerned with several serious problems regarding both building and repairing the upper parts of dam cores constructed in cold regions by means of ice- and cryogel-soil composites generated by the method of cryotropic gel formation.

The rationale for using PVA is the excellent mechanical and thermo physical properties of cryogels and their availability.

The strengthening action of additives of PVA is due to the formation of a continuous grid of a plastic polymeric phase in ice.

In cold regions the technology of using frozen soils can include the following procedures: obtaining some coarse grained frozen soil by blast-hole drilling; grinding it with different types of machines; converting it into a plastically-frozen state, placing it into water (a polymer solution); soil compaction. For example, the technology of dam construction with local frozen soils placed into water is quite effective (Pechovich and Razgovorova, 1979).

This technology makes it possible to avoid such labour intensive work as thawing frozen soils, and subsequently making arrangements for their storage and insulation. The advantage of this technology proves that soils can be used in a plastically-frozen condition which means they do not have to be thawed.

DESCRIPTION OF EXPERIMENTS

Two types of soil samples have been tested:

1. Ice-soil composite samples obtained by means of CGF (cryogel ice-soil composite).
2. Control soil samples prepared in the conditions identical to the above without using the methods of CGF (wet sand without cryogel).

In order to prepare the samples of the first type a mixture of dispersed soil and a 10 % water solution of PVA with an addition of 1.0 % of boric acid by weight was used. The PVA solution was obtained at a temperature 70 - 80 ^{o}C in a dry oven. When freezing samples were kept at negative (-20 ^{o}C) temperatures for at least 4 hours, they were thawed at room temperature and if necessary were cooled again to the test temperature. It is important to note that there are types of PVA which can be dissolved at low temperatures. Higher molecular mass contributes to higher viscosity, and lower degree of hydrolysis leads to lower solubility. At 5 % acetate group content the PVA swells in cold water and dissolves in water at temperatures 70 - 90°C. At 10 - 15% acetate group content the polymer dissolves in cold water, but precipitates at temperatures of more than 40°C. The control samples were prepared by means of mixing. They contained the same quantities of dispersed soil and water as the cryogel samples. The dispersed soil was represented by friable fine sand where the fractions of diameter 0.1 – 0.25 mm were prevalent. All cryogel ice-soil composite samples were tested after one cycle of freezing – thawing. Three series of tests were carried out at room temperature on both control soil and the composite at normal pressures varying between 100-300 kPa and deformation speed of 2.0 mm/min. The normal pressures and the rate were chosen in the range as advised by the Russian standard (GOST 12248-2010). This rate of shearing was taken to represent an undrained loading condition. All the tests were run immediately after the soil had been placed and compacted in a shear box. Such a situation represents mainly in-situ conditions. The diameter and height of the shear box were 63.5 mm and 20 mm respectively. The tests were conducted with computer controlled shear box equipment using different load and deformation transducers. Six twin-specimens were tested. The statistical data processing was done in accordance with the Russian standard (GOST 20522-96). The experiments were carried out using one-plane shear method on the shear machine 27-WF2180. The experiment's set up and data-logging systems are shown in Fig. 2.

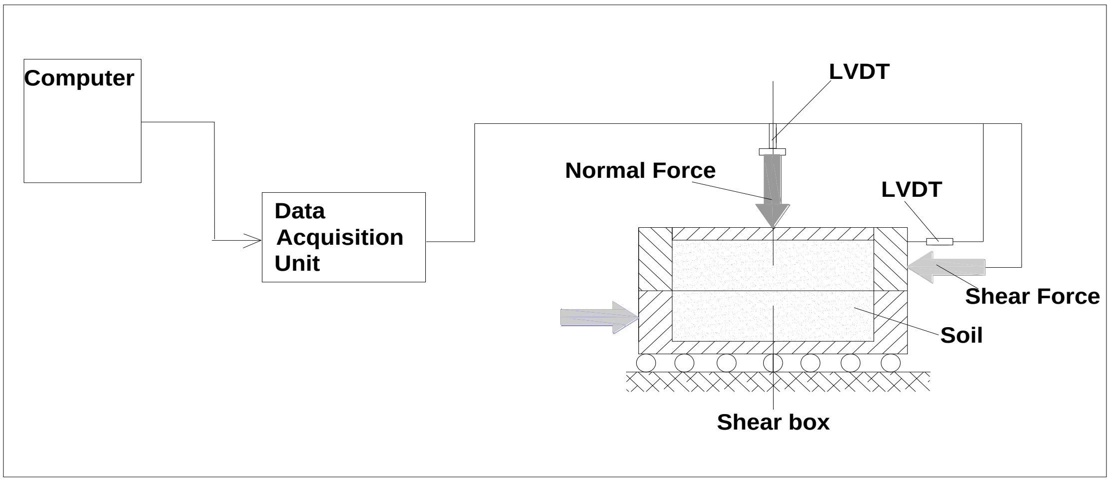

Figure 2: Computer controlled experimental setup of direct shear test.

DISCUSSIONS AND RESULTS

The laboratory research undertaken showed that the frozen anthropogenic soils obtained by means of CGF on the basis of PVA retain the properties of a solid body during thawing even after one cycle of freezing-thawing.

It was proved that the strength parameters of cryogels after several cycles of freezing-thawing improve (Lozinsky, 2002). It is obvious that shear strength parameters of ice-soil composites are not getting worse. It is important as freeze-thaw cycle is a weathering process that frequently occurs in cold regions.

The shear test diagrams (Fig. 3,4)representing shear stress versus strain at normal pressure 100 kPa show that ice-soil composites are stronger than control soil samples both at negative (-20^{o}C) and positive (+20 ^{o}C) temperatures. It is very significant that cryogel composites show extraordinary plastic properties both in frozen and thawing conditions. Even with the general deformation of shear exceeding 10 mm and more, no cracks between the two halves of the sample were observed.

It was also shown that the properties of soils obtained by means of CGF (in our case cryogel with sand) are very different from the properties of the control soils. Furthermore, these properties can be regulated by means of different additives. The possible range of a few characteristics is shown in Table 1 (frozen condition) and in Table 2 (thawing condition).

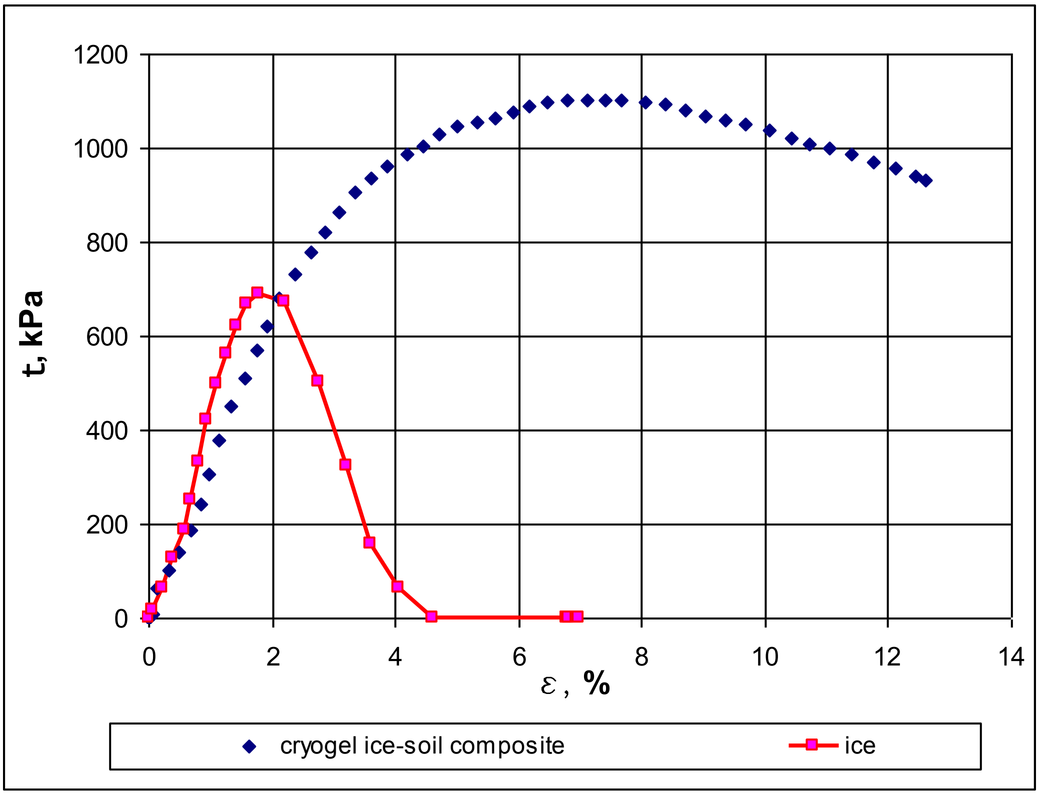

Figure 3. Shear stress τ versus shear strain ε of ice compared with ice-soil composite in frozen condition.

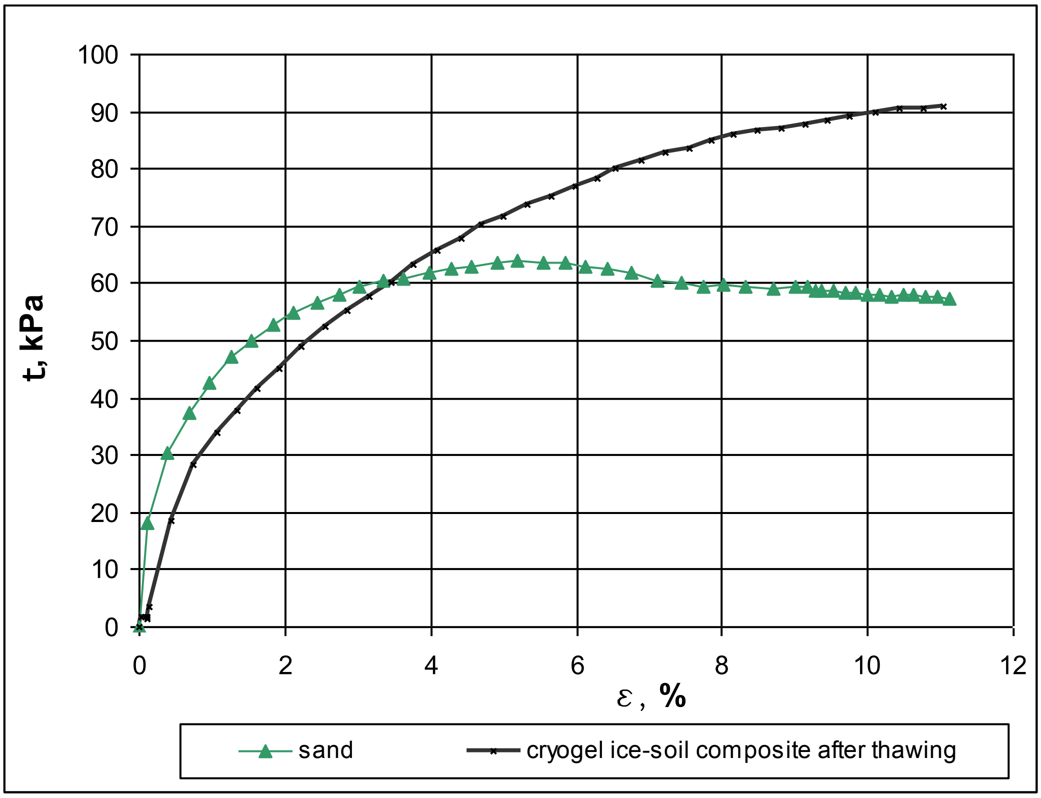

Figure 4. Shear stress τ versus shear strain ε of sand compared with cryogel soil composite in thawing condition.

Table 1.The properties of a cryogel ice-soil composite in comparison to ice at a negative temperature (-20^{o}C).

Properties	Ice	Cryogel ice-soil composite
Shear strength, MPa	0.5 – 1.0	1.0 -1.5
Young's modulus, MPa	3000 - 5000	2000 - 3000
Poisson's ratio	0.34 – 0.37	0.36 - 0.43
Density, g/cm^3	0.91-0.93	1.24-1.57
Moisture content, %	100	18 - 25
Dry density, g/cm^3	0	1.05 – 1.26

Table 2. The properties of a cryogel ice-soil composite after thawing in comparison with sand at a positive temperature (+20^{o}C).

Properties	Sand	Cryogel soil composite
Angle of internal friction	22 – 25	22 – 30
Cohesion, MPa	0	0.005 – 0.04
Young's modulus, MPa	20 – 40	0.5 – 5.0
Poisson's ratio	0.30-0.32	0.42-0.46
Permeability, cm/s	10^{-2} – 10^{-3}	10^{-6} – 10^{-9}
Density, g/cm^3	1.60-1.75	1.15-1.40
Moisture content, %	7 – 10	12 – 20
Dry density, g/cm^3	1.50 -1.60	1.03 – 1.07

Considering the information contained in the tables, it is clear that the method of CGF is very promising in solving the problems occurring in the freezing-thawing contact zone of hydro engineering structures. Low deformation and density properties of cryogel composites after thawing present some technological difficulties in using the material, but it should be noted that at high pressure these properties transform to those of the used sand.

The technology of strengthening a frozen soil by means of the method of CGF for the construction of watertight elements in weirs is protected by patents of the Russian Federation № 1600406 and № 2342484. The material presents a wide range of advantages, such as: its good regulated characteristics including high plasticity and being watertight; the possibility of using it in both fresh and sea types of water; its being environmentally sound etc.

There are a number of problems in cold regions related to constructing dams. The first one is connected to freezing the sides of the clay core of the dam to the banks (Fig. 5, zone 2 and Fig 7, zone 4). If it is a thaw type dam it often leads to horizontal cracks appearing at the point of contact between the frozen and thawing parts of the core. The same may happen in the frozen type dams in the event of freezing columns breaking down which often happens in practice. This kind of crack is very dangerous and may lead to the dam being destroyed.

The second problem concerns the dams constructed on a fissured rock foundation. Erosion of the clay core often happens in the contact area between the core and the rock (Fig.5, zone 4 and Fig. 6, zone 8). It necessitates the widening of the base of the core and sometimes the construction of a concrete layer on the rock. Both measures are very expensive. Disregarding the problem presents even greater risk than in the first case, because repairs are by far more labour intensive and costly.

The third problem deals with building dams in cold regions when the construction of the core in winter time is extremely difficult. The other aspect of this problem is connected with clay availability needed for the core which should be in the proximity of the building site.

The first of the problems mentioned could be solved by using cryogel soil composite for constructing a diaphragm in the upper part of the dam as shown in Fig. 7. This kind of diaphragm could also be used for repairs. Besides the composite may also be used in the area where the core touches the banks (Fig. 5, zone 5) as due to its plasticity it will allow the core sides to settle and therefore lessen tension related stresses in the core during the thawing process. This measure can be used for effecting repairs.

The second problem could be solved with using the cryogel composite as a thin layer at the foundation of the core as being watertight it will prevent dangerous erosion (Fig. 7, zone 6). It will also allow reducing the width of the core.

The third problem is connected with the two mentioned above. If there is shortage of clay in the district it is possible to use the cryogel composite diaphragm not only in the upper part but instead of the clay core. This solution will certainly lengthen the period when it is possible to build since sub zero temperatures will only help to construct the cryogel diaphragm accelerating the process of gel formation. It should be noted that positive temperatures will not stop gel formation but will only make it longer.

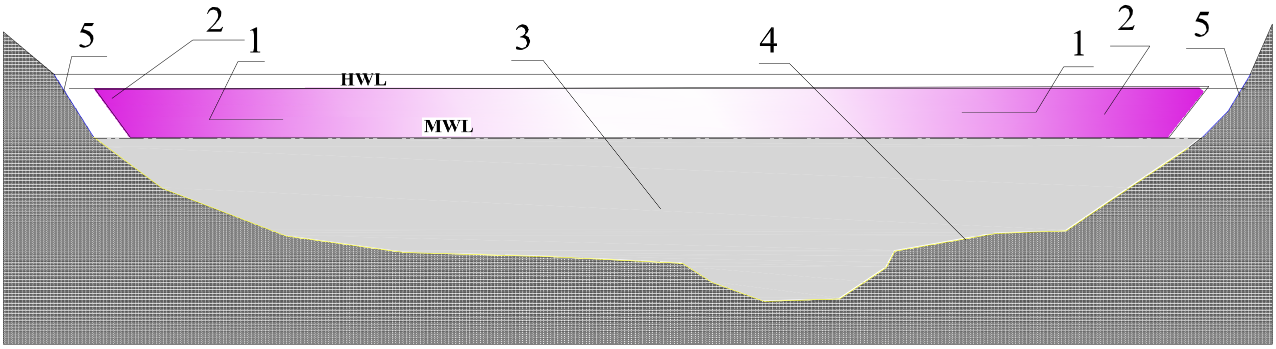

Figure 5. Longitudinal section of a dam of the thaw type on fissured rock foundation in a cold region. 1 – crack; 2 – risk zone; 3 – clay core of the dam; 4 - rock foundation; 5 – zone where the core freezes to the banks; HWL – head water level; MWL – minimum water level.

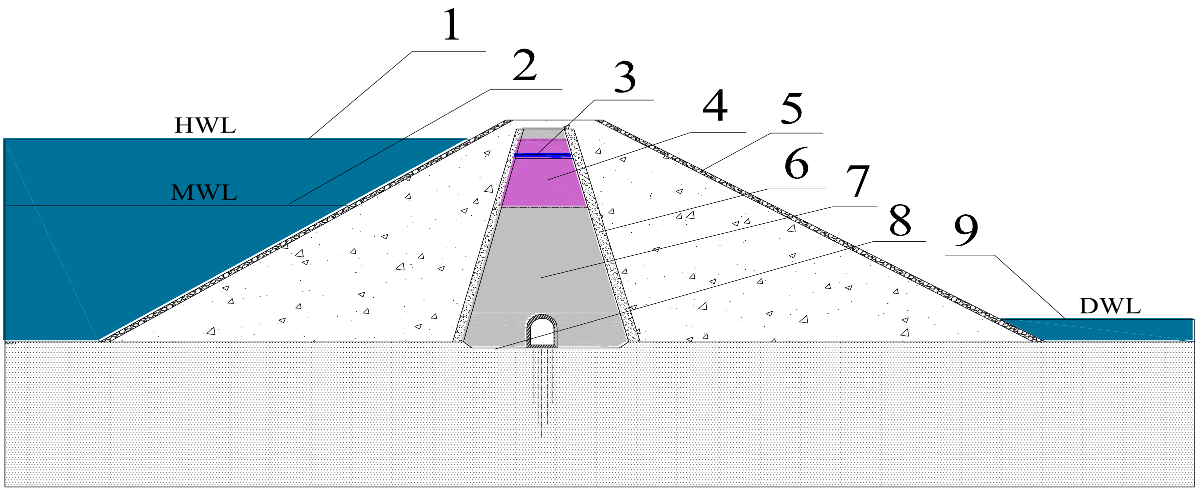

Figure 6. Cross section of the dam. 1 – head water level; 2 – minimum water level; 3 – crack; 4 – zone of risk; 5 - downstream pavement; 6 – transitional layer; 7 – core; 8 – zone of possible erosion; 9 – downstream water level.

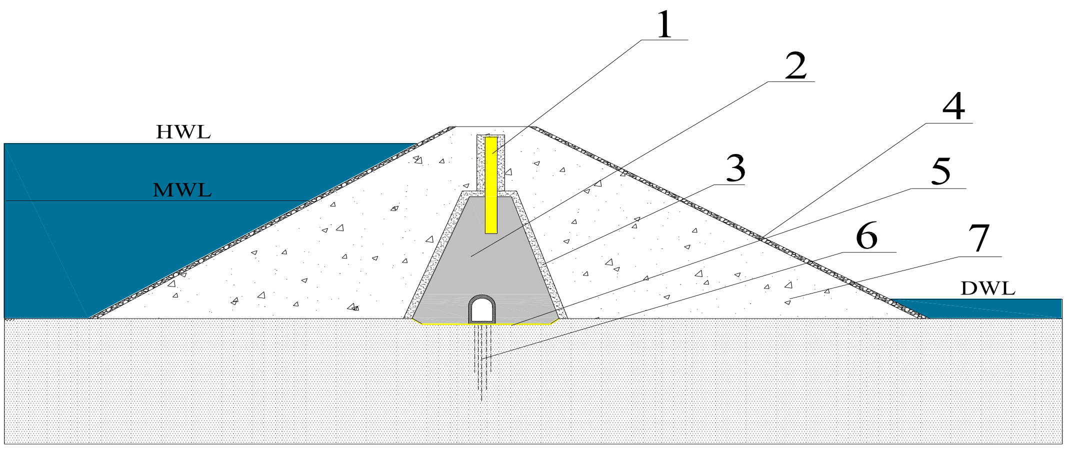

Fig.7. Cross section of the dam with the cryogel ice-soil diaphragm in the upper part of the core and cryogel erosion protection; 1 – cryogel ice-soil diaphragm; 2 – core; 3 - transitional layer; 4 - downstream pavement; 5 – cryogel layer to prevent erosion; 6 – cement screen; 7 - rock fill.

The fact that freezing-thawing cycles just improve the strength properties of cryogel composites makes the construction of the core in winter time even more advantageous.

It is also known that during earthquakes the most dangerous zone is situated in the upper part of the dam. Considering the extraordinary plastic properties of the proposed material it would be fair to say that using a cryogel diagram will certainly improve matters should an earthquake strike.

We have shown just a few examples of using cryogel composites in dam building and repair work, but the range of possible applications may be by far wider. One of the possibilities is using porous cryogel composites obtained with the help of foam technology. It creates material with quite low thermal conductivity which is less than 0.3 W/m ^{o}C (tests were performed by the method of thermal probe).

CONCLUSION

The experimental data show that ice-soil composites, obtained by using the method of cryotropic gel formation, are sufficiently strong and watertight during thawing. Three zones of possible use in dams of both frozen and thaw types in cold regions were introduced: a diagram in the upper part of the dam and contact areas between the banks and the foundation of the dam. There are certainly other fields of application of the composites in dams both in frozen and thaw conditions. One of the possibilities associated with using foam technology in frozen constructions is very promising.

The method is quite new and needs further research. The laboratory stage being fairly developed, it is necessary to perform a number of medium-sized and full-sized experiments to work out technologies and to put such promising opportunity to good use.

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