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Daniel Garlikowski
Krzysztof Lejcuś
Henryk Orzeszyna
Andrzej Pawłowski

STUDY OF ULTRAFINE BINDERS BASED ON MINERAL WASTE FROM BEŁCHATÓW AND BOLESŁAWIEC FOR THE CONSTRUCTION OF HYDRAULIC CUT-OFF WALLS

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Autorzy:
Daniel Garlikowski, Krzysztof Lejcuś,
Henryk Orzeszyna, Andrzej Pawłowski

Opiniodawca
prof. dr hab. inż. Adam Niedzielski

Redaktor merytoryczny
dr hab. inż. Krzysztof Pulikowski, prof. nadzw.

Opracowanie redakcyjne
Janina Szydłowska

Korekta
Elżbieta Winiarska-Grabosz

Łamanie
Teresa Alicja Chmura

Projekt okładki
Krzysztof Wyszatycki

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1. INTRODUCTION

Hydraulic cut-off walls can be produced with the use of numerous different materials – natural materials, plastics (synthetics), construction materials such as steel or concrete. As the constructed cut-off walls remain in direct contact with the soil and water environment, for their construction should be used suitably modified natural materials, which only slightly differ from the environment. Another advantage could be the existence of deposits of such materials in the proximity of the application site what eliminates the need for long-distance transport, sometimes even from remote continents.

Materials used for the construction of hydraulic cut-off walls have to meet high quality requirements. They have to be durable, resistant to deformation, and waterproof. The examination of usability, particularly of new materials, requires extens studies that enable a comprehensive evaluation of their current parameters and allow to predict the development of their characteristics in the future, during usage of the constructed objects.

This monograph is devoted to the study of ultrafine binders based on clay, which can be used as injection material for the construction of hydraulic cut-off walls. The study was conducted within the project No.: WKP-1/1.4.1/1/2006/69/69/623/2006/U/KW/1/2006, realised by the Consortium, led by Przedsiębiorstwo Robót Geologiczno-Wiertniczych G. Janik & R. Kuś S. Spółka Jawna in Sosnowiec PRGW. The study was conducted on samples containing different amounts of inject, prepared in the laboratory from the same materials as those used in practice, and on undisturbed samples collected in the field from a section of the flood bank of the Vistula river in the region of Samocice, where hydraulic cut-off walls are constructed with the DSM (Deep Soil Mixing) technology. The company uses the results in its ongoing activities, including, among others, the modernisation of the flood embankments.

Flood banks undoubtedly play a very significant role in the creation of the country's flood protection. Most of the levees were constructed several decades and some even over a hundred years ago. For example, the last significant modernisation of the embankments in the region of Odra took place at the beginning of the 20th century. Since that time, our knowledge related to the construction and exploitation of banks has significantly changed. Initially, banks were constructed from random soils, which were usually collected from the inter-embankment zone, or from the embankment adjacent area. The route, height and structure of the transverse section was rather a result of the engineering intuition of their constructors than of the results of studies and analyses related to such structures. A significant part of the current banks not only has not been modernised since the beginnings of the 20th century, but they have not been undergoing regular maintenance, which is necessary for their reliability. In this period, several flood freshets took place in Poland. They caused numerous damages, that still have not been repaired everywhere. These are mostly filtration-related damages, which cause a significant decrease in the resistance of the bank, yet they are not always clearly visible. A significant part of the damages related to poor exploitation and the presence of animals has not been repaired, either. The factors listed above have contributed to the poor state of repair of a significant part of the Polish flood banks, which need modernisation so that they can guarantee protection during flood freshets.

The basic element of the modernisation of banks is the sealing of their body. Insufficient level of mastery of new technologies, and the lack of equipment for the implementation thereof leads to the common application of screens and cut-off walls made of cohesive soils or different types of synthetic geomembranes. However, the installation of these materials faces a series of limitations related to construction and technology, and it is almost always accompanied by a large amount of earth works. The technologies of construction of leakproof cut-off walls in a subsoil, which have been improved for several years, nowadays allow to perform tasks related to modernisation of banks without the need to move large amounts of soil or to engage heavy equipment [Borys and Rycharska 2006]. However, even in this area there is an ongoing search for solutions that would be optimal in terms of quality of the applied product, and of a decrease in production costs. Przedsiębiorstwo Robót Geologiczno-Wiertniczych G. Janik & R. Kuś S. J. has taken up such activity by means of developing the formulas of injection grouts with the use of materials available in Poland – clay and sludge of dusty sand granulation, which could be applied in the technologies of thin cut-off walls, DSM (Deep Soil Mixing) and low-pressure injection for the construction of various types of hydraulic cut-off walls. The proposed materials could replace bentonite, which is used in injection mixtures along with cement [Zielińska 2006]. Injection mixtures with bentonite are frequently available on the market in the form of ready products, which usually increases the costs of their application.

2. AIM AND SCOPE OF THE STUDY

The aim of the project was to examine injection materials that use ultrafine binders, and to determine the achievable parameters characterising "hardened" injects and mixtures of injects and soils. This study does not encompass the technological issues related to non-hardened grout prepared for application, which was analysed by the leader of the consortium. In order to determine the characteristics of the inject itself, as well as of the inject mixed with soil, a programme of laboratory tests was prepared, both on samples formed in the laboratory and those collected from flood banks. These were both basic and special tests, taking into consideration the specifics of the planned applications, encompassing soils used for the construction of flood banks, injection materials for the production of hydraulic cut-off walls, and mixtures of soils and injection grout. During the designing stage of the tests, different aspects of usage and effects of application of fine binders were taken into account, including the ability to prevent filtration-related damages of flood banks, ability to fill all types of cavities, zonal strengthening of the cross-section as well as the subsoil stabilisation of service roads.

2.1. Tests of samples prepared in the laboratory

The laboratory tests included two types of injection materials – one, whose main ingredient was clay from Bełchatów, and the other one, prepared with use of sludge from Bolesławiec, as well as two types of soils – non-cohesive soil – medium-grained sand, and cohesive soil – loamy sand. Tests conducted on samples prepared in the laboratory enabled us to precisely monitor the proportions of soil and injection grout, and thus to determine the characteristics of such two-ingredient composite depending on the range penetration of the injection.

The programme included the following tests:

- Basic physical parameters (bulk density, particle density, water content, maximum dry density – Proctor compaction test)
- Filtration
- Soaking collapsibility
- Shrinkage
- Californian Bearing Ratio (CBR) determined with dynamic method
- Resistance to frost – frost heave

- Bending strength
- Compressive strength
- Shear strength testing in direct shear apparatus
- Triaxial tests.

2.2. Laboratory tests of samples taken in the field

Samples for laboratory tests were taken from the hydraulic cut-off wall on the right-side section of the flood bank of the Vistula river, in the proximity of the village Samocice. The cut-off wall was constructed in 2007 from grout based on clay from Bełchatów. The cut-off wall, at the level of the body of the embankment, was constructed with use of the DSM method, and below, down to the impermeable layer of the subsoil, with use of low-pressure injection method. Testing material was taken from the pit situated next to the cut-off wall constructed with use of DSM method, in the upper part of the bank. On the 22.02.2008, the soil adjacent to the diaphragm was uncovered, as well as the wall of the cut-off wall. From the wall of the embankment body, on three levels (from the depth of 0.3, 0.7 and 1.3 m below ground level), 32 undisturbed samples were taken, each of the volume of 100 cm^3, and from the diaphragm 25 undisturbed samples, of the volume of 100 cm^3, 2 samples of the volume 785 cm^3 and 4 samples of the volume of 1 886 cm^3, were collected.

The detailed scope of the tests is presented below.

Undisturbed samples and natural moisture samples, taken and kept in steel cylinders, were subjected to the following tests:

- basic physical parameters (bulk density, particle density, water content, maximum dry density – Proctor compaction test, density index)
- filtration
- soaking collapsibility
- shrinkage
- resistance to frost – frost heave
- shear strength tests in direct shear apparatus.

The tests concerned both the injection material taken from the central part of the cut-off walls constructed in the selected section of the bank, and the soil itself, as well as the transition zone, consisting of a mixture of soil and injection grout.

3. METHODOLOGY OF THE TESTS AND PREPARATION OF SAMPLES

3.1. Laboratory tests

3.1.1. Preparation of medium sand and loamy sand mixtures with injection grout

Injection grouts were prepared according to the formula developed by PRGW*. The injection material consisted of medium sand or dusty sand, and 10, 25, 50 or 100% addition of two grouts produced either from clay from Bełchatów or from sludge from Bolesławiec. The mixture was produced by means of adding, to the given medium or loamy sand mass, a definite weight percentage of one of the two grouts. The material, that contained 10 and 25% of the grout, had a plastic consistency, so the samples were formed by means of light kneading in the sampler. Mixtures that contained 50 and 100% of the grout and pure injection grouts had a liquid state, so that they were poured into the samplers.

The specific mixtures, after forming, were kept in closed samplers in bags made from PELD foil, for 48 hours. Only after that period hardened samples were pushed out of the samplers and locked in double plastic bags, where they were kept without access to air. Only in case of samples prepared for the test of Californian Bearing Ratio (CBR_d) using dynamic method (light drop weight tester with CBR device), the formed samples remained in steel cylinders that are part of the test equipment, until starting the test, One group of the samples was maturing tightly closed in double plastic bag (without access to air), and the other one was immersed in water.

3.1.2. Tests of basic physical parameters

The tests of physical parameters of the soils were conducted in compliance with polish standard PN-88/B-04481 Building soils. Testing of soil samples. The granulometric composition was determined with use of the sieve method and hydrometric method. The moisture content of the soil samples was determined with use of the dryer method, with a minimum of 24 h drying in the temperature of 105°C.

* geological company – leader of the project

3.1.3. Filtration tests

Soil samples for testing of the coefficient of permeability (k) were taken to measurement cylinders (undisturbed samples) or, like samples of mixture, were formed in samplers. We used cylinders of 785 cm^3 volume (cylinders of the height of 100 mm and inside diameter of 100 mm) and cylinders of 1 886 cm^3 volume (cylinders of 50 mm height 2 and inside diameter of 98 mm). Samples taken in the field were tightly wrapped in several layers of foil. Mixtures of medium and loamy sand with the grout, in case of 10 and 25% grout addition, were formed in samplers, by means of thorough mixing, and the others were poured into containers. Each time the bulk density (ρ) and moisture content (w) were controlled. The maximum dry densities (ρ_s) of ingredients and mixtures were also determined. Samples of mixtures, that shrank in the maturing process, were sealed, on the whole surface of contact between the sample and the cylinder in which the permeability tests were conducted, with use of polymer glue.

The tests of water permeability were conducted in a specially constructed filtration apparatus (Fig. 1). It consists of two galvanized steel plates with fitted flanges. The measurement cylinder containing the undisturbed sample or sample formed in laboratory is placed between the plates. In both plates a shallow pit with the same, as sample, diameter had been milled off, in which non-woven filtration geotextile was placed. This enables water supply to the whole surface of the cross-section of the sample, as well as free outflow of water from the whole surface of the sample. The contact surfaces between the end plates and edges of the cylinders containing the samples were precisely adjusted, which ensured the required leakproofing after the apparatus was assembled. In the central parts of both plates, gauges were installed in order to enable cutting off the flow. The lower plate is connected with a Mariott bottle by an elastic hose, and water from the upper one flows to the measurement cylinder.

Measurements were made at hydraulic gradient ranging from 2 to 17, depending on the type of soil or mixture. Prior to the measurement, water was flown through the sample for at least 48 h. For each sample 5–10 measurements were made, and extreme values were rejected. Distilled water was used for the tests. For each measurement, the following parameters were recorded: volume of water (V_w – cm^3), hydraulic gradient (i), measurement time (t – s) and water temperature (T – °C). The resulting values of coefficient of permeability (k_T) were then calculated to determine the coefficient of permeability at 10ºC (k_{10}).

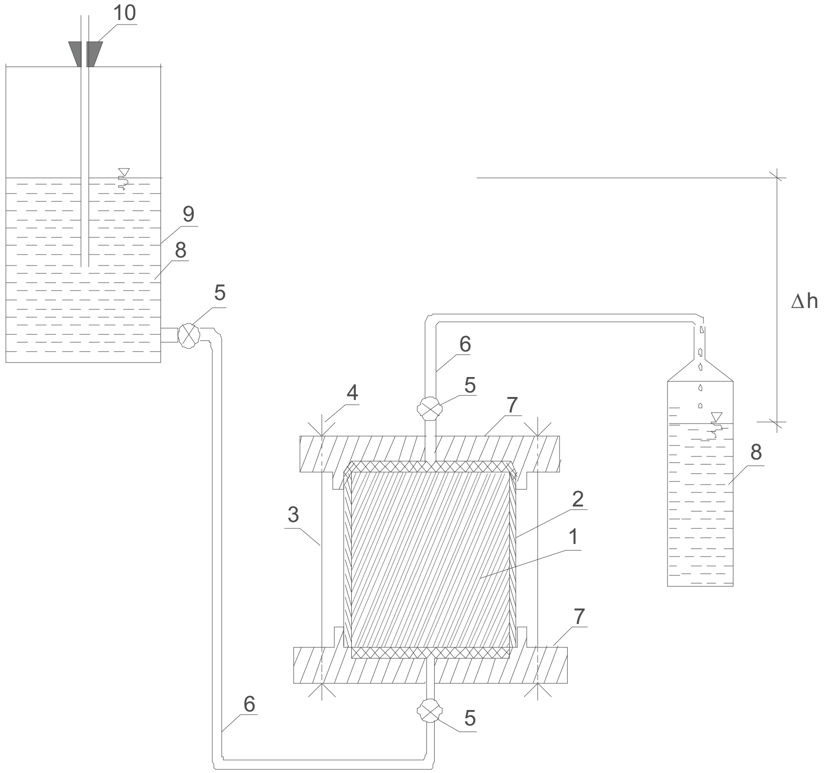


Fig. 1. Scheme of the filtration test device. 1 – sample, 2 – cylinder, 3 – screws, 4 – screw caps, 5 – gauge, 6 – rubber hose, 7 – steel plate, 8 – measurement cylinder, 9 – Mariott bottle, 10 – plug

3.1.4. Tests of soaking collapsibility

The soaking collapsibility test was conducted in Endell's hydrometer (Fig. 2). A basket loaded with shots is attached to the bottom of the open-top measurement cylinder of a diameter of 30 mm and height of 450 mm. The sample is put into the basket, and then the whole apparatus is immersed in a cylinder filled with water. Samples tested for the soaking collapsibility were formed in the shape of cylinders, of a diameter of 38 and 40 mm high, and had water content w_z as during compaction or were in air-dry state w_{sps} (the samples with water content w_z were compacted and then left in room temperature to dry). The subsequent positions of the hydrometer in time allow to determine the loss of weight of the sample. The course of soaking is presented on a semi-logarithmic scale. Basing on the course of soaking, the time of disintegration of a defined percent of sample mass is determined. Time $t_{50\%}$, i.e. the time, which after 50% of the sample mass had been disintegrated, was assumed as a conclusive to analyse the soaking collapsibility of a soil of known dry bulk density ρ_d and initial water content w_z or w_{sps}.

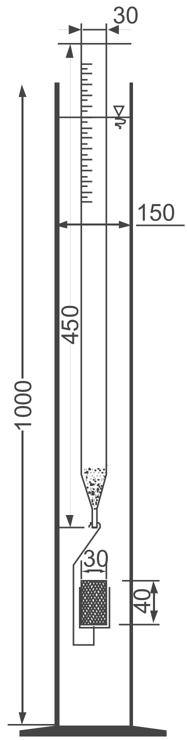


Fig. 2. Endell's hydrometer

3.1.5. Shrinkage test

The test was conducted for both types of injection material (i.e. those containing clay from Bełchatów, as basic ingredient, or those containing sludge from Bolesławiec). Also, injection mixtures with medium-grained sand and loamy sand containing 10, 25, 50 or 100% of grout in relation to the amount of sand, were prepared for the tests. Samples of grouts or of mixtures containing high amounts of grout, 50 and 100%) were formed by means of pouring the injection grout or mixture into metal samplers of known volume. The remaining samples, due to their plastic consistency, were lightly kneaded in samplers. The value of shrinkage of the samples of specific soils and mixtures was determined on the basis of measurement of the height and diameter of cylindrical samples, whose initial diameter was 47 mm and initial height – 55 mm. In order to enhance the accuracy of shrinkage measurement, new samplers were used. After having dried to air dry state, the diameter of the sample was measured twice with 0.1 mm accuracy, at three cross-sections along the height, and sample's height at two cross-sections.

3.1.6. Test in direct shear apparatus

The tests were conducted in a direct shear apparatus – in a 60x60 mm box. A box of this size can be used for testing soils that contain no more than 5% (by weight) of 2–4 mm fraction. The apparatus was produced in the Jagielloński University and it guarantees sufficient measurement accuracy and maintaining adequate parameters of the test (measurement of the shear force and normal force, with measurement error, in recalculation, not higher than, 1 kPa and a mechanical drive of constant displacement speed with ± 0.015 mm/min precision for the speed 0.05 mm/min). The samples were 15–18 mm high. The vertical force remained constant during single shear, and the value of the force acting on the shearing plane was determined by measuring of the proving ring deformation. The measurement was made with use of a dial gaugewith 0.01 mm accuracy.

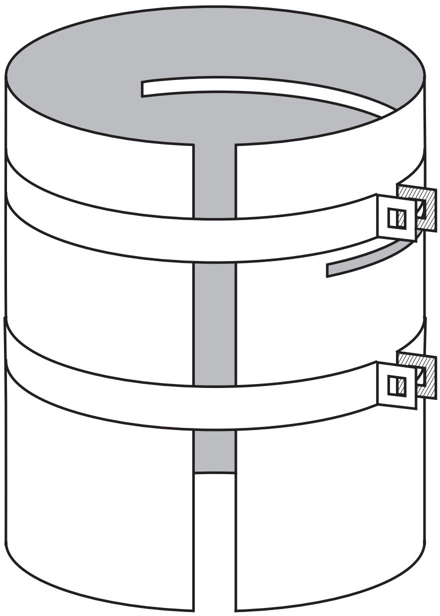


Fig. 3. Cylinder for cutting samples

Both types of grouts, as well as their mixtures with medium sand were tested. The samples were prepared in steel cylinders of a diameter and height of 100 mm. After the grout has hardened, a "disc", that was slightly higher than the height of the sample in direct shear apparatus, was cut off. Due to the fragility of the material, the cylindrical sample was placed inside a PVC pipe, cut longitudinally and across (Fig. 3) at approx. 18 mm from the top edge. Then, the pipe was pressed by two clasps, in order to fix the sample. The cut across, reaching a little bit more then half of the diameter, formed a guideline for the cutting. After the sample had been cut on one side, it was rotated by 180°, in order to cut it through at full width. From a round "slice" prepared in this manner, a sample was cut out, with use of a square frame. Then the sample was placed in the box of the direct shear apparatus. The upper and lower parts of the box were connected by screws that prevented them from changing their positions against one another during the preparation of the test. After mounting the box on the plate of the apparatus, connecting the drive and applying vertical load, the protection screws were removed and the test began. Because of the bonds created by the presence of binder in the tested material, for each new vertical stress a new sample was prepared.

Mixtures of two types of injection material were tested – grout on the base of Bełchatów clay and grout containing sludge from Bolesławiec, whose formula was developed by the enterprise coordinating the tests – Przedsiębiorstwo Robót Geologiczno-Wiertniczych from Sosnowiec. Grouts were mixed with medium-grained sand with 10, 50 and 100% of grout to soil ratio (by weight), (respectively 1:10, 1:2, 1:1 grout to soil ratio). The groutt itself was also tested.

3.1.7. Bending and compressive strength

For the tests of bending and compressive strength, we used the same devices and forms as are usually applied for the testing of bending strength of cement mortar beams according to PN-EN 196-1:2006 standard, with slight modifications based on the results of similar experiments carried on samples of cohesive soils, which are significantly weaker than cement mortar samples [Quandt 2000]. The dimensions of beams prepared for tests were equall 40x40x160 mm. Two injection materials were tested. The main component of the first one was clay from Bełchatów, in the other material sludge from Bolesławiec was used. The detailed formula of the grout was prepared by Przedsiębiorstwo Robót Geologiczno-Wiertniczych G. Janik & R. Kuś S. J. Apart from samples of grout, mixtures were prepared, consisting of grout and medium sand in the proportion 1:1 (100% weight of inject proportionally to the amount of sand), 1:2 (50% weight of inject proportionally to the amount of sand), 1:4 (25% weight of inject proportionally to the amount of sand) and 1:10 (10% weight of inject proportionally to the amount of sand). The samples matured at the temperature of 20°C in tightly sealed bags made from polyethylene foil. At the moment of testing they were at least 28 days old.

Initially, bending tests were conducted in a hydraulic press for testing of cement mortar beams of the same size. The beam was supported on its whole width, at two places 100 mm apart. In the standard test of cement mortar specimens the beam is subjected to a force applied at half its length, but in order to achieve the maximum bending moment at a longer length, similarly to Quandt [2000] we applied two forces, each at 1/3 of the length. The plan of the test is shown on Figure 4.

Due to low resistance of the samples, similar to the case of testing the bending strength of cohesive soils, the sample was placed between two flat sheets of steel (0.5 mm). The surface of the sheets was lubricated with silicone lubricant in order to reduce friction, and covered with thin polypropylene foil. The calculated bending strength was taking into account the stiffness of steel sheet layers. The view of the sample in the hydraulic press is shown in Photo 1.

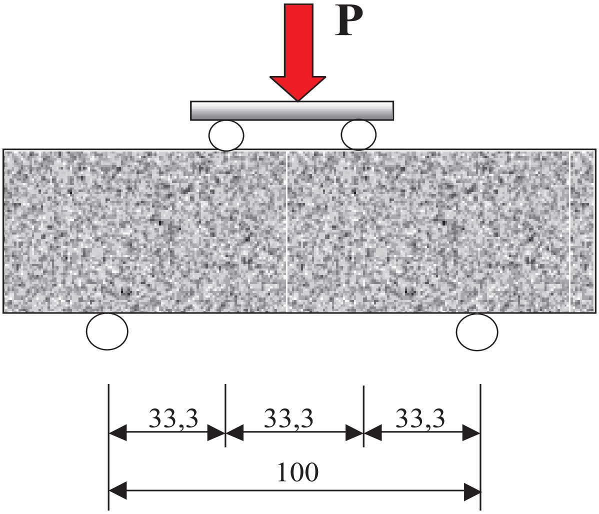
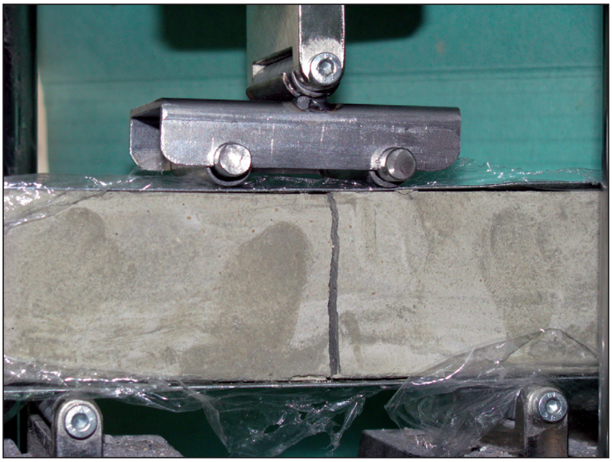
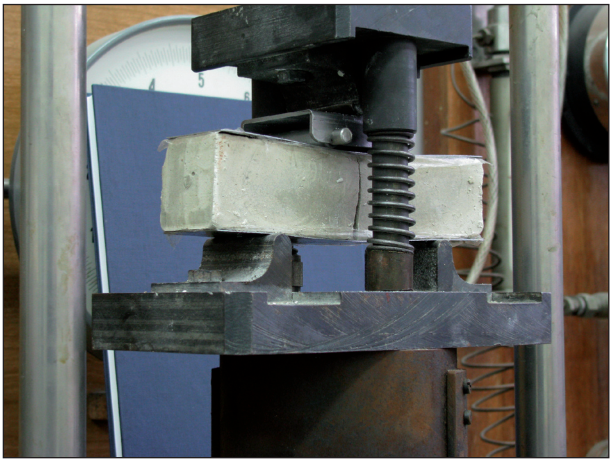


Fig. 4. Plan of the supports and applied force location during the test of bending strength



Phot. 1. The view of the sample in the hydraulic press after the end of the test

After the first series of tests was completed, it was found, that the bending strength of samples containing a small amount of grout was too low to be determined in a press used for testing much stronger cement mortar beams. The beams were destroyed very quickly, and the values of forces were nearby or below the limits of measurement range of the hydraulic press. Because of that, the subsequent series of tests were conducted in an appropriately adapted triaxial compression apparatus (Phot. 2). This solution permitted to make much more accurate readings of the destructive force, especially in the low value range, and to control the speed of deformations increase more precisely. The apparatus chamber was replaced by a steel pipe supplementary element supporting a standard set for testing the bending strength, to whose top surface the force was applied. The value of the force was read on the basis of indications of the dial gauge, which measured the deformation of the proving ring.



Phot. 2. Test of bending strength with use of the triaxial compression apparatus

After the test of bending strength, both parts of the broken sample (Phot. 3) were subject to test of compressive strength. Also in this case, the strength of the weaker samples proved to be below the lower limit of the measurement range. Due to that, the force sensor, that stopped further compression by showing the maximum value of the compressing force, did not detect the moment of destruction. Thus, the measurement of compressive strength of weaker samples can be quite inaccurate, as the moment of destruction was determined visually, and at that point, beyond the functioning of automatics, the value of the force was read. During the analysis of the results of the tests of compressive strength, values that significantly diverged from the mean were rejected.

Each test of beam's bending strength was performed twice for each proportion of medium sand and injection material. In case of grout containing clay from Bełchatów, one series was tested in hydraulic press, and the other with use of the triaxial compression apparatus, whereas both series of samples containing sludge from Bolesławiec, as they were much weaker, were tested only in the modified triaxial compression apparatus.

Phot. 3. View of the fractured sample after the test of bending strength

3.1.8. Triaxial tests

As complementary tests shearing strength tests in triaxial apparatus were conducted. Only mixtures of medium sand with grout containing clay from Bolesławiec in the proportion 1:1 (100% weight of inject in relation to the weight of sand) and loose sand without grout were tested. Samples containing injection material were prepared in steel cylinders of a diameter and height of 100 mm and then, after they were removed from the cylinder, smaller samples for the triaxial tests were cut out in a typical device used for the preparation of samples from cohesive soil (Phot. 4), having a diameter of approx. 38 mm and the approximate height of 78 mm. Due to higher resistance during the forming of samples containing inject than in the case of soil, a sharp knife was used to remove excess material, instead of a steel string placed on a frame. Samples taken from the remaining material were used to determine water content of the soil or mixture.

Phot. 4. Device used for forming samples

The prepared samples were measured and weighed, and then they were placed on the pedestal of the apparatus. A cylindrical element transmitting the load was put on the top. On the outside, a rubber membrane was placed, sealed at the bottom and at the top with two rubber rings. After that, the chamber of the apparatus was filled with water. A piston was put inside from the top and connected with a semi-circular ending of the proving ring equipped with a dial gauge ensuring 0.01 mm measurements accuracy. A separate gauge of identical measurement accuracy measured the vertical movements of the sample. The speed of vertical movements of the base of the chamber equalled 8 mm/h, which was similar to the shearing speed adopted for the direct shear tests. The real velocity of deformation of the sample was slightly lower due to the deformations of the proving ring, which were taken into consideration during the analysis of the test results. The chamber was connected to an electronic pressure controller that provided stable pressure during the whole time of the test. The tests were conducted at three values of pressure in the chamber – 12.5, 25 and 50 kPa. The test started after the application of pressure and the setting of gauges. The sample was not subjected to consolidation, and during the test a valve for pore water was open, enabling potential outflow of water from the sample (Phot. 5).

Phot. 5. Sample of medium sand after the test in the triaxial compression apparatus

The test results were analysed using the $K_{f,}$ line determined with use of the method of smallest squares, and on that basis the parameters of the Mohr's circles envelope were determined, i.e. the angle of internal friction (Φ) and cohesion (c). This is schematically presented on Figure 5. The following formulas were used for calculations:

$$\sin(\Phi) = tg(\alpha) \Rightarrow \Phi = \arcsin(\Phi)$$
$$c = d / \cos(\Phi)$$

Strength parameters were determined on the base of the stress deviator maximum values.

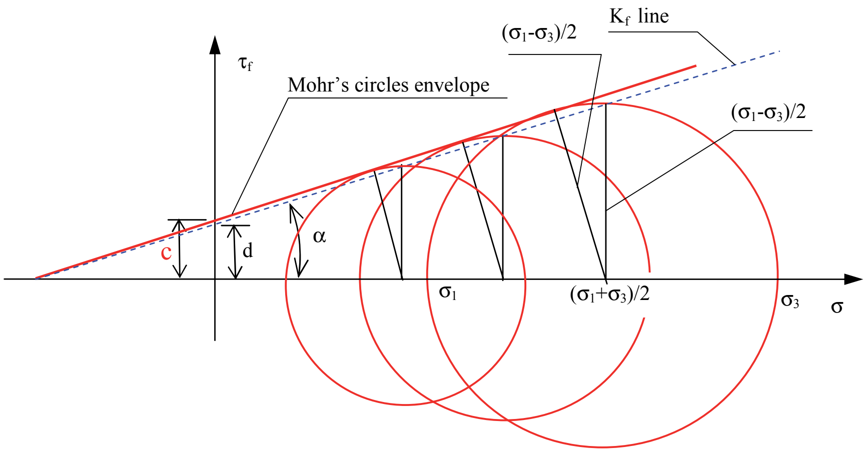


Fig. 5. Scheme of method for K_f line determination

3.1.9. Frost heave – resistance to frost

The sensitivity and susceptibility of soils to frost, in literature referred to as frost heave, or sometimes frost resistance (German: Frosthebung), is a phenomenon that is very difficult to describe, and it is not easy to determine precisely whether we are dealing with soils that are sensitive to frost or soils that are not. Most of the methods that enable evaluation use very simple indicators, which often prove unreliable. The best results are achieved with use of equipment that reflect the actual phenomenon of freezing.

All studies modeling the phenomenon of freezing adopt similar principles, i.e. freezing the soil sample from the top, lateral insulation and water flow to the sample only from the bottom direction. In order to determine frost heave we used the apparatus designed by Transport and Road Research Laboratory TRRL in the UK, that enables to conduct the tests in compliance with the British standard (BS.812,1989).

The basis of the apparatus is a tight cooling chamber, equipped with a temperature controller that allows to control the temperature in the range from – 10 to – 30°C. The adopted research methodology uses a specified freezing temperature of -17°C. Inside the chamber, a container with water is placed. The temperature of water during the test must range from 3 to 4.5°C. There is a plate above the container, in which eight prepared samples of soil are placed. Each sample is placed in a container and put on a perforated base immersed in water (open soil-water system), which enables free capillary rise in samples. The space between the samples of tested soil is filled with sand, up to the upper edge of the sample. The plan of the apparatus used for tests is presented in Figure 6.

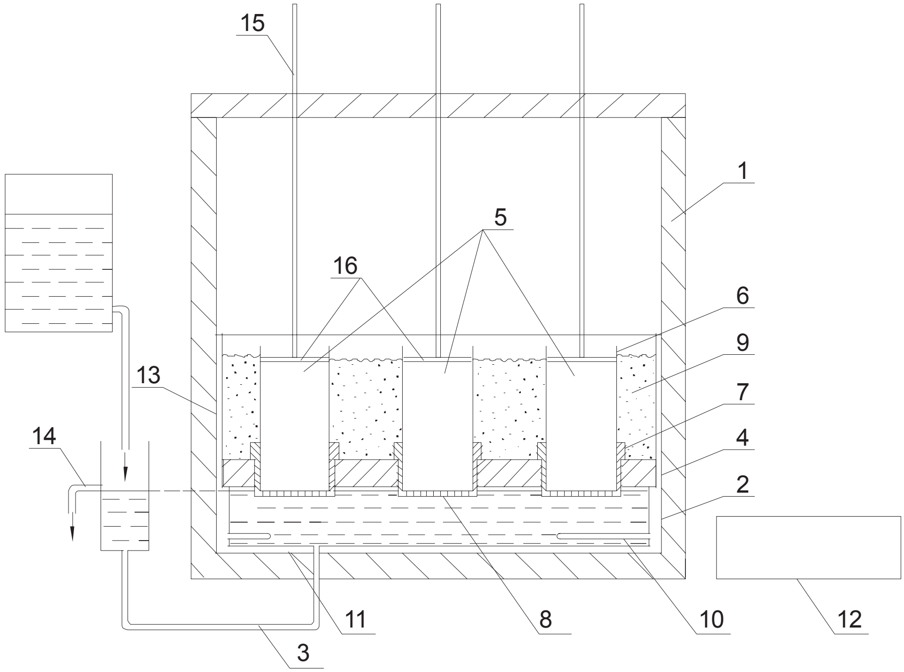
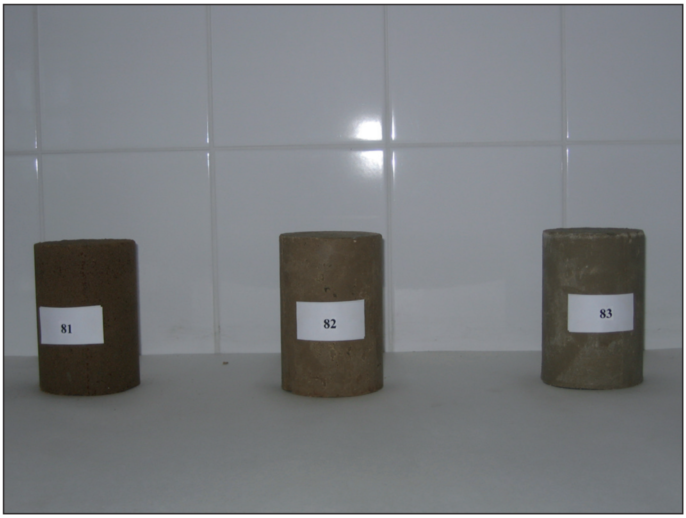


Fig. 6. Plan of the apparatus for testing the frost heave of soils
1 – cooling chamber; 2 – container with water; 3 – compensation container; 4 – wooden board with openings for the samples; 5 – sample of soil; 6 – foil; 7 – sample container; 8 – perforated basis; 9 – gravelly sand; 10 – heater; 11 – temperature sensor; 12 – temperature controller; 13 – steel sheet case; 14 – outflow; 15 – measurement pole with scale in milimeters; 16 – cork base

The aim of the apparatus is to follow the process of soils heave during freezing and to model various initial conditions, what allows to describe this process in quantitative and qualitative terms. The apparatus enables to determine the frost heave of any soil or other granular material in laboratory conditions. The test allows to assess the susceptibility of soil to freezing on the basis of the increase in height of frozen samples Δh expressed in milimeters. According to this criterion, soils, whose samples increase in height is below 9 mm after 4 days of testing, are not susceptible to frost heave, soils samples showing increase by 9–15 mm are questionable, and if the increase exceeds 15 mm, the soil is classified as susceptible to frost heave.

Samples used in the tests (Phot. 6) had the diameter of 101.6 mm (4 inches) and the height of 152.4 mm (6 inches). The samples were formed in a tripartite cylinder (Phot. 7), that was selected to avoid any deformations and porosity changes that often occur during the pressing of samples out. All tests were repeated three times, and the evaluation of frost heave took into consideration the largest recorded increase of frost heave, as potentially the most dangerous.



Phot. 6. Samples of soil mixtures prepared for frost heave tests

Phot. 7. Tripartite cylinder used for the forming of soil samples

Data related to samples:

- Samples were prepared from soils of damaged structure. Samples' composition is presented in Table 1. Injects on the basis of clay from Bełchatów and sludge from Bolesławiec were tested, as well as their mixtures with medium sand and loamy sand and additions such as cement and water-glass, with various proportions of used ingredients.
- Tested soils and mixtures of soils and injects were compacted in order to achieve density similar to that achieved in the field at specific initial water contents.
- All soils and mixtures were tested after 7 and 42 days of maturing in temperature of approx. 20°C, protected from loss of moisture.
- Parameters and conditions of the test:
- Time of the test – 4 days (96 hours).
- Constant freezing temperature of – 17ºC.
- Possibility of constant, free capillary rise from the bottom container (open soil-water system).
- Temperature of water in the container that was in contact with the samples: +4ºC. Constant temperature controlled by thermostat.
- Propagation of the freezing temperature zone from top to bottom of the sample.
- Space between samples was filled with coarse sand.

Table 1

Basic composition of mixtures used in the tests

No.	Basic ingredient	Type of soil	Addition 1	Addition 2
1.	Clay from Bełchatów	–	Cement	Water-glass
2.	Clay from Bełchatów	Medium sand	Cement	Water-glass
3.	Clay from Bełchatów	Loamy sand	Cement	Water-glass
4.	Sludge from Bolesławiec	–	Cement	Water-glass
5.	Sludge from Bolesławiec	Medium sand	Cement	Water-glass
6.	Sludge from Bolesławiec	Loamy sand	Cement	Water-glass

3.1.10. Californian Bearing Ratio (CBR_d) determined with dynamic method

Due to a very big number of samples to be tested, and the need to keep the formed samples (mixtures of medium sand and loamy sand with two types of grout: clay from Bełchatów and sludge from Bolesławiec) in the measurement cylinder for the whole maturing period, the measurements of Californian Bearing Ratio (CBR) were conducted after 14 days of maturing of samples. The measured samples matured in water and in conditions without access of air and water.

As the method of applying load on a sample in a case of light drop-weight device ZFG (dynamic method) is different from the classic method that consists in pushing the piston at standardized speed, we determined, for comparative purposes, the Californian Bearing Ratio for medium sand and loamy sand in a state of compaction achieved in compliance with the most common standard sample preparation procedure for CBR tests, according to polish standards BN-70/893105 and PN-S-06102.

The samples were formed in a steel cylinder of the diameter d=150 mm and the height of 175 mm, following the same procedure as for CBR standard tests (BN-70/893105 and PN-S-06102), and then they were put into foil bags. After two days of hardening of the sample, the full bottom of the sampler was replaced with a perforated bottom with filtration paper, and load was applied on the top surface of the sample (stresses applied to the sample – 19.6 kN/m^2). Some of the samples were immersed in water for the period of 14 days ("wet sample"), and the other formed samples hardened without access to air or water ("dry samples"). Prior to the measurement of CBR, they were immersed in water for 4 days.

Samples prepared according to the procedure described above were penetrated with a piston of 20 cm^2 area, that was hit by a weight of 10 kg mass, falling from the height of 0.70 m (Phot. 8).

Phot. 8. Light drop-weight device ZFG for determing the Californian Bearing Ratio with dynamic method

3.1.11. Column tests

The objective of these tests was to model penetration of injection grout into the soil and to evaluate the degree of saturation with inject in various zones. The column, made from a PVC pipe of the diameter of 0.30 m and the height of 1.20 m, was filled with medium sand. Inside, along the axis of the column, an injection lance of 20 mm diameter with 10 mm diameter openings was placed. The grout was delivered by gravity from an external container.

3.2. Field tests

As the methodology of preparation and conduct of the tests of samples collected in the field was usually the same as in case of samples prepared in the laboratory, which was described in ction 3.1, in this section we will only point out those elements that were different.

3.2.1. Tests of physical parameters

The tests were conducted in compliance with the standard PN-88/B-04481 and the description section 3.1.2.

3.2.2. Tests of soaking collapsibility

The tests were conducted in compliance with the description in section 3.1.4.

3.2.3. Strength testing in direct shear apparatus

The apparatus and the parameters of the test were described in section 3.1.6. The specimens were cut out from the collected core with use of a steel frame of a square cross-section and the size 60x60 mm. The excess material was removed with a sharp knife. In the case of non-cohesive soils the lower part of the sample was protected with foil for transport. Then the sample was placed in the box of the direct shear apparatus, whose upper and lower parts were connected with screws that prevented them from moving during the preparation of the test. After mounting the box on the plate of the apparatus, connecting the drive and applying the vertical weight, the protective screws were removed and the test began. In most of the cases 2 series of tests were conducted for specimens cut from a collected undisturbed sample core. Each series encompassed shearing at 4–5 different vertical stresses. The initial stress was selected so, that it was similar to the original stresses at the depth, which from the sample had been collected.

3.2.4. Frost heave tests

The frost heave tests of samples collected from the cut-off wall of the flood bank in Samocice were conducted in the same way as described in section 3.1.9.

4. TEST RESULTS

4.1. Results of laboratory tests

4.1.1. Results of tests of basic physical parameters

The physical parameters of the soil were tested according to the description in section 3.1.2. The results of these tests, including bulk density, water content, maximum dry density, particle density and the coefficient of permeability, are presented in Tables 2–4. An analysis of grain size distribution of all tested materials, i.e. medium sand, loamy sand, inject based on clay from Bełchatów and inject based on sludge from Bolesławiec was conducted, too (Fig. 7). Porosity and void ratio was determined. In the case of medium sand the tests also covered the determination of the maximum and minimum void ratio.

Table 2

Basic physical parameters of medium sand and its mixtures with inject

No.	Sample	ρ	w	ρ_d	ρ_s	n	e	k
		[g/cm³]	[%]	[g/cm³]	[g/cm³]	[-]	[-]	[cm/s]
1	2	3	4	5	6	7	8	9
		MEDIUM SAND						
1.	**Medium sand, loose**	1.541	1.20	1.523	2.65	0.42	0.72	9.01E-03
2.	**Medium sand, loose**	1.551	1.20	1.533	2.65	0.41	0.71	8.95E-03
3.	**Medium sand, compacted**	1.796	1.20	1.775	2.65	0.32	0.48	5.83E-03
4.	**Medium sand, compacted**	1.785	1.20	1.764	2.65	0.33	0.48	5.48E-03
		MEDIUM SAND WITH THE ADDITION OF INJECT BASED ON CLAY FROM BEŁCHATOW						
1.	**Medium sand + 10% clay Bełchatów**	1.797	10.12	1.632	2.651	0.38	0.62	8.51E-03
2.	**Medium sand + 25% clay Bełchatów**	1.905	13.72	1.675	2.653	0.37	0.58	1.57E-06
3.	**Medium sand + 50% clay Bełchatów**	1.961	27.98	1.532	2.655	0.42	0.73	1.12E-06
4.	**Medium sand + 100% clay Bełchatów**	1.718	49.15	1.152	2.659	0.57	1.31	5.88E-07

Table 2 cont.

1	2	3	4	5	6	7	8	9
		MEDIUM SAND WITH THE ADDITION OF INJECT BASED ON SLUDGE FROM BOLESŁAWIEC						
1.	**Medium sand + 10% sludge Bolesławiec**	1.648	3.77	1.588	2.656	0.40	0.67	1.12E-02
2.	**Medium sand + 25% sludge Bolesławiec**	1.819	9.87	1.656	2.664	0.38	0.61	1.80E-03
3.	**Medium sand + 50% sludge Bolesławiec**	2.032	20.69	1.684	2.717	0.38	0.61	4.28E-06
4.	**Medium sand + 100% sludge Bolesławiec**	1.948	35.36	1.439	2.694	0.47	0.87	1.12E-05

Table 3

Basic physical parameters of loamy sand and its mixtures with inject

No.	**Sample**	**ρ**	**w**	**ρ_d**	**ρ_s**	**n**	**e**	**k**
		[g/cm³]	**[%]**	**[g/cm³]**	**[g/cm³]**	**[-]**	**[-]**	**[cm/s]**
		LOAMY SAND						
1.	**Loamy sand before compaction**	1.282	8.30	1.184	2.67	0.56	1.26	1.76E-04
2.	**Loamy sand before compaction**	1.294	8.28	1.195	2.67	0.55	1.23	1.82E-04
3.	**Loamy sand after compaction**	2.075	8.12	1.920	2.67	0.28	0.39	5.45E-07
4.	**Loamy sand after compaction**	2.125	8.15	1.965	2.67	0.26	0.36	5.10E-07
		LOAMY SAND WITH THE ADDITION OF INJECT BASED ON CLAY FROM BEŁCHATÓW						
1.	**Loamy sand + 10% Bełchatów clay**	1.898	6.38	1.784	2.671	0.33	0.50	1.39E-03
2.	**Loamy sand + 25% Bełchatów clay**	2.024	14.93	1.761	2.671	0.34	0.52	3.31E-05
3.	**Loamy sand + 50% Bełchatów clay**	1.954	26.79	1.541	2.672	0.42	0.73	3.94E-06
4.	**Loamy sand + 100% Bełchatów clay**	1.903	49.02	1.277	2.674	0.52	1.09	8.98E-07
		LOAMY SAND WITH THE ADDITION OF INJECT BASED ON SLUDGE FROM BOLESŁAWIEC						
1.	**Loamy sand + 10% Bolesławiec sludge**	1.853	9.19	1.697	2.675	0.37	0.58	3.09E-03
2.	**Loamy sand + 25% Bo-lesławiec sludge**	1.971	10.58	1.782	2.682	0.34	0.51	2.92E-05
3.	**Loamy sand + 50% Bolesławiec sludge**	2.032	20.69	1.684	2.717	0.38	0.61	4.28E-06
4.	**Loamy sand + 100% Bolesławiec sludge**	1.889	30.12	1.452	2.728	0.47	0.88	1.67E-05

Table 4

Basic physical parameters of injects

No.	Sample	ρ	w	ρ_d	ρ_s	n	e	k
		[g/cm³]	[%]	[g/cm³]	[g/cm³]	[-]	[-]	[cm/s]
		INJECT 100 %						
1.	**Inject on the base of clay from Bełchatów**	1.279	202.36	0.423	2.686	0.84	5.35	6.08E-07
2.		1.244	201.12	0.413	2.686	0.85	5.50	6.18E-07
3.	**Inject on the base of sludge from Bolesławiec**	1.696	100.21	0.847	2.788	0.70	2.29	8.12E-06

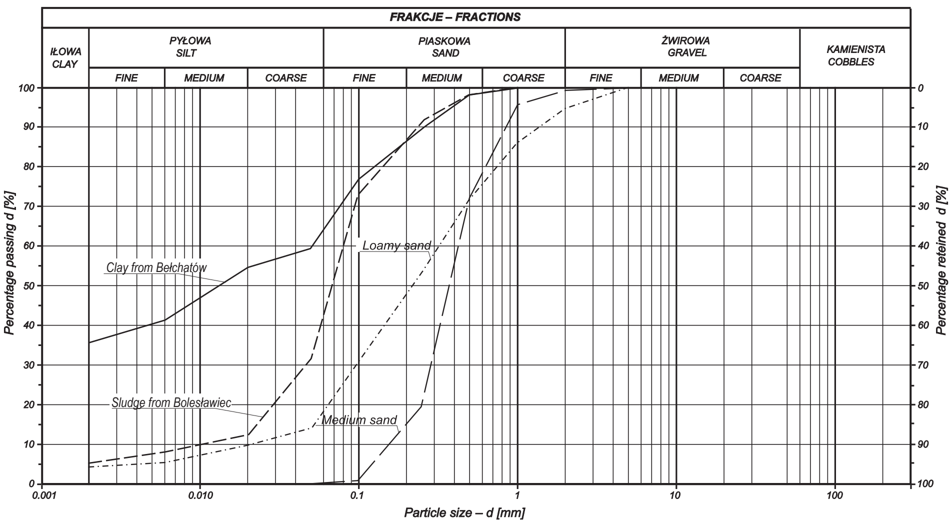


Fig. 7. Curves of grain size distribution for sludge from Bolesławiec (granulation equivalent to dusty sand), clay from Bełchatów, medium sand, and loamy sand (P_g – loamy sand, P_g – medium sand)

In case of mixtures of loamy sand and inject based on the sludge from Bolesławiec a significant correlation ($R^2 = 0.71$) can be observed between the maximum dry density and the amount of inject added to the mixture. It becomes even more notable in case of mixture of loamy sand with inject based on clay from Bełchatów. A similar tendency, though not as obvious as in the case of the mixture of medium sand and sludge from Bolesławiec, can be observed in case of mixtures of medium sand with injects. These correlations show that the possibility of compaction of mixtures is limited in case of a larger percentage of inject addition (Fig. 8–10).

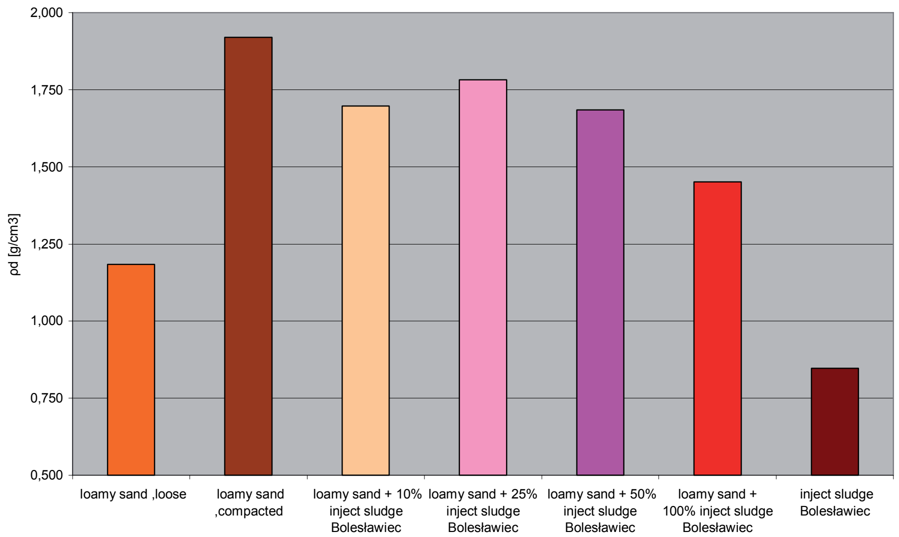


Fig. 8. Changes in maximum dry density ρ_d for loamy sand and its mixtures with inject based on sludge from Bolesławiec

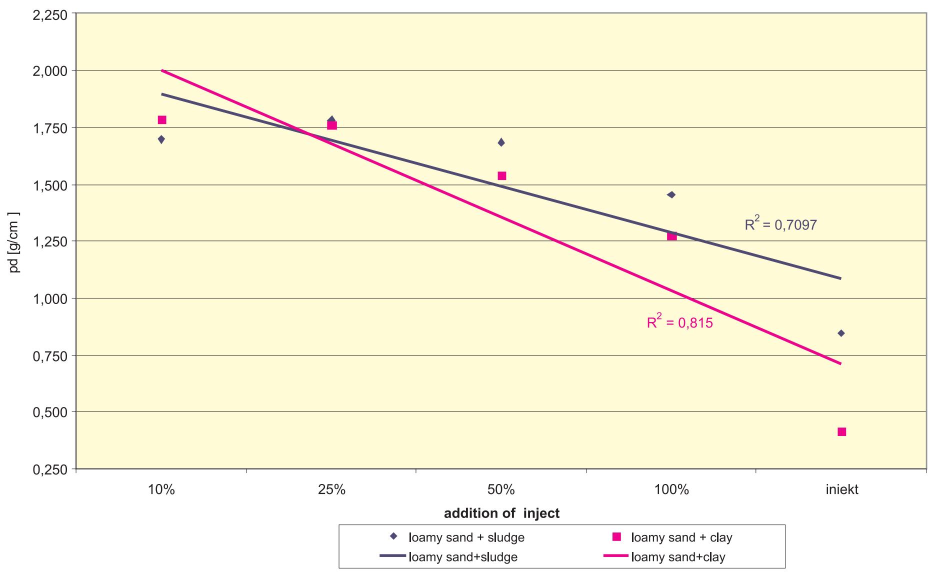


Fig. 9. Correlation between maximum dry density and the amount of inject in mixture (for loamy sand)

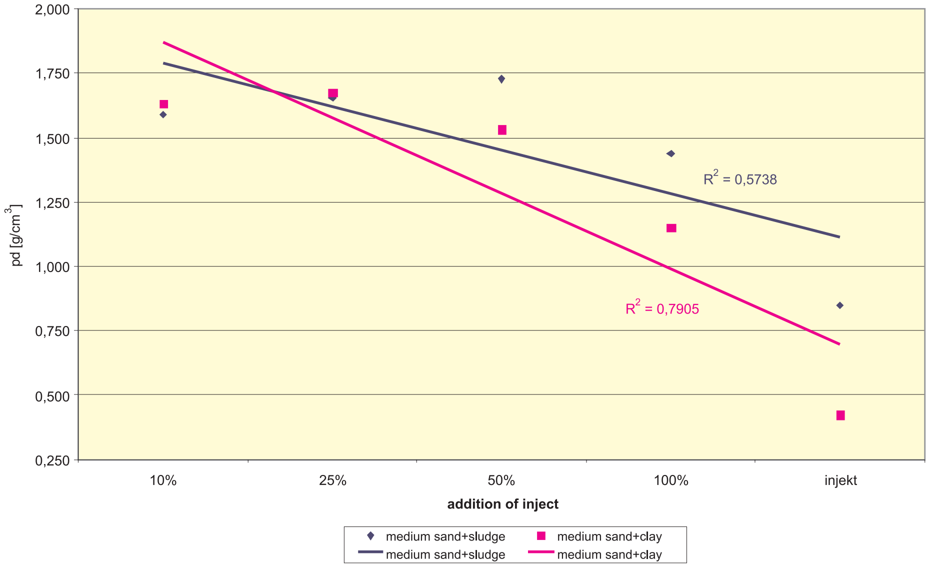


Fig. 10. Correlation between maximum dry density and the amount of inject in mixture (for medium sand)

4.1.2. Filtration tests

The results of the measurements of the permeability coefficient k (also called water permeability coefficient) of mixtures of medium sand and inject prepared on the basis of clay from Bełchatów show a large variability (Tab. 2–4). The coefficients of permeability of the mixtures were compared with the coefficients obtained for medium sand in two different states of compaction and with the coefficient of permeability determined for the injects themselves. (Fig. 11). It was determined, that 10% content of inject based on clay Bełchatów in the mixture with sand does not have a significant influence on the coefficient of permeability. The tests showed, that the value of this coefficient is even slightly lower for compacted medium sand than for the mixture of medium sand with 10% addition of inject. Just 25% addition of inject significantly influences reduction of soil permeability. In this case, the value of the coefficient of permeability is comparable with values characteristic for clays [Pazdro 1977]. A further increase of the amount of inject in mixtures with sand leads to a gradual, slight reduction of water permeability.

In order to determine the extent, in which the inject fills the spaces between grains of soil, the porosity of medium sand in specific mixtures was determined. As inject was mixed with dry sand, it can be assumed that the amount of sand contained in a volume unit equals its dry density. By determination of the volume of inject per volume unit, the extent, to which porous space is filled by the inject was determined (Tab. 5). It was proven that in case of 10 and 25% addition of inject the compaction of grain particles was equivalent to loose state of soil. The addition of larger amounts of inject leads to form a matrix consisting of grains of soil suspended in the injection material, which contact each other in smaller and smaller extent.

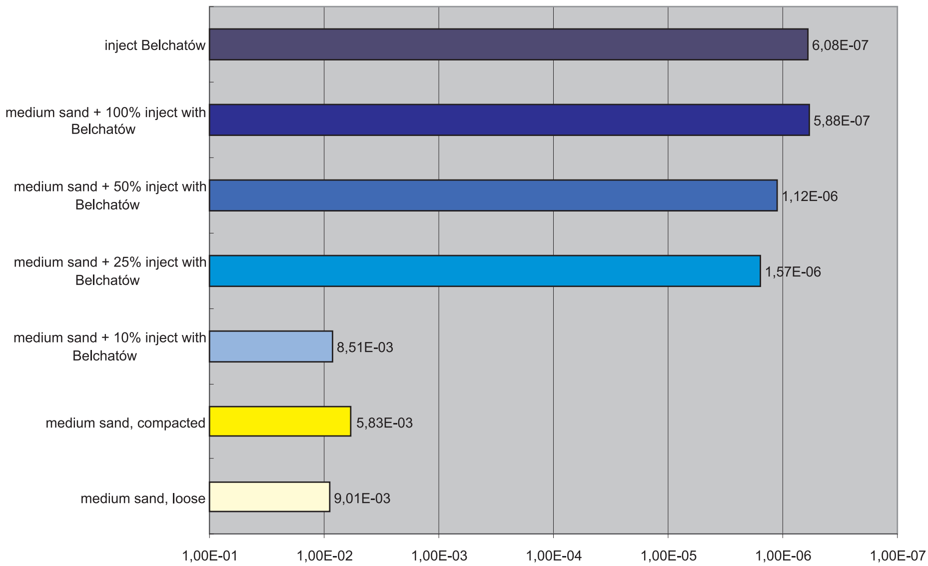


Fig. 11. Coefficients of permeability of medium sand and mixtures of medium sand with inject made with clay from Bełchatów

Table 5

Content of inject made with clay from Bełchatów in mixtures with medium sand

No.	Sample	ρ	Amount of inject	$\rho_{d\ of\ soil}$	n (of soil)	$\frac{V_{inject}}{V_{mixture}}$	$\frac{V_{inject}}{V_{pores}}$
		[g/cm³]	[g/cm³]	[g/cm³]	[-]	[-]	[-]
		MEDIUM SAND WITH ADDITION OF INJECT MADE WITH CLAY FROM BEŁCHATÓW					
1.	**Medium sand + 10% clay Bełchatów**	1.797	0.163	1.634	0.384	0.130	0.341
2.	**Medium sand + 25% clay Bełchatów**	1.905	0.381	1.524	0.425	0.302	0.71
3.	**Medium sand + 50% clay Bełchatów**	1.961	0.654	1.307	0.507	0.519	~1.0
4.	**Medium sand + 100% clay Bełchatów**	1.718	0.859	0.859	0.676	0.682	~1.0

Permeability coefficient tests proved, that yet 25% addition of inject causes a significant change in the coefficient value – by 3 orders of magnitude – in comparison with the coefficient of permeability of medium sand. By 25% inject addition approx. 70% of the spaces in the soil skeleton were filled. Such mixtures (medium sand with at least 25% inject) can be considered as practically impermeable in the conditions of flood banks rising the water level. By 50% addition of inject and by "half to half" mixtures (100% addition of inject) values of the coefficient are similar to those obtained for the inject based on clay from Bełchatów itself, because, as it can be seen in Table 5, the space between grains is completely filled with injection material.

A similar large variability occurs in case of mixtures of medium sand with injects based on a sludge from Bolesławiec. The addition of inject in the amount of 10% does not provide satisfactory results. It even causes a slight increase the of permeability coefficient value. It is probably a result of sand grains aggregation cemented by particles of inject, which amount is too small at this proportion, to create a structure, that would efficiently limit water filtration in the pores of the mixture. A significant change in the coefficient of permeability was achieved just by 50% addition of inject, when over 80% of the space between grains was filled (Tab. 6). The bulk density of the injection grout based on sludge from Bolesławiec is higher than in case of the application of clay from Bełchatów, thus the same weight proportion means a smaller volume of the addition, so at 25% content of inject the filling of the porous space reaches approx. 48 %, which proved to be an insufficient value to increase the tightness of the mixture. When the amount of injection material is further increased (50, 100%), the coefficient of permeability decreases gradually, proportionally to the inject's filling degree of space between grains of soil. For 100% addition of inject the value of the coefficient of permeability decreases nearly 3 orders of magnitude in comparison to that of medium sand itself. At the same time, a significant decrease in soil dry density is observed: from $\rho_d = 1.729$ to $\rho_d = 1.439$ g/cm^3 respectively for 50 and 100% addition of inject. In the analysed series, the lowest coefficient of permeability was noticed in case of the inject based on sludge from Bolesławiec itself, with very low dry density of its soil skeleton - $\rho_d = 0.847$ g/cm^3. The values of the coefficient of permeability measured for mixtures of medium sand with an addition of inject based on sludge from Bolesławiec in the amount of 50% and higher, can be compared to the values presented for loamy sand in various states of compaction, which permeability coefficient, according to various authors, is reaching values ranging from 1.00E-05 – 3.00E-07 cm/s [e.g. Czyżewski et al. 1973, Kollis 1966].

Table 6

Content of inject based on sludge from Bolesławiec in mixtures with medium sand

No.	Sample	ρ	Amount of inject	$\rho_{d\ of\ soil}$	n (of soil)	$\frac{V_{inject}}{V_{mixture}}$	$\frac{V_{inject}}{V_{pores}}$
		[g/cm³]	[g/cm³]	[g/cm³]	[-]	[-]	[-]
		MEDIUM SAND WITH ADDITION OF INJECT BASED ON SLUDGE FROM BOLESŁAWIEC					
1.	Medium sand + 10% sludge from Bolesławiec	1.648	0.150	1.498	0.435	0.088	0.203
2.	Medium sand + 25% sludge from Bolesławiec	1.819	0.364	1.455	0.451	0.215	0.476
3.	Medium sand + 50% sludge from Bolesławiec	2.032	0.677	1.355	0.489	0.399	0.817
4.	Medium sand + 100% sludge from Bolesławiec	1.948	0.974	0.974	0.632	0.574	0.908

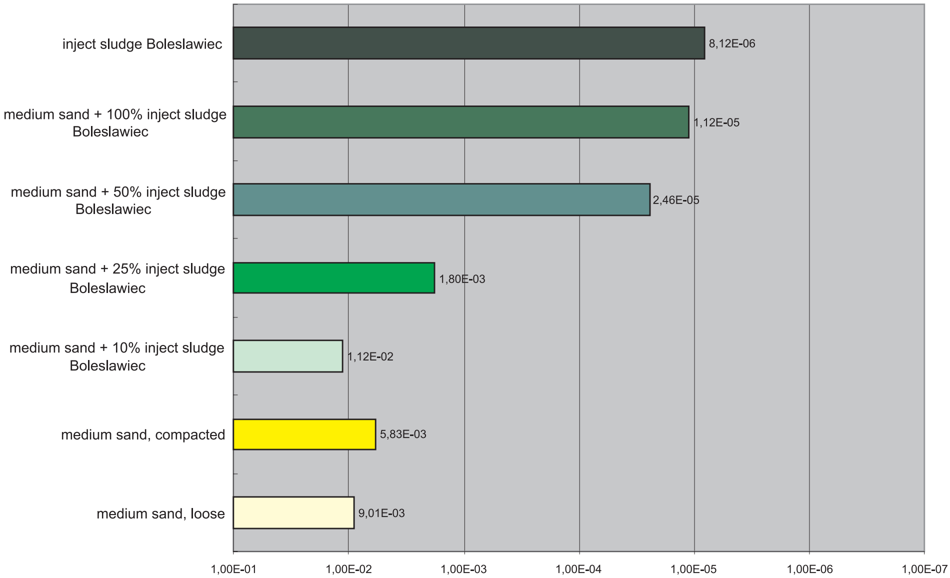


Fig. 12. Coefficients of permeability of medium sand and mixtures of medium sand with inject based on sludge from Bolesławiec

Similarly, as in the case of mixtures of medium sand with injects based on clay Bełchatów and sludge from Bolesławiec, in mixtures of loamy sand with inject based on clay from Bełchatów one can notice the tendency of reduction of the coefficient of permeability along with the increase of inject addition (Fig. 13) and filling degree of pore space by the inject (Tab. 7 and 8). From the point of view of described mixtures application as hydraulic cut-off walls, it should be admitted, that the mixture of loamy sand with the addition of inject based on clay from Bełchatów in the amount of 50% or higher leads to satisfactory outcomes. However one should remember that the value of the coefficient of permeability is not the only conclusive parameter for the usability of a given mixture as a basis for the construction of cut-off walls. It should be also noted that the loamy sand itself is characterised by a significantly higher variability of the coefficient of permeability than medium sand. This is due to its very good compactibility.

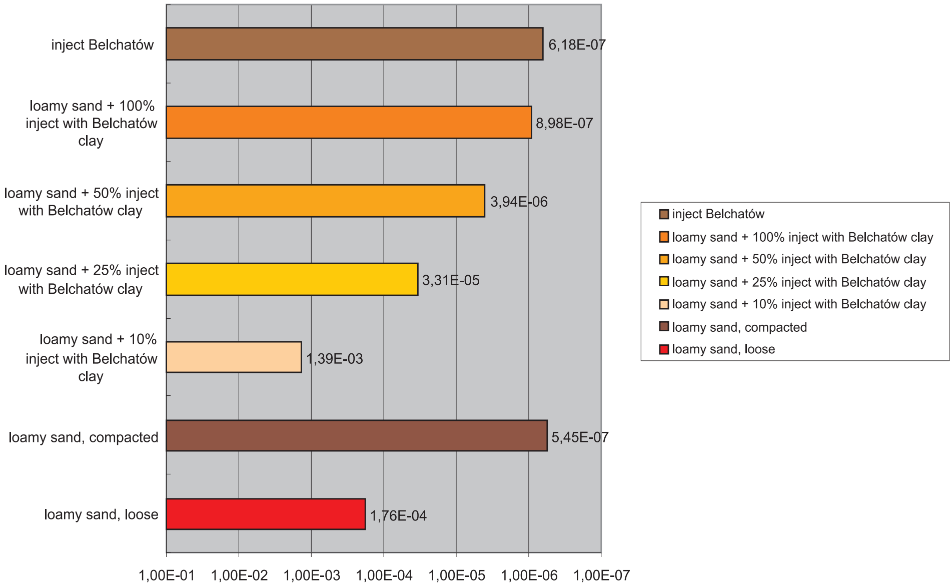


Fig. 13. Coefficients of permeability of loamy sand and mixtures of loamy sand with inject based on clay from Bełchatów

Table 7

Content of inject based on clay from Bełchatów in mixtures with loamy sand

No.	**Sample**	**ρ**	**Amount of inject**	**$\rho_{d\ of\ soil}$**	**n (of soil)**	**$\frac{V_{inject}}{V_{mixture}}$**	**$\frac{V_{inject}}{V_{pores}}$**
		[g/cm³]	**[g/cm³]**	**[g/cm³]**	**[-]**	**[-]**	**[-]**
		LOAMY SAND WITH ADDITION OF INJECT BASED ON CLAY FROM BEŁCHATOW					
1.	**Loamy sand + 10% clay Bełchatów**	1.898	0.173	1.725	0.354	0.137	0.387
2.	**Loamy sand + 25% clay Bełchatów**	2.024	0.405	1.619	0.394	0.321	0.816
3.	**Loamy sand + 50% clay Bełchatów**	1.954	0.651	1.3037	0.512	0.517	~1.0
4.	**Loamy sand + 100% clay Bełchatów**	1.716	0.858	0.858	0.676	0.680	~1.0

Table 8

Content of inject based on sludge from Bolesławiec in mixtures with loamy sand

No.	Sample	ρ	Amount of inject	$\rho_{d\ of\ soil}$	n (of soil)	$\frac{V_{inject}}{V_{mixture}}$	$\frac{V_{inject}}{V_{pores}}$
		[g/cm³]	[g/cm³]	[g/cm³]	[-]	[-]	[-]
		LOAMY SAND WITH ADDITION OF INJECT BASED ON SLUDGE FROM BOLESŁAWIEC					
1.	**Loamy sand + 10% sludge from Bolesławiec**	1.853	0.168	1.685	0.369	0.099	0.269
2.	**Loamy sand + 25% sludge from Bolesławiec**	1.971	0.394	1.577	0.409	0.232	0.568
3.	**Loamy sand + 50% sludge from Bolesławiec**	2.032	0.677	1.355	0.493	0.399	0.811
4.	**Loamy sand + 100% sludge from Bolesławiec**	1.889	0.945	0.945	0.646	0.557	0.862

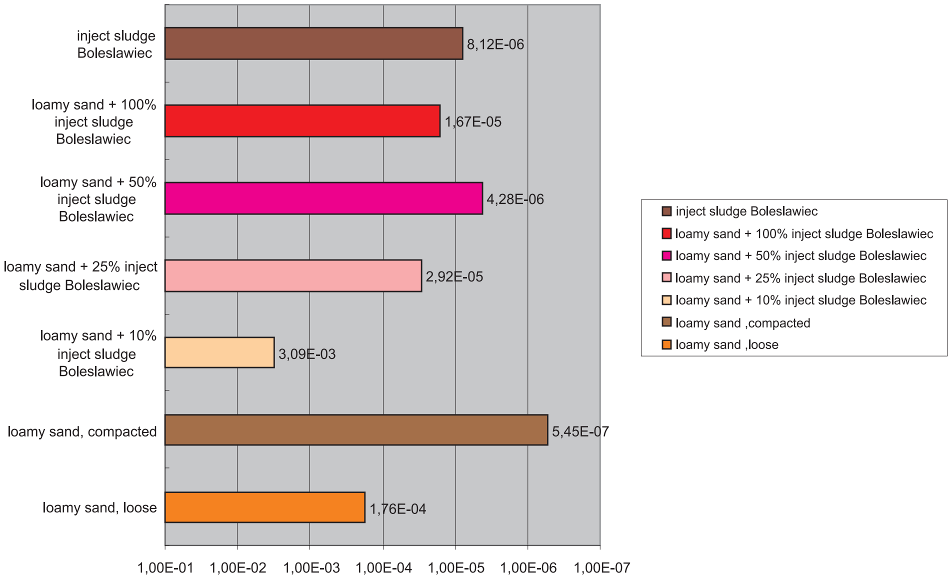


Fig. 14. Coefficients of permeability of loamy sand and mixtures of loamy sand with inject based on sludge from Bolesławiec

A slight differences to the previous cases can be observed in the case of loamy sand mixtures with injects based on sludge from Bolesławiec. The clear correlation between the decrease of the coefficient of permeability and the increase in the amount of inject added, is disturbed here. The mixture with an addition of 100% of inject has a higher coefficient of water permeability than the mixture with a 50% addition of inject. It is also comparable with the result obtained for mixture with 25% addition of inject, whereas in the previous cases these results were significantly different. This is probably the result of the differences in grain size distribution of the specific injects. Sludge from Bolesławiec contains significantly less of the dusty fraction (Fig. 7), than clay from Bełchatów.

4.1.3. Results of soaking collapsibility tests

Soaking is a process connected with cohesion and results in stability loss of soil immersed in water. This process is accelerated in case of flowing water – then we have a washing out process. The resistance of soils to soaking is a measure of the durability of its structural bondings.

Total or partial loss of the natural soil structure or of structure acquired in the process of compaction is a result of hydration of clay particles and organic colloids (the growth of water films on the surface of these particles). According to Grabowska-Olszewska and Sergiejew [1980], soaking is a heave that leads to disintegration.

Simultaneously with the destructive influence of hydration of particles, another destructive agent is air in the pores, compressed by moving menisci of capillary water and tearing the soil mass when its pressure exceeds the value of cohesion. The process of washing out, which is influenced by numerous external factors that are difficult to simulate in laboratory conditions, is mainly depended on the soil's resistance to soaking, and a quantitative evaluation of soaking collapsibility is a sufficient indicator of tendencies that will occur during washing out– soils that soak fast, are susceptible for fast washing out.

Studies on soaking were developed by geologists, who attributed them a highly important factor in the prediction of landslide processes on natural slopes after long-term rainfall. Most of the studies on soaking presented in literature, apart from those presented by Śliwa [1960], are of a descriptive nature and present a qualitative analysis of soaking, what excludes comparisons possibilities.

Studies on soaking of clayey silts of varied granulation and the comparison of disintegration time of 50% mass of the tested samples [Orzeszyna 1990] have undoubtedly proved that:

- soils compacted at moisture content lower than optimum moisture content (the "dry side" of the compactibility diagram) have the lowest resistance to soaking,
- soils compacted at humidity equal to the moisture content of Sr ~ 0,90 have the highest resistance to soaking,
- soils compacted at optimum moisture content and higher, show a very large decrease in resistance to soaking after they are dried to air dry state.

Each series of samples prepared for soaking resistance tests contained mixtures of medium sand and loamy sand with injects based on clay from Bełchatów or sludge from Bolesławiec (10, 25, 50 and 100% weight of inject related to the weight of dry soil), as well as the injects themselves. Formed samples matured for 14 days. Half of the total amount of samples were kept in such condition, that initial the water content (water content they had at the moment of forming (w_z)) was maintained, whereas the rest samples were drying in room temperature, reaching the moisture content w_{sps}. During the soaking collapsibility resistance tests only medium sand samples with 10% addition of both injects lost 1 to 3% of their weight in the initial stage of soaking. In the case of other mixtures and both injects, during 5 000 minutes (3.5 days) of soaking not even a slight loss of mass was observed. The final moisture contents of mixtures and injects samples measured at the end of soaking were equivalent to degree of saturation $S_w > 85\%$, which means, that the pressure of pore air compressed by moving menisci of capillary water penetrating the tested material was lower than the resistance of bondings created between soil particles.

The conducted soaking resistance tests proved that injects and their mixtures are highly resistant against soaking in water. This is also true for mixtures with cohesive soils, which was proven in tests of soils from the cut-off wall of the flood bank in Samocice (described in section 4.2.2). Structural bondings, that emerge during hardening, ensure the form stability of cut-off walls made from the tested materials during soaking in water.

4.1.4. Shrinkage

In cohesive soils build in the surface layer, beside the soil volume decrease caused by external pressure, similar volume changes, in the form of shrinkage, are caused by drying. Shrinkage can be a result of evaporation from the surface of the ground or a result of plants transpiration, whose root systems are located in the surface zone of the soil structure. Effects of shrinkage are cracks and fissures. They increase the permeability and the depth of direct soil penetration by soaking waters, and in flood banks they will intensify the process of soaking of the surface layers of upstream slopes. In case of cut-off walls, shrinkage fissures, which may build up in the top zone of the cut-off wall body, will decrease theirs efficiency.

It is generally assumed that shrinkage of cohesive soils is caused by capillary forces. The pores between particles create a system of connected capillaries of varied diameters. When, despite of some amount of trapped air, all pores are filled with water, then free water creates flat menisci on the surface of soil (Fig. 15).

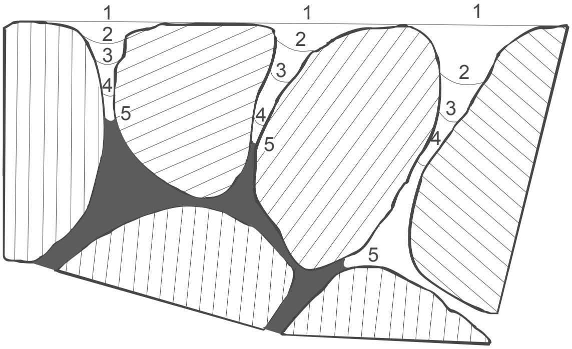


Fig. 15. Idealised cross-section of pores of saturated soil

The pressure on the surface of the meniscus is equal to the internal liquid pressure and, by a flat meniscus, equals atmospheric pressure. Along with surface evaporation or the absorption of surface water by root system of plants and the evaporation through leaves, the pore water surface moves deep into the pores, to the subsequent positions numbered from 2 to 5 (Fig. 15). Each of these positions is characterised by menisci, whose curvature depends on the current tension of pore water.

By a given tension, the curvatures of all menisci are equal. In such a state, the tension in pore water (Fig. 16) can be calculated from the following relation:

$$\frac{p\pi d^2}{4} = T\pi d$$

p – pore water pressure (Pa),
T – water surface tension (N/m),
d – capillary diameter (m).

$$p = \frac{4T}{d}$$

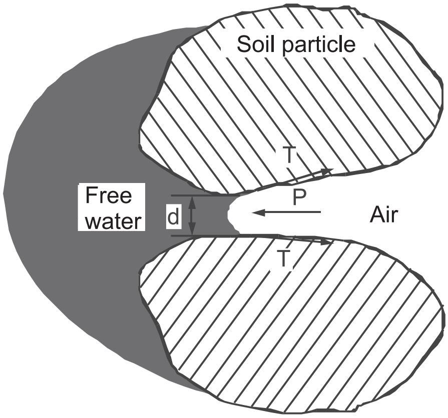


Fig. 16. Meniscus on the surface of dry particles

The reaction of the menisci acts on the particles of soil causing pressure between them. All menisci of a specific curvature are generating a load on the soil below their level as if caused by an elastic surface of tension equal to p. The soil is compressed by this pressure to a density that depends on the compressibility of a given soil. The reduction of communication pores diameters leads to the increase in the curvature of menisci when moving from position 2 to 5 (Fig. 15). The compressing tensions are increasing, and at the moment of achieving the smallest diameter (position 5) the pore water pressure reaches its maximum. In the soil space, where the pores are filled with water, on all passages there are no pores with lower diameter. A further loss of water from such closed system does not increase shrinkage. The moisture content measured at this point is called a shrinkage limit.

Means and Parcher [1963] explain the course of shrinkage by using a diagram of the relationship between pore diameters, void ratio and pressure causing shrinkage (Fig. 17). In a soil sample, in which, despite of soil grains, water fills the total or partial volume of the pores, changes in volume may occur as a result of evaporation of non-compressible water. On the diagrams this will be indicated by a decrease in the value of the void ratio. The relation between the diameter of the external, internally communicated pores, and the void ratio **e** is shown by curve **A**. The relation between the void ratio **e**, and the pressure that can be created by menisci in the pores of a diameter **d** is shown by curve **C**. Curve **B** is the curve of compressibility of the tested soil.

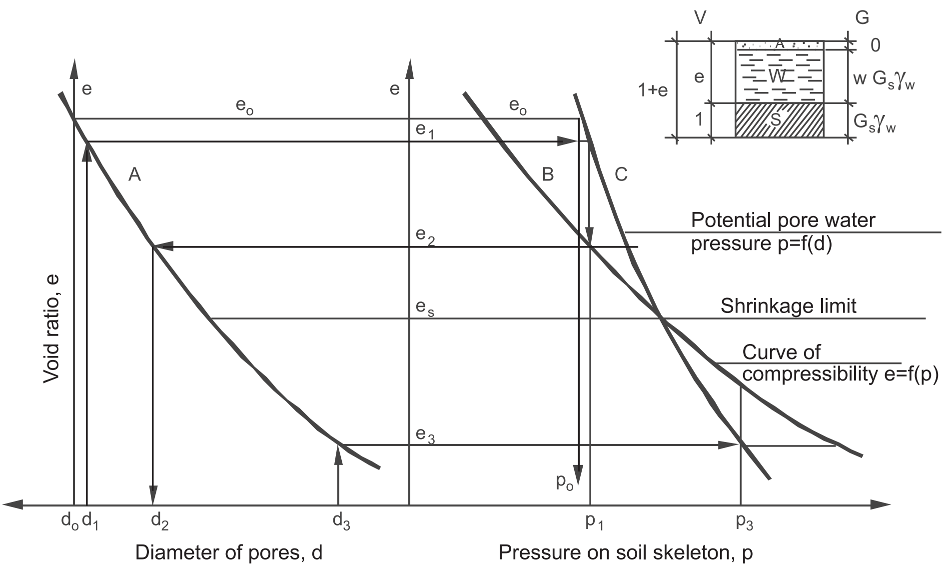


Fig. 17. Relation between the diameter of pores, void ratio and pressure causing shrinkage

At the beginning of the shrinkage process, the soil has a certain porosity, which is expressed by the void ratio $\mathbf{e_o}$. This state is equivalent to the pore water surface in the form of menisci supported on pores of the diameter d_o, capable of creating a capillary pressure of the value p_o acting on the soil skeleton. When evaporation occurs, pressure will be applied to the soil. It has a value $\mathbf{p_1}$ correspondingto the diameter of pores $\mathbf{d_1}$ of, which will in turn cause the decrease of porosity to the value $\mathbf{e_2}$ and change in the actual diameter of pores to $\mathbf{d_2}$. This reduction of the diameters of pores means a higher pressure potential.

Increased pressure can further reduce the volume, and thus the progress of evaporation of pore water deepens the shrinkage process. However the ability to increase shrinkage cannot continue infinitely. As curve **B** shows, pressure $\mathbf{p_1}$ is able to compress the mass of soil to a volume equivalent to $\mathbf{e_2}$. So, evaporation from soil by $\mathbf{e_1}$, leads to further shrinkage. It is possible yet to achieve a state of porosity that would be equivalent to $\mathbf{e_3}$? Pore water at this porosity is able to create pressure between grains of the value $\mathbf{p_3}$ as it can be seen on the ordinate on curve **C**. But, in order to achieve a coefficient of porosity equal to $\mathbf{e_3}$, a higher pressure is necessary, whose value can be read on curve **B**. Pressure $\mathbf{p_3}$**,** is unable to shrink the soil to $\mathbf{e_3}$, and the shrinkage process will end at the porosity $\mathbf{e_s}$, at the point of intersection of curves **B** and **C**.

The measurement procedures of soil samples volume during shrinkage tests, are presented in the polish standard PN-88/B-04481, in American standards ASTM D 427-83, ASTM D 3877-80 and in Earth Manual [1974], in Means and Parcher paper [1963]. They are limited to more or less complicated method of immersion of the tested samples in mercury. The procedures of accurate measurement of the extent of shrinkage are quite inconvenient (particularly for 100 cm^3 volume samples), and for soils of a low compaction – difficult to carry out, as samples plunged into mercury tend to collapse or their edges are breaking off.

Taking into consideration the need to measure a big amount of samples, and mainly due to the need to maintain work safety when working with toxic mercury vapours, the measurements of the shrinkage of samples collected from the flood bank and those formed from the specific mixtures, were conducted with use of an approximating method. The measurement error in the approximating method compared to the standard method usually does not exceed 2%. As all samples were tested with use of the same method, it is possible to make reliable comparisons reflecting the nature of the phenomenon. Samples for the measurement of shrinkage were formed in new, not deformed samplers, of the diameter of 4.7 cm and the height of 5.5 cm.

4.1.4.1. Determination of injects and their mixtures shrinkage

Mixing the ingredients of both injects, according to the prescription, resulted in injection grouts of liquid consistency. Mixtures prepared with medium sand and loamy sand with the addition of 10, 25, 50 and 100% of both injects had a liquid consistency, too. Samples for shrinkage test were formed in compliance with the description in section 3.1.5
Values of pure injects shrinkage are relatively high:

- inject based on Bełchatów clay – **23.4%**,
- inject based on Bolesławiec sludge – **17.0%**.

Mixtures of medium sand and loamy sand with 10% addition of both inject did not show any shrinkage.

With the increase of both injects addition, mixtures have shown increasing value of shrinkage, which is presented on Figures 18–21.

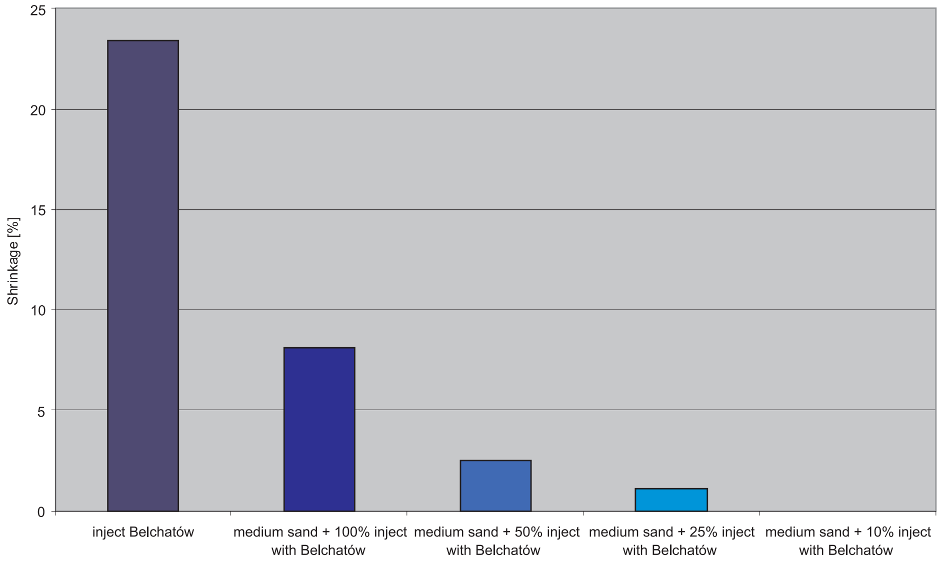


Fig. 18. Shrinkage of medium sand and clay from Bełchatów mixtures

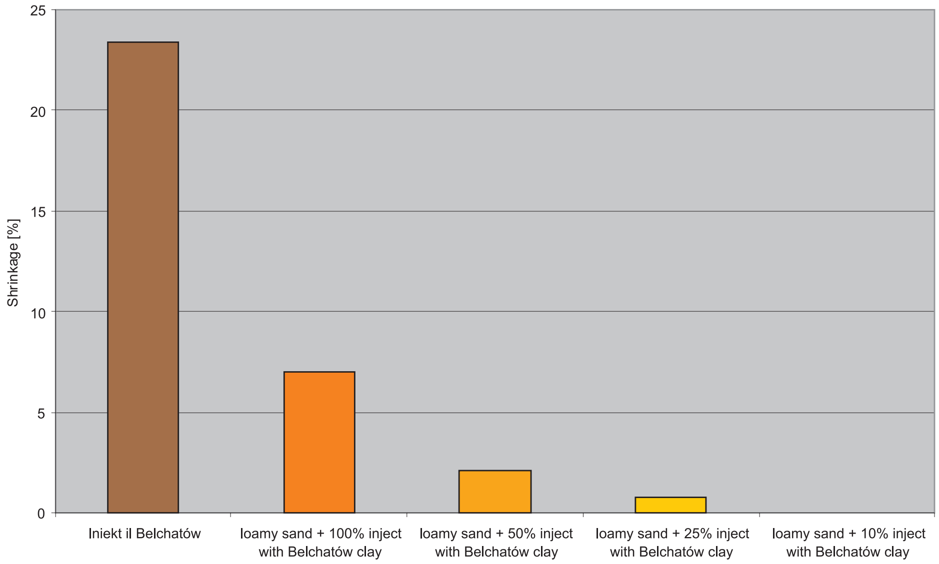


Fig. 19. Shrinkage of loam sand and inject with Bełchatów clay mixtures

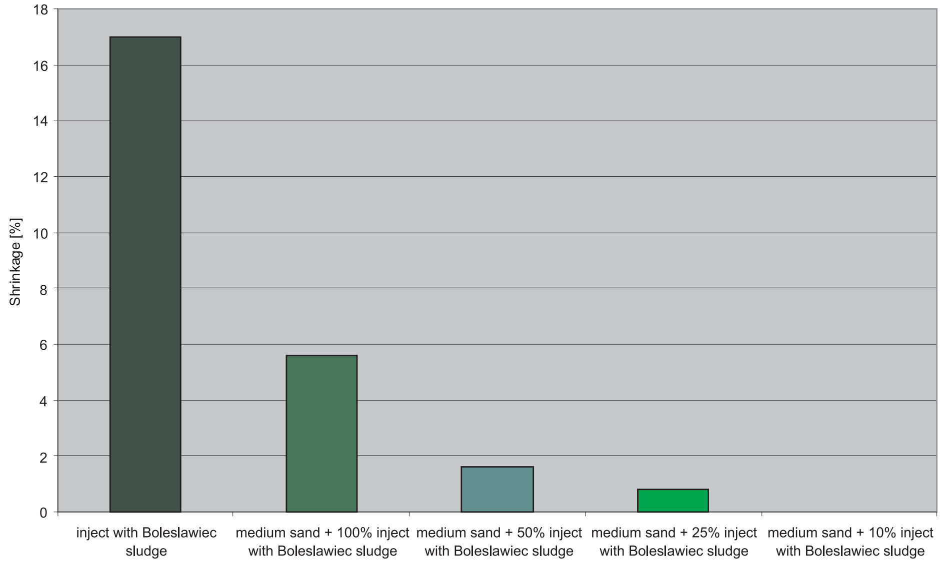


Fig. 20. Shrinkage of medium sand and sludge from Bolesławiec mixtures

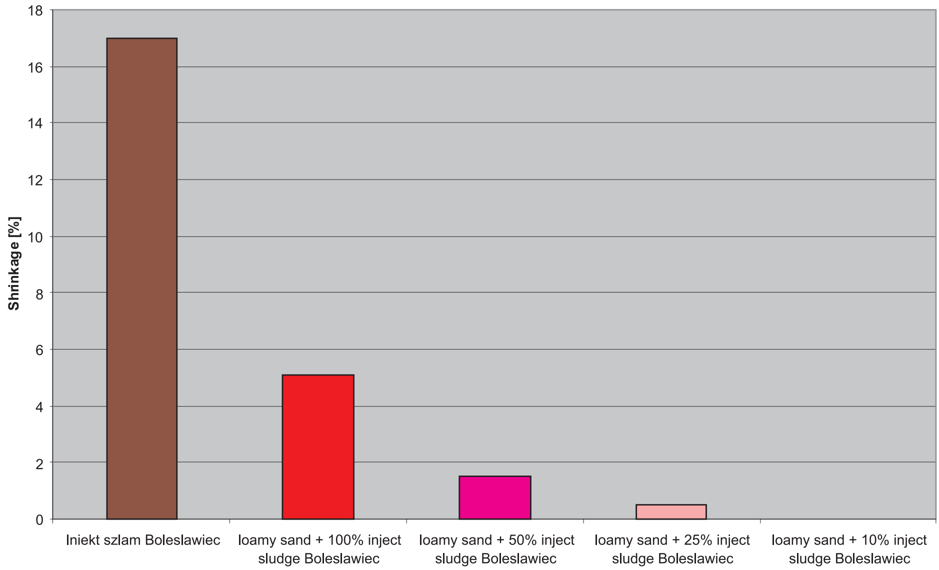


Fig. 21. Shrinkage of loamy sand and sludge from Bolesławiec mixtures

The analysis of the test results shows that in case of large content of inject in the mixture (25–100%) the value of shrinkage is influenced both by the type of inject and by the type of soil. Among mixtures with 100% addition of injects, the shrinkage of mixtures with the addition of inject containing clay from Bełchatów was by 1.9 to 2.5% higher than that of mixtures with the addition of inject based on sludge from Bolesławiec (Fig. 22). Mixtures with 50% and 25% addition of injects show similar tendencies, although the differences in shrinkage for mixtures with 50% addition range from 0.6 to 0.9%, and for mixtures with 25% addition the shrinkage differs by 0.3% (Fig. 23 and 24). Samples of mixtures with loamy sand showed a smaller degree of shrinkage; a higher shrinkage was observed in case of mixtures with medium sand with the same amount and type of inject.

Shrinkages – as high as 23.4% of the inject based on clay Bełchatów and 17.0% shrinkage of inject based on sludge from Bolesławiec, as well as the values of shrinkage in the amount of several percent of mixtures of medium sand and loamy sand with the addition of 25, 50 i 100% of grouts – are so significant, that they point to the need to protect the upper zone of constructed cut-off walls from drying. Because mixtures of medium and loamy sand with 10 % addition of each of injects result in non-shrinking materials (Fig. 25), use of mixtures with a small amount of inject in case of flood banks cut-off wall upper zone protection should be considered and investigated.

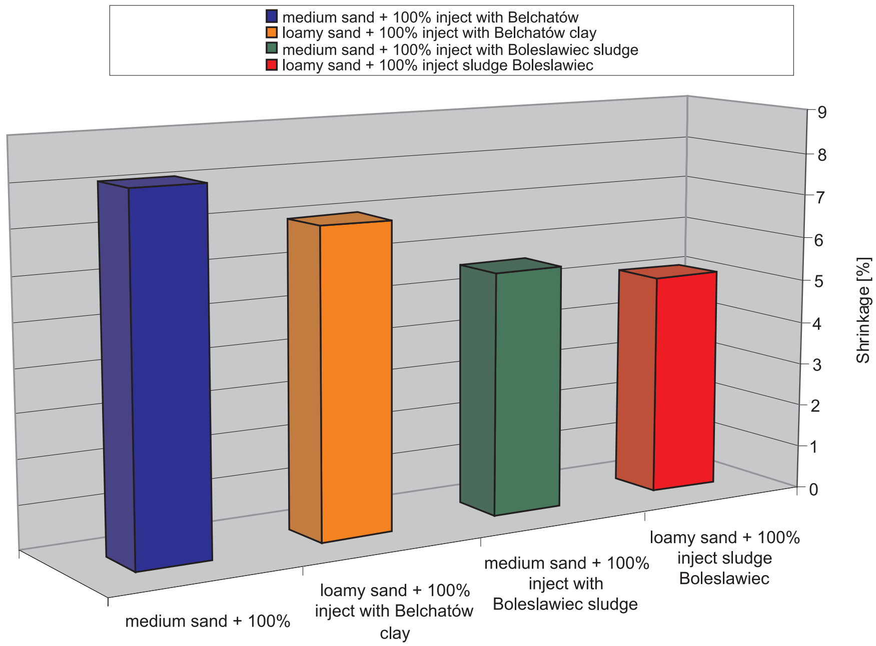


Fig. 22. Shrinkage of mixtures with 100% addition of injects

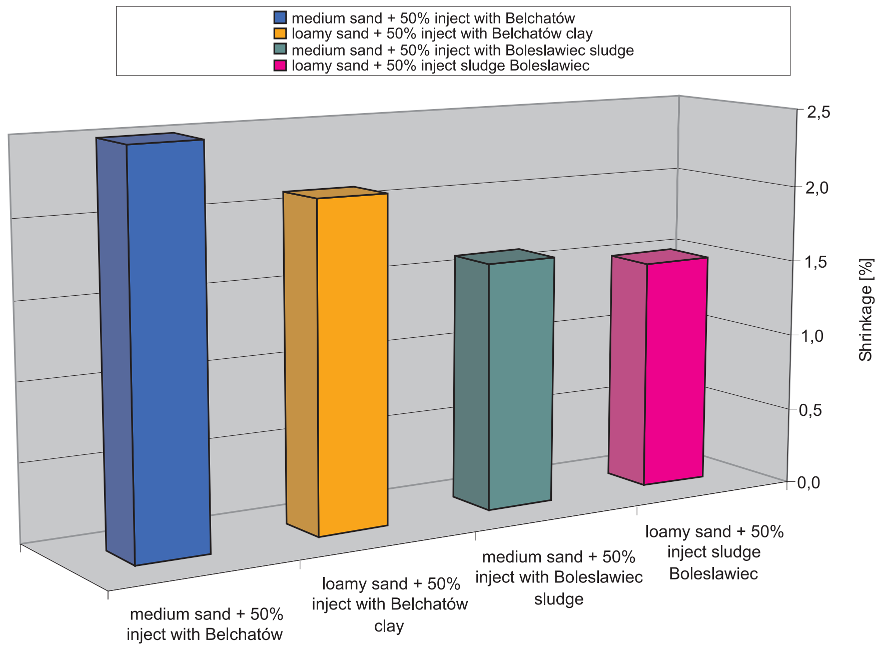


Fig. 23. Shrinkage of mixtures with 50% addition of injects

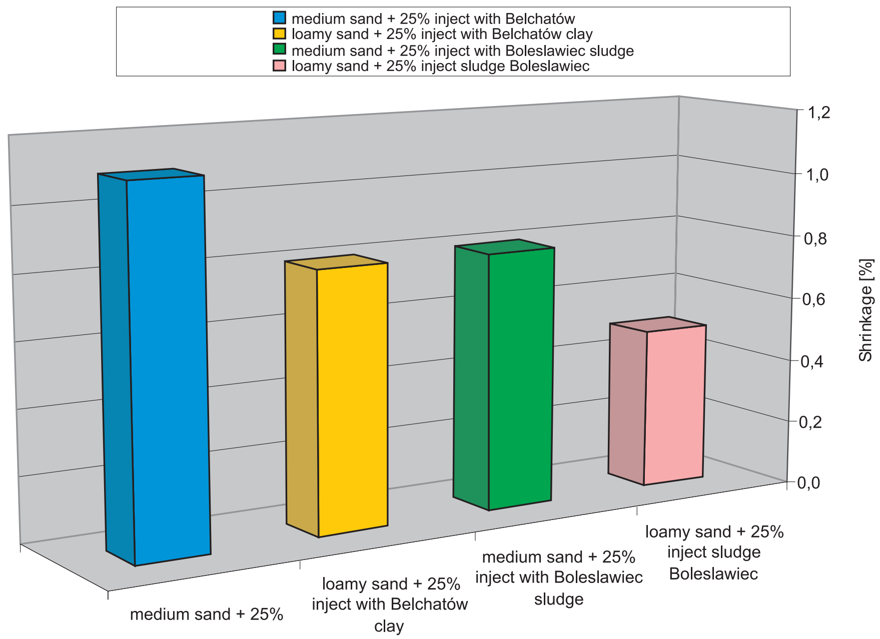


Fig. 24. Shrinkage of mixtures with 25% addition of injects

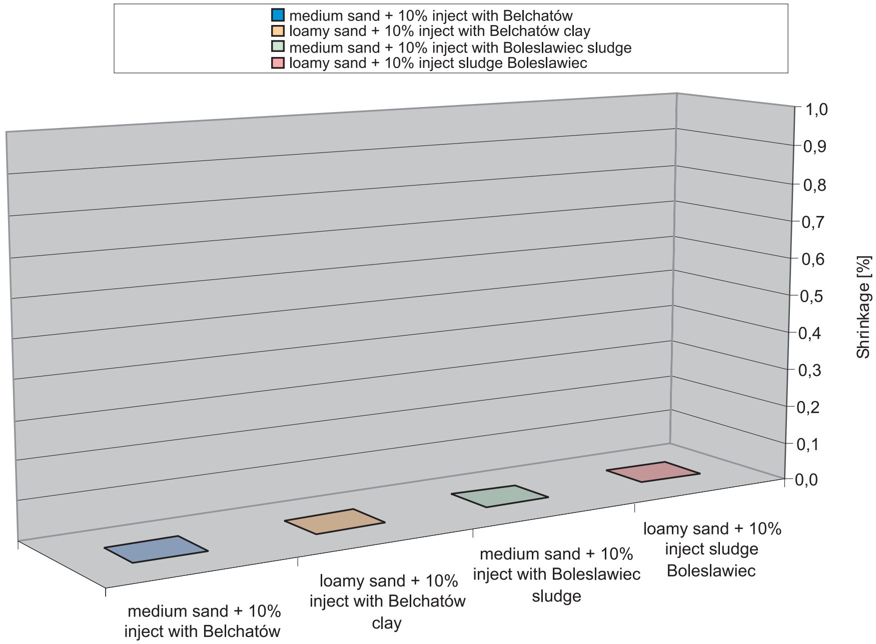


Fig. 25. Shrinkage of mixtures with 10% addition of injects

4.1.5. Shear strength

Strength tests conducted on samples collected from the experimental section of the flood bank were supplemented by tests of samples prepared in laboratory conditions. The primary aim of these tests was to determine the influence of saturation of soil with binder (grout) on the strength parameters of the mixtures. Laboratory conditions allow to form samples with a controlled proportion of ingredients, i.e. of specific proportions of inject and soil.

Figure 26 shows the comparison between shear strength of the mixture of inject based on clay from Bełchatów and one based on medium sand. Figure 27 shows the shear strength for different compositions of mixtures and growing values of normal stresses.

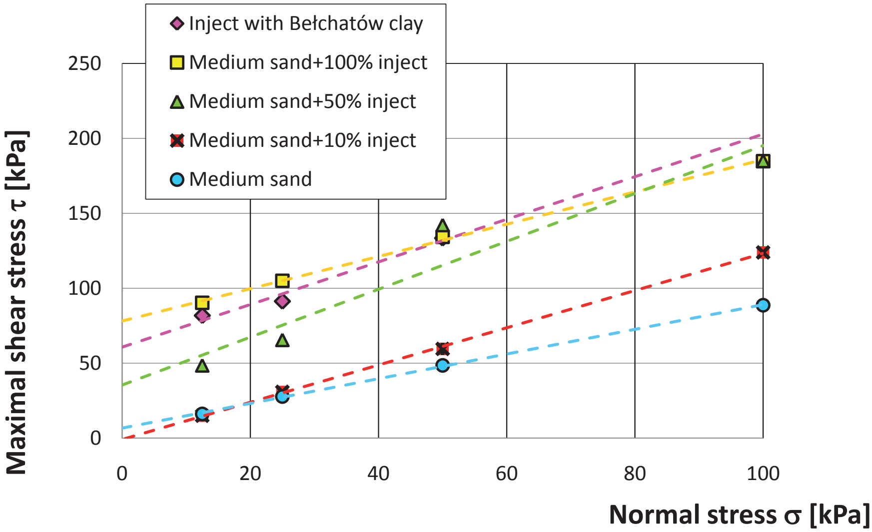


Fig. 26. Shear strength of medium sand mixtures with inject based on clay from Bełchatów

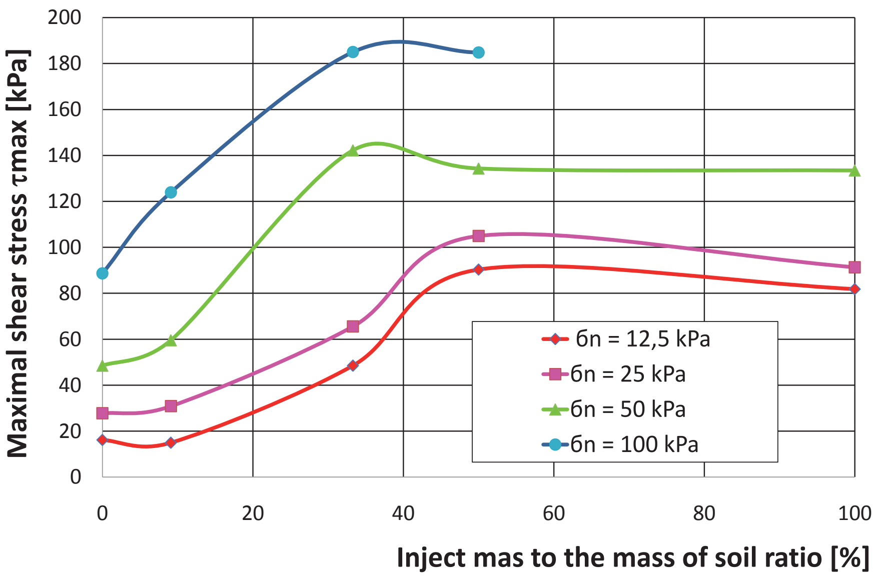


Fig. 27. Relation between the shear strength and the composition of mixture of medium sand with inject based on clay from Bełchatów by various normal stresses

As is shown in Figure 26, the application of inject to the medium sand results, first of all, in the increase of cohesion. The angle of internal friction also increases if compared with the angle of internal friction of pure sand in loose state (Tab. 9). Lower angle of internal friction increase and, higher than in case of pure inject, increase of cohesion for mixtures with 100% content of inject, seems to be caused by the heterogeneity of samples. This however does not affect the general conclusions resulting from the analysis of the increase strength parameters and the absolute increase of shear strength (Fig. 26 and 27). It was found that only higher amounts of inject cause a significant strength increase, mainly connected with cohesion. A relation between the absolute increase in shearing strength and vertical stresses was observed – this increase is higher for higher stresses, although in the zone of higher stresses (50–100 kPa) it has a tendency to stabilise. The dependence between vertical stresses and shearing resistance increase is most remarkable in case of 10% content of inject with clay from Bełchatów in mixture with medium sand. The highest increase in shearing strength in the whole range of normal stresses was noticed, when the content of inject to the amount of soil ratio reached at least 100% (inject to soil proportion 1:1 and higher). The pure inject based on clay from Bełchatów, due to its binding properties, is characterised by better strength parameters than medium sand. Mixed in the right proportion with medium sand, it increases its shearing strength. Even a small amount of inject in the mixture (10–50% of the weight of sand) is advantageous, as it increases its cohesion and the angle of internal friction.

Table 9

Influence of content of inject based on clay from Bełchatow on the strength parameters of its mixtures with medium sand

No.	Type of material	Φ	c	ΔΦ[1]	Δc[1]	$\Delta\tau_{max.}$[1] for σn [kPa]			
						12,5	25	50	100
		deg	kPa	deg	kPa	kPa	kPa	kPa	kPa
1.	Medium sand (loose)	39.5	6.7	–	–	–	–	–	–
2.	Medium sand +10% inject	51.2	~0	11.7	0	0	3.1	11.05	35.2
3.	Medium sand +50% inject	57.9	35.5	18.4	28.8	32.36	37.8	93.7	96.3
4.	Medium sand +100% inject	47.1	78.21	7.6	71.50	74.2	77.2	85.8	96.1
5.	Inject	54.9	60.8	15.4	54.1	65.7	63.6	84.9	no data available

[1] Increase related to the values determined for medium sand

The inject containing sludge from Bolesławiec in mixtures with medium sand also causes an increase in shearing strength in comparison to the strength of the sand itself, but to a lesser extent than it was in the case of clay from Bełchatów (Tab. 10). This results from the lower resistance of the tested inject. The influence of its presence in the mixture on strength parameters is shown on Figures 28 and 29. The best effects of mixture strengthening were achieved when the amount of inject was 50–100% of the soil weight. The influence of normal stresses on mixtures strength increase was also observed. At higher normal stresses (50 and 100 kPa) the strengthening effect is visible in a broader range of soil to inject ratio. Under this stresses, even by small contents of inject – 10% of the soil amount – a significant strength increase, as compared to the shearing resistance of medium sand, is observed.

Table 10

Influence of content of inject based on sludge from Bolesławiec on the strength parameters of its mixtures with medium sand

No.	Type of material	Φ	c	ΔΦ[1)]	Δc[1)]	$\Delta\tau_{max.}$[1)] for σn [kPa]			
						12.5	25	50	100
		[deg]	[kPa]	[deg]	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]
1.	Medium sand (loose)	39.5	6.7	–	–	–	–	–	–
2.	Medium sand +10% inject	50.1	7.7	10.6	1.0	7.68	8.44	–	38.64
3.	Medium sand +50% inject	50.5	21.35	11.0	14.6	18.12	23.24	38.36	51.94
4.	Medium sand +100% inject	46.0	33.9	6.5	27.2	21.08	36.41	47.66	43.79
5.	Inject	41.2	24.9	1.7	18.2	1.9	20.28	49.54	11.08

[1)] Increase related to the values determined for medium sand

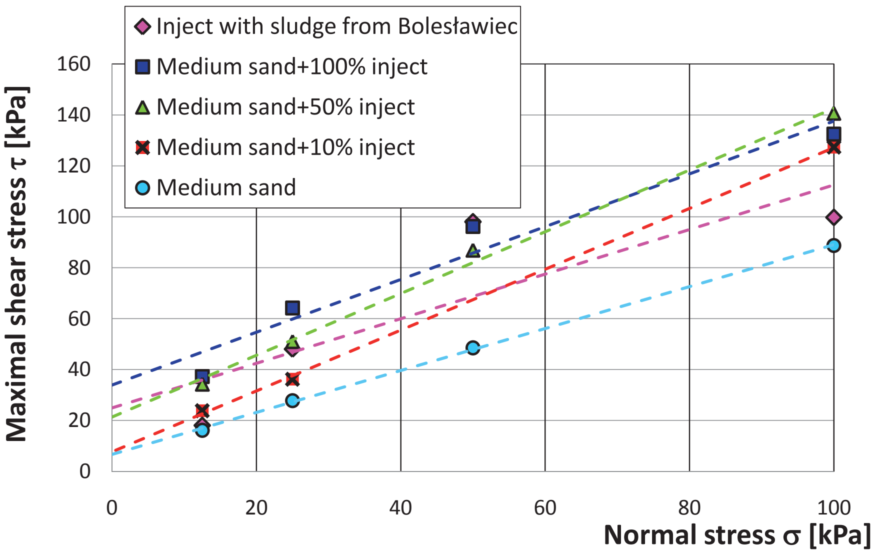


Fig. 28. Shear strength of medium sand mixtures with inject based on sludge from Bolesławiec

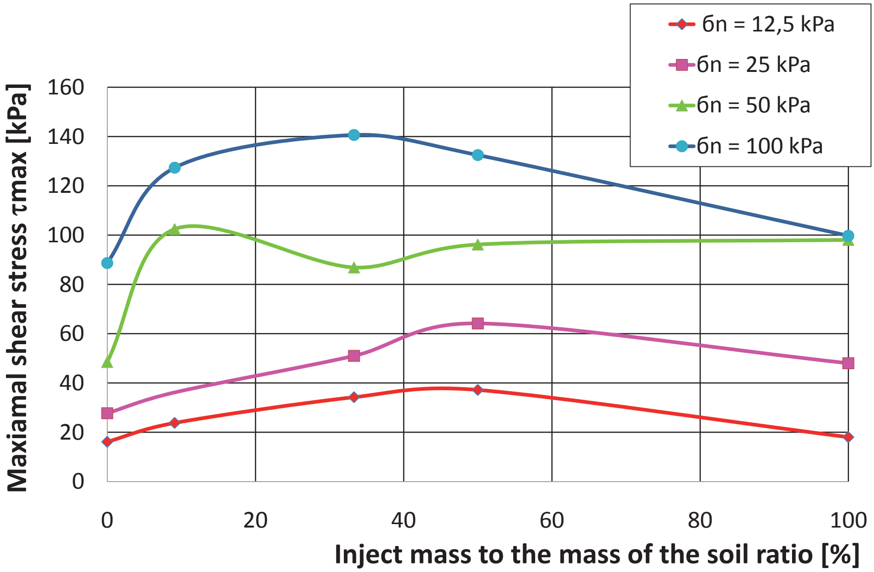


Fig. 29. Relation between the shear strength and the composition of medium sand mixture with inject based on sludge from Bolesławiec by various normal stresses

4.1.6. Triaxial tests

Only medium sand, medium sand mixed with inject based on clay from Bełchatów, and inject based on clay from Bełchatów were tested in the triaxial apparatus. According to the description in section 3.1.8. The tests were interpreted with use of the K_f line connecting the tops of Mohr's circles and on this basis equations of Mohr's circles envelopes were determined for the tested materials.

Table 11

Results of the triaxial tests

No.	Type of material	Equation for straight-line Mohr's circles envelope	Φ [deg]	c [kPa]
1.	Medium sand – loose state	$\tau_{f'} = 0.816\ \sigma_n$	**39.2 °**	
2.	Inject clay Bełchatów + medium sand (1:1)	$\tau_{f'} = 1.144\ \sigma_n + 101.09$	48.8 °	101.09
3.	Inject with clay from Bełchatów	$\tau_{f'} = 1.117\ \sigma_n + 118.86$	48.2 °	118.86

Mohr's circles envelopes are presented in Figure 29a.

The conducted triaxial tests confirmed the detailed conclusions based on the results of strength testing in direct shear apparatus. However, by the same composition of mixtures, the obtained values of cohesion were higher than in tests in the box apparatus, whereas angles of internal friction were on the same level.

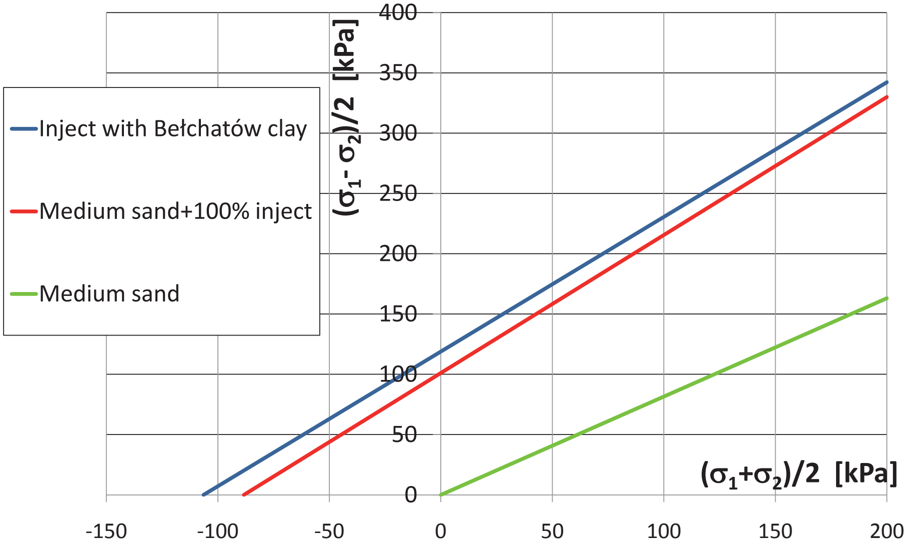


Fig. 29a. Mohr's circles envelopes

4.1.7. Bending and compressive strength

4.1.7.1. Bending strength

The tests of bending strength were conducted in accordance with the description in section 3.1.7. Their results are presented in Figures 30 and 34. Apart from the determination of the bending tensile strength, they also enable the evaluation of the resistance to deformation, e.g. in case of uneven subsidence of the ground. The effects of mixing the inject with the soil were analysed and the most optimal proportions of injects to the tested soils from the point of view of bending strength were chosen. In order to determine the compressive strength, halves of the beams that had broken in the bending strength test, were compressed in a press used for testing of cement mortar samples. The specification of the values of bending and compressive strength obtained in the experiment is presented in Tables 12–15.

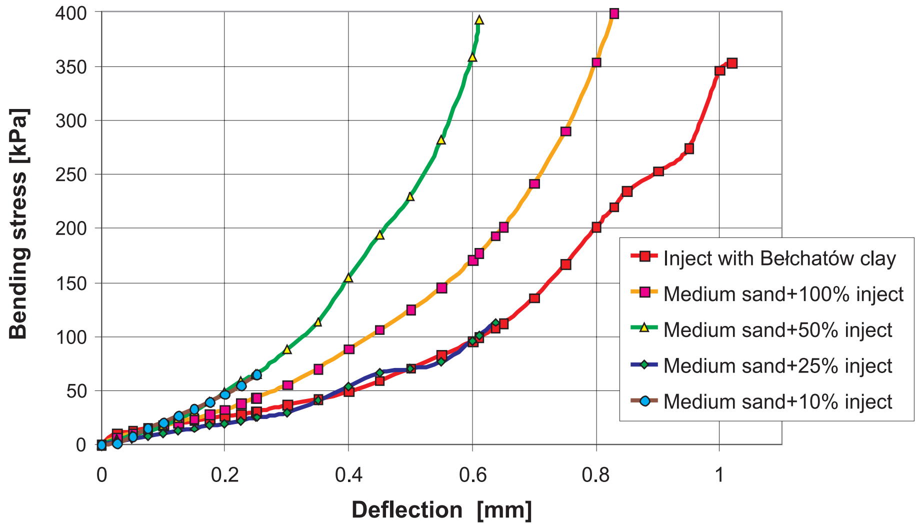


Fig. 30. Bending strength tests of medium sand and inject with clay from Bełchatów for various degrees of saturation with injects

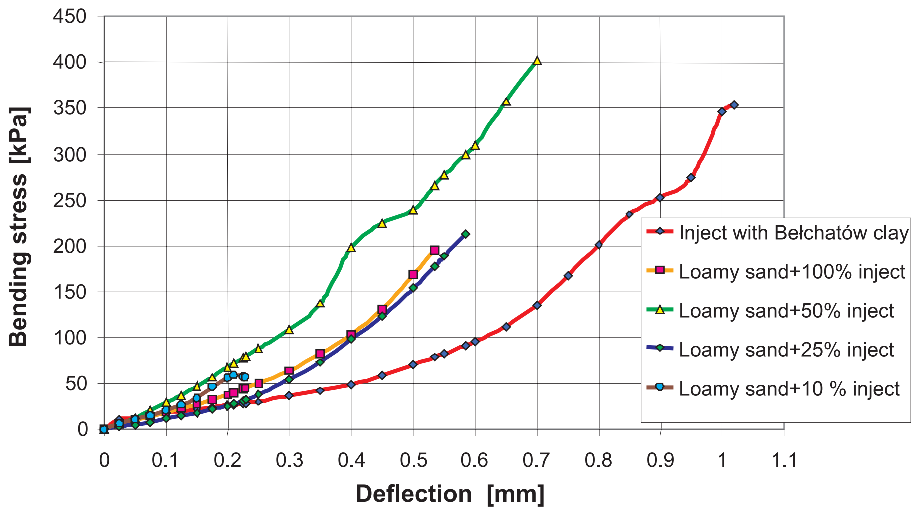


Fig. 31. Bending strength tests of loamy sand and inject with clay from Bełchatów for various degrees of saturation with injects

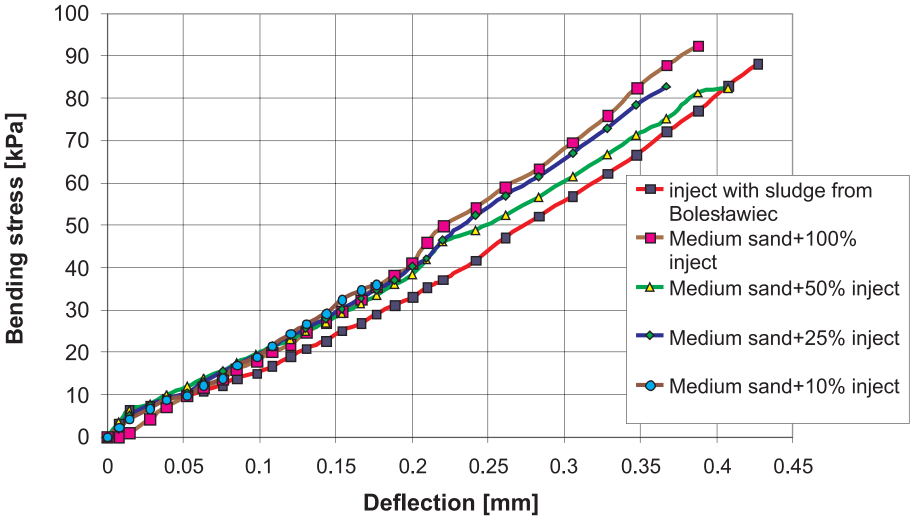


Fig. 32. Bending strength tests of medium sand and inject with sludge from Bolesławiec for various degrees of saturation with injects

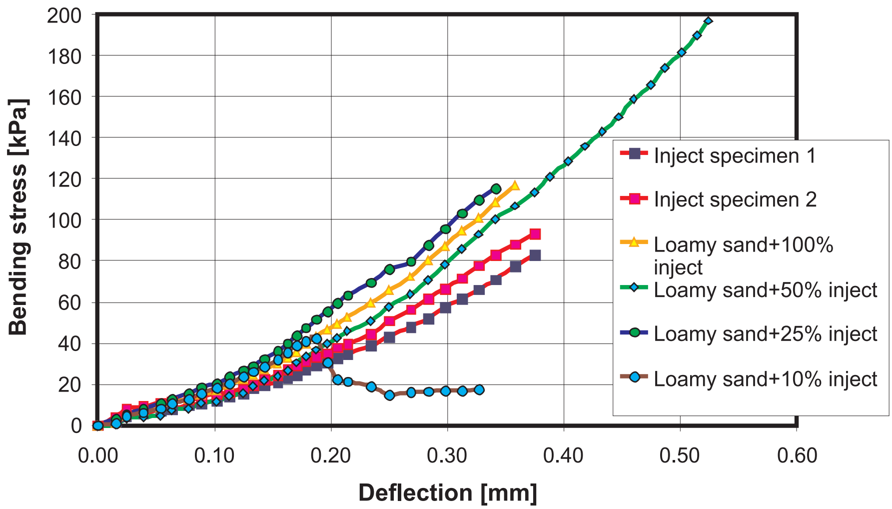


Fig. 33. Bending strength tests of loamy sand and inject with sludge from Bolesławiec by various degrees of saturation with injects

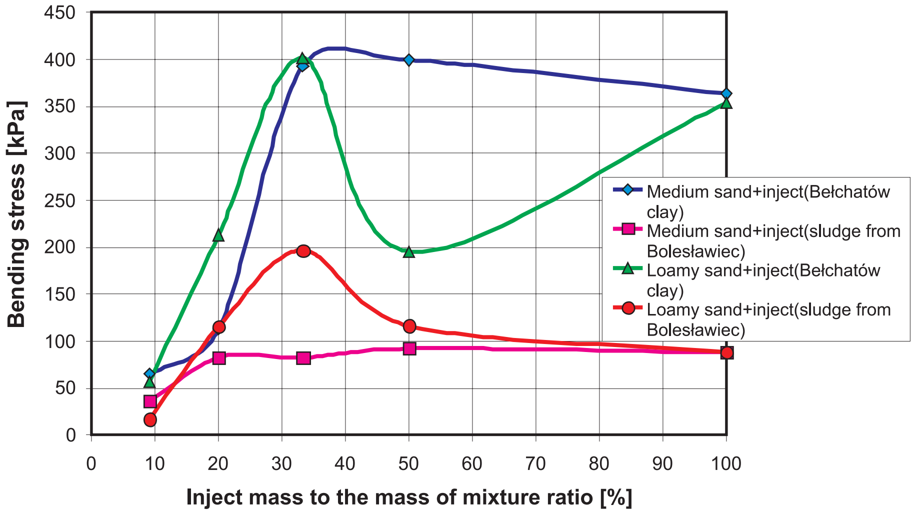


Fig. 34. Influence of soil type of and inject type and content on bending strength

Table 12

Results of bending and compressive strength test of medium sand and clay from Bełchatów mixtures

Type of material	Bending strength		Bulk density		Compressive strength		
		mean		mean			mean
	[kPa]	[kPa]	[t/m³]	[t/m³]	[kPa]	[kPa]	[kPa]
Inject	329.69	341.6	1.27	1.26	946.88	991.88	1070.47
	353.50		1.24		1190.63	1152.50	
Medium sand + inject 100% (1:1)	398.90	402.98	1.65	1.63	1544.38	1534.38	1622.66
	407.05		1.61		1698.75	1713.13	
Medium sand + inject 50% (2:1)	330.65	365.33	1.79	1.81	1253.75	1240.63	1318.44
	400.00		1.83		1407.50	1371.88	
Medium sand + inject 25% (4:1)	116.25	115.62	1.85	1.87	504.38	603.75	673.13
	114.98		1.89		844.38	740.00	
Medium sand + inject 10% (10:1)	99.69	83.06	1.59	1.56	18.13	30.00	22.97
	66.43		1.52		22.5	21.25	

Table 13

Results of bending and compressive strength test of medium sand and sludge from Bolesławiec mixtures

Type of material	Bending strength		Bulk density		Compressive strength		
		mean		mean			mean
	[kPa]	[kPa]	[t/m³]	[t/m³]	[kPa]	[kPa]	[kPa]
Inject	82.83	88.15	1.48	1.47	–	–	63.04
	93.46		1.46		62.12	63.96	
Medium sand + inject 100% (1:1)	98.37	92.37	1.87	1.86	131.88	195.00	171.10
	86.37		1.85		195.00	162.50	
Medium sand + inject 50% (2:1)	94.52	82.30	2.01	2.00	207.50	298.75	232.03
	70.08		1.98		205.00	216.88	
Medium sand + inject 25% (4:1)	80.13	82.77	1.88	1.90	90.00	98.75	105.47
	85.40		1.92		99.38	133.75	
Medium sand + inject 10% (10:1)	36.33	36.02	1.54	1.60	30.63	27.50	30.47
	35.71		1.65		24.38	39.38	

Table 14

Results of bending and compressive strength test of loamy sand and clay from Bełchatów mixtures

Type of material	Bending strength		Bulk density		Compressive strength		
		mean		mean			mean
	[kPa]	[kPa]	[t/m³]	[t/m³]	[kPa]	[kPa]	[kPa]
Inject	329.69	341.6	1.27	1.26	946.88	991.88	1070.47
	353.50		1.24		1190.63	1152.50	
Loamy sand + inject 100% (1:1)	402.98	402.98	1.73	1.73	701.88	718.75	710.31
Loamy sand + inject 50% (2:1)	401.37	401.37	1.91	1.91	796.88	866.88	831.88
Loamy sand + inject 25% (4:1)	213.00	213.00	2.01	2.01	616.25	590.00	603.13
Loamy sand + inject 10% (10:1)	57.08	57.08	1.82	1.82	21.25	23.13	22.19

Table 15

Results of bending and compressive strength test of loamy sand and sludge from Bolesławiec mixtures

Type of material	Bending strength		Bulk density		Compressive strength		
		mean		mean			mean
	[kPa]	[kPa]	[t/m^3]	[t/m^3]	[kPa]	[kPa]	[kPa]
Inject	82.83	88.15	1.48	1.47	–	–	63.04
	93.46		1.46		62.12	63.96	
Loamy sand + inject 100% (1:1)	116.56	116.56	1.89	1.89	93.13	221.25	157.19
Loamy sand + inject 50% (2:1)	197.05	197.05	1.96	1.96	238.13	208.75	223.44
Loamy sand + inject 25% (4:1)	115.37	115.37	2.01	2.01	76.88	537.5	307.19
Loamy sand + inject 10% (10:1)	17.34	17.34	1.87	1.87	19.38	22.50	20.94

The application of inject containing clay from Bełchatów, as a basic component, yields better effects measured as bending strength, than in the case of inject containing sludge from Bolesławiec. In following phases of the test, at the same deformations, the tensile stresses while bending mixtures of inject with soil tend to be higher than the stresses in the inject itself, which proves that their stiffness is higher. In terms of bending strength, the optimum mixtures proved to be the mixtures of medium sand and both types of inject with inject amount equal 50–100% of the soil weight . In case of loamy sand the optimum composition of the mixture is approx. 50% of inject proportionally to the weight of soil. For such proportion the highest bending strength values were achieved, whereas the range of optimal proportions is significantly narrower than in case of medium sand. At a degree of soil saturation with inject that differed from the optimum, the limit bending tensile strength of mixtures decreased at least by 40%.

Although the inject with clay from Bełchatów has a lower bending strength than some of the mixtures, it is more resistant to deformation. The deflection of the tested beam, at the moment of a crack emergence on the tension side, reached 1/100 of its length, whereas even for the most optimum mixtures the beams were destroyed already at deflection that was lower by 20–30%.

Inject containing sludge from Bolesławiec is characterised by a significantly lower bending strength and lower resistance to deformation. Significantly lower differences in tensile stresses are observed at the same values of deflection of beams containing different proportions of soil and binder. A significant increase in strength was observed only in case of sample of loamy sand and 50% of inject proportionally to the weight of sand. Also the value of deflection, at which the beam was destroyed, was in this case by approx. 40% higher than for the inject itself and for the remaining mixtures. Theirs bending strength was higher than that of inject itself. It is worth noting, that the proportion 50% inject to soil ratio presented beneficial characteristics also in the tests of both types of soil with clay from Bełchatów.

The curves presenting the bending strength as a function of the type of soil and the type and amount of inject (Fig. 43) show that it is primarily the type of soil that decides about the nature of the curve. In case of medium sand with inject containing clay from Bełchatów, as well as sludge from Bolesławiec, an initial increase in strength is observed along with the increase in the amount of inject in the mixture, and after a specific degree of saturation with inject is achieved, further changes in the amount of inject in the sample have only a slight influence on the changes in strength. Thus, in a wide range of proportions, the beneficial influence of the application of inject is visible, significantly higher in case of application of clay from Bełchatów, but showing similar tendencies in case of both injects.

In a case of loamy sand, a clear maximum is visible, when the amount of inject in the sample amounts to approx. 33.3% (50% inject proportionally to the weight of soil), and much worse effects when other proportions were used.

This analysis shows that for different types of soil the effects of the application of the same inject may vary, so the determination of the optimum proportions of soil to inject or the prediction of the expected effects of the application of injects requires separate tests each time.

The deflections of samples at the moment of achieving tensile bending strength were adopted as a measurement of resistance to deformation. Mixtures containing inject with clay from Bełchatów are characterised by a higher resistance to deformation – in the limit state the deflections are bigger than in case of mixtures with sludge from Bolesławiec. The influence of the proportion of ingredients on the limit state deflection is also higher if clay from Bełchatów is applied. In case of sludge from Bolesławiec the samples are characterised by a very small differentiation of the deflection value at the moment of achieving limit bending strength, with the exception of mixtures containing a small amount of inject (10%) and for loamy sand with 50% addition of inject, which was considered the optimum in reference to bending strength.

The tests of bending strength can be a useful tool for the evaluation of mixtures of soil with inject, at the same time allowing for a simultaneous analysis of two parameters – bending strength and resistance to deformation.

4.1.7.2. Compressive strength

Compressive strength test is always accompanying the bending strength investigation. As the data presented in Tables 12–15 show, there is a general relation between bending and compressive strength, i.e. higher bending strength can be assigned to higher compressive strength. Part of the results, where the compressive strength is lower than the tensile bending strength, should be considered as unreliable. The cause for these inaccuracies are the limitations of the measuring equipment used. The hydraulic press for the compression of cement mortar beams, controlled by a computer, is unable to identify a maximum force in case of destructive forces lower than approx. 0.6–0.8 kN, and it continues the test until the farthest limit position of the piston is reached. Although the machine was stopped manually at the moment of observed disintegration of the sample, the accuracy of such measurement has proved to be too low, despite of the fact that the controlling system reads the highest force recorded from the start of the test to the stop. This leads to the conclusion that the apparatus applied as a standard in strength tests of cement mortar beams is suitable only for tests of the strongest mixtures, such as inject containing clay from Bełchatów with medium sand, if the amount of inject to the amount of sand ratio is not lower than 50%. In case of weaker samples it is necessary to construct an apparatus of higher sensitivity, e.g. with use of the drive of the triaxial apparatus and adequate steel prove ring, in a similar way as it was done in case of bending strength tests.

4.1.8. Resistance to frost – frost heave

4.1.8.1. Standard criteria for the classification of soils and grainular materials in terms of frost heave. Evaluation of tested materials

The frost resistance of soils and the susceptibility to frost is usually referred to as frost heave, (German: Frosthebung), less often as frost swelling [Skarżyńska 1967]. Damages caused by the influence of frost on the soil are a phenomenon belonging to the fields of interest of geology, climatology, soil mechanics, physics and chemistry, so they are a result of a very complex process.

The phenomenon of damages caused by the influence of frost on soils has a regional nature, dependent on the climate, and concerns those areas, where the soils periodically freeze and melt.

The process of frost heaves forming is governed by a large number of factors, which can be divided into two groups:

- internal factors, resulting from the physical properties of soils,
- external factors, deciding about the conditions of soils freezing.

Not all soils demonstrate the ability to create ice lenses, i.e. to undergo frost heave during freezing. Soils that are prone to this phenomenon are called frost – susceptible soils.

The process of frost heave arising, connected with the creation of ice lenses in soil, depends on the fulfilment of three conditions:

- the temperature inside the soil must be sufficiently low, and has to last for a sufficient period of time, so that the water contained in the soil can freeze,
- the table of ground water has to be situated sufficiently close to the border of freezing zone, so that water can migrate in the direction of the arising and growing ice lenses,
- the soil has to be susceptible to frost heave, i.e. sensitive to frost and prone to form ice lenses.

There are different evaluation methods of soils susceptibility to frost. In general, they can be divided into three basic groups:

- group I – includes methods based on the analysis of grain size distribution curves of soils. On this basis, soils are divided into frost-susceptible, and non-susceptible to frost heave, with the exclusion of highly plastic clays, which are low sensitive to frost,

- group II – methods used in cases when the methods from group I do not yield undoubtful results, or in case of contrary results. The test of grain size distribution of the soil is then supplemented by other tests, including the determination of liquid limit, liquid and plasticity index, capillarity, negative pressure pF and others,
- group III – eincludes the most accurate methods of determination of frost heave of soils, i.e. laboratory tests of frost heave on physical models. Tests of this type should reflect the natural conditions in the most accurate possible way.

In the past years numerous theories, based on various assumptions, were presented, whose aim was to describe the mechanisms of frost heave generation and forms of ice crystallisation in freezing soils. Numerous mathematical models describing the mechanisms of the processes of freezing and melting of soils were created.

In practice, the risk evaluation of frost heaves forming in a subsoil is determined on the basis of the so-called frost heave criteria. The ones, most often applied in the past, include the criteria of Casagrande, Dücker, Beskow, Keil, Schaible, Wiłun and Rolla [Croney and Jacobs 1967, Keil 1957, Rolla 1977, Ruckli 1950, Wiłun 2000]. Nowadays, in polish engineering practice, the criterion contained in the standard "PN-S-02205: 1998 Roads. Earth works. Specifications and testing" is applied. Actually obligatory standard takes into account the content of particles of the diameter of 0.02 and 0.075 mm, the values of capillary head and the content of sand (Tab. 16).

Table 16

Classification of soils in terms of frost heave according to polish standard PN-S-02205

No.	Specification of properties	Units	Groups of soils		
			Non-frost susceptible	Doubtful	Frost susceptible
1.	Type of soil		non-clayey gruss, gravel, gravelly sand, coarse sand, medium sand, fine sand, non-decomposed slag	silty sand clayey weathered rock (detritus), clayey gruss, clayey gravel, clayey gravelly sand	**Low susceptibility:** sandy clay loam, clay loam, silty clay loam, clay, sandy clay, silty clay **high susceptibility:** silt, sandy silt sandy loam, loam, silty loam, varve clay
2.	Content of particles ≤ 0.075 mm ≤ 0.02 mm	[%]	< 15 < 3	15 to 30 3 to 10	> 30 > 10
3.	Capillary head H_{kb}	[m]	< 1.0	1.0 ÷ 1.3	> 1.3
4.	Content of sand		> 35	25 to 35	<25

The results of the preliminary evaluation of frost heave based on the grain size distribution curve of soils and their mixtures are presented in Table 17. Grain size distribution curves are presented in Figure 7 and 35.

Table 17

Preliminary evaluation of frost heave of tested soils and their mixtures

No.	Type of soil	Particles content [%]	
		≤0.075 mm	≤ 0.02 mm
1.	clay Bełchatów	**68** susceptible	**54** susceptible
2.	Medium sand+100% clay Bełchatów	**13** non-susceptible	**10** susceptible
3.	Medium sand+50% clay Bełchatów	**8** non-susceptible	**6** doubtful
4.	Medium sand+25% clay Bełchatów	**4** non-susceptible	**3** non-susceptible
5.	Medium sand+10% clay Bełchatów	**1.5** non-susceptible	**1** non-susceptible
6.	Sludge Bolesławiec	**9.0** non-susceptible	**12.5** Susceptible
7.	Loamy sand	**6.5** non-susceptible	**9.5** doubtful
8.	Medium sand	**0.0** non-susceptible	**0.0** non-susceptible

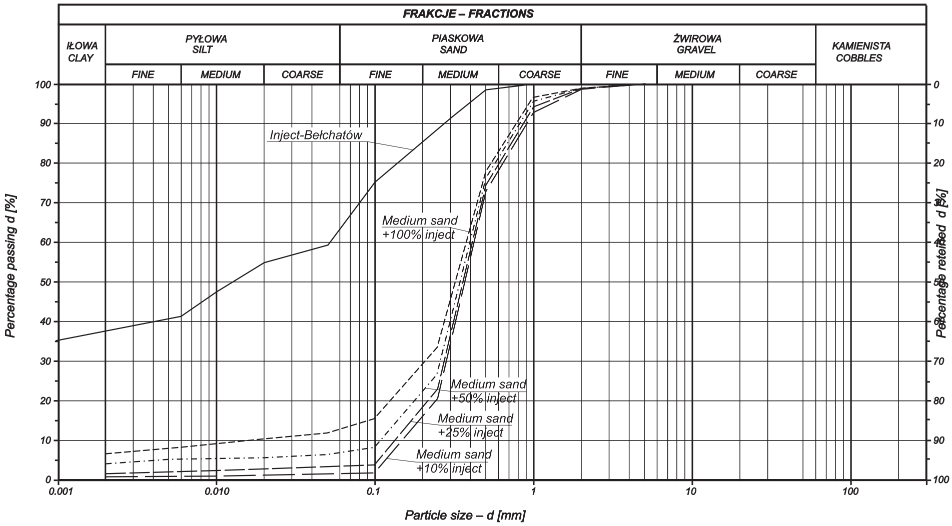


Fig. 35. Grain size distribution curves for clay from Bełchatów and its mixtures with medium sand

According to the criterion contained in the standard, the tested soils and their mixtures present extremely varied levels of frost heave susceptibility. Inject containing clay from Bełchatów is, according to this criterion, certainly frost-sensitive. Its subsequent mixtures with medium sand, along with the decrease of the amount of inject, show a tendency to decrease frost heave, but the determination of their susceptibility is not unquestionable. Already for the mixture of medium sand +100% inject with clay from Bełchatów the criterion of fine particles content leads to divergent results. The same is observed in the evaluation of frost heave of sludge from Bolesławiec and loamy sand. A very significant element of the conducted tests is the activity of cement as an ingredient of the evaluated soil mixtures, which is not taken into account by the indicators used for evaluation. Thus, the criteria presented here above were applied for indicative purposes only. By this type of tests the most suitable evaluation method of frost heave of tested soil mixtures are laboratory frost heave tests on physical models. Tests of this kind reflect natural conditions and can take into consideration the time factor, which is highly significant in case of soil mixtures containing cement or lime.

Laboratory test of frost heave

For many years numerous research centres throughout the world have been working on the development of a laboratory soil frost heave test. All tests modelling the phenomenon of freezing of soil adopt similar procedure, i.e. freezing soil sample from top to bottom, lateral insulation, and water inflow to the sample from the bottom.

One of many tests of this type has been designed in the Transport and Road Research Laboratory TRRL, in the United Kingdom. The original form of this test was developed in 1967 [Croney and Jacobs 1967], and the guidelines were contained in the report RL 90. Roe and Webster [1984], basing on the previous test, developed a more efficient testing procedure, which they described in the report "Specification for the TRRL frost – heave test". Its current version is the test described in the BRITISH STANDARDS INSTITUTION publication of 1989, section 124 entitled "Methods for determination of frost heave".

The test, that allows to evaluate the susceptibility of soil or of other grainy materials to freezing basing on the increase in height Δh of samples frozen in various initial conditions, is described in section 3.1.9.

Before the test, the samples matured for either 7 or 42 days, as it was necessary that the samples achieve a state allowing on safe dismantle. Forming of samples with pure inject was impossible or very difficult, because of the material consistency. The liquid substance, which was the initial form of the inject, needed, on average, several days to achieve such a state of aggregation that allowed to take it out of the form and to obtain a stable sample of specific dimensions. Problems connected to the stability of samples containing small amounts of inject and a high amount of medium sand were observed, too. The adopted 7-day period of maturing for all samples allowed to avoid unexpected and uncontrolled deformations. The forty-two-day period of maturing of samples was required in order to determine, whether the addition of cement and water-glass influences a further improvement of the tested properties in longer periods of time.

4.1.8.2. Analysis of the results of frost heave tests

The primary objective of the conducted series of tests was to determine, whether the ultra-fine soils used for injections are sensitive to low temperatures. In case of a positive answer one should attempt to assess the scope of damage that might occur, and possibly suggest some specific remedies.

At the begining, a comprehensive series of experiments was planned. Eight series of tests were prepared. Each of them consisted of fifteen samples of a varying content of each components – injects and soils. The first series contained three samples prepared from pure inject made from clay Bełchatów with additions of water-glass and cement. The samples were kept for 7 days in constant humidity conditions, and then they were tested according to the previously described procedure. The results of the test are presented in Figure 36.

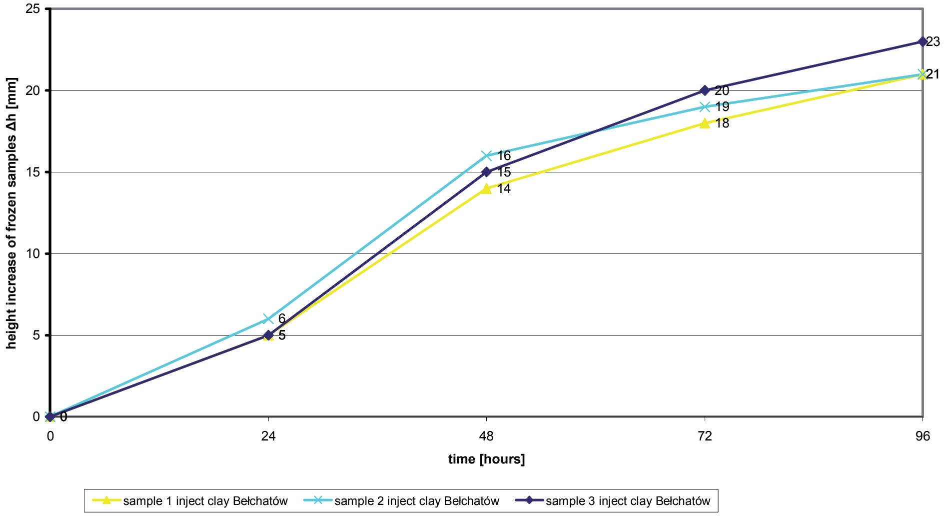


Fig. 36. Frost heave test of inject made with clay from Bełchatów after 7 days of samples maturing

The assumed criterion foresees that, if after 96 hours the increase in the height of the sample exceeds 15 milimeters, then the material from which it was made, is classified as susceptible to frost heave. In the tested case, the sample exceeded the critical height already after 48 hours of test. After 96 hours the largest recorded value of height increase among the three samples amounted to 23 mm. The next series consisted of mixture of medium sand and inject (100%) containing clay from Bełchatów, water-glass and cement. The course of the test is shown in Figure 37. The highest recorded increase in height after 96 hours equalled 15 mm. This mixture, which matured for 7 days, should also be classified as material susceptible to frost heave. However, a tendency to weaken the frost heave effect was observed, along with the increase of medium sand content in the mixture. This tendency was confirmed in the test of samples containing, apart from medium sand, 50% addition of inject made of clay from Bełchatów. After 96 hours of test, the height of the samples increased by 9÷10 mm (Fig. 38), which is the lower level adopted for soils of questionable susceptibility to frost heave. Height of samples containing 25 or 10% of inject increased by several milimeters during appropriate test time (Fig. 39 and 40). The obtained results confirmed that these two mixtures are completely safe in terms of sensitivity to freezing temperatures.

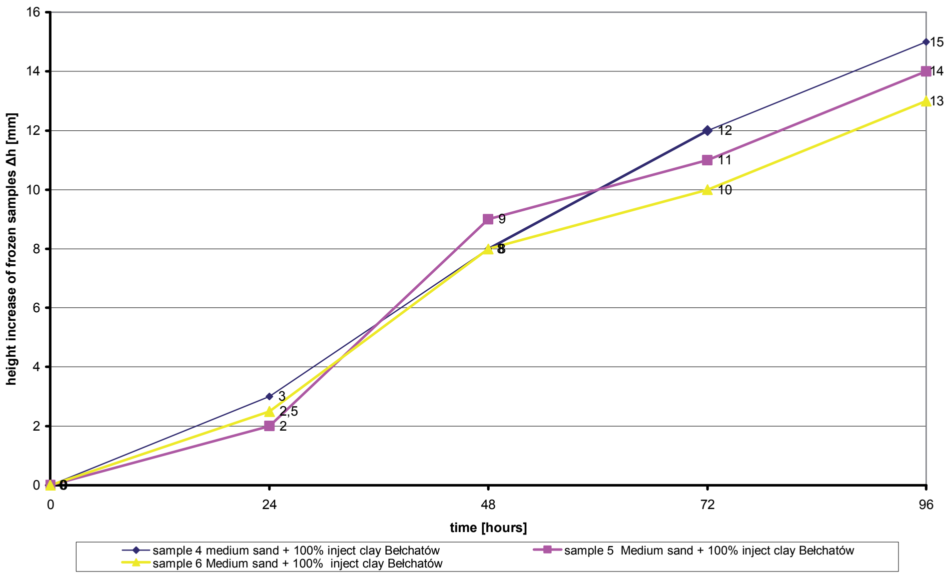


Fig. 37. Frost heave test of mixtures of medium sand and inject made with clay from Bełchatów (100%) after 7 days of samples maturing

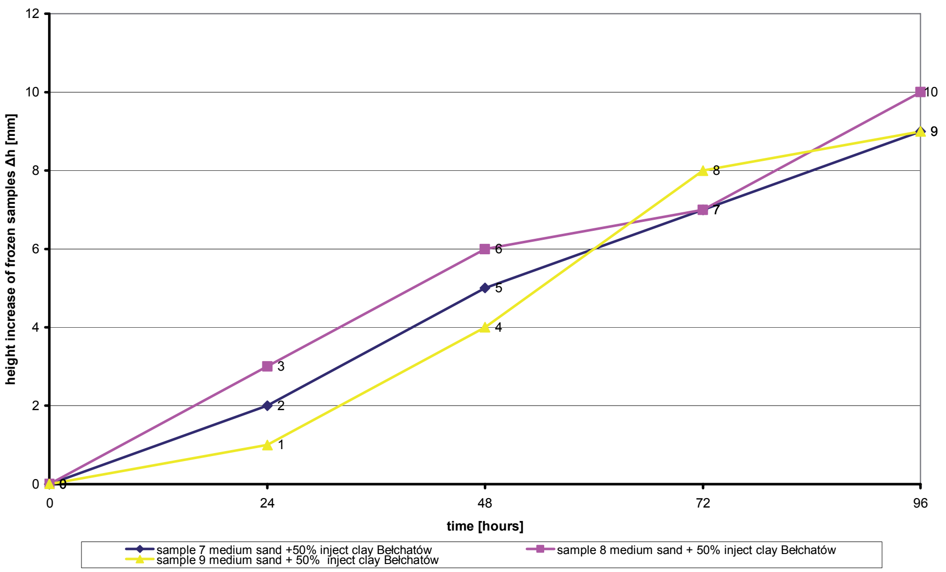


Fig. 38. Frost heave test of mixture of medium sand with inject made from clay from Bełchatów after 7 days of samples maturing

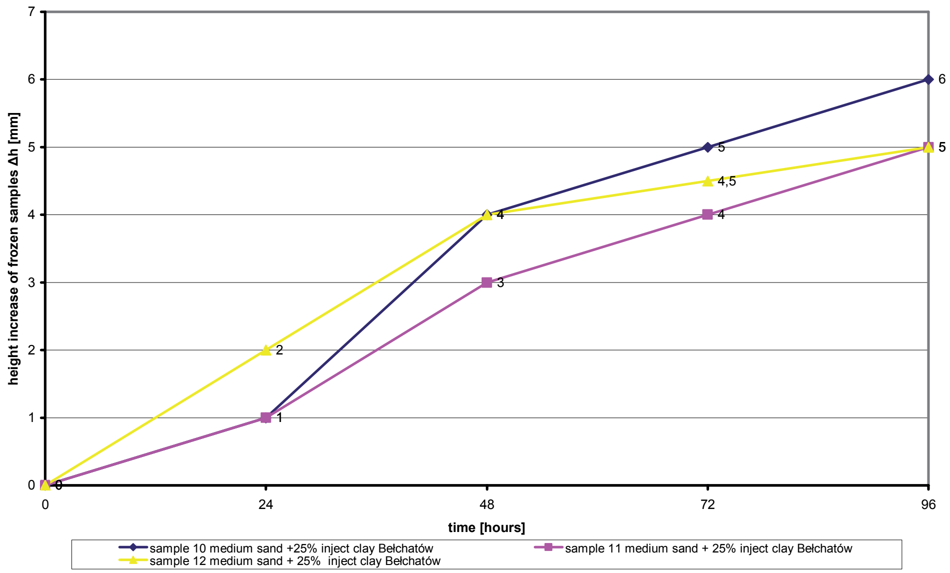


Fig. 39. Frost heave test of mixture of medium sand with inject made from clay from Bełchatów (25%) after 7 days of samples maturing

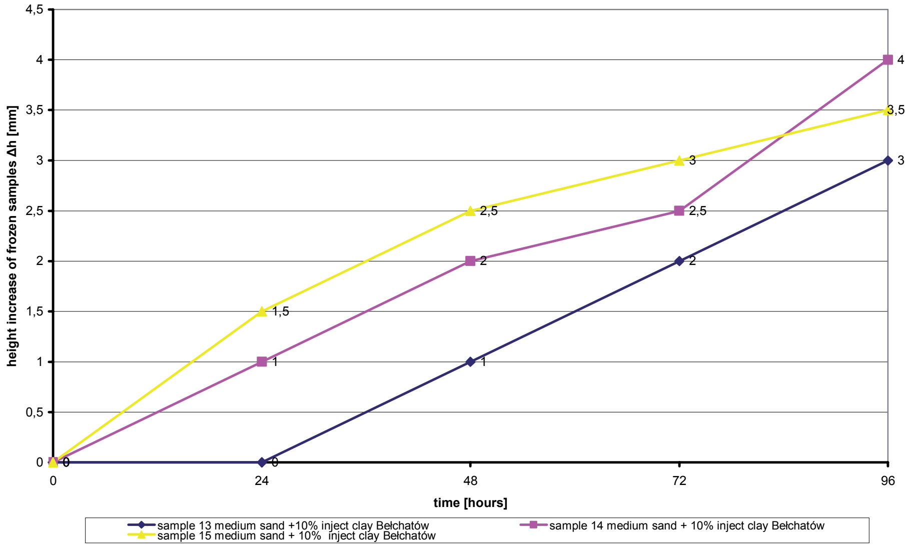


Fig. 40. Frost heave test of mixture of medium sand with 10% inject made from clay from Bełchatów after 7 days of samples maturing

The following series of tests was conducted in the same way as the previous one, the only difference was the fact that the samples had matured for 42 days before the test. Height increases of frozen samples containing clay from Bełchatów, i.e. the most susceptible mixture from the previous series, after 96 hours of test did not exceed 9 milimeters. The results of these tests are presented in Figure 41. The remaining mixtures of medium sand with clay from Bełchatów that had matured for 42 days, showed very small increases in height during freezing. They ranged from 5 milimeters for 100 % addition of inject (Fig. 42) to 2 milimeters for 10% inject addition (Fig. 45). All mixtures of soil tested in this series, as well as the pure inject, having matured for 42 days, should be classified as non-susceptible to frost heave.

The following series consisted of mixtures of medium sand with inject prepared from sludge from Bolesławiec. For the tests, whose results are presented in Figures 46–55, samples, like the previous ones, were kept for 7 days in the temperature of 20°C and tested after this time. Samples of inject made from sludge from Bolesławiec with the addition of water-glass and cement increased the height by over 15 mm (mean value) already after 72 hours, which means that they have to be classified as susceptible to frost heave. After the following 24 hours the increases in the height of samples ranged from 17 to 19 milimeters. The course of the test is presented in Figure 49. These values are by three to four millimeters lower than those obtained in the test of the inject from clay from Bełchatów also maturing for 7 days. Considering the content of fine particles in both injects (sludge from Bolesławiec contain much less grains finer then 0,075 mm if compared with clay from Bełchatów – see Fig. 15), higher differences in samples height increase could be expected. The analysis of the remaining mixtures of inject with sludge from Bolesławiec allows us to determine that the mixture of medium sand and 50 or 100% of inject is questionnable in terms of frost heave (Fig. 56, 57). The remaining mixtures from this series should be classified as non-susceptible to frost heave. The forty-two-day period of maturing of samples made from a mixture of inject containing sludge from Bolesławiec with medium sand, because of the bondings created during that time, significantly reduced the value of frost heave. Height increase of none of the tested samples was bigger than 7.5 milimeters. The test results are presented in Figures 51–55. Longer (42 days) period of maturing enables to reduce samples frost heave to a value that allows to classify them as safe in terms of frost heave.

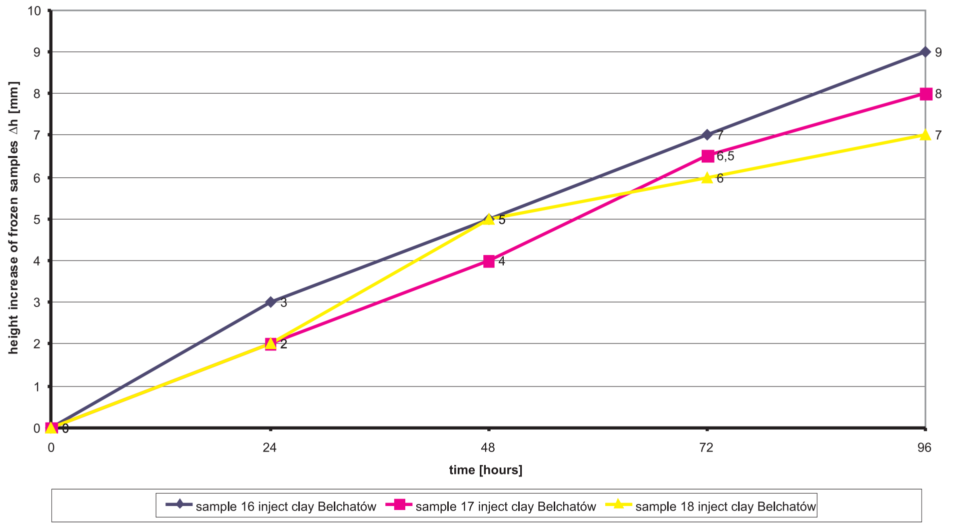


Fig. 41. Frost heave test of inject made from clay from Bełchatów after 42 days of samples maturing (inject test accompanying tests series of mixtures with medium sand)

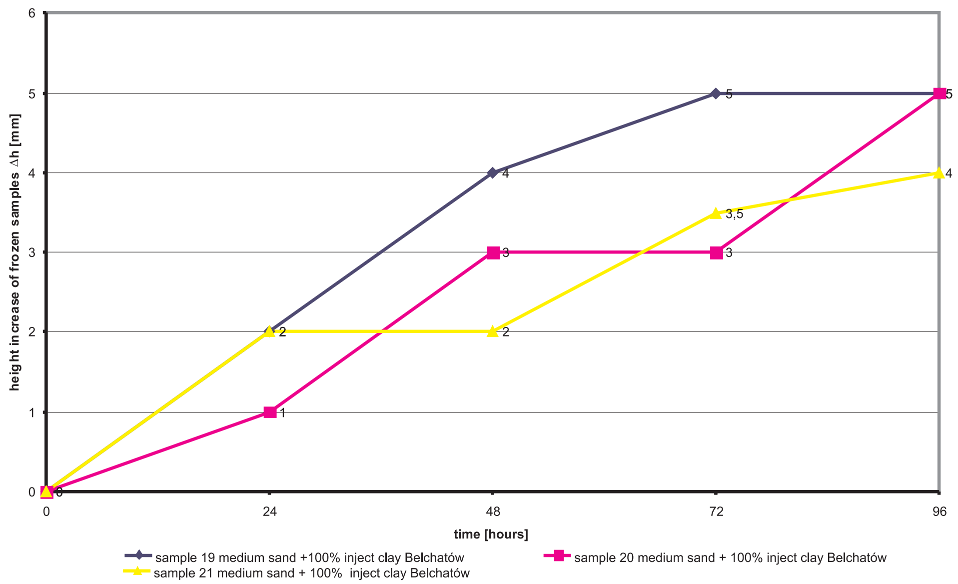


Fig. 42. Frost heave test of mixture of medium sand with 100% inject made from clay from Bełchatów after 42 days of samples maturing

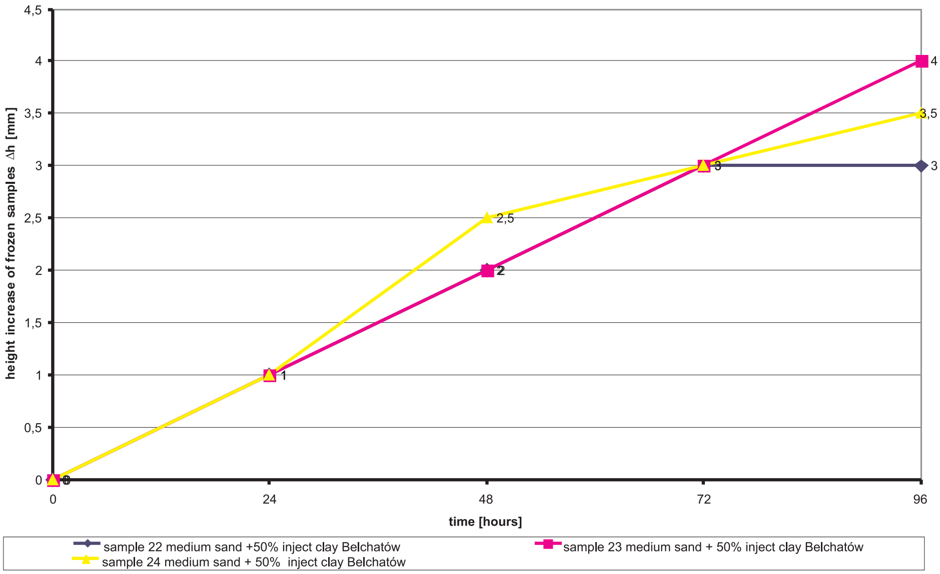


Fig. 43. Frost heave test of mixture of medium sand with 50% inject made from clay from Bełchatów after 42 days of samples maturing

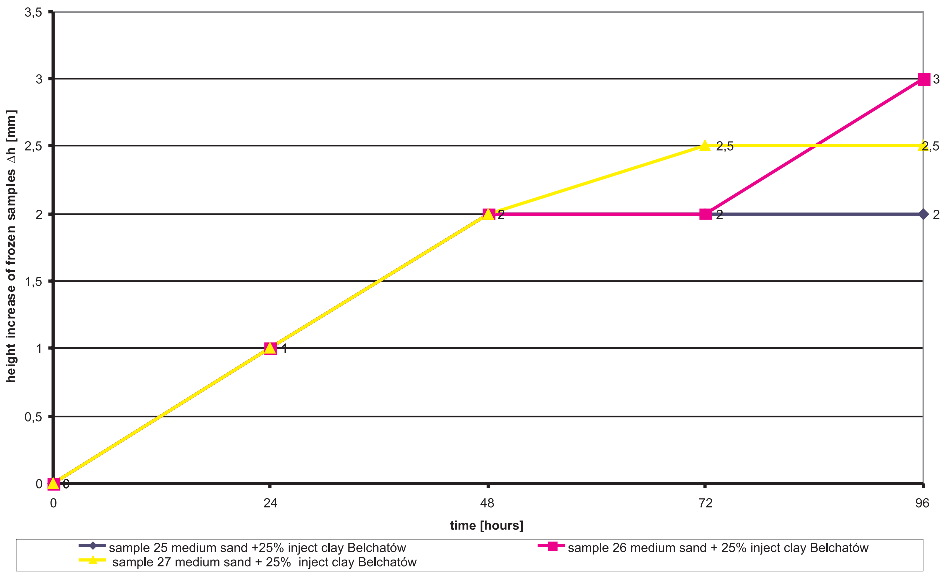


Fig. 44. Frost heave test of mixture of medium sand with 25% inject made from clay from Bełchatów after 42 days of samples maturing

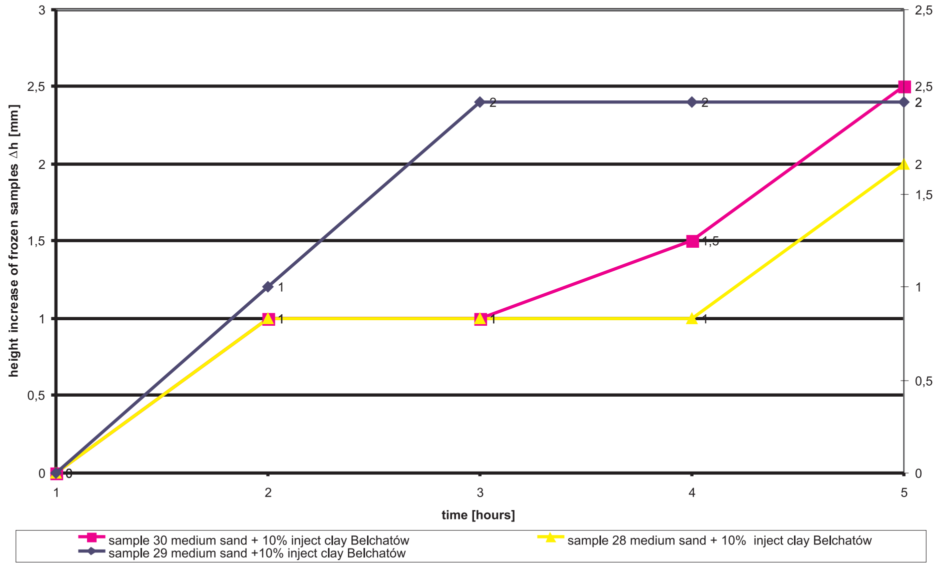


Fig. 45. Frost heave test of mixture of medium sand with 10% inject made from clay from Bełchatów after 42 days of samples maturing

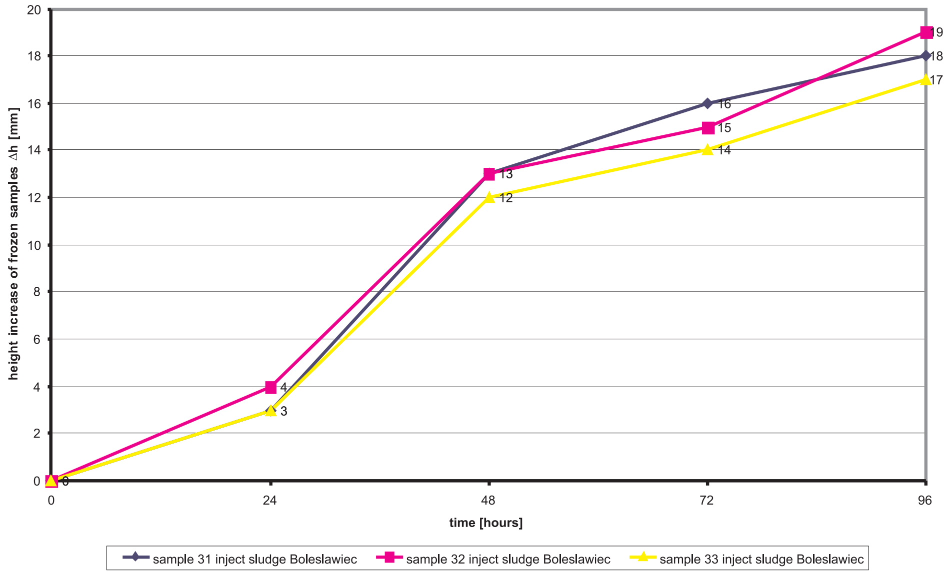


Fig. 46. Frost heave test of inject made from sludge from Bolesławiec after 7 days of samples maturing

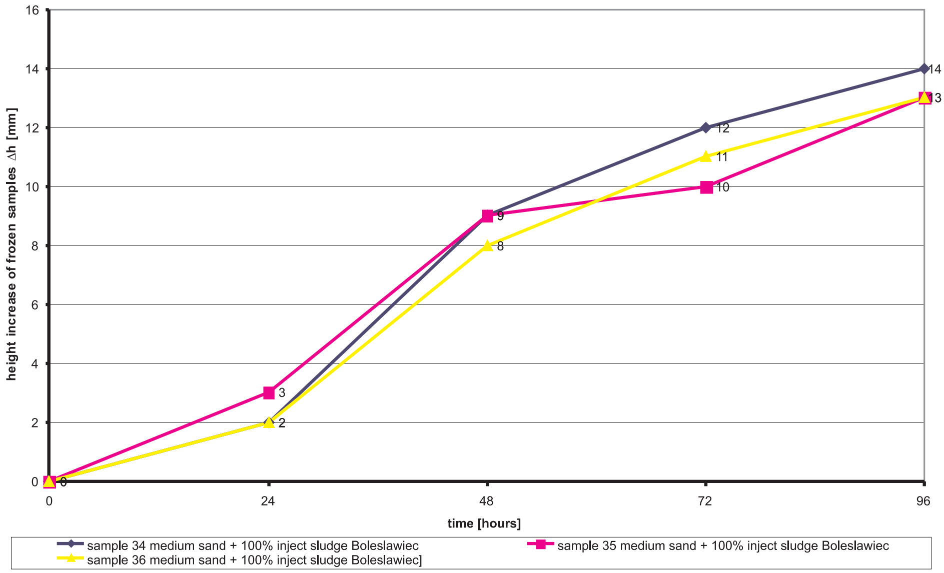


Fig. 47. Frost heave test of mixture of medium sand with 100% inject made from sludge from Bolesławiec after 7 days of samples maturing

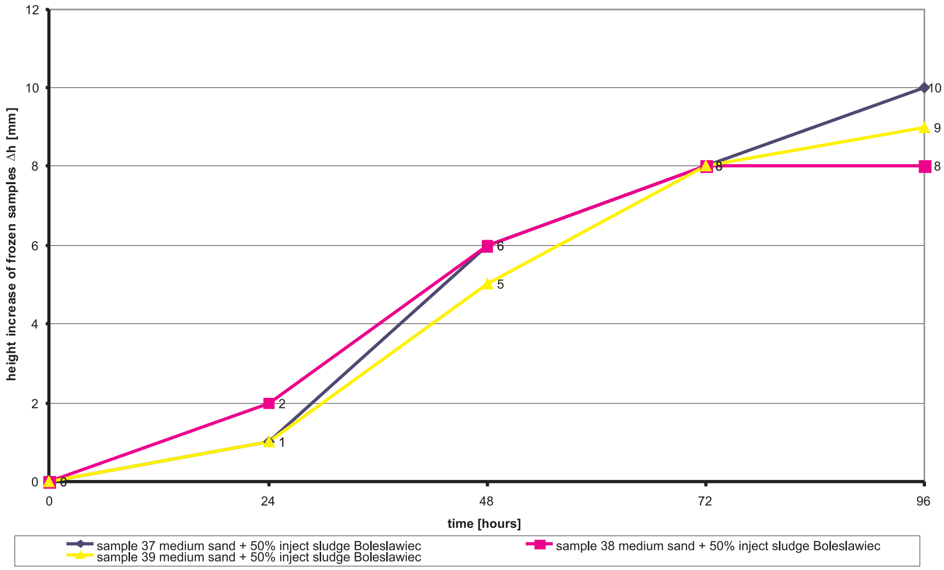


Fig. 48. Frost heave test of mixture of medium sand with 50% inject made from sludge from Bolesławiec after 7 days of samples maturing

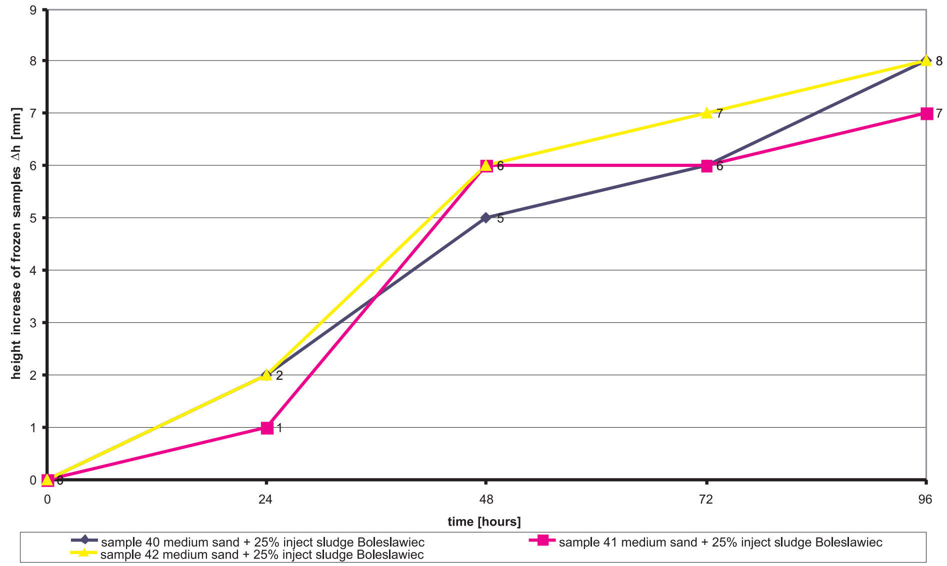


Fig. 49. Frost heave test of mixture of medium sand with 25% inject made from sludge from Bolesławiec after 7 days of samples maturing

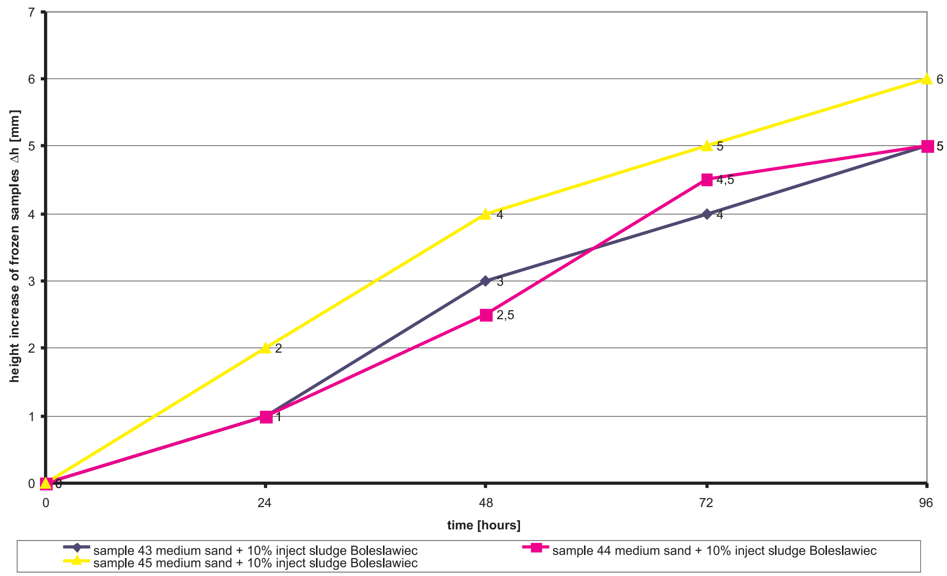


Fig. 50. Frost heave test of mixture of medium sand with 10% inject made from sludge from Bolesławiec after 7 days of samples maturing

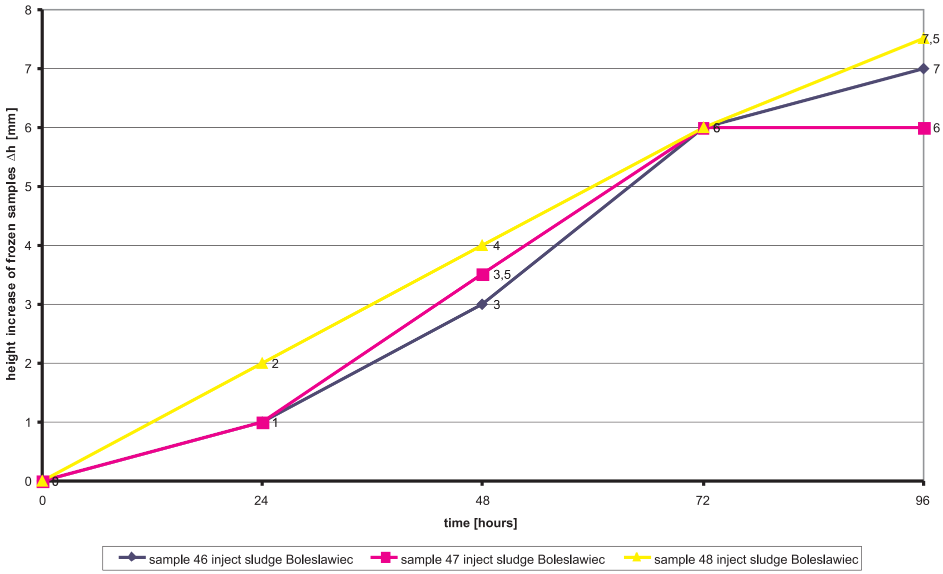


Fig. 51. Frost heave test of inject made from sludge from Bolesławiec after 42 days of samples maturing

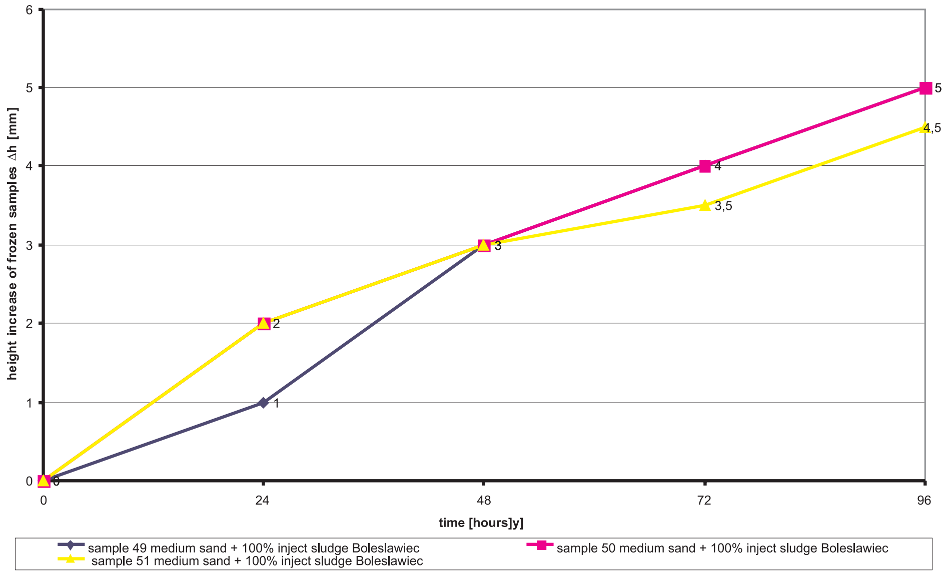


Fig. 52. Frost heave test of mixture of medium sand with 100% inject made from sludge from Bolesławiec after 42 days of samples maturing

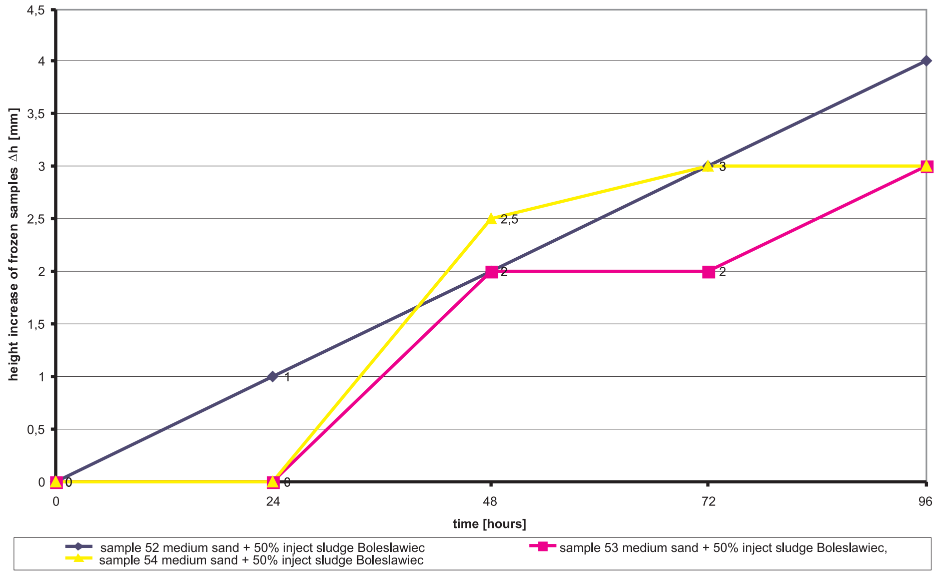


Fig. 53. Frost heave test of mixture of medium sand with 50% inject made from sludge from Bolesławiec after 42 days of samples maturing

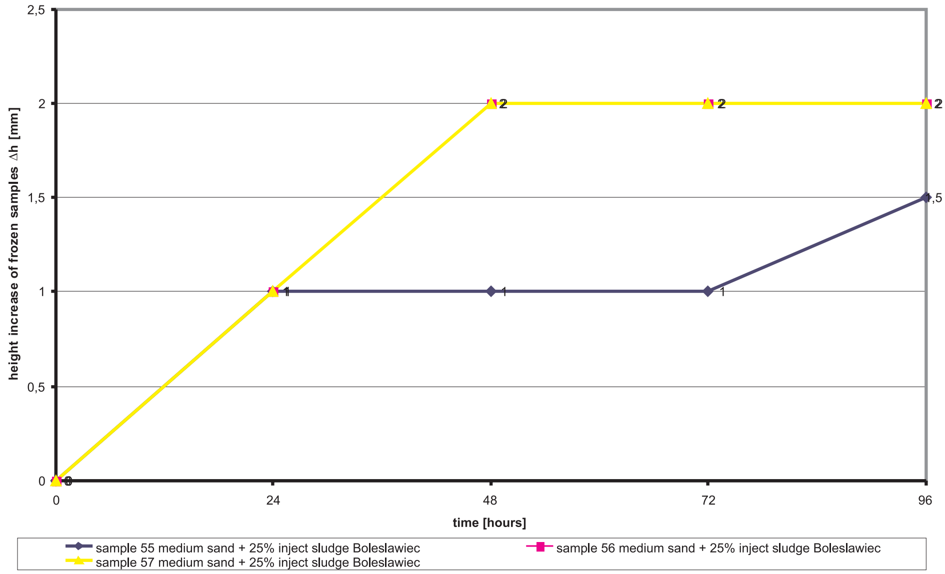


Fig. 54. Frost heave test of mixture of medium sand with 25% inject made from sludge from Bolesławiec after 42 days of samples maturing

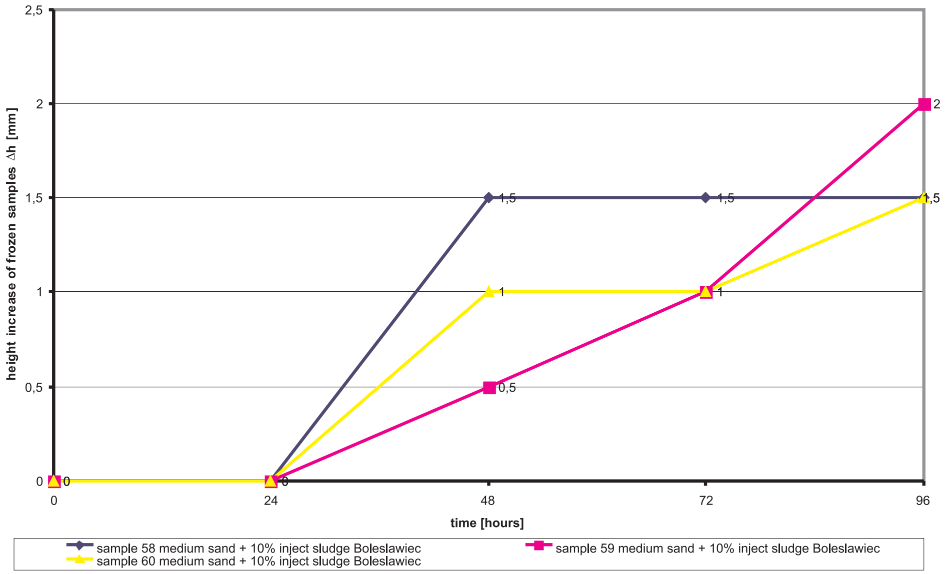


Fig. 55. Frost heave test of mixture of medium sand with 10% inject made from sludge from Bolesławiec after 42 days of samples maturing

Although the inject with clay from Bełchatów used for the preparation of samples from loamy sand had the same composition as the inject used in mixtures with medium sand, samples of inject prepared for the second tested soil were tested again for frost heave. The first series of pure inject, like in the previous test, was tested after a 7-day maturing period. The conducted tests of frost heave of pure inject confirmed its high susceptibility to the influence of low temperatures, as determined earlier. The next series of results, presented in Figure 57, allowed to determine that mixture of loamy sand with the addition of 100% inject from clay Bełchatów is only questionable in terms of frost heave. The same situation was observed in case of mixture with the addition of 50% inject. Decreasing the amount of inject in the mixture to 25 or 10% made it insensitive to frost (Fig. 59 and 60). The tests of pure inject and of mixtures of loamy sand with clay from Bełchatow after 42 days of maturing show that they can be classified as soils insusceptible to frost heave (Fig. 61–65).

Two final series of tests were conducted on mixtures of loamy sand with inject made from sludge from Bolesławiec (Fig. 66–75). Only pure inject was susceptible to frost heave. All remaining mixtures (loamy sand with 100, 50, 25 or 10% of inject with sludge from Bolesławiec) were resistant to frost heave already after 7 days of maturing.

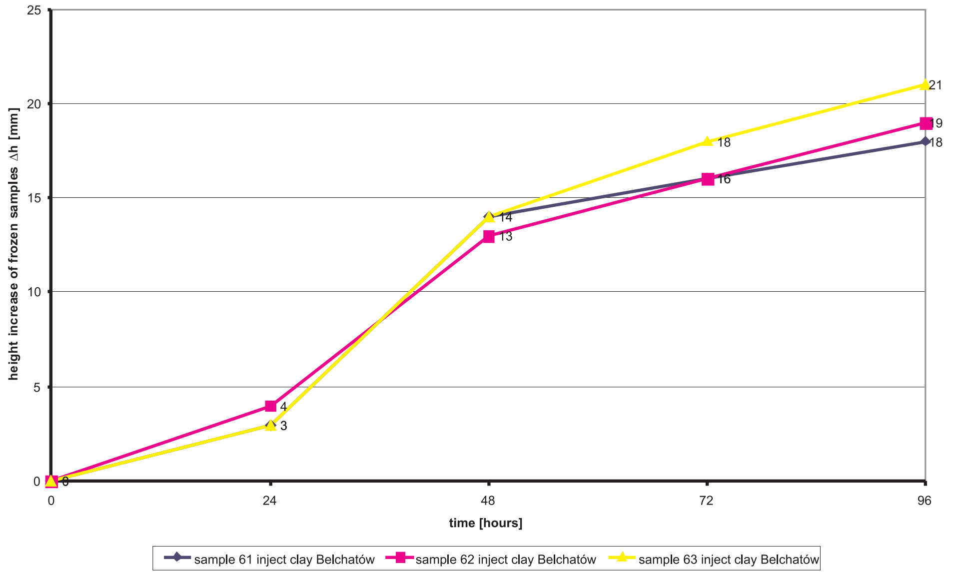


Fig. 56. Frost heave test of inject made from clay from Bełchatów after 7 days of samples maturing (inject tests accompanying tests series of mixtures with loamy sand)

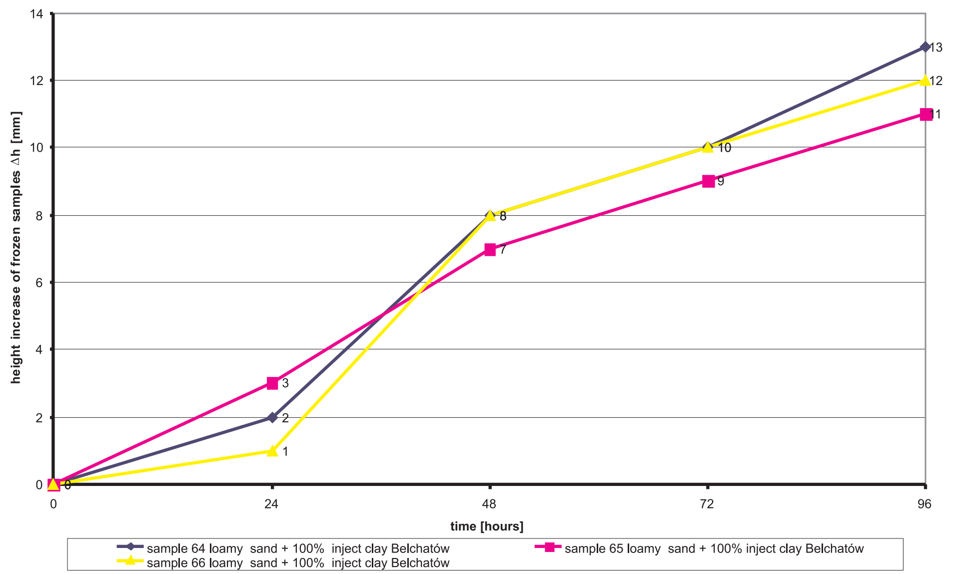


Fig. 57. Frost heave test of mixture of loamy sand with 100% inject made from clay from Bełchatów after 7 days of samples maturing

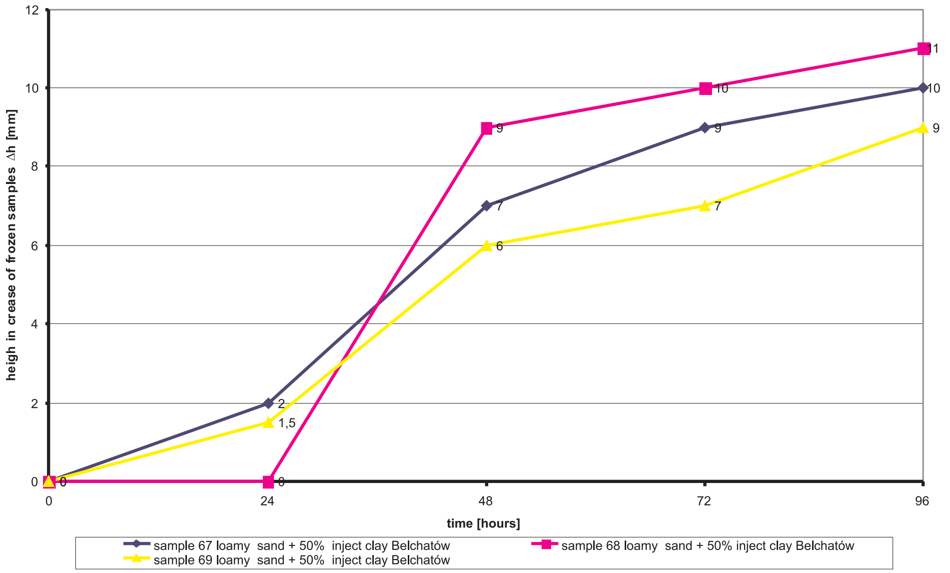


Fig. 58. Frost heave test of mixture of loamy sand with 50% inject made from clay from Bełchatów after 7 days of samples maturing

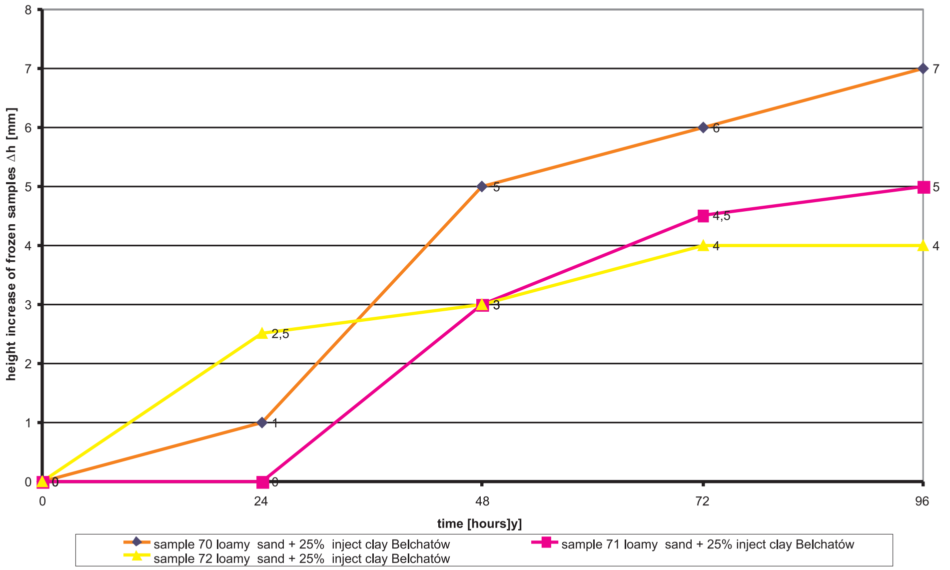


Fig. 59. Frost heave test of mixture of loamy sand with 25% inject made from clay from Bełchatów after 7 days of samples maturing

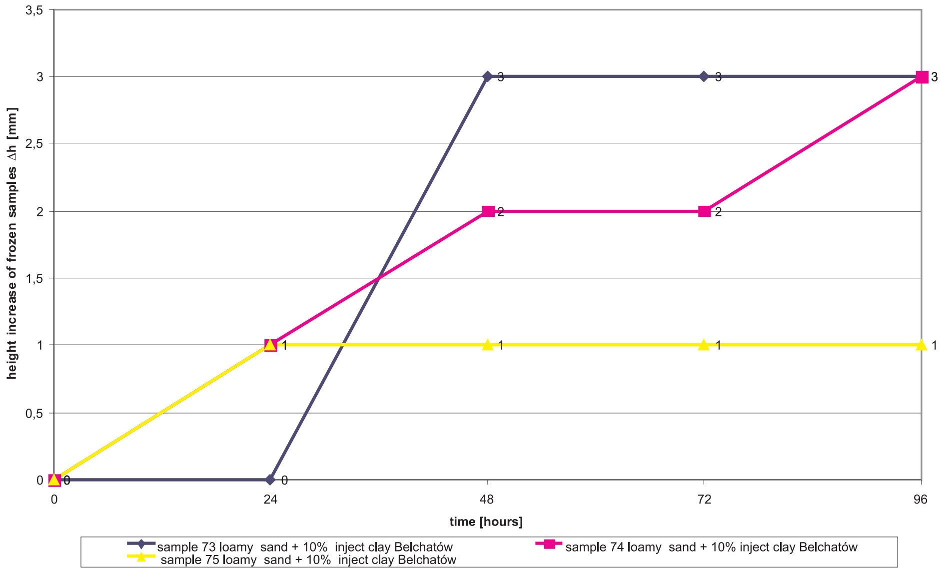


Fig. 60. Frost heave test of mixture of loamy sand with 10% inject made from clay from Bełchatów after 7 days of samples maturing

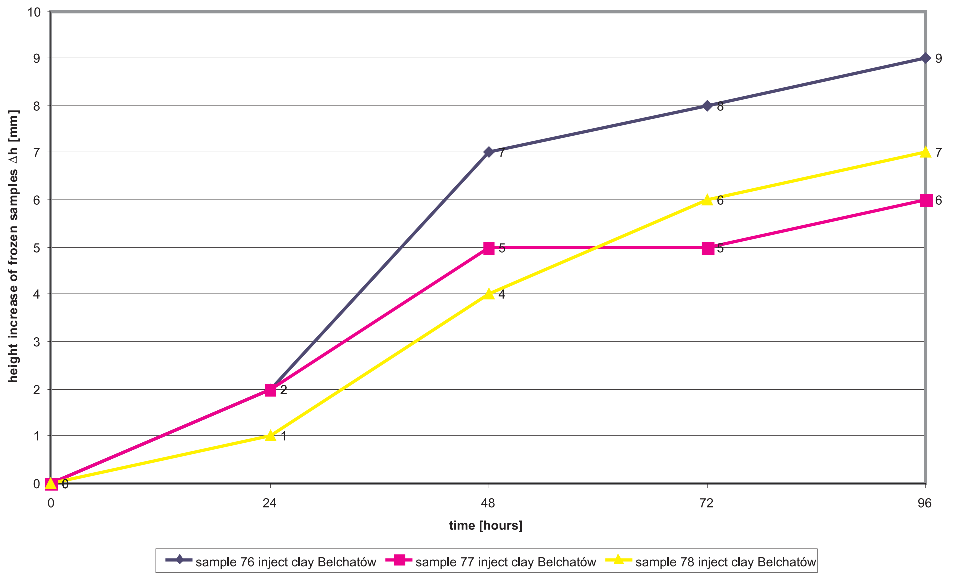


Fig. 61. Frost heave test of inject made from clay from Bełchatów after 42 days of samples maturing (inject tests accompanying test series of mixtures with loamy sand)

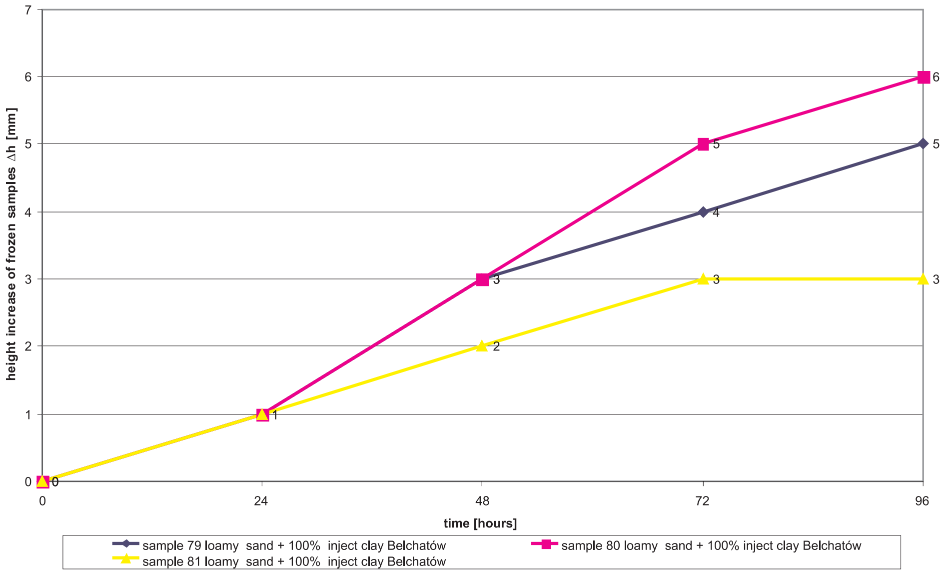


Fig. 62. Frost heave test of mixture of loamy sand with 100% inject made from clay from Bełchatów after 42 days of samples maturing

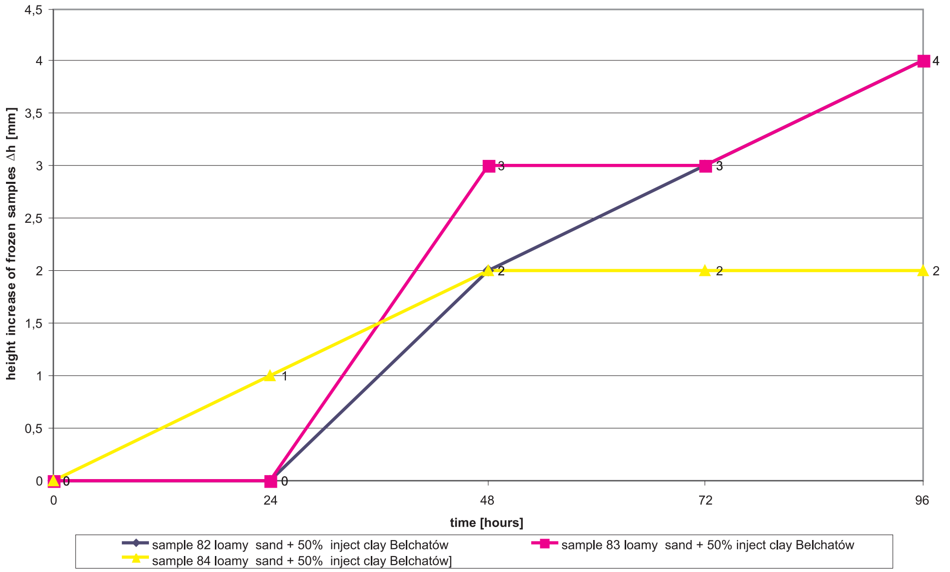


Fig. 63. Frost heave test of mixture of loamy sand with 50% inject made from clay from Bełchatów after 42 days of samples maturing

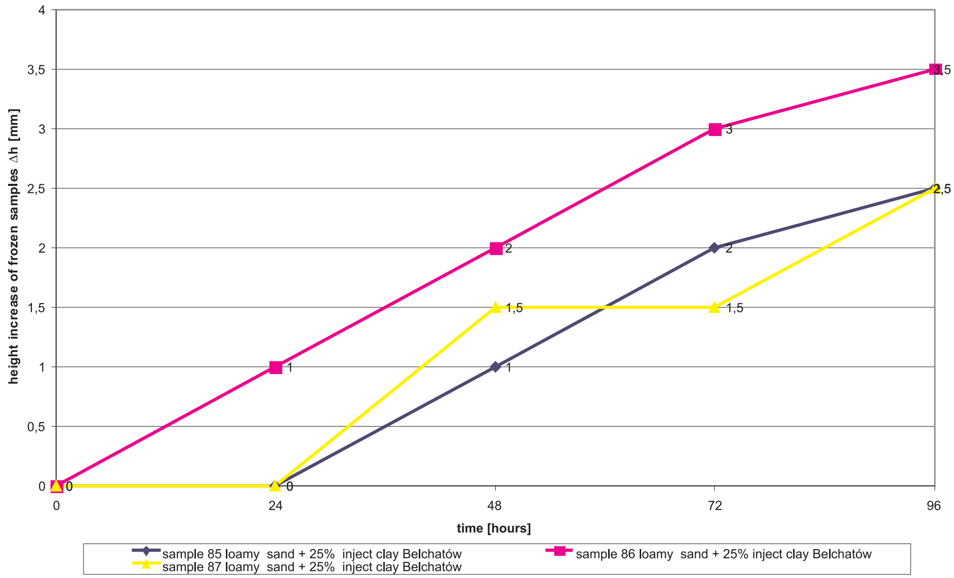


Fig. 64. Frost heave test of mixture of loamy sand with 25% inject made from clay from Bełchatów after 42 days of samples maturing

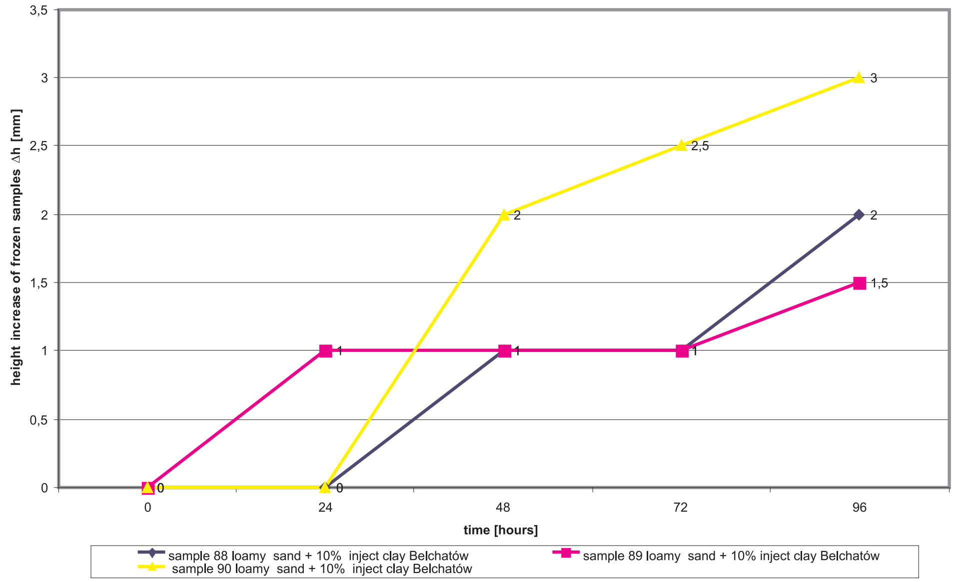


Fig. 65. Frost heave test of mixture of loamy sand with 10% inject made from clay from Bełchatów after 42 days of samples maturing

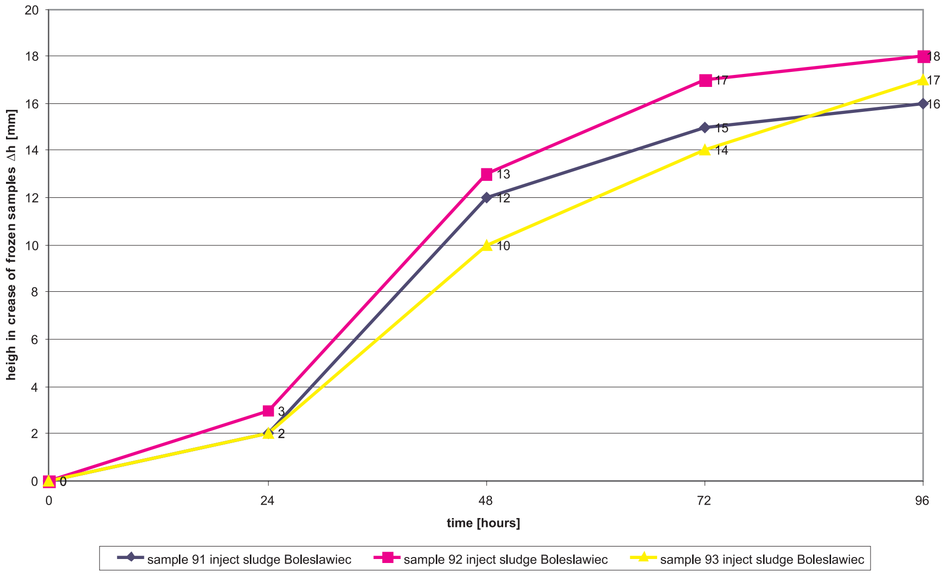


Fig. 66. Frost heave test of inject made from sludge from Bolesławiec after 7 days of samples maturing (inject tests accompanying tests of mixtures with loamy sand)

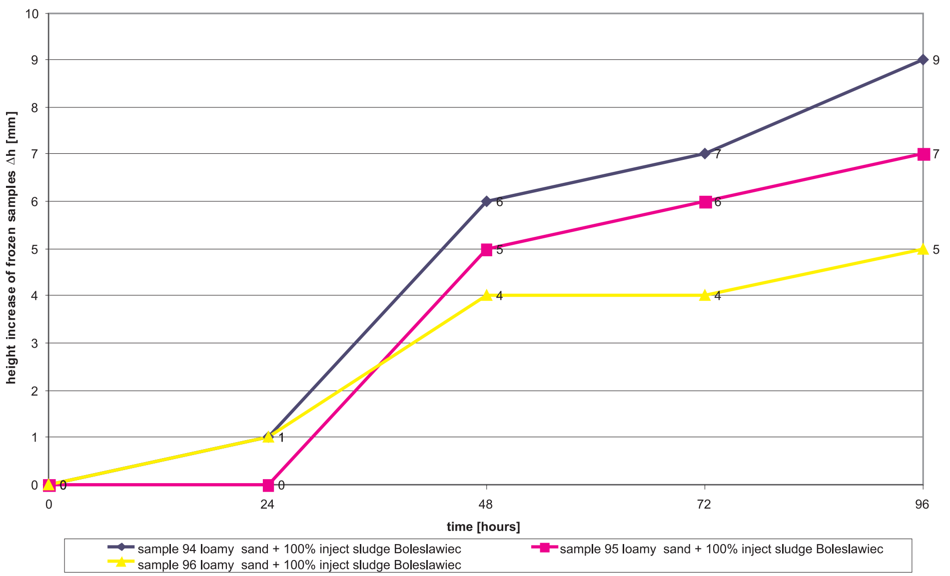


Fig. 67. Frost heave test of mixture of loamy sand with 100% inject made from sludge from Bolesławiec after 7 days of samples maturing

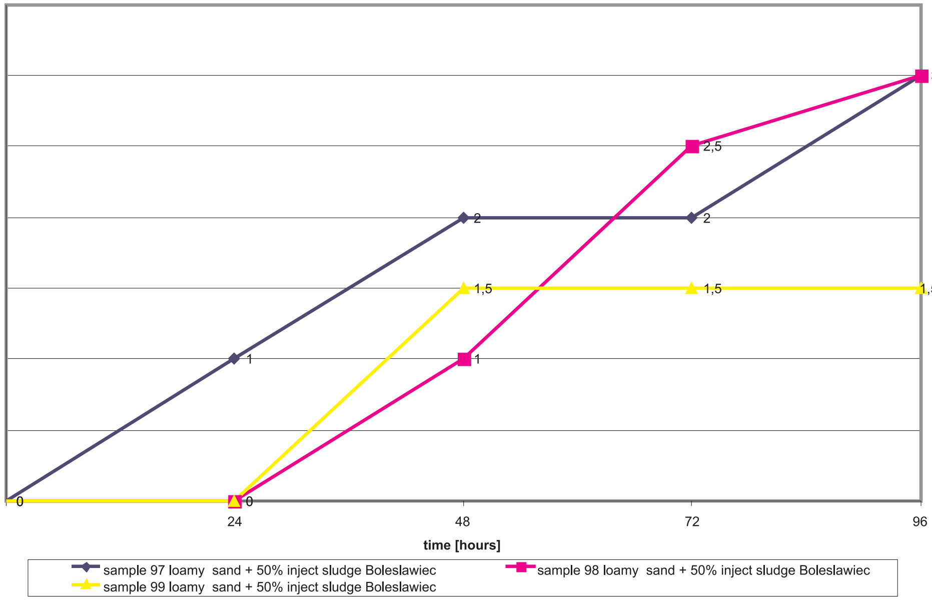


Fig. 68. Frost heave test of mixture of loamy sand with 50% inject made from sludge from Bolesławiec after 7 days of samples maturing

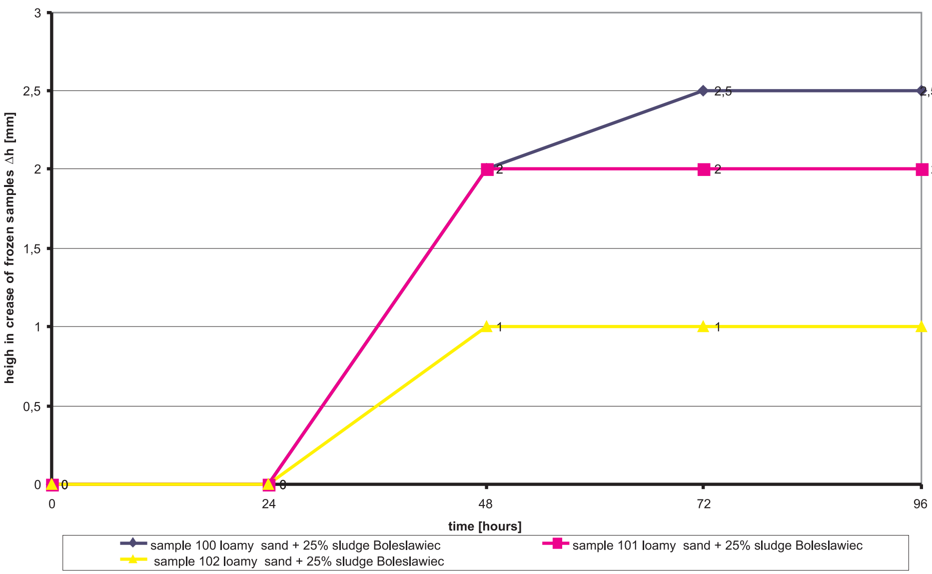


Fig. 69. Frost heave test of mixture of loamy sand with 25% inject made from sludge from Bolesławiec after 7 days of samples maturing

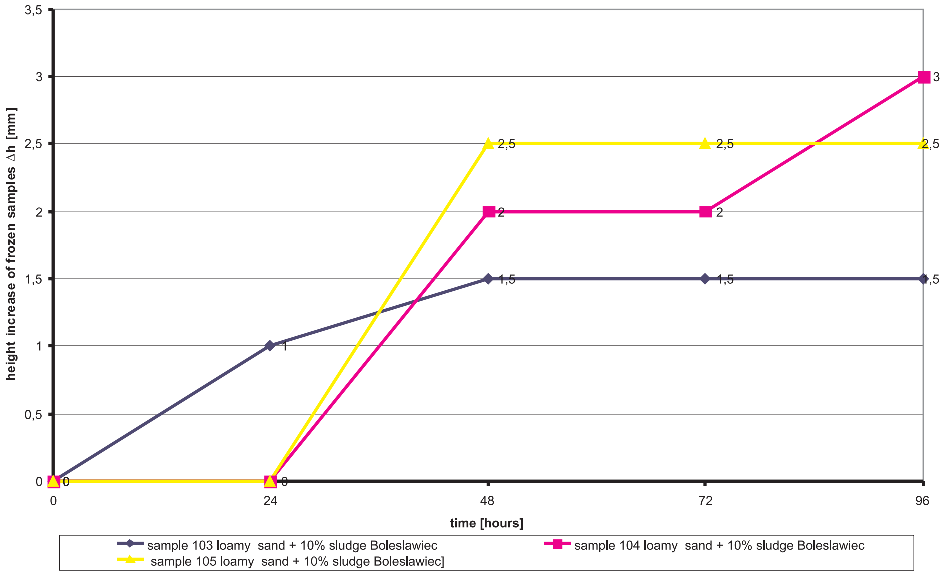


Fig. 70. Frost heave test of mixture of loamy sand with 10% inject made from sludge from Bolesławiec after 7 days of samples maturing

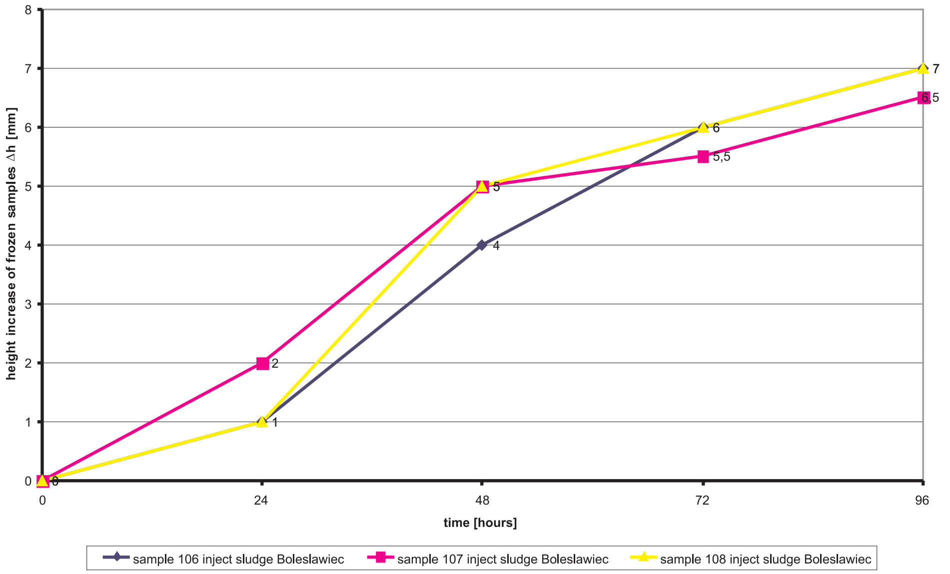


Fig. 71. Frost heave test of inject made from sludge from Bolesławiec after 42 days of samples maturing (inject tests accompanying tests series of mixtures with loamy sand)

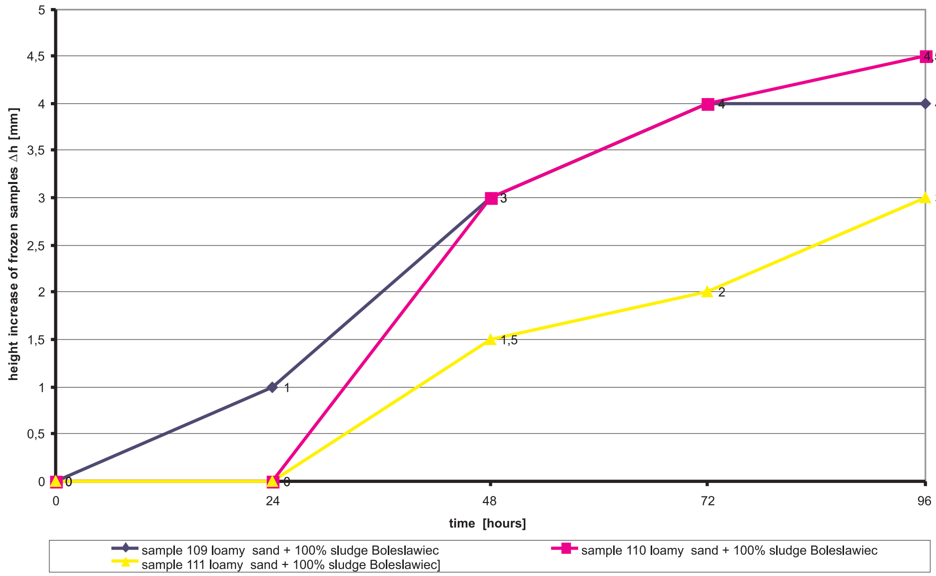


Fig. 72. Frost heave test of mixture of loamy sand with 100% inject made from sludge from Bolesławiec after 42 days of samples maturing

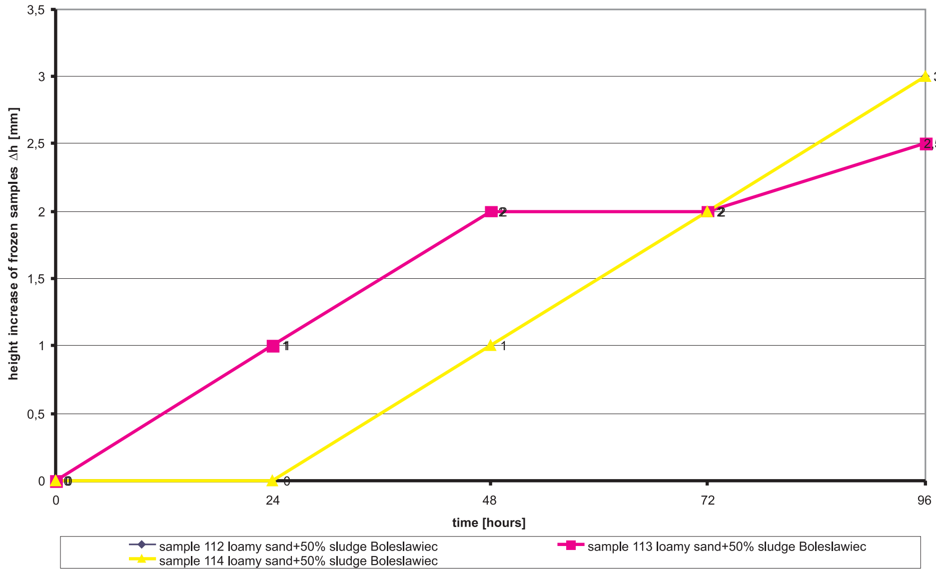


Fig. 73. Frost heave test of mixture of loamy sand with 50% inject made from sludge from Bolesławiec after 42 days of samples maturing

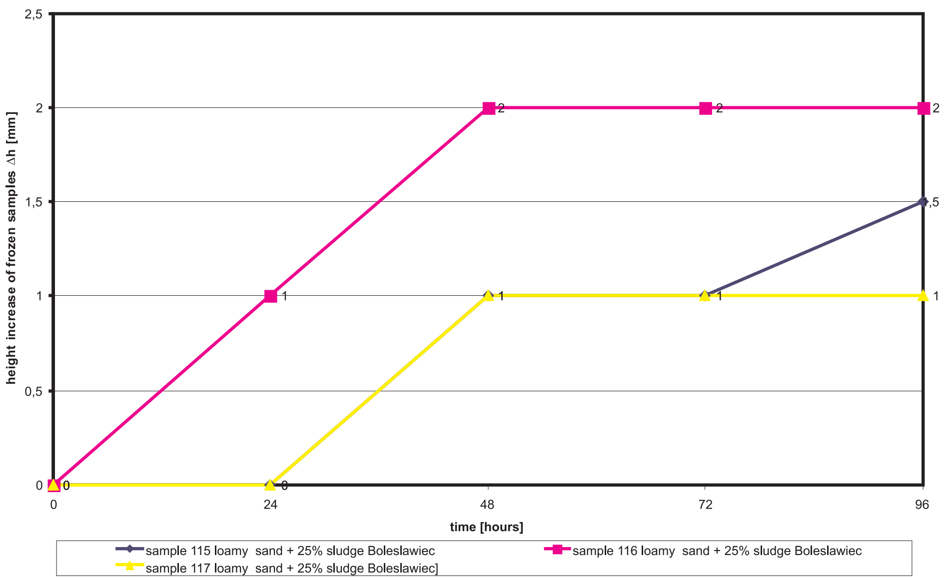


Fig. 74. Frost heave test of mixture of loamy sand with 25% inject made from sludge from Bolesławiec after 42 days of samples maturing

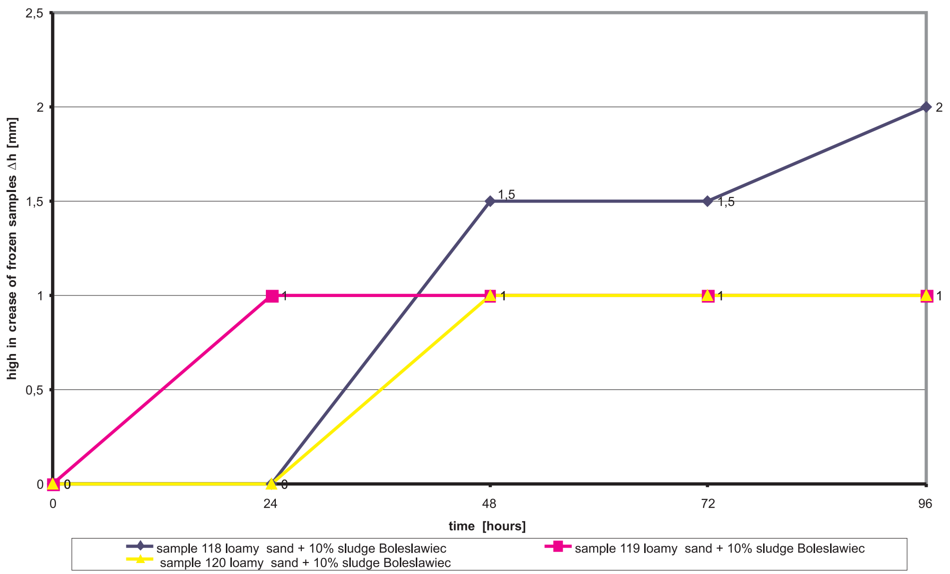


Fig. 75. Frost heave test of mixture of loamy sand with 10% inject made from sludge from Bolesławiec after 42 days of samples maturing

4.1.8.3. Conclusion concerning frost heave tests

Figures 76–79 show summary frost heave diagrams of samples made with both injects and made with mixtures of medium or loamy sand that showed the highest susceptibility to frost heave, i.e. those containing 100% of inject proportionally to the amount of soil, tested respectively after 7 and 42 days of maturing. Longer (42 days) maturing time reduced the frost heave of both injects and their mixtures with soil to a three times lower level. The tested injects are susceptible to frost heave in the first, shorter maturing period. The level of increase of frozen samples after 96 hours of test qualifies both injects, according to the assumed criterion, to the group of soils unconditionally susceptible to frost heave. In mixtures of injects with medium and loamy sand the susceptibility is significantly reduced. If a mixture contains injects mixed with tested soils in 1:1 proportion, their frost heave susceptibility falls to the level of soils that are questionable in terms of frost heave. A further increase in the amount of soils in mixtures with injects reduces their susceptibility to frost heave.

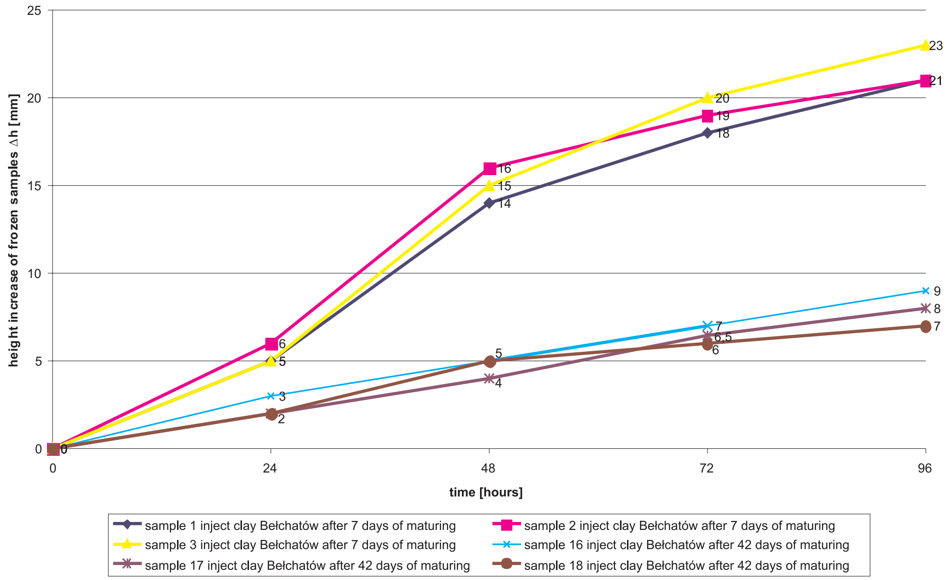


Fig. 76. Comparison of frost heave tests of inject made from clay from Bełchatów results after 7 and 42 days of maturing

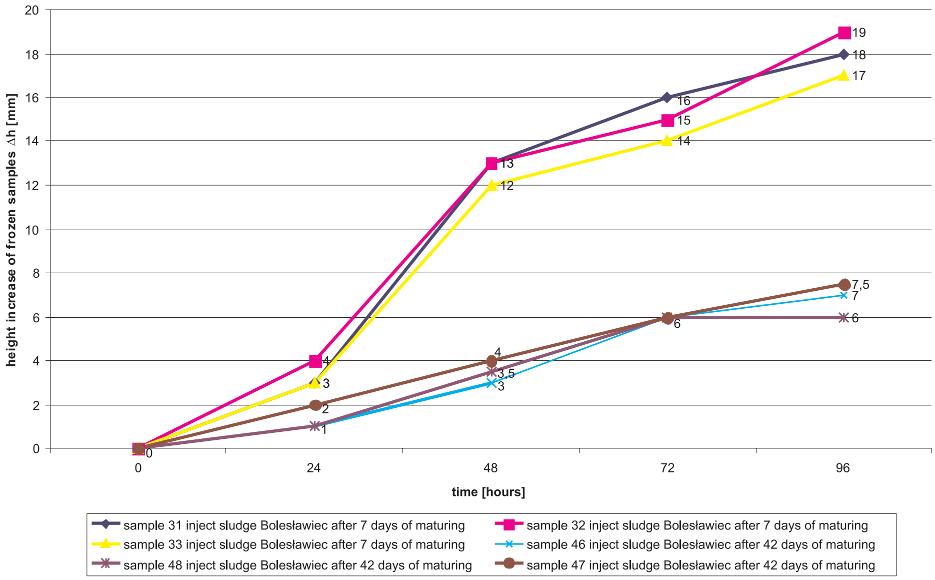


Fig. 77. Comparison of frost heave tests of inject made from sludge from Bolesławiec results after 7 and 42 days of maturing

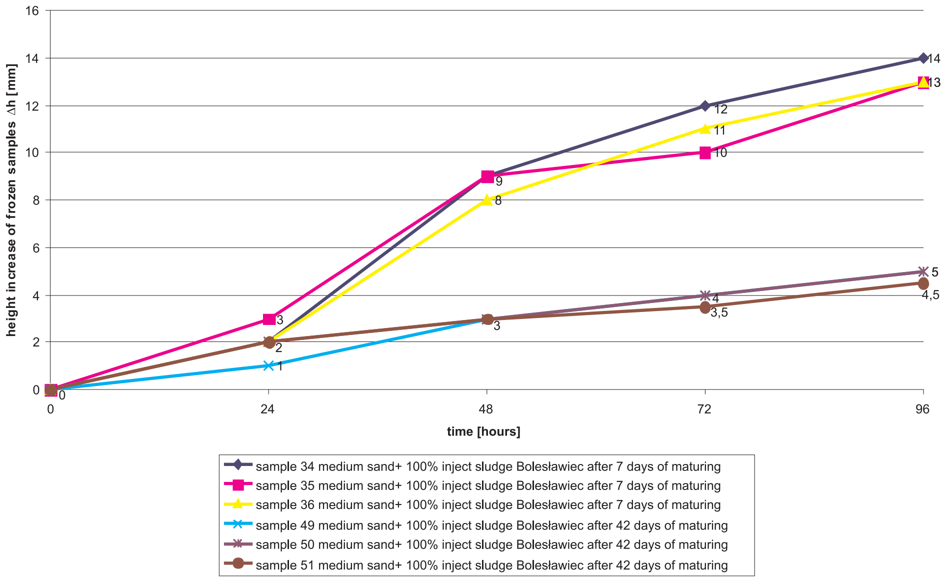


Fig. 78. Comparison of frost heave tests of mixture of medium sand with inject made from clay from Bełchatów results after 7 and 42 days of maturing

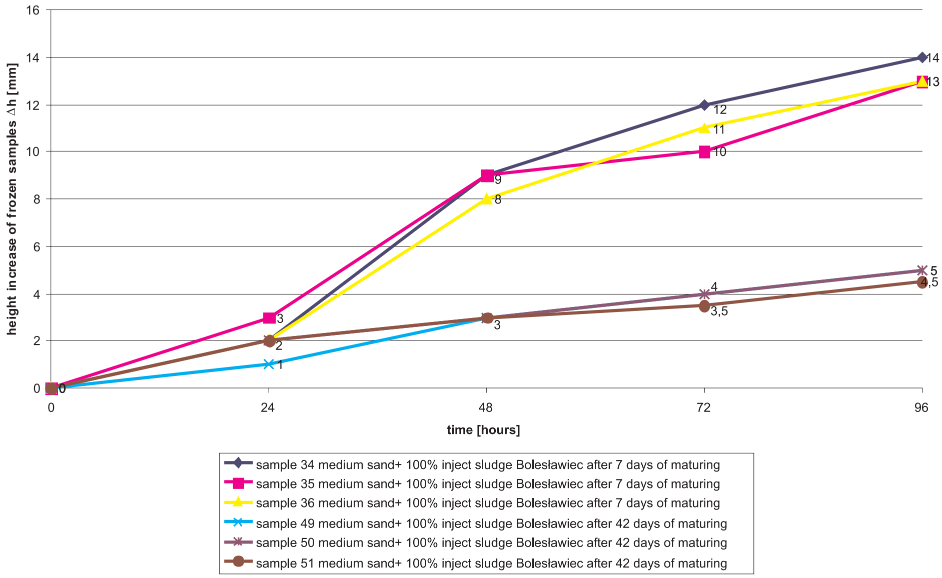


Fig. 79. Comparison of frost heave tests of mixture of medium sand with inject made from sludge from Bolesławiec results after 7 and 42 days of maturing

The phenomenon of frost heave is very complex and depends on numerous factors. Its intensity can be influenced by such factors as compaction, initial moisture content, content of calcium compounds and other. The conducted tests focused on the reproduction of conditions that emerge while the inject is injected into the soil with use one of three technologies. It is difficult to evaluate the influence of compaction and initial moisture content of soils. There is no doubt on the positive influence of calcium compounds, contained in the cement added. Already in the 1960s [Brandl 1967, Ruckli 1950] it was determined, that the frost heave of samples with an addition of calcium compounds was much higher in the initial stage than for samples without this addition. In the conducted tests this influence is difficult to evaluate, if it ever existed. The phenomenon is so complex that it requires a separate, large series of tests to be explained. The obtained results confirmed that, due to bonding processes, the resistance to frost heave changes in time. The final evaluation of mixtures of soils with injects and of pure inject in terms of frost heave can be performed only after a prolonged maturing period, as "immature" samples presented a significantly lower resistance to frost heave and were usually classified as susceptible to frost heave. The tests by Garlikowski [1996] conducted on anthropogenic soils showed, that the stabilisation of soils with calcium compounds significantly reduces the level of frost heave already after 14 days of maturing of samples. The period of 42 days proved to be sufficient for both injects and all mixtures containing them to become totaly resistant to the influence of freezing temperatures. It was not tested, whether the bonding processes are still active after the end of this period. Some researchers observed beneficial changes in properties (increased resistance) after even longer maturing period, e.g. 60-day [Borys and Rycharska 2006].

The test results show that in case of injection works conducted in winter one should take into account the possibility of disadvantageous freezing phenomena before the period of bonding of injects is finished. It is possible that in place of the realized cut-off wall down to the freezing depth, small stratifications caused by freezing water can emerge, which could, in following melting period, cause potential leaks. That is why injection works should be performed in the spring, summer or early autumn when ground temperatures are above zero, in order to prevent the emergence of potential frost heave.

It is difficult to determine unequivocally which of the factors has the greatest influence on the reduction of frost heave as the samples mature. This could be caused by cement, that creates bondings inside the soil, increasing its resistance, and thus reducing the frost heave. Neither the influence of water-glass that influences the soil environment by disturbing the capillary rise ability of ground water and thus limiting the possibility of growth of ice crystals, nor the simultaneous, beneficial influence of both these factors can be excluded.

4.1.9. Californian Bearing Ratio (CBR) determined with dynamic method

The Californian Bearing Ratio CBR is expressed in terms of the percent relation between unit load p, which has to be applied to cause a long cylindrical piston of cross-section area of 20 cm^2 (d = 5,0 cm) to penetrate a suitably prepared sample of soil to a specific depth of 2.5 mm or 5.0 mm, at steady speed of 1.25 mm/min, plotted against the comparative unit load p_p, which is a constant value, equal to the pressure needed to cause the same plunge, at the same speed to penetrate standard material (crushed stone of standard compaction).

The bearing ratio CBR is determined as percentage, according to the formula:

$$(CBR) = \frac{p}{p_p} \times 100$$

where:

p – pressure needed to penetrate a suitably prepared sample of tested aggregate to the depth of 2.5 mm or 5.0 mm by a piston of 20 cm^2cross-section area,

p_p – comparative pressure, which, at the piston penetration to 2.5 mm depth equals 7 MN/m^2, and to 5.0 mm equals 10 MN/m^2.

For the purposes of designing, conducting, and commissioning soil-works connected with road building, the polish standard PN-S-02205 is applied. According to this standard, the achievement of required bearing parameters by the subsoil is tested by means of determination of the relative density I_s and of the value of the stiffness ratio I_o. For direct measurement of the I_s parameter, approximately 24 hours are needed to confirm the result, and the determination of the I_o ratio is time-consuming. Another technical test performed in order to evaluate the bearing ratio of the subsoil, according to the Regulation of the Transport Minister … Journal of Laws.99.43.430 (appendix "Method of geotechnical investigation conducting and of the determination of the ground-water conditions of the base of the pavement – scope of tests of the subsoil for roads earthstructures") is the determination of the Californian Bearing Ratio (CBR). The procedure of determination of this ratio, foreseen in the polish standards (BN-70/893105; PN-S-06102), is very time-consuming. In case of tests of natural subsoil or the tests of bearing ratio of the compacted layer of ground, the determination of CBR requires to collect a large sample of undamaged structure to the CBR sampler, which is always very difficult.

Having assumed, that the measurement procedure should be quite simple and allow to test large areas of sub soil in a quick and systematic manner, the company ZORN developed a CBR piston for in situ determination of the CBR with dynamic method. The CBR light drop-weight device by ZORN is a mechanical device, co-operating with a dynamically loaded plate ZFG-2000. This equipment allows to determine the CBR of samples prepared in the laboratory, as well as of the soil of the subsoil or soil build in, without the need to collect samples to the cylinder and to conduct the test in a stationary apparatus in the laboratory.

The measurement of the CBR determined with dynamic method, relays on pressing a 50 mm diameter steel piston into the soil by means of lowering a 10 kg weight falling along a rail from the height of 70 cm. The penetration of the piston, as the subsidence factor s [mm] and the value of the CBR ratio [%] is read and recorded electronically by the acceleration sensor. The dynamic CBR device is more and more commonly applied in tests, mainly due to the simplicity of the determination method and the possibility to obtain a result immediately after the test. These are the reasons, why the dynamic CBR method was used for the purposes of the bearing ratio determination of the tested injects and mixtures.

Due to the ground-water conditions, according to point 3 of the Appendix to the regulation of the Minister of Transport… Journal of Laws 99.43.430 (Table point 3.1), the soil base of the road pavement on the top of the flood bank or at the foot of the outer slope should be classified as poor (see Tab. 17 below).

"3. Land and water conditions of the soil base of the pavement

3.1. Water conditions

Water conditions are determined according to the classification specified in the Table:

Table 17

Soil base of road pavement classification according to the regulation of the Transport Minister

Characteristics		Water conditions in case of presence of a free water level		
		< 1 m	1 m to 2 m	> 2 m
1		2	3	4
Trenches ≤1 m	a)	poor	average	average
	b)	poor	average	good
Embankments ≤1 m	a)	poor	average	average
	b)	average	average	good
Trenches >1 m	a)	poor	average	good
	b)	average	average	good
Embankments >1 m	**a)**	**poor**	average	good
	b)	average	good	good

explanation:
a) unpaved roadsides,
b) paved, tight roadsides and a good outflow of surface waters."

Soils that most commonly appear in the bodies of flood banks and in the subsoil in the adjacent area, in case of using the same classification as for base of roads soil, should be classified as belonging to the bearing groups of G2 i G4 – Table a, point 3.3 (gray colour in the quoted Tables).

Most of the soils, due to their value of CBR in the range of 0% < CBR < 10%, determined according to BN-70/893105, PN-S-06102, after four days of saturation with water, should also be classified as belonging to the bearing groups G2, G3 i G4 – Table b, point 3.3. (Tab. 18 and 19).

"3.2. Subsoil conditions

Base soils are classified depending on their susceptibility to water and frost, according to Polish Standard. The characteristics of the soil should be determined basing on laboratory tests of its parameters specified in Polish Standard. The main evaluation criterion is the content of fine particles of soil, and additional criteria: sand equivalent and capillary head are applied in questionable cases. The sand equivalent is the criterion of evaluation of non-cohesive soils, in particular those similar to little cohesive. If the evaluation based on tests conducted with use of different methods are divergent, then the most disadvantageous result is adopted.

3.3. Determination of the soil base bearing groups
The bearing groups of the base are specified in Tables a and b:

Table 18a

Classification of subsoil condition according to the polish standards BN-70/893105, and PN-S-06102

Type of the subsoil	Subsoil bearing group for water conditions		
	good	average	poor
1	2	3	4
Soils non-susceptible to frost heave: gruss (non-clayey), gravels and gravely sands, coarse, medium and fine sands, non-decomposed slags	G1	G1	G1
Questionable soils: silty sands	G1	G2	**G2**
Questionable soils: loamy weathered rock and loamy gruss, loamy gravel and loamy gravely sand	G1	G2	G3
Soils little susceptible to frost heave*): clay loam, sandy loam and silty clay loam, clay, sandy and silty clay	G2	G3	**G4**
Soils very susceptible to frost heave1): sandy loam, silty loam, silt, loam, varve clay	G3	G4	**G4**

*) In soild, semi-solid or hard-plastic state ($I_L \leq 0{,}25$).

Table 19b

CBR values of pavement soil base bearing groups

Californian Bearing Ratio (CBR)*)	Pavement soil base bearing group of
1	2
10% ≤ CBR	G1
5% ≤ CBR < 10%	**G2**
3% ≤ CBR < 5%	**G3**
CBR < 3%	**G4**

*) The test of the Californian Bearing ratio CBR is conducted pursuant to Polish Standard, but after four days of saturation with water".

Soil base belonging to the groups G2 to G4 should be improved to the bearing ratio of group G1 by means of soil exchange, stabilisation with cement, limestone or active fly ash, or by strengthening with geosynthetics. In point 5.3 of the standard it is also accepted to improve the top soil layer of the base with other methods, provided that the required characteristics of the soil base are achieved. Such other method of improvement can be the stabilisation of the soil occurring in the subbase with use of the tested injects.

CBR determined with dynamic method on samples prepared according to the CBR testing procedure described in BN-70/893105 and PN-S-06102, for medium sand with ρ_d = 1.820 g/cm^3 maximum dry density, which is the equivalent of compaction ratio I_S = 0.989 (98,9% Proctor) , achieved a value of 57%, and for loamy sand with ρ_d = 1.911 g/cm^3 maximum dry density, which is the equivalent of compaction ratio I_S = 0.989 (98,9% Proctor), achieved a value of 55%.

Among the tested injects only the "wet" sample (see the description of samples preparation in section 3.1.10) of the inject containing clay from Bełchatów achieved the bearing ratio equivalent to CBR_d = 22%. The CBR_d values for "dry" samples of both injects and for the "wet" sample of inject made from sludge Bolesławiec were equal to zero (Fig. 80–83).

In cases of both "wet" and "dry" samples made of medium sand mixtures with inject containing clay from Bełchatów (Fig. 88) the CBR_d values depend from inject content and they are falling with increasing inject content. Samples with 10% addition of inject showed CBR_d = 30% and mixtures with 50% addition of inject CBRd =20% "Dry" samples of inject and mixture with 100% addition of inject have CBRd= 0%, and this is why these values are not visible on the diagram.

In case of loamy sand mixtures with inject made from clay from Bełchatów (Fig. 89) the CBRd value for "dry" samples increases from the 18% level for mixtures with 10% addition of inject to the 34% level for mixtures with 25% addition of inject, whereas mixtures with a higher content of inject and pure inject have a CBR_d = 0%. For "wet" samples the CBR_d values for all mixtures except for the mixture with 25% addition of inject, remain on the level of approx. 20%. For the mixture with 25% inject, CBR_d value equals 34%. For "dry" samples, with the exclusion of mixtures with 10 and 25% addition of inject, and for pure inject CBR_d value equals 0%.

All "wet" samples made of medium sand mixtures with inject based on sludge Bolesławiec show the values of Californian Bearing Ratio CBR_d exceeding 20% and samples' with 25% addition of inject CBR_d values are reaching nearly 40%. A similar results are obtained in case of "dry" samples excluding the mixture with 100% addition of inject characterized by CBR_d value = 0% (Fig. 82).

In case of "wet" samples of loamy sand mixtures with inject based on sludge from Bolesławiec results are similar as in case of medium sand mixtures with sludge from Bolesławiec, whereas by "dry" samples less results above zero was observed. Only mixtures with 25 and 10% addition of inject achieve positive values on the level of 30% (Fig. 83).

Most CBR_d values of the analysed wet samples exceed 15%, and in case of mixtures with 25% addition of both injects the value exceeds 39%. It should be noted, that these values were obtained at low densities of samples. Maximum dry densities of medium sand mixtures fall within the range from 1.150 to 1.737 g/cm^3, whereas for loamy sand they range from 1.281 to 1.807 g/cm^3. The densities resulted only from mixing the soil with injects – the samples were not compacted. Taking into account the fact that a qualified soil base for road pavement should belong to the category G1, with CBR>10%, mixtures of medium and loamy sand with both injects, even at such low densities, achieve values which allow to classify them in this category.

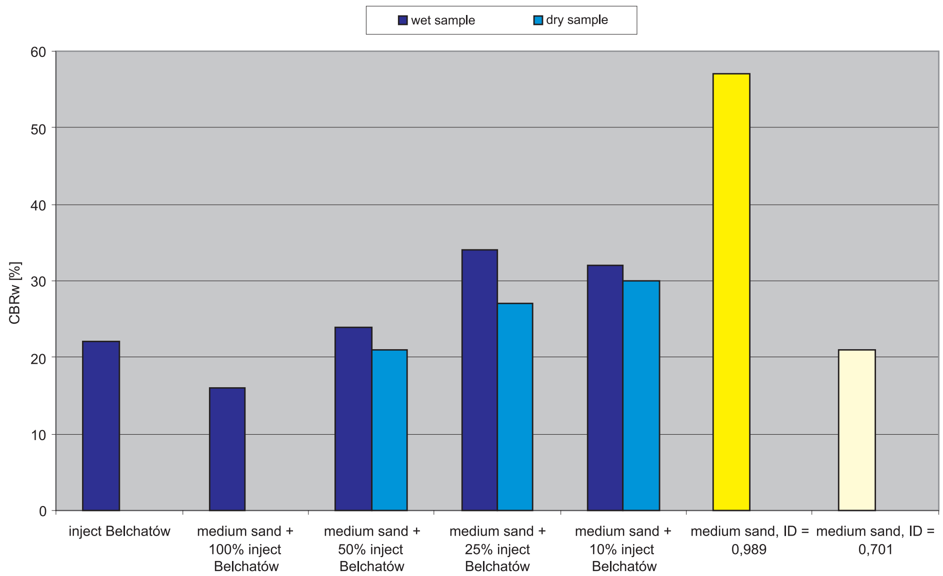


Fig. 80. Bearing ratio values of medium sand and its mixtures with inject made of clay from Bełchatów

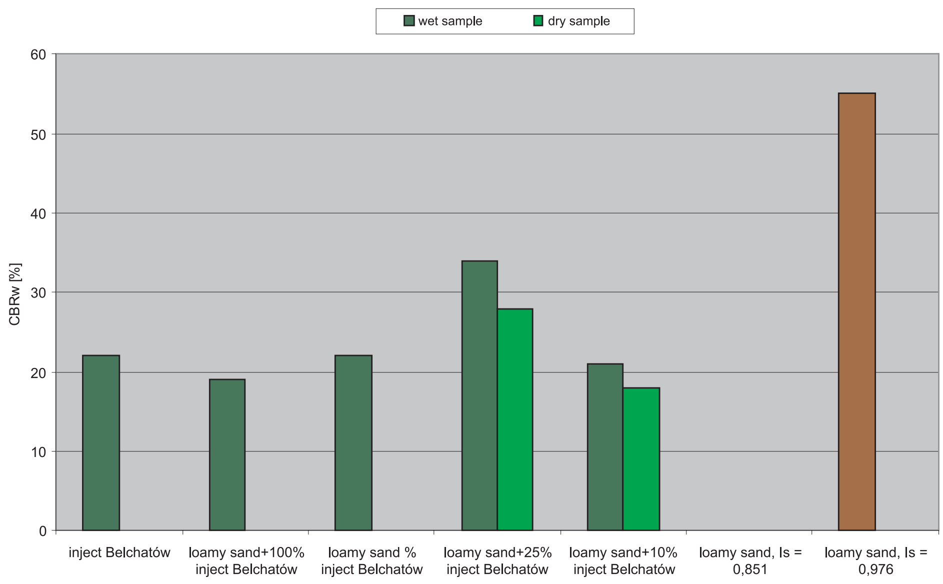


Fig. 81. Bearing ratio values of loamy sand and its mixtures with inject made of clay from Bełchatów

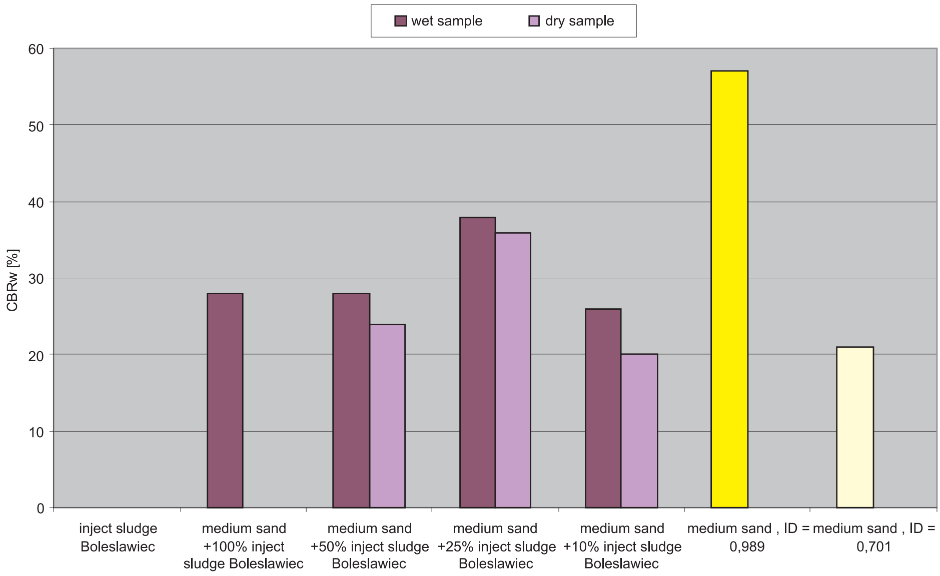


Fig. 82. Bearing ratio values of medium sand and its mixtures with inject made of sludge from Bolesławiec

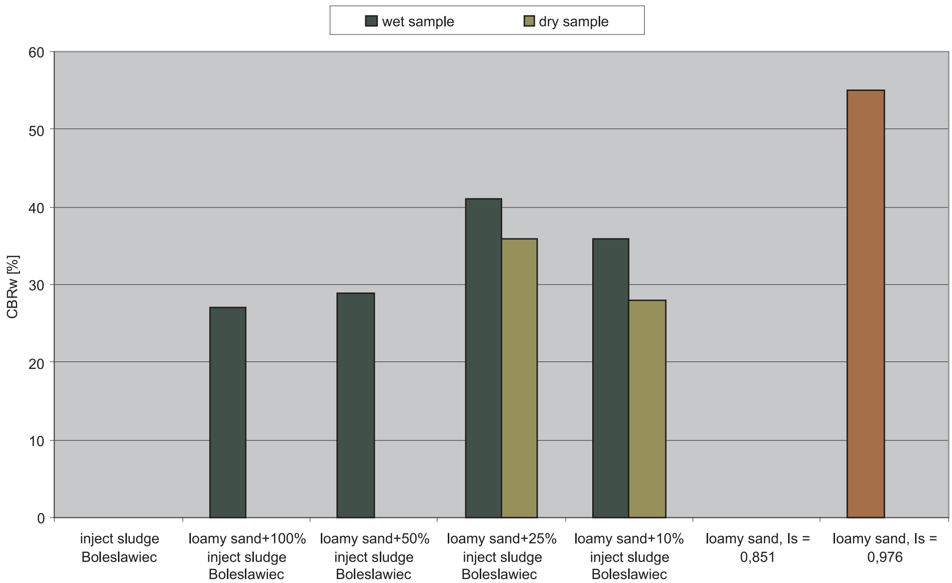


Fig. 83. Values of the bearing ratio for loamy sand and its mixtures with inject from sludge Bolesławiec

It should be noted that mixtures with 10 and 25% addition of injects show the parameters characteristic for soils of plastic consistency, and they can be compacted using standard methods, while mixtures with 50 and 100% addition of injects present the characteristics typical for soils of liquid consistency, so that compaction is not possible. In case of considering analysed mixtures application as soil base for road pavements, mixtures with 10 and 25% addition of injects should be tested by compaction levels resulting from the course of Proctor's compactibility curve.

4.1.10. Column tests

Medium sand placed in a PVC column, of the 0.30 m diameterand 1.20 m height was injected with the grout containing clay from Bełchatów. The grout was injected from a gravity container into the column. The lance, of 2 cm diameter with 1 cm diameter openings was placed inside the column. In such conditions the range of the injection reached a maximum of several centimetres. The injection caused a local displacement of sand, in which the inject created an irregular structure resembling a ring surrounding the lance. Due to that it was attempted to inject the grout under pressure. The introduction of pressure of approx. 0.5 atm in the container with the injection grout caused a further displacement of sand, but did not lead to mixing of soil with inject. Initial results show that model tests with use of columns do not cause the expected mixing of inject with soil and thus they are unsuitable for the purpose of tracking the mechanism of inject penetration in soil environment. That is why, a reconnaissance was performed in real conditions, and the parameters of soils from the exposure of the section of injected flood bank in the region of Samocice near Tarnów were measured.

4. 2. Results of tests in the field

4.2.1. Tests of physical parameters

Physical parameters tests results of samples collected from the flood bank section in Samocice are presented in Tables 18 and 19. Table 18 presents the values of basic parameters of the soil adjacent to the constructed cut-off wall, while Table 19 presents these values for samples collected from the cut-off wall core .

In the cross-section of the DSM cut-off wall, the silty loam embedded in the embankment body has a varied level of injection grout content, as a result of mixing with the stirrer. From the sample WP-44, from locations differing in colour and in the macroscopically evaluated content of injection grout, 5 specimens were collected. After drying the specimens were pulverised, and then grain size distribution was determined with use of areometric method. It was found, that the deeper shade of grey matched a lower content of injection grout. Silty loam, as a result of being mixed with grout, after the destruction of bonds that formed during the hardening of additives: cement, clay and water-glass, changed its original grain size distribution becoming a soil of of loamy sand, sandy silt, silt or loam granulation.

Table 18

Physical parameters of soils embedded in the flood bank body

Sample	**P**	**w**	**ρ_d**	**ρ_{ds}**	**Is**	**S_k**	**σ**	**τ**
	[g/cm^3]	[%]	[g/cm^3]	[g/cm^3]	[-]	[%]	[kPa]	[kPa]
1 – silty loam containing inject	1.765	24.83	1.414			5.8	88	18
2 – silty loam	1.856	19.69	1.551	1.68	0.92	2.40	147	28
3 – silty loam	1.903	19.43	1.593	1.68	0.95	1.80	137	25
4 – silty loam	1.763	21.51	1.451	1.68	0.86	4.70	118	21
5 – silty loam containing inject	1.867	27.07	1.469			4.40	108	20
6 – silty loam	1.931	24.45	1.552	1.68	0.93	1.80	128	22
7 – silty loam containing inject	1.763	25.50	1.405			3.60	79	13
8 – silty loam containing inject	1.768	27.20	1.39			2.80	79	17
9 – silty loam containing inject	1.824	27.38	1.432			5.80	108	19
10 – silty loam containing inject	1.775	26.34	1.405			4.60	79	16
11 – silty loam	1.823	23.33	1.478	1.68	0.88	3.90	118	20
12 – silty loam containing inject	1.91	28.94	1.481			3.10	108	19
13 – silty loam	1.843	25.71	1.466	1.68	0.87	3.70	108	22
14 – silty loam	1.856	22.05	1.521	1.68	0.91	2.90	128	22
15 – silty loam	1.789	24.95	1.432	1.68	0.85	4.10	98	20
16 – silty loam	1.859	24.54	1.493	1.68	0.89	3.70	118	24
17 – silty loam containing inject	1.811	26.21	1.435			4.60	108	22
18 – silty loam containing inject	1.82	26.51	1.439			4.40	128	22
19 – silty loam	1.794	24.76	1.438	1.68	0.86	3.90	108	22
20 – silty loam	1.776	25.45	1.416	1.68	0.84	3.90	98	18
21 – silty loam	1.819	23.30	1.475	1.68	0.88	4.20	118	22
22 – silty loam	1.698	24.06	1.369	1.68	0.81	5.40	29	10

Table 19

Physical parameters of the material from the hydraulic cut-off wall constructed with use of DSM method

Sample	ρ	w	ρ_d	ρ_{ds}	Is	S_k	σ	τ
	[g/cm^3]	[%]	[g/cm^3]	[g/cm^3]	[-]	[%]	[kPa]	[kPa]
1	2	3	4	5	6	7	8	9
24 – silty loam containing inject	1.676	27.26	1.317			5.70	20	9
25 – silty loam containing inject	1.825	50.10	1.216			7.10	20	10
26 – silty loam containing inject	1.639	31.93	1.242			6.70	29	10
27 – silty loam containing inject	1.691	26.35	1.338			5.30	49	12
28 – silty loam	1.765	23.70	1.427	1.68	0.85	4.60	98.1	22
29 – silty loam	1.742	25.70	1.386	1,68	0.83	4.70	79	15
30 – silty loam	1.728	22.98	1.405	1.68	0.84	4.20	88	18
31 – inject	1.708	52.60	1.119			6.60	235	38
32 – inject	1.642	47.29	1.115			3.90	235	36
33 – inject	1.672	42.55	1,173			0.80	412	48
34 – inject	1.669	41.78	1.177			0.40	471	53
35 – inject	1.745	43.88	1.213			0.00	451	51
36 – inject	1.768	39.56	1.267			0.30	491	54
37 – inject	1.68	42.76	1.177			0.00	383	47
38 – inject	1.698	45.54	1.167			0.90	314	42
39 – inject	1.663	50.77	1.103			3.20	334	45
40 – inject	1.654	55.20	1.066			3.80	157	28
41 – inject	1.67	57.57	1.06			4.50	79	14
42 – inject	1.695	52.16	1.114			5.90	275	49
43 – inject	1.64	53.85	1.066			4.20	432	46
44 – inject	1.69	54.16	1.096				235	42
45 – inject	1.795	51.36	1.186				432	40
46 – inject	1.707	49.73	1.14				432	50
47 – inject	1.686	42.84	1.18				422	40
48 – inject	1.717	43.29	1.198			2.60	432	51
49 – inject	1.698	42.01	1.196			3.40	491	55
50 – inject	1.713	41.09	1.214				471	51
51 – inject	1.738	42.22	1.222			5.80	491	52
52 – inject	1.658	42.56	1.163				363	46
53 – inject	1.644	43.84	1.143				275	41

Table 19 cont.

1	2	3	4	5	6	7	8	9
54 – inject	1.733	43.71	1.206				471	54
55 – inject	1.671	48.43	1.126			2.40	334	43
56 – inject	1.62	51.55	1.069			4.30	275	46
57 – inject	1.711	52.39	1.123				294	44
58 – inject	1.679	52.66	1.100			4.70	304	47
59 – inject	1.654	53.97	1.074			4.70	216	40
60 – inject	1.642	53.35	1.071			2.40	235	46
61 – inject	1.621	53.68	1.055				253	44
62 – inject	1.614	54.12	1.047				137	59

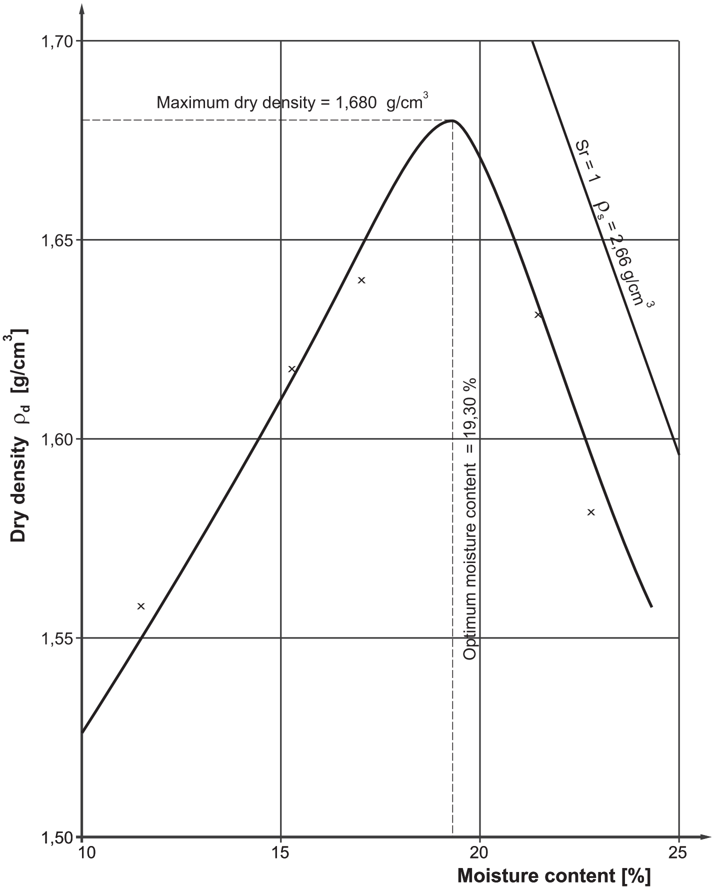
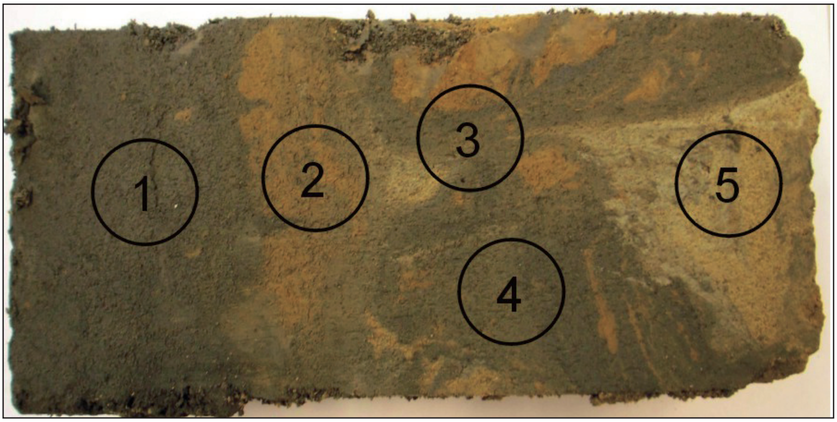


Fig. 84. Proctor compaction curve of silty loams embedded in the flood bank, according to the Polish standard PN-88/B-04481, method I

Photos 9–11 show the cross-sections of samples 44, 46 and 61. Different colours of soil show the differences in the degree of mixing of the native soil with inject.

Phot. 9. Cross-section along sample DP-46

Phot. 10. Cross-section along sample WP-61



Phot. 11. Cross-section along sample WP-44 and locations, which from soil was collected to analyse grain size distribution (marked with subsequent numbers)

4.2.2. Soaking collapsibility

In order to evaluate the nature of structural bonds of natural soil particles embedded in the flood bank and of its mixtures with grout used for the construction of the cut-off wall, tests of soaking collapsibility were conducted. Figure 94 shows the course of soaking of samples of undisturbed structure – samples A and A' collected from the flood bank body and samples of damaged structure, formed by moisture content close to optimum moisture content – samples B and B' and moisture content close to natural moisture content – samples C i C'. Samples marked with ('), are samples, that were formed at moisture content w_z, and then left to dry in room temperature, so that the samples reached a moisture content of air dry state w_{sps}. The moisture contents w_{sps} in case of the tested samples equalled approximately 9.0%. The times of 50% weight disintegration of tested samples are presented below:

- samples of undisturbed structure:
  - A - ρ_d = 1.390 g/cm^3 at w_r = 27.70%, $t_{50\%}$ = 13',
  - A' - ρ_d = 1.390 g/cm^3 at w_r = w_{sps}, $t_{50\%}$ = 5.2',
- samples of damaged structure:
  - B - ρ_d = 1.680 g/cm^3 at w_r = 19.3%, $t_{50\%}$ = 135',
  - B' - ρ_d = 1.680 g/cm^3 at w_r = w_{sps}, $t_{50\%}$ = 16',
  - C - ρ_d = 1.489 g/cm^3 at w_r = 27.34%, $t_{50\%}$ = 2226',
  - C' - ρ_d = 1.489 g/cm^3 at w_r = w_{sps}, $t_{50\%}$ = 20',
- samples collected from the DSM cut-off wall:
  - sample WP-44, ρ_d = 1.072 g/cm^3 by w_r = 53.46%, $t_{50\%}$ >7200'
  - sample WP-44, ρ_d = 1.056 g/cm^3 by w_r = 52.75%, $t_{50\%}$ >7200'

– sample WP-44, ρ_d = 1.074 g/cm^3 by w_{sps} = 5.34%, $t_{50\%}$ >7200’
– sample DP-46, ρ_d = 1.118 g/cm^3 by w_r = 49.17%, $t_{50\%}$ >7200’
– sample DP-46, ρ_d = 1.165 g/cm^3 by w_{sps} = 6.12%, $t_{50\%}$ >7200’
– sample WP-61, ρ_d = 1.048 g/cm^3 by w_r = 54.71%, $t_{50\%}$ >7200’
– sample WP-61, ρ_d = 1.053 g/cm^3 by w_r = 51.86%, $t_{50\%}$ >7200’
– sample WP-61, ρ_d = 1.044 g/cm^3 by w_{sps} = 5.87%, $t_{50\%}$ >7200’
– sample WP-61, ρ_d = 1.057 g/cm^3 by w_{sps} = 5.11%, $t_{50\%}$ >7200’

During the soaking of all samples collected from the cut-off wall within the period of 5 days, no decrease in weight was noticed. Thus, it should be assumed that silty loam mixed with injection grout based on clay from Bełchatów using DSM method is not affected by soaking.

The soils of the cut-off wall constructed with use of DSM method are characterised by:
– range of bulk densities 1,614 ≥ ρ ≤ 1.795 g/cm^3,
– range of moisture content 41.09 ≥ w_n ≤ 57.57%,

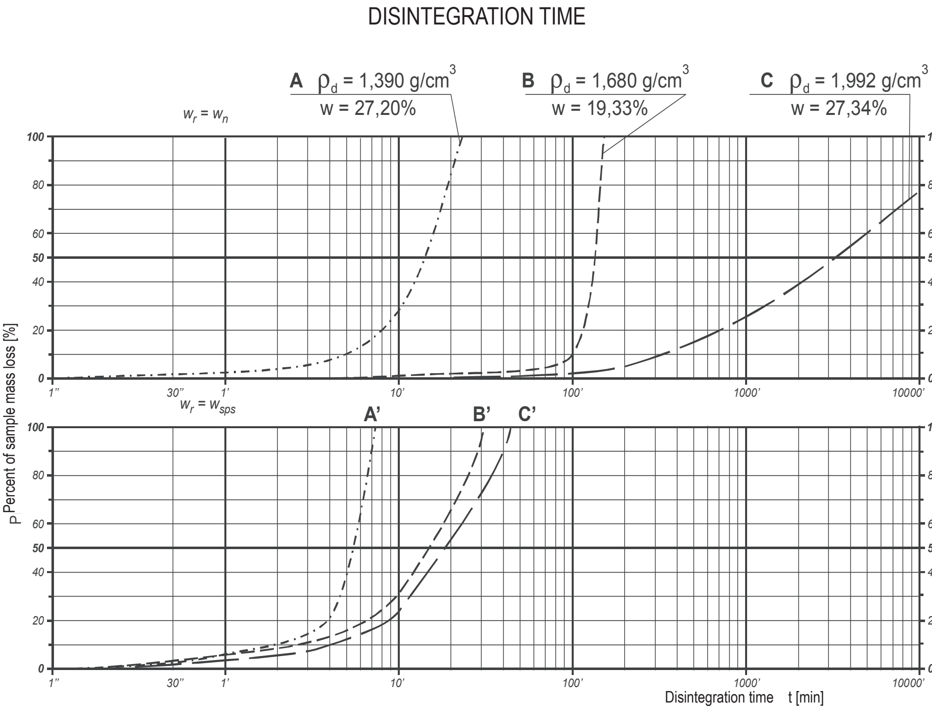


Fig. 94. Course of soaking collapsibility test of silty loams embedded in the right side of Vistula flood bank near Samocice

4.2.3. Frost heave

It is very difficult to test the frost heave of soils created with the DSM technology as a result of mixing inject with soil in the flood bank in Samocice. The formed mixture that contains, apart from mineral soils, also water-glass and cement, cannot be clearly classified in terms of frost heave with use of traditional methods, i.e. those using the grain size distribution curve, capillary head or the sand equivalent. This is why for the evaluation of the frost heave of this cut-off wall the same procedure was used as for mixtures prepared and tested in the laboratory. The results obtained from two samples are presented in Table 20. As the increase in height of samples during 96 hours of freezing did not exceed 15 mm, it can be assumed that, similarly to samples prepared in the laboratory, the material taken from the cut-off wall constructed with use of DSM technology is not susceptible to frost heave. However, it should be noted, partly as a result of tests of samples formed in controlled conditions, that in the initial period of maturing, before the bonding process is completed, the material can be much less resistant to frost.

Table 20

Results of frost heave tests of the soils in the hydraulic cut-off wall constructed with use of DSM method in the flood bank of the Vistula river in Samocice

Sample No.	Initial bulk density of sample	Initial moisture content	Initial maximum dry density	Height increase Δh of frozen samples in time			
	ρ	w_p	ρ_d	24h	48h	72h	96h
	[g/cm³]	[%]	[g/cm³]	[mm]			
Sample No. WP 45	1.795	51.36	1.186	3.0	5.0	7.0	7.0
Sample No. WP 47	1.686	42.84	1.180	2.0	4.0	6.0	6.0

4.2.4. Tests of mechanical parameters

For samples collected from the exposure (test pit) in the flood bank of the Vistula river, two series of strength tests in direct shear apparatus were conducted. One of the samples was taken from the cut-off wall constructed with use of DSM technology, whereas the other – from soil from outside the cut-off wall zone. The following results were obtained:

– soils from the cut-off wall:
angle of internal friction: **Φ = 42.77°**, cohesion **c = 31.69 kPa**,
ρ_d = 1.678 g/cm³ and **w = 24.02%**,

– silty loams**:** angle of internal friction: **Φ = 23.60°**, cohesion **c = 14.0 kPa**,
ρ_d = 1.370 g/cm³ and **w = 25.24%.**

4.2.5. Shrinkage tests

The shrinkage values of cut-off wall soils in the flood bank in Samocice determined in the tests fall into the range from 0 to 6.6%. This shows a possibility of forming shrinkage fissures in the top zone of the cut-off wall. In case of the flood bank of Vistula river in Samocice, the cut-off wall is protected from surface drying by a 0.3–0.5 m thick layer of silty loams at the top, but the confirmation of large values of shrinkage of the tested injects and their mixtures can signal the necessity to undertake some actions in order to protect the upper parts of the hydraulic cut-off walls from drying through.

5. CONCLUSION

In comprehensive tests the injects prepared with use of clay from Bełchatów and sludge from Bolesławiec, containing cement and water-glass as binders, presented good characteristics from the point of view of their application as hydraulic cut-off walls, e.g. in flood banks. The obtained results point to the inject containing clay from Bełchatów as a material of more positive characteristics, which however does not exclude the sludge from Bolesławiec, although in the designing process it should be taken into consideration that its parameters are worse and might prove insufficient for specific applications. However, they fall into the wide range of values listed in reference publications [e.g. Bruce 2000, Borys and Rycharska 2006, 2008].

The type of soil with which the inject interacts as well as the soil amount have a significant influence on the characteristics of the created mixture. Mixtures of medium sand and of loamy sand with both types of inject in the amount of 10–100% proportionally to the weight of soil were tested. In case of a non-cohesive soil the presence of injects increased its shearing and bending strength, resistance to frost and water tightness. In case of loamy sand, parameters of the mixtures were also better than those of the soil itself, except for the coefficient of water permeability, which increased after application of the inject.

The comparison of the test results of samples prepared in the laboratory with samples collected from a section of the flood bank of the Vistula river in the area of Samocice proved, that in real conditions a positive change in the parameters of soil in the sealed structure is also achieved. However, even with the use of DSM method, which is the most close to the methodology of samples preparation in the laboratory, a uniform mixture of soil with inject is not achieved. Outside the core of the hydraulic cut-off wall, in the embankment consisting of pure inject, and in adjacent areas there are zones of different inject saturation levels, located in an irregular way along the height of the cut-off wall, depending on the type and state of soil.

The adopted methodology of testing allows to prepare a reliable specification of injects and of their mixtures with soil, which can create a basis for predictions of the behaviour of these materials in a real structure. Although one could roughly assume, that the behaviour of the analysed injects interacting with other cohesive and non-cohesive soils should be similar, which can be used for the purposes of preliminary evaluation, but prior to application in specific soil conditions a full scope of tests should be conducted in order to measure the parameters necessary for the designing and construction of hydraulic cut-off walls.

Summary test results are presented in Table 21.

Table 21

Summary test results

No.	Inject to soil weight ratio	ρ_s	ρ	ρ_d	w	k_{10}	Φ[1)]	c[1)]	$f_{ct,fl}$	f_c	CBR_d wet/dry sample	Frost heave[2)]	Soaking $T_{50\%}$	Shrinkage
	%	[t/m³]	[t/m³]	[t/m³]	[%]	[m/s]	[deg]	[kPa]	[kPa]	[kPa]	[%]	[mm]	[min]	[%]
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Soils used in tests													
1.	0 – Medium sand, loose	2,65	1.55	1.53	1.20	8.98E-03	39.5	6.7	–	–		–	–	
2.	0 – Medium sand. compacted	2,65	3,58	1,77	1,20	5,66E-03			–	–	21/-	–	–	
3.	0 – Loamy sand, loose	2,67	1,29	1,19	8,29	1,79E-04			–	–		–	–	
4.	0 – Loamy sand, compacted	2,67	2,10	1,94	8,14	5,28E-07			–	–	55/-	–	–	
5.	Inject Bełchatów	2,69	1,26	0,42	201,74	6,18E-07	54,9	60,8	341,6	1070,41	22/0	9,0	>5000	23,4
6.	Inject Bolesławiec	2,79	1,70	0,85	100,21	8,12E-06	41,2	24,9	88,15	63,04[3)]	0/0	7,5	>5000	17,0
	Medium sand + inject with clay from Bełchatów													
1.	10	2,651	1,797	1,632	10,12	8,51E-03	51,2	~0	83,06	22,97[3)]	32/30	2,5	>5000	0,0
2.	25	2,653	1,905	1,675	13,72	1,57E-06	–	–	115,62	673,13	34/37	3,0	>5000	1,1
3.	50	2,655	1,961	1,532	27,98	1,12E-06	57,9	35,5	365,33	1318,44	24/21	4,0	>5000	2,5
4.	100	2,659	1,718	1,152	49,15	5,88E-07	47,1	78,21	402,98	1622,66	16/0	5,0	>5000	8,1

Table 21 cont.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Medium sand + inject with sludge from Bolesławiec													
1.	10	2,656	1,648	1,588	3,77	1,12E-02	46,0	33,9	36,02	30,47[3)]	26/20	2,0	>5000	0
2.	25	2,664	1,819	1,656	9,87	1,80E-03	–	–	82,77	105,47	38/36	2,0	>5000	0,8
3.	50	2,717	2,032	1,684	20,69	4,28E-06	50,5	21,35	82,30	232,03	28/24	4,0	>5000	1,6
4.	100	2,694	1,948	1,439	35,36	1,12E-05	50,1	7,7	92,37	171,10	28/0	5,0	>5000	5,6
	Loamy sand + inject with clay from Bełchatów													
1.	10	2,671	1,898	1,784	6,38	1,39E-03			57,08	22,19[3)]	21/18	3,0	>5000	0,0
2.	25	2,671	2,024	1,761	14,93	3,31E-05			213	603,13	34/28	3,5	>5000	0,8
3.	50	2,672	1,954	1,541	26,79	3,94E-06			401,37	831,88	22/-	4,0	>5000	2,1
4.	100	2,674	1,903	1,277	49,02	8,98E-07			402,98	710,31	19/-	6,0	>5000	7,0
	Loamy sand + inject with sludge from Bolesławiec													
1.	10	2,675	1,853	1,697	9,19	3,09E-03			17,34	20,94	36/28	2,0	>5000	0,0
2.	25	2,682	1,971	1,782	10,58	2,92E-05			115,37	307,19	41/36	2,0	>5000	0,5
3.	50	2,717	2,032	1,684	20,69	4,28E-06			197,50	223,44	29/-	3,0	>5000	1,5
4.	100	2,728	1,889	1,452	30,12	1,67E-05			116,56	157,19	27/-	4,5	>5000	5,1

Key to the Table:

[1)] Based on strength tests in direct shear apparatus.

[2)] Tests on samples after 42 days of maturing. (frost heave: < 9 mm – soil non-susceptible to frost heave, 9–15 mm – borderline soil, > 15 mm soil susceptible to frost heave)

[3)] Questionable result – beyond the lower limit of sensitivity of the hydraulic press used for compression of samples

Abbreviations: ρ_s – particle density, ρ – bulk density, ρ_d – maximum dry density, k_{10} – coefficient of permeability for water temperature +10°C, Φ – angle of internal friction, c – cohesion, $f_{ct,fl}$ – bending tensile strength, f_c – compressive strength, CBR_d – Californian Bearing Ratio (CBR) determined with dynamic method, $T_{50\%}$ – half-life period – time of 50% weight loss in the soaking collapsibility test

Conclusions resulting from the performed tests:

1) SOAKING: Conducted tests of soaking collapsibility proved a high resistance of injects and their mixtures against soaking in water. Structural bonds that emerge during hardening ensure the structural durability of the formed cut-off walls during soaking in water.

2) SHRINKAGE: Unlike the case of all other parameters, the most positive parameters related to shrinkage are shown by mixtures of medium sand and loamy sand with 10 % addition of each of the injects. They do not present any shrinkage.

3) COEFFICIENT OF PERMEABILITY: The conducted analysis shows without doubt, that more positive values of the coefficient of permeability are achieved by mixtures containing clay from Bełchatów, in case of both medium and loamy sand.

4) CBR_d: Mixtures of medium sand and loamy sand characterised by values of $CBR_d > 20\%$ can be qualified as sub soils for road pavements in the category G1.

5) SHEARING STRENGTH: In the strength tests in direct shear apparatus, mixtures containing medium sand and inject with clay from Bełchatów showed a larger increase in shearing strength than mixtures of identical proportions of soil to inject, but with sludge from Bolesławiec. The highest values in shearing strength were achieved for the addition of inject ranging from 50–100%.

6) BENDING STRENGTH: The test of bending strength can be a useful tool for the evaluation of the efficiency of the inject or and of mixtures of soil with inject application, as it allows for simultaneous analysis of two parameters – bending strength and resistance to deformation. The measure of the latter was the deflection value at the moment of sample breaking during the bending. In order to achieve a sufficient accuracy for measuring weaker samples it is necessary to use a more precise equipment than that used normally for the tests of bending strength of cement mortar beams.

It was proven that the type of soil determines the nature of the curve illustrating the relation between bending strength and type of soil and inject type and amount . The positive influence of the application of inject on bending strength is much higher when clay from Bełchatów is used.

7) FROST HEAVE: Basing on the tests of frost heave conducted after 7 days of maturing of samples it was proven, that inject and mixtures with 100% addition of inject are susceptible to frost heave, whereas both injects as well as all mixtures containing them, proved to be absolutely resistant to frost after 42 days of maturing.

In case of injection works conducted in the period when temperatures fall below zero, one should take into account the possibility of occurrence of negative frost-related phenomena in the surface area of the cut-off wall down to the depth of freezing.

REFERENCES

ASTM D 3877-80 (1985) (The American Association for Testing and Materials Designation): Test Methods for One-Dimensional Expansion, Shrinkage, and Uplift Pressure of Soil-Lime Mixtures.

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STUDY OF ULTRAFINE BINDERS BASED ON MINERAL WASTE FROM BEŁCHATÓW AND BOLESŁAWIEC AS A MATERIAL FOR THE CONSTRUCTION OF HYDRAULIC CUT-OFF WALLS

Summary

This monograph presents complex studies on injects whose basic component, apart from cement and water-glass, was fine-grained material from local sources in the form of clay from Bełchatów or sludge from Bolesławiec. The parameters of pure injects, as well of injects in mixtures with natural soils, represented by medium sand and loamy sand were investigated. Basic physical properties of the tested injects and their mixtures with soils were determined, as well as a series of parameters that are significant in terms of potential application, first of all in hydraulic cut-off walls – water permeability, shearing strength, bending and compressive strength, resistance to soaking, frost heave, shrinkage, CBR_d, It was proven that, due to the bonding properties of injects, after a suitable maturing period most of the soil parameters improved – those related to durability and to resistance to environmental factors – water, temperature, environment. The effect of interaction between inject and soil depends on the amount of inject in the mixture. The best results, sometimes enabling to achieve better parameters than in the case of pure inject, were achieved at large amounts of injection material – 50–100% proportionally to the weight of soil. Differences were observed between mixtures of medium sand and loamy sand with injects, primarily in the determination of the coefficient of permeability. In the case of medium sand, the injects, gradually filling the porous space between grains of soil, cause an increase in its tightness up to the level similar to that determined for pure inject. In the tests of loamy sand, that was characterised by a low value of the permeability coefficient even in the absence of an inject, a slight increase in water permeability after the application of an inject was sometimes observed.

Comparing the injection material containing clay from Bełchatów to the one whose main component was sludge from Bolesławiec, it was noted that particularly in the case of strength and frost heave parameters the application of the first inject, based on clay from Bełchatów, gives better effects than the other material. However, this does not mean that sludge from Bolesławiec cannot be used in hydraulic cut-off walls, as the values of parameters determined in the tests are also sufficient for this type of application.

We have also tested undisturbed samples collected from the core of the vertical hydraulic cut-off wall constructed with the use of DSM (Deep Soil Mixing) method, in the flood bank of the Vistula river, and from the area of soil adjacent to the core. In the flood bank an inject containing clay from Bełchatów was applied. The achieved results were similar to those of samples formed in the laboratory.

The methodology used for the tests was essentially the same as that used for testing soils. However, it should be noted that the tested injects act as a binder, so after an appropriate period of maturing the mixtures of inject with soil lose their grainy nature and become solids. It was however determined that the methodology described in this monograph can be useful for testing injects and mixtures of injects with soils, enabling comprehensive comparisons of the characteristics of this type of materials and evaluation of predicted effects of their application.

Key words: hydraulic cut-off wall, flood embankments, mineral wastes

BADANIA ULTRADROBNYCH SPOIW NA BAZIE MINERALNYCH ODPADÓW Z BEŁCHATOWA I BOLESŁAWCA JAKO MATERIAŁU DO BUDOWY PRZESŁON HYDROIZOLACYJNYCH

Streszczenie

W monografii przedstawiono kompleksowe badania iniektów, których podstawowym komponentem, oprócz cementu i szkła wodnego, był materiał drobnoziarnisty pochodzący ze źródeł krajowych w postaci iłu z Bełchatowa lub szlamu z Bolesławca. Badano cechy zarówno samych iniektów, jak też iniekty w mieszankach z gruntami naturalnymi reprezentowanymi przez piasek średni oraz piasek gliniasty. Określono podstawowe właściwości fizyczne badanych iniektów i ich mieszanek z gruntami oraz szereg parametrów istotnych z punktu widzenia potencjalnych zastosowań, przede wszystkim w przesłonach hydroizolacyjnych – wodoprzepuszczalność, wytrzymałość na ścinanie, na zginanie i ściskanie, odporność na rozmakanie, na pęcznienie mrozowe, skurcz, CBRd, Stwierdzono, że dzięki właściwościom wiążącym iniektów, po odpowiednim okresie dojrzewania, następuje poprawa większości parametrów gruntu – wytrzymałościowych oraz w zakresie odporności na działanie czynników środowiska – wody, temperatury, obciążeń itp. Efekt współdziałania iniektu z gruntem zależy od jego ilości w mieszance. Najlepsze efekty, czasem pozwalające na uzyskanie parametrów lepszych niż dla samego iniektu, uzyskiwano przy wysokich zawartościach materiału iniekcyjnego – 50–100% w stosunku do masy gruntu. Zauważono różnice między mieszankami piasku średniego i piasku gliniastego z iniektami, przede wszystkim przy wyznaczaniu współczynnikami filtracji. W przypadku piasku średniego iniekty, wypełniając stopniowo przestrzeń porów między ziarnami gruntu, powodują wzrost jego szczelności aż do poziomu zbliżonego do poziomu ustalonego dla samego iniektu. W badaniach piasku gliniastego, który i bez obecności iniektu charakteryzował się małą wartością współczynnika filtracji, po jego aplikacji niekiedy obserwowano niewielki wzrost wodoprzepuszczalności.

Porównując materiał iniekcyjny wykorzystujący ił z Bełchatowa oraz iniekt, którego głównym składnikiem był szlam z Bolesławca, stwierdzono, że szczególnie w zakresie wytrzymałości oraz pęcznienia mrozowego użycie pierwszego z iniektów, na bazie iłu z Bełchatowa, daje lepsze efekty w stosunku do drugiego z materiałów. Nie oznacza to jednak, że szlam z Bolesławca nie może być stosowany w przesłonach izolacyjnych, gdyż określone w badaniach parametry wykazują wartości wystarczające dla tego typu zastosowań.

Badaniom poddano również próbki NNS pobrane z rdzenia pionowej przesłony hydroizolacyjnej wykonanej metodą DSM (Deep Soil Mixing) w wale przeciwpowodziowym Wisły oraz z obszaru gruntu przylegającego do rdzenia. W wale zastosowano iniekt z iłem z Bełchatowa. Uzyskane wyniki badań były zbieżne z wynikami badań próbek uformowanych w laboratorium.

W badaniach wykorzystywano przede wszystkim metodykę stosowaną w badaniach gruntów. Należy jednak zauważyć, że badane iniekty działają jako spoiwo i po odpowiednio długim okresie dojrzewania mieszanki z gruntem tracą charakter ośrodka ziarnistego, stając się ciałem stałym. Stwierdzono jednak, że metodyka opisana w monografii może być w pełni przydatna w badaniach iniektów oraz mieszanek iniektów z gruntami, umożliwiając wszechstronne porównania charakterystyk tego typu materiałów i ocenę prognozowanych efektów ich aplikacji.

Słowa kluczowe: przesłony przeciwfiltracyjne, wały przeciwpowodziowe, odpady mineralne