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The use of quicklime for soil thawing in pile foundation setting

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ABSTRACT

Due to the fact that in the winter period, which in the Northern regions of the Republic of Kazakhstan lasts up to 6 months, and in the Southern regions – up to 4 months, construction companies are forced to suspend construction and installation works on the foundations. As a result, the total duration of construction of facilities increases, which leads to additional financial expenses. Therefore, new technological solutions are needed for the construction of foundations in winter, to ensure the continuity of construction and installation work. The purpose of the study is to develop a formula of chemical reagents for thawing and protection from the freezing of seasonally frozen soil in places where pile foundations are driven in winter conditions. For the study, a three-component mixture of chemical reagents of the following composition, wt.%, was selected: quick lime (CaO) – 75, calcium chloride (CaCl) – 20, sodium chloride (NaCl) – 5. The choice of the specified composition is determined by taking into account their specific chemical properties and special reactions when interacting with water and frozen soil. The active components of quick lime (CaO) are converted to Ca(OH)2 when interacting with a wet environment or water. This process is accompanied by spontaneous heat release. In the course of the study, a new composition of a chemical reagent based on quick lime was developed for local thawing and protection from the freezing of seasonally frozen clay soil in the areas of driving pile foundations. This composition has advantages in terms of reducing energy costs for thawing seasonally frozen soil, since when interacting with water, the proposed chemical reagent spontaneously releases heat (t = 100oC) and does not cool down for a long time despite the negative ambient temperature of the air.

Keywords: Temperature, Device, Scientific and experimental work, Heat generation, construction.

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1. Introduction

The population of the Republic of Kazakhstan has increased by 4.5% since 2015 and reached more than 18 million people by 2020. The urban population has amounted to 10.4 million, and the rural population – 7.7 million. The level of urbanisation is about 57.4%. Therefore, in all cities of the Republic of Kazakhstan, multi-storey residential complexes, large business centres, as well as industrial buildings and structures are being built [1-6]. Currently, pile foundations are very often used in the construction of buildings and structures due to their high load-bearing capacity and cost-effectiveness. In the northern, eastern and western regions of the Republic of Kazakhstan, one of the most common problems is the immersion of piles in frozen soils during their seasonal freezing [7-12]. The problem is that seasonally frozen soils in an undisturbed state have high strength (Table 1).

Table 1. Strength indicators of seasonally frozen soils, most common in the Republic of Kazakhstan at a temperature of -10^{o}C

Type of soil	Temporary resistance of frozen soil at a temperature of -10^{o}C, kg/cm^2	
	on compression	stretching
Loam	35-50	10-15
Sandy loam	55-80	15-25
Sand	up to 120	30-40

Notably, one of the important problems of immersion of piles in frozen soils is the inevitability of destruction of the head of the pile foundation, which leads to corrosion destruction of reinforcement and concrete. Analysis of pile foundation construction technologies in seasonally frozen soils allowed for the conclusion that even with a small depth of freezing, the accuracy of pile driving can be sharply reduced. At the same time, the probability of deviation of the piles from the design position is up to 10-15 cm, which is not an acceptable value. In turn, this will lead to a decrease in their load-bearing capacity [13-19]. Practical observations of the condition of piles driven into a layer of frozen soil have shown that in more than 90% of cases, the body of the piles is damaged by hammer blows. Therefore, many scientists, based on the conducted scientific and experimental studies, have come to the consensus that at a frost depth of more than 0.4 m, the soil in the places of pile driving should be thawed and protected from freezing by various methods [20-26]. However, the analysis of conventional methods of thawing seasonally frozen soils showed their high labour intensity and significant economic expenses [27-31]. Therefore, the driving of piles in winter requires additional work associated with the use of additional equipment and preliminary thawing of the soil. As a result, the labour intensity, duration, and cost of work increase [32-35]. Therefore, the main task when submerging piles in frozen soils is to avoid the destruction of the pile foundation using progressive methods of thawing the soil and protecting it from freezing.

Research in the line of foundation construction in frozen ground conditions considers many factors such as the behaviour of frozen ground and the interaction of soil with piles during lateral loading. The results show that the deformation rate inside the seasonally frozen layer usually decreases with increasing depth and distance from the ground-pile interface. A change in the deformation rate by three to four orders of magnitude can occur inside the seasonally frozen layer. Such a large variation in the strain rate can have a significant impact on the characteristics of a side-loaded pile in the frozen state, and its impact should be taken into account [35-42]. The paper [42-46] describes the environmental aspects of pile foundations, including the parameters of the geological environment, depending on the performance characteristics. The main parameters are taken into account: thermal conductivity, heat diffusivity, specific heat capacity, and soil moisture. The influence of temperature and ground water is also considered, as well as recommendations for the design and installation of pile foundations.

In the construction of monolithic pile foundations, the heat of cement hydration can cause an increase in ground temperature and a decrease in the load-bearing capacity of the pile foundation [47-54]. The observed temperature data showed that the pile foundation for buildings and structures without any cooling measures took two years to reach natural freezing. In such cases, a cold-air refrigerant system is proposed to reduce the re-freezing time [55-62]. As evidenced by the experiments in developed countries of the world, the most effective method was the thawing of soils at negative temperatures with the use of chemical reagents. The use of this method allows building facilities all year round, which significantly reduces duration of construction works. To achieve this goal, it is proposed to use the method of thawing frozen soils at negative temperatures as a basis for the construction of foundations in seasonally frozen soils of the Republic of Kazakhstan.

The purpose of the study is to develop a formula of chemical reagents for thawing and protection from the freezing of seasonally frozen soil in places where pile foundations are driven in winter conditions.

In the furtherance of this goal, it was necessary to solve the following tasks:

– to study of the physical and mechanical properties of the soil in the places of driving pile foundations;

– to choose chemical reagents that provide spontaneous heat generation and prevent soil freezing;

to conduct laboratory scientific and experimental studies on the kinetics of thawing of frozen soil, depending on the amount of chemical reagent applied and the time [63-66].

2. Material and methods

For this purpose, the soil for the construction of a residential building in Nur-Sultan (Republic of Kazakhstan) was chosen as the object of study. At the initial stage of research, scientific and experimental work was carried out to investigate the physical and mechanical properties of the soil, the results of which are presented in Table 2 [67-70].

Table 2. Physical and mechanical properties of the soil for the construction of a residential building in Nur-Sultan

Name of the soil	Sampling depth, m	Particle density, Ps g/cm^3	Natural humidity, W %	Plasticity number, Ip	Index of liquidity, I_L	Porosity coefficient, e	Water saturation coefficient, Sr unit fraction
Loam	0.5	2.7	10.4	9.9	-0.52	0.722	0.34

For further study, a three-component mixture of chemical reagents was selected, which includes the following components, wt.%: quick lime (CaO) – 75, calcium chloride (CaCl) – 20, sodium chloride (NaCl) – 5. The choice of the specified composition is conditioned by taking into account their specific chemical properties and special reactions when interacting with water and frozen soil. Quick lime is the most common and affordable building material and is widely used not only in construction, but also in agriculture to improve soil fertility. Its main active components – CaO turns into Ca $(OH)_2$ when interacting with a wet environment or water. This process occurs with the spontaneous release of heat. The main idea of the study is to use this thermal energy for local thawing of seasonally frozen soil in the places of driving pile foundations. For the study, a standard powdered slow-quenching quick lime of the 1st grade according to GOST 9179-2018 "Building lime. Technical conditions" (EN 459-1: 2010, NEQ) [14] were used. The content of active CaO + MdO – not less than 90%.

Currently, there are several technological methods of driving piles into frozen soils. If the frost depth of the soil does not exceed 0.7 meters, then it is enough to use more powerful hammers and vibrating hammers to drive the piles. If the frost depth exceeds 0.7 meters, it is necessary to establish conditions for the immersion of piles close to summer conditions [71-77]]. One of the most effective methods of foundation construction in seasonally frozen soils is the use of bored piles, which are quite well driven into the wells with the help of a jackhammer. However, before installation, a preparatory stage is necessary – drilling, and this is very difficult in conditions of frozen ground. The essence of the method is to create wells in which reinforced concrete piles are installed. At the same time, modern drilling rigs of increased capacity are required. One of the ways to solve the problem of foundation construction in winter conditions is the use of screw piles [78; 79]. The technology of the device of the screw foundation in conditions of sub-zero temperatures differs from the summer installation only by the greater labour intensity of screwing piles, the implementation of which requires the use of mechanized equipment. Figure 1 shows fragments of pile foundations in seasonally frozen soils [80-86].

a b

Figure 1. Fragments of the device of pile foundations in seasonally frozen soils: a – work on preliminary drilling of seasonally frozen soils in the places of pile driving; b – driving of a reinforced concrete pile into seasonally frozen soil in Nur-Sultan

The technology of improving the construction properties of permafrost soils by thawing with chemical reagents deserves special attention [87-91]. Thawing of frozen soils at a negative temperature is carried out by injecting into their volumes concentrated aqueous solutions of salts, anhydrous liquefied and gaseous chemicals that can actively thaw ice and protect thawed soils from possible subsequent freezing. At the same time, compaction of soils combined with thawing at negative temperature is recommended by separate injection of liquefied ammonia and a solution of calcium chloride or other reagents capable of interacting with soil solutions and mineral particles to form a cementing material [92-97]. Solutions of reagents for thawing frozen, especially gravelly-sandy soils can be fed into the ground by gravity without applying external pressure. However, the injection rate is sharply reduced [98-103].

3. Results and discussion

To establish the maximum temperature of the heat released during interaction with water, laboratory tests were carried out according to the following method: quick lime in the amount of 100 g was poured into a glass chemical dish. Then, water at room temperature (t=20-22°C) in an amount of 150 g was added to the dishes with quick lime [104-108]. To measure the temperature of the generated heat, a thermometer was installed in the center of the glass dish to a depth of half the height of the quick lime filled in, as shown in Figure 2.

a b

Figure 2. Fragment of the measurement of the temperature of heat release during the interaction of quick lime with water: a – installation of a thermometer for the experiment; b – measurement of the heat release temperature

The findings showed that after the interaction of quick lime with water, a violent reaction was observed with the release of water vapour. Notably, the violent reaction did not begin immediately, but after 5-7 minutes. In parallel, the heat release temperature began to rise [109-115]. After 20 minutes, the heat release temperature has amounted to 100°C. This process is explained as follows. In the process of interaction of quick lime with water, the reaction occurs:

$$CaO + H_2O = Ca(OH)_2 + 15.5 \text{ kcal}, \qquad (1)$$

where: 1 kcal = 4.1868×10^3 J.

In this case, the reaction proceeds rapidly, with a large release of heat – 15.5 kcal per gramme-molecule or 277 kcal per 1 kg of lime. Water, penetrating into the depth of calcareous grains, enters into chemical interaction with CaO, and the heat released in this case turns the water into a boiling state, which leads to the release of steam. It is this effect of heat release with the release of steam that is meant to be used for local thawing of seasonally frozen soil [116-121]. The additional use of calcium chloride (CaCl) and sodium chloride (NaCl) in the composition of the chemical reagent is necessary for additional intensification of the thawing process of seasonally frozen soil and the exclusion of its re-freezing. To study the effect of heat release of quick lime when interacting with water in real winter conditions, a laboratory sample of seasonally frozen soil at an ambient temperature of t = -20°C was prepared (Figure 3).

a b

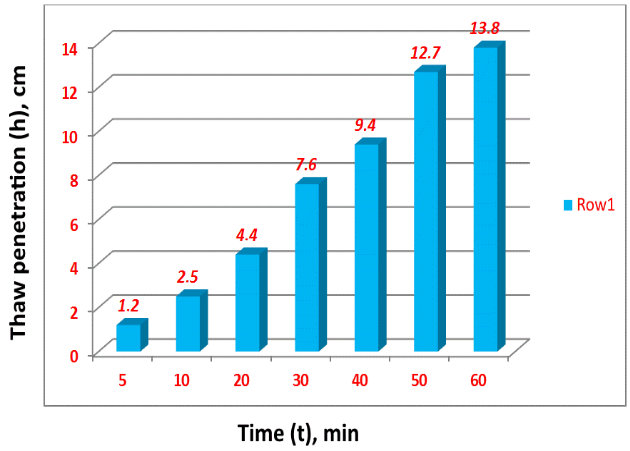
Figure 3. Fragments of preparation of a laboratory sample of seasonally frozen soil at ambient temperature t = -20°C: a – laboratory sample of seasonally frozen soil; b – preparation of samples for experiments

The size of the laboratory sample of seasonally frozen soil – 30 cm in diameter and 20 cm in depth. At the initial stage of the study, chemical reagents were previously prepared based on the quick lime of the following composition by wt%: quick lime (CaO) – 82, calcium chloride (CaCl) – 15, sodium chloride (NaCl) – 3.0. For the purpose of carrying out experimental work, a chemical reagent based on quicklime with a thickness of 1.0 cm, 2.0 cm and 3.0 cm was filled in on the surface of a laboratory sample of seasonally frozen soil. To study the depth of thawing depending on the thickness of the backfill of the chemical reagent and on the time, experiments were conducted for each backfill separately in the open air in winter [122]. The outside air temperature was t = -20°C. Water at room temperature (t = +22°C) was added to the surface of the chemical reagent. After the addition of water, the time of the rapid reaction was recorded and the heat release temperature was measured in parallel using a thermometer and the depth of thawing of seasonally frozen soil by drilling. The interval between measurements was 10 minutes. (Figure 4).

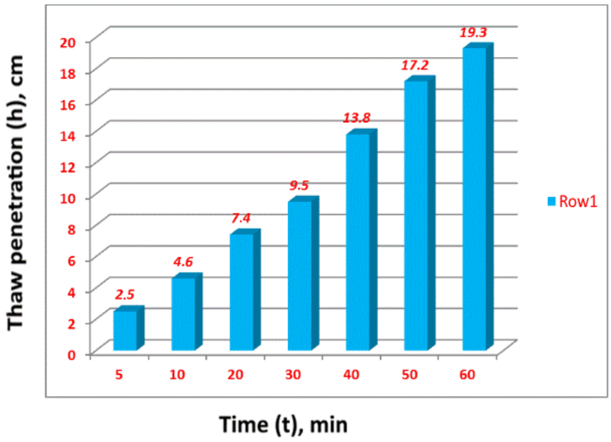
a b

Figure 4. Beginning of experimental work on thawing a laboratory sample of seasonally frozen soil using a chemical reagent based on quicklime: a – the moment of adding water; b – the moment of observing the temperature of heat release and measuring the depth of thawing

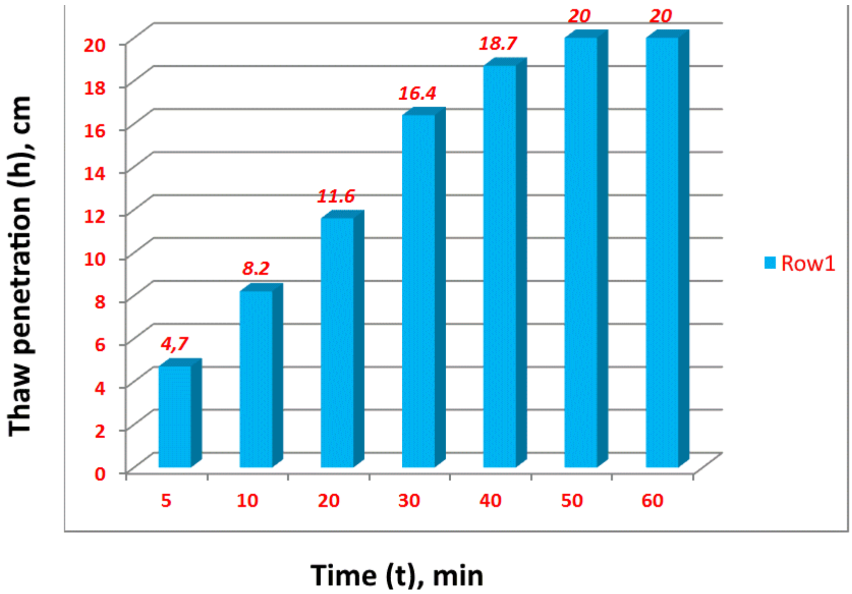
The results of the conducted experiments are presented in Figure 5.



a



b



c

Figure 5. The dependence of the depth of thawing of a laboratory sample of seasonally frozen soil on the time at the thickness of the backfill layer of a chemical reagent based on quicklime: a – at a layer thickness of 1.0 cm; b – at 2.0 cm; c – at 3.0 cm

As evidenced by the experimental results, when the chemical reagent backfill, thickness is 1.0 cm, there is a gradual increase in the depth of thawing of the soil, depending on the time. After a time of 5 minutes, the thawing depth was only 1.2 cm. In this case, the reaction of quick lime was not strongly manifested. However, the temperature at the thawing site tends to increase to 100°C despite the low outdoor temperature (t = -20°C). The most intense thawing is observed, starting from 40 minutes, where the thawing depth reach 9.4 cm. With an Increase of thickness of the chemical reagent backfill to 2 cm, the intensive start of thawing begins as early as 20 minutes. In such case, the thawing depth reaches up to 11.6 cm. Further, the thawing process is more intense and after a time of 60 minutes, the thawing depth is 19.3 cm. The most intensive thawing of seasonally frozen soil is observed at the chemical reagent backfill thickness of 3.0 cm. At the same time, after a time of 10 minutes, the thawing depth is already 8.2 cm [123-125]. Further, with increasing time, an intensive thawing process is observed and after a time of 50 minutes reaches a maximum mark of 20 cm. Notably, in this case of the experiment, the complete thawing of the laboratory sample of seasonally frozen soil is completed 10 minutes earlier than in the previous two conditions (Figure 6) [126].

a b

Figure 6. Fragments of a thawed sample of seasonally frozen soil when using a chemical reagent based on quicklime: a – the process of checking the thawed laboratory seasonally frozen soil; b – the appearance of a completely thawed sample of frozen soil

4. Conclusion

1. A new composition of a chemical reagent based on quick lime was developed for local thawing and protection from freezing of seasonally frozen clay soil in the areas of driving pile foundations. The proposed chemical reagent has the following composition by wt%: quick lime (CaO) – 82, calcium chloride (CaCl) – 15, sodium chloride (NaCl) – 3.0.
2. A distinctive feature of the proposed composition of the chemical reagent is that for local thawing of seasonally frozen loam soil, the spontaneously released heat of quicklime in interaction with water is used. Under laboratory conditions, it was found that the heat generated as a result of the chemical reaction of quicklime reaches up to 100^{o}C despite the negative temperature of the outside air (t = -20^{o}C).
3. Under laboratory conditions, experimental studies of the thawing process of a laboratory sample of seasonally frozen clay soil were carried out using the developed composition of a chemical reagent based on quick lime. The main regularities of the change in the thawing depth depending on the backfill thickness and time at ambient temperature t = -20^{o}C were investigated.
4. It was found that the intensity of thawing of a laboratory sample of seasonally frozen soil depends on the thickness of the backfill of a quick lime-based chemical reagent. At the same time, the most intense and relatively rapid thawing was observed at a chemical reagent backfill thickness of 3.0 cm.

The developed composition of the chemical reagent based on quick lime has advantages in terms of reducing energy costs for thawing seasonally frozen soils, since when interacting with water, the proposed chemical reagent spontaneously releases heat (t = 100^{o}C;) and does not cool down for a long time despite the negative ambient temperature. And the content of CaCl and NaCl in the composition excludes the re-freezing of seasonally frozen loam soil.

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