MATEC Web of Conferences **245**, 06005 (2018) https://doi.org/10.1051/matecconf/201824506005
EECE-2018

Thermal Properties of Conventional and High-strength Concrete

Tatiana Musorina[1,*], *Alexsander* Katcay[1], *Mikhail* Petrichenko[1] and *Anna* Selezneva[1]

[1]Peter the Great St. Petersburg Polytechnic University, Polytechnicheskaya 29, St. Petersburg, 195251, Russian Federation

Abstract. Important characteristics for the Nordic countries: a freeze-thaw resistance and an ability of a material to keep heat inside the building. This paper aims to define the thermophysical properties of a high-strength concrete, compare the discovered performance with the conventional concrete properties. With this object in mind two experiments in cold chamber "CHALLENGE 250" have been conducted and followed by analysis. In these experiments, the insulation of facades is beyond the framework of the investigation. Only the thermophysical properties of concrete are taken into account. The samples were affected by temperature fluctuations. Results from the experiments show that strength characteristics of a material are in indirect ratio to accumulation properties of a structure. This conclusion is directly related to porosity of material and additives. During 70 minutes, with outside temperature being below zero, the temperature inside the concrete dropped to an average. As the outside temperature increases significantly to more than zero, the temperature inside the concrete has become below average (continued to decline) in 70 minutes. The more strength of material, the better thermophysical properties. High-strength concrete is less susceptible to temperature fluctuations, therefore more heat-resistant. As mentioned in the paper below, the material has one disadvantage: this is a large cost per cubic meter.

1 Introduction

The application of a high grade concrete allows to reduce the self-weight of structures and the concrete area, to create a higher, bigger and smarter constructive form of the elements.

High-strength concrete is a heavy-weight or fine-grained concrete which corresponds to compression breaking strength over 70 MPa. It is made of a Portland cement and plasticizers based binder [1-4].

High strength allows reducing of the cross section and weight of structures. High technology facilitates the work with concrete mix, due to reduced setting and construction time. Moreover, high-strength concretes have an affordable production technology, as they are made of concrete mixtures based on the existing production facilities and traditional materials. The structures made of high-strength concrete have high chemical resistance and durability [5-6], as a result they can be used in harsh climatic conditions, typical for cold

---

[*] Corresponding author: tamusorina@mail.ru

regions of the Nordic countries. In addition, the material exhibits excellent characteristics during an earthquake, which is an extremely acute problem in seismically dangerous areas such as Kamchatka in Russia, Indonesia or Japan. Results from experiments show that high-strength concrete is able to dissipate more energy than conventional reinforced concrete structures, thereby preventing the destruction of buildings.

However, at the moment there are no recommendations on how to use the advantages of the new material to the greatest extent. In addition, in comparison with conventional concrete high-strength concrete has different fracture mechanics parameters thus the destruction of the material is explosive. All this facts and the high cost of high-strength concrete (compared to conventional), associated with high-energy consumption during production, makes it difficult to implement this new material.

High strength is achieved by the use of high-strength cements and fillers, extremely low water-cement ratio, the maximum permissible consumption of cement, the use of superplasticizers and complex additives, as well as the implementation of special conditions for mixing, compaction and hardening of the concrete mixture. If all conditions are met, a particularly dense, strong and monolithic structure is created.

Moreover high-strength concrete has much earlier strength gain than traditional concrete. The reason for this is the low water-cement ratio, as well as greater heat generation due to rapid hydration and high cement content [7-8].

During binding to water and its evaporation, the cement milk turns into a cement stone of a smaller volume. As a result, pores are being formed between the grains of the filler, reducing the final strength. The number of voids can be reduced by increasing the amount of cement and adding to the mixture a substance which will improve the sliding of the grains of the filler relative to each other. Actually, this class of additives is called plasticizers.

Another modification of concrete – nanoconcrete – also has high conductivity. The properties of nonconcrete were described [4] in complete detail, especially strength, density, permeability, plasticity, fire resistance and water absorption.

The construction of high-strength concrete allows a client and a constructor to keep their options open regardless of complexity of architectural solutions and to build designs of any height, including high-rise construction. When combined with durable fittings, it plays an important role in modern construction, especially in prestressed concrete structures.

Annually the amount of new types of concrete with improved characteristics grows. However, each new material have to be tested for a large number of properties, such as strength, frost resistance, workability, water resistance, thermal conductivity, fire resistance, etc. But there are often time limits for investigators, who switches their focus only to practical improvements because of the increasing pace of new materials development. In particular, high-strength concrete is required to be tested only for strength, frost resistance and water resistance according to regulations [9-10].

Determination of thermal conductivity

Experimental methods for determination of the thermal conductivity coefficient are based on certain theoretical prerequisites and on evaluation of the amount of heat passing through the test sample of normalized dimensions for a certain time at a given temperature difference. Modern experimental methods for determining thermal conductivity and test instruments can be divided into two groups:

1) based on stationary measurements;
2) based on the method of measurement in non-stationary mode [11-14].

Stationary measurement is a mode in which all considered thermal parameters do not change with time. A method based on the regularities of stationary thermal regime, as shown by theoretical and experimental studies [15-17], provides greater accuracy and reliability of determining the true value of λ – thermal conductivity. Measurements can be made in a wide temperature range-from 20 to 700 °C. However, the tests, conducted according to this method, are quite complex, time-consuming and have a long duration – 10 hours or more. A method requires devices operating in the transient heat flux, inferior to the reliability and accuracy of the measurement stationary regime method. The temperature range is limited, but the speed of measurements (10 − 30 min) contributes to the development of this method, and it`s application for operational control in production is very promising.

Materials with a conductivity less than 0.175 W/(m·˚C) are considered to be insulating. Application of modern thermal insulation materials with conductivity less than 0.05 W/(m·˚C) allows to obtain significant technical and economic effect by reducing the thickness of the walling or reduce the energy costs for heating buildings.

Dry air enclosed in small closed pores has the minimum conductivity. In this case, the thermal conductivity of air is minimal and counts 0.023 W/(m·˚C). Therefore, the increase in porosity of the material is the main way to reduce thermal conductivity.

The thermal conductivity of the materials increases significantly with hydration. This is because of the moisture which falls into the pores and partly replaces the air, increasing the thermal conductivity of the material since the thermal conductivity of water is greater in 25 times ($\lambda = 0.58$ W/(m·˚C)) than the thermal conductivity of air [18-24].

Summing up previous information, the thermal conductivity of materials depends on the following factors:

1) physical condition and structure, which are determined by the phase state of matter;
2) a degree of crystallization and size of crystals;
3) anisotropy of the thermal conductivity of crystals and the direction of heat flow;
4) a volume of porosity of the material and the characteristics of the porous structure;
5) chemical composition and presence of impurities (the latter especially affects the conductivity of crystalline bodies);
6) maintenance conditions, depending on temperature, pressure, humidity of the material [25-27].

Such an important characteristic, especially for the Nordic countries, as a thermal conductivity was overlooked. For the widespread implementation of a high-strength concrete in construction it is necessary to take into account how successful material resists low temperatures and to create comfortable thermal and humidity conditions, considering the fact that most of the cities in the Nordic countries are located in a cold climate. In this regard, it is necessary to test and compare types of concrete.

*Goa**l***

It is apparent from the foregoing that in order to reasonably conclude about the thermal properties of high-strength heavy concrete, it is necessary to examine it and verify how thermal properties differ from the properties of conventional concrete.

Tasks

To achieve the objectives of the article it is required:

1. to conduct experiments to study the thermophysical properties of materials;
2. to compare properties of both types of concrete;
3. graphically see the difference between the characteristics of the concrete;
4. perform price analysis.

2 Methods

2.1 Materials

The paper considers only the thermophysical properties of one layer of the structure for the Northern countries – the concrete layer. The thermal insulation layer was not taken into account for the purpose of the experiment.

In the course of the experiment 1 sample of high-strength heavy concrete and 1 sample of ordinary concrete were made with the following compositions:

Table 1. Composition of concretes

№	Concrete	Cement, [kg]	Slag, [kg]	Sand, [kg]	Crushed stone, [kg]		Water, [kg]	Water-cement ratio	Plasticizer PF 3196 0.5%, [kg]	Density, [kg/m^3]	Strength, [MPa]
					5-10 mm, [kg]	10-20 mm, [kg]					
1	high-strength heavy concrete	380	76	798.4	273	728.5	175	0.38 (0.47)	1.90	2428	70.1
2	conventional concrete	312	-	604	1116		220	0.71	-	2252	20

Figure 1. High-strength concrete

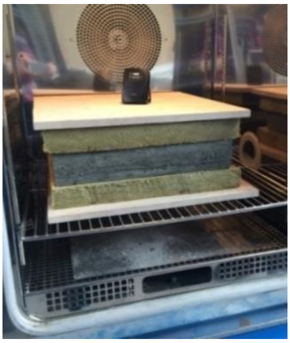

Figure 2. Chamber conditions for reinforced concrete structure

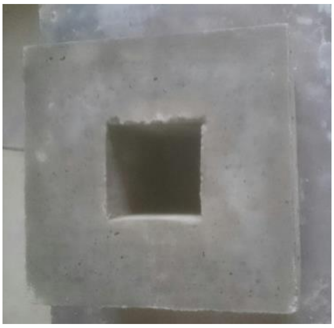

Figure 1.1 High-strength concrete (top view)

Figure 2.1 Chamber conditions for reinforced concrete structure (top view)

The Characteristics of the materials*:*

Cement:

- Shale cement plant, “Tsesla”, Slantsy, Leningrad Oblast;

-Blast Furnace slag <35%;

-Activity at the age of 2 days 20.7 MPa;
-Normal density 25.2%.
Large aggregate – granite rubble:
-Rubicon, field “Ilmenioki” ;
-Silty and clay particles <0.75% ;
-Flaky grain grains 13.5%;
-Density 1370 kg/m^3;
Sand:
- Cement-concrete products, Sertolovo, Leningrad Oblast, field “Ostrovskoe”;
Fillers are tested in an accredited scientific and testing laboratory "Polytech-SKiM-Test"
Chemical additives produced by "MC Bauhemi": Superplasticizing - MS-PowerFlow 2695.

Reinforced concrete:
- Moisture 2%;
- Thermal conductivity 2.04 $\mathrm{W/(m\cdot{}^\circ C)}$;
- Heat absorption 17.98;
- Coefficient of vapor permeability 0.03 mg/(m·h·Pa).

High-strength concrete:
- Maximum permissible moisture increment in the material, concrete = 2% by weight
- Moisture 3%;
- Thermal conductivity 1.86 $\mathrm{W/(m\cdot{}^\circ C)}$;
- Heat absorption 16.77;
- -Coefficient of vapor permeability 0.03 mg/(m·h·Pa).

Thermal resistance of high-strength concrete certain:

$$R = \frac{\delta}{\lambda}$$

Then in dry operational conditions ($\delta = 0{,}1m, \lambda = 1{,}74\ \mathrm{W/(m\cdot{}^\circ C)}$):

$$\frac{\delta}{\lambda} = \frac{0.1}{1.74} = 0{,}057\ m^2 \cdot {}^\circ\mathrm{C/W}$$

In wet operational conditions ($\delta = 0{,}1m, \lambda = 1{,}86\ \mathrm{W/(m\cdot{}^\circ C)}$):

$$\frac{\delta}{\lambda} = \frac{0.1}{1.86} = 0{,}054\ m^2 \cdot {}^\circ\mathrm{C/W}$$

2.2 Methods of Research

The stationary thermal mode is an idealized model of a heat transfer. With temperature of an external source or with a profuseness of a heat source changing in time, a reactivity of a wall can be observed which appears as:

1) In reduction of temperature change of a source solid medium (material of a wall structure);

2) In existence of "delay" in reaction of a wall design to temperature change and/or power of a source.

Both effects represent influence of jet resistance of a wall protection. For example, there is no accumulation of warmth in a wall structure in the conditions of a stationary heat transfer. Distribution of temperature in a wall design is defined by extreme temperatures. At the unsteady heat transfer inertia of temperature distribution and accumulation of warmth are defined by the size of local derivative temperature. The stationary modes of a heat transfer turn out as a limit case of the quasistationary (periodic) modes at increase in the period of change of boundary conditions (t_0) indefinitely. At the same time the local derivative of temperature meets to 0 evenly on x: $\frac{\partial T}{\partial t} \xrightarrow[t_0 \to \infty]{} 0, \forall x \geq 0$.

The traditional method, which is used in heat conductivity of firm environments, is connected with Fourier's theory. For Fourier's equation two ideas are the cornerstone of solutions of limit tasks.

– interpretation of operator s $\partial t := d/dt$ the translator of group of shifts that is especially convenient in non-stationary tasks, allowing to express obviously delay (inertia) of the temperature field of a protection of rather external source of warmth.

Solution of the Cauchy problem for the first order equation:$\partial u/\partial t \pm \partial u/\partial x = 0, u(0,x) - \varphi(x) = 0$, it has the form of a solitary traveling wave, direct or reflected, given by the shift of the initial condition: $u(t,x) = exp\left(\mp t \frac{\partial}{\partial x}\right) \varphi(x) = \varphi(x \mp t)$.

An easily proved switching formula is valid: if $(\partial_t - \alpha)^n x(t) = y(t), x(0) = \cdots = \partial_t^{(n-1)} x(0) = 0$, where $n > -1$ is an integer, then $x(t) = \partial_\tau^{-1}(exp(\alpha(t-\tau)))\partial_\tau^{-(n-1)} y(\tau)$, where $\partial_\tau^{-1}(z(t))$ is any prime of the density $z(t)$;

The use of fractional powers of the ∂_t operator and mutually inverse relations arising from the solution of the Abel integral equation. These integral relations are generated by the ring of unbounded differentiation operators $\partial t := d/dt$, acting on space $S(E^1)$. Fractional powers of the operator are interpreted as follows $\partial_\tau^s \coloneqq (d/dt)^s$. Let $n > 0, n \in N$ be a positive integer. Then the solution of the homogeneous Cauchy problem for the equation of order n is: $\partial_t^n x(t) = y(t), x(0) = \partial_t x(0) = \cdots = \partial_t^{(n-1)} x(0) = 0$, is:

$$x(t) = \partial_t^{-n} y(t) = \frac{1}{\Gamma(n)} \int_0^t y(t-\tau)\tau^{n-1} d\tau.$$

For positive integer values of n, a known result is obtained. This formula (Dirichlet) is convenient to give the following form:

$$x(t) = \frac{1}{\Gamma(n)} \int_0^t y(t - \tau^{1/n}) d\tau,\ n > -1.$$

Examples.

Suppose time and length (t, x) are already normalized, namely as the length scale is used $(at_0)^{1/2}$, and as the time scale – period (t_0). Given:

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2}, D(T) = (t, x \colon |t| > 0, x > 0),$$
$$T(t,0) - T_w(t) = 0, T_w(t \pm 1) - T_w(t) = 0,$$

the temperature at any point of the half-plane is a periodic function of time:

$$T(t \pm 1, x) - T(t,x) = 0, \forall x \geq 0.$$

The second limit problem sets the value of the derivative of the desired temperature at the point $x = 0$:

$$-\left(\frac{\partial T}{\partial t}\right)_{x=0} = q_w(t), q_w(t \pm 1) - q_w(t) = 0,$$

It is assumed that the solid medium is homogeneous and isotropic, or scalar. This means that the transfer coefficient is a scalar constant.

If $a = a(T)$, then type the Boussinesq equation is obtained, with nonlinearity at the highest derivative: $\partial T/\partial t = \partial/\partial x\,(a(T)\,\partial T/\partial x)$. In turn, this equation associated with the equation of the world.

It is easy to check that the solution of the first limit periodic problem has the form:

$$T(t,x) = exp(-x\partial_t^{1/2}) T_w(t).$$

Next, for the heat flux density at $x = 0$, $q_w(t) = -(\partial T/\partial x)_{x=0}$, a simple expression is obtained:

$$q_w(t) = \partial_t^{1/2} T_w(t) = \frac{2}{\sqrt{\pi}}\frac{d}{dt}\int\limits_0^\infty T_w(t-z^2)dz = \frac{2}{\sqrt{\pi}}\int\limits_0^\infty T_w(t-z^2)dz, \qquad \text{(a)}$$

and the point is the derivative of the whole argument.

The solution of the second limit periodic problem in a symbolic form is:

$$T(t,x) = exp(-x\partial_t^{1/2})\partial_t^{-1/2} q_w(t),$$

and then for the temperature at the point x=0 the expression is obtained:

$$q_w(t) = \partial_t^{1/2} q_w(t) = \frac{2}{\sqrt{\pi}}\int\limits_0^\infty q_w(t-z^2)dz, \qquad \text{(b)}$$

Formulas (a), (b) – reciprocal relations of Abelian type.

In the formula (a) we define the thermal resistance as:

$$r := \frac{T_w(t)}{q_w(t)} = \frac{\partial_t^{-1/2} T_w(t)}{T_w(t)}. \qquad \text{(c)}$$

The formula (c) below is obtained informally. From it, in particular, formal equality: $r = \partial_t^{-1/2}$.

The solution of the first limit problem can be represented as formal power series:

$$T(t,x) = 1/2\left(ch\left(x\partial_t^{1/2}\right) - sh\left(x\partial_t^{1/2}\right)\right)T_w(t) = 1/2\sum_{k=0}^{\infty}\frac{x^{2k}\partial_t^k}{(2k)!}T_w(t)$$
$$-1/2\sum_{k=0}^{\infty}\frac{x^{2k+1}\partial_t^k}{(2k+1)!}\left(q_w(t)\right), q_w(t) = \partial_t^{1/2}T_w(t).$$

In particular, in the mixed limit problem of thermal conductivity$q_w(t) = B(T_f - T_w)$, where $B = B(t)$ is the coefficient of external heat transfer number Biot, $T_f = T_f(t)$ – source temperature (fluid). It was considered that both the number of Biot and the source temperature are periodic, with a primitive period$t = 1$, functions of time. By virtue of the previous expression:

$$T(t,x) = 1/2\sum_{k=0}^{\infty}\frac{x^{2k}\partial_t^k}{(2k)!}T_w(t) - 1/2\sum_{k=0}^{\infty}\frac{x^{2k+1}\partial_t^k}{(2k+1)!}B(t)\left(T_f(t) - T_w(t)\right).$$

In the problems of construction heat engineering, as a rule, it is considered that the coefficient of external heat transfer (number Biot) B – is a constant parameter. Then:

$$T(t,x) = 1/2\sum_{k=0}^{\infty}\frac{x^{2k}\partial_t^k}{(2k)!}T_w(t) - 1/2\,B\sum_{k=0}^{\infty}\frac{x^{2k+1}\partial_t^k}{(2k+1)!}T_f(t) +$$
$$1/2\,B\sum_{k=0}^{\infty}\frac{x^{2k+1}\partial_t^k}{(2k+1)!}T_w(t).$$

Let $B \ll 1$ and then: $T(t,x) = 1/2\sum_{k=0}^{\infty}\frac{x^{2k}\partial_t^k}{(2k)!}T_w(t);$ conversely, if $B \ll 1$, then:

$$T(t,x) = 1/2\sum_{k=0}^{\infty}\frac{x^{2k}\partial_t^k}{(2k)!}\frac{dT_f}{dt} - 1/2\sum_{k=0}^{\infty}\frac{x^{2k+1}\partial_t^k}{(2k+1)!}\left(q_w(t)\right) = 1/2\left(T_f(t) + x^2/2\frac{dT_f}{dt}\right) -$$
$$1/2\,xq_w.$$

We estimate the average wall temperature as the arithmetic mean of the wall thickness temperature:

$$T_m(t) := \int_0^1 T(t,x)dx,$$

and then for the average thickness of the wall temperature is obtained such an expression:

$$T_m(t) = 1/2\sum_{k=0}^{\infty}\frac{\partial_t^k T_w(t)}{(2k+1)!} - 1/2\,B\sum_{k=0}^{\infty}\frac{\partial_t^k T_f(t)}{(2k+2)!} + 1/2\,B\sum_{k=0}^{\infty}\frac{\partial_t^k T_w(t)}{(2k+2)!}.$$

Active layer of thermal conductivity, uniform wall fence of final thickness.

Important: in stationary processes the amount of enthalpy in the medium is constant. Since T(t,x) is a monotonically decreasing coordinate function, the value of $I(t)$ can be estimated by the theorem of the mean (Bonn):

$$I(t) = T_w(t)\delta(t).$$

Moreover, δ(t) can be interpreted as the thickness of the temperature boundary layer, or as the thickness of the active layer of thermal conductivity, or as the integral thermal resistance of the solid medium.

The integral relation is obtained from the heat equation:

$$\frac{dI}{dt} = \left(\frac{\partial T}{\partial x}\right)_0^{\infty} = q_w(t) = \partial_t^{1/2}T_w(t).$$

Direct calculation of the integral $I(t)$ leads to equality:

$$I(t) = \partial_t^{1/2}T_w(t),$$

from which it directly follows that

$$\delta(t)T_w(t) = \frac{2}{\sqrt{\pi}}\int_0^{\infty} T_w(t-z^2)dz\,, q_w(t) = \frac{2}{\sqrt{\pi}}\frac{d}{dt}\partial_t^{-1/2}T_w(t).$$

$$\delta(t) = \frac{2}{\sqrt{\pi}T_w(t)}\int_0^{\infty} T_w(t-z^2)dz \coloneqq r.$$

For the first limit aperiodic heat conduction problem, the expression for $\delta(t)$ takes the form:

$$\delta(t) = \frac{2}{\sqrt{\pi}T_w(t)}\int_0^{\sqrt{t}} T_w(t-z^2)dz.$$

The value of $\delta(t)$ is interpreted as the thickness of the temperature boundary layer. At $0 < x < \delta(t)$the temperature gradient changes (decreases) to small (almost zero) values at $x > \delta$.

The thickness of the active thermal conductivity layer δ(t) can be interpreted as follows. By definition, $\delta(t) = \frac{\partial_t^{-1/2}T_w(t)}{T_w(t)}$, and therefore formally get: $\delta(t) = \partial_t^{-1/2}$. Consequently, $q_w(t) = \partial_t^{1/2}T_w(t) = \frac{T_w(t)}{\delta(t)}$ it turns out the local law of Fourier.

Using these considerations, it is easy to obtain a useful identity:

$$\partial_t^{-1/2}T_w(t) = \sqrt{2\int_0^{\infty} {T_w}^2(t-\tau)d\tau}.$$

Indeed, the equality is just:

$$\delta(t) = \frac{U_w(t)}{T_w(t)},$$

$$\delta(t) = \frac{T_w(t)}{\partial_t U_w(t)},$$

Where $U_w(t) \coloneqq \partial_t^{-1/2} T_w(t)$, in the usual notation: $d/dt\left({U_w}^2/2\right) = {T_w}^2(t)$, where from is obtained the required identity. Suppose $T_w(t) = Ct^m, m \in E^1$. Then for the thickness of the temperature boundary layer an expression is obtained:

$$\delta_m(t) = \sqrt{t}\frac{\Gamma(m+1)}{\Gamma(m+3/2)} = \sqrt{t}\frac{m!}{(m+1/2)!},$$

$$\delta_0(t) = 2\sqrt{\frac{t}{\pi}}, \delta_1(t) = \frac{4}{3}\sqrt{\frac{t}{\pi}},$$

$$\delta_m(t) = \sqrt{\frac{t}{e}}, m \gg 1.$$

that is, the thickness of the temperature boundary layer is constant in time and decreases with increasing frequency of the process n. At large n>>1 the skin effect is observed: the temperature field is "locked" in a thin layer $0 < x < \delta$.

Suppose the frequency n of the periodic process be given, and $0 < x < \Delta$. Then at $\Delta \gg \delta$ the wall fence is "conductive" thin: the entire temperature gradient, from T_w to 0, is triggered in a thin boundary layer. On the set of values $\delta < x < \Delta$ the wall as an active thermal resistance (thermal barrier) is useless and accumulates heat.

The experiment consists of simulation of the real conditions of typical structure in a cold climate which undergoes drastic temperature changes in few hours during the same day. In order to simulate the indoor conditions the box was build (imitation of a closed room). It consists of the following elements: a wooden board, a heater, a reinforced concrete sample (fig. 1, 2).

The appropriate sensors and equipment were installed inside the “box” in accordance to real characteristics of buildings [28]. The both surfaces (up and down) were sealed with a thermal isolation (to simulate a roof and a floor of a typical internal environment). The experiments were conducted as follows: the initial temperature of the air inside the chamber was 25°C, followed by a drastic drop down to 0°C, and then the temperature was risen to the initial temperature. The temperature inside the “box” was registered for both specimens. In this way, it is possible to study the behavior which really applies in real life conditions. That is a basis for future conclusions about the material. As it was explained before and in accordance with the object of this paper, the main idea is to simulate with all possible details conditions of an environment. Similar conditions were considered in the works [29-32].

2.3 Initial data

The sample was placed in a chamber (initial temperature inside the structure was approximately 21°C) and was kept to an air of temperature 0°C degrees. The sample was at 0°C degrees for 30 minutes. Then followed an increase of temperature in the chamber up to 25°C degrees. The sample was heated until the sensor inside the structure began to register an increase of temperature. Due to the fact that the material is thermally stable, it continues to cool down, even if the chamber has above zero temperature. Then the material was cooled until the temperature of the sensor began to fall.

Sensors were installed at the top of the structure and inside the structure to determine the temperature during the experiment (fig. 1.1, 2.1).

3 Results and Discussion

The results of the experiment are shown at fig.3, where we can see changes in temperature of concretes which depends on temperature in the “box” through time.

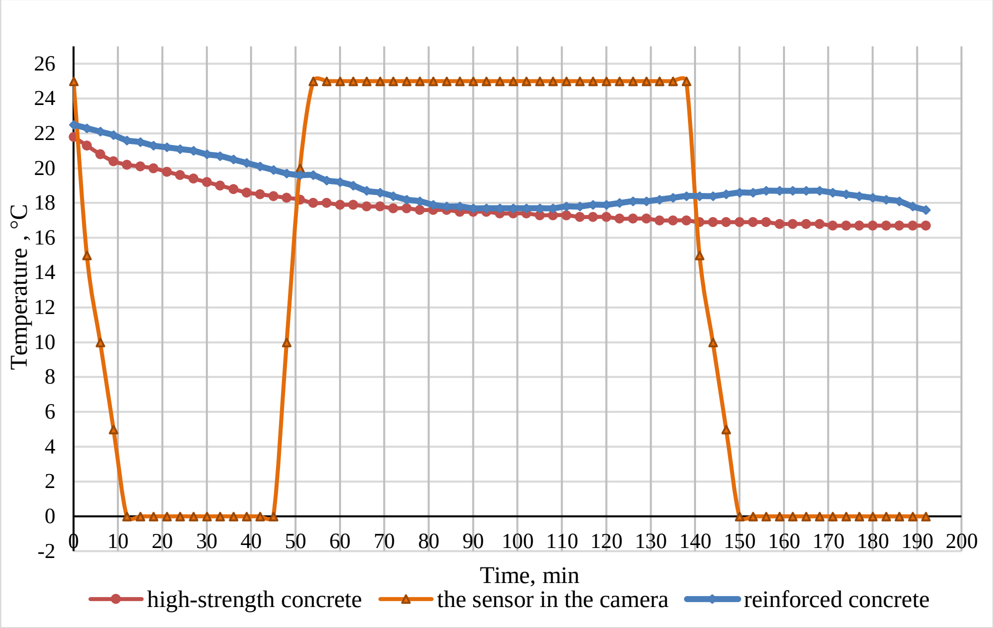

Figure 3. Graph of temperature of concrete change from temperature in “the box” through time

Zero temperature kept in the camera until the moment when fall of temperature for high-strength concrete has been stabilized. During this time, temperature of high-strength concrete has fallen on 4 degrees while the one of conventional concrete has changed only 2 degrees and continued to go down. Further temperature in the camera lifted up to 25 degrees within 10 min. At air temperature in the camera 25 degrees temperature of high-strength concrete changes by only 1 degree (within 75 minutes). During this time usual concrete has fallen by 2 degrees, 30 minutes later, has begun to rise. Within the next 10 minutes temperature of air in the camera became 0 degrees again. As shown in graphics, remained air temperature is invariable for high-strength concrete – 17 degrees. While the temperature of the conventional concrete within 20 minutes has risen by 1 degree, and then began to go down again.

In usual concrete existence of sinks and different voids in the form of the cracks, opened or reported among themselves, which are formed as a result of temperature deformations, serves to development of corrosion that strongly reduces durability of a concrete design.

As a result of the experiments it can be concluded that the greater the strength of the material the better it`s thermal resistance. Despite the changes in temperature in the camera (from lowering to the boost), the temperature inside the material gradually continues to drop and there are fewer temperature fluctuations in the high-strength concrete.

Due to the high accumulation ability, there is the "extinction" of the temperature oscillations approximately in 5 times. So, inside the sample average temperature is about +18˚C during the whole experiment. It was decreasing slowly enough, approximately 0.1 for 3 minutes.

To achieve large changes (fluctuations) in high-strength concrete it is necessary to create a greater difference in temperature, for example from +30˚C to -10˚C. The results of the experiment can be seen in fig. 4.

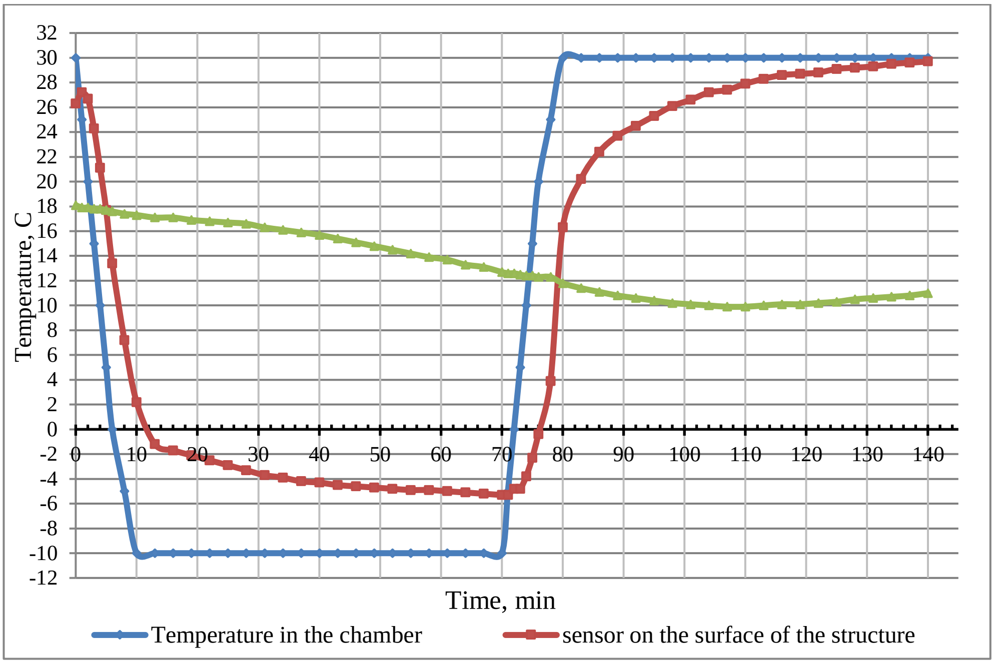

Figure 4. Graph of temperature of concrete change from temperature in "the box" through time

At fig. 4 it can be seen that large temperature variations can be obtained with a greater difference of an external temperature. The graph shows that when the temperature in the chamber was rising, the room temperature continued to fall, and only after 30 minutes the concrete's temperature began to increase. This implies that high strength concrete is a good heat accumulator.

As a result of the experiment, it turned out that high-strength concrete resists external temperature changes better than conventional concrete.

This result is driven by the physical structure of the materials. Because of the specificity of solidification high-strength concrete has fewer pores. The presence of pores in the material affects the ability of the material to resist external temperature changes. Reducing the number of pores allows not only to increase the strength characteristics at times but also to improve the thermal properties. Thus, the higher the strength of concrete, the smaller the pores, the smaller the pores, the higher the thermal properties.

It should be noted that similar results were obtained in the article "Justification of constructive measures to increase energy efficiency of wall barriers" [15]. The conclusions of this work indicated that materials with high thermal conductivity play the role of a heat storage device. In addition, there was a tendency of heat-insulating materials to quickly change the temperature depending on an external environment, but bricklayers have quenched fluctuations of temperature already in external layers of a wall design. In our experiment, high-strength concrete was more heat-conductive and less dependent on external temperature fluctuations than concrete with standard strength.

It is well known that the use of an adequate thermal energy storage (TES) systems in the building and industrial sector presents high potential in energy conservation. Advantages of using TES in an energy system are the increase of the overall efficiency and better reliability, but it can also lead to better economics, reducing investment and running costs, and less pollution of the environment and less CO2 emissions [25-26].

However, for a complete and objective assessment of the material, the disadvantages of high-strength concrete application merit mention [33-34].

First of all, one of the disadvantages of high-strength concrete is the effect of high temperatures (fire). High temperature is one of the most detrimental effects that causes durability problems in constructions. This effect can cause permanent damages in constructions, can shorten the service life and may cause casualties, thus affecting the construction's sustainability. When concrete is exposed to a high temperature effect such as fire, important changes may occur in its mechanical, physical, and thermophysical properties. As a result of these changes, especially high strength concrete (HSC) may exhibit damages such as cracks and spalling [10].

The next disadvantage of the high-strength concrete is the high cost. Thus, the cost of high-strength concrete with compression breaking strength over 70 MPa is 6650 rub/m^3, that is almost two times expensive than the cost of conventional concrete with class B25 – 3750 rub/m^3. However, not everything is so clear. In the study [7] the economic efficiency of the use of high-strength concrete was analyzed. It states that in compressed structures, in addition to reducing the cross section of the column from 600x600 mm to 400x400 mm, the use of reinforcement was almost five times reduced - from 1055.5 cm^2 to 195.9 cm^2. Therefore, the cost of column materials was decreased by 57%.

4 Conclusions

Optimal microclimatic conditions of the room are the basis of the public health. Modern society pays more attention to the creation of a comfortable microclimate in the room while reducing the cost of it is running. In connection with these goals, there is a growing interest in new improved technologies, in particular in the high-strength concrete. Below are the key steps and conclusions for the study of the thermal and economic efficiency of the high-strength concrete:

1. In the course of the work, an experiment was conducted to study the thermophysical properties of materials, which clearly demonstrated the importance of thermophysical characteristics;
2. Based on the experiment, the comparative analysis of thermophysical properties of two materials was carried out. It was found that: the higher the strength characteristics of the material (the minimum number of pores), the higher it is thermal properties (on average by 5%)
3. The graphs clearly show the difference in the properties of two materials. Thus, the more the strength of the material, the higher its conductivity. This is due to the fact that conventional concrete has porosity, while pores of high-strength concrete are filled with a plasticizer and slag (supplement).

   It follows from the experiments that high-strength concrete is more actionable as a storage of heat. Therefore high-strength concrete effectively dampens fluctuations of the temperature. So that during the cycle the temperature of the high-strength concrete stabilizes;
4. The cost analysis showed that the cost of materials is reduced by almost 57% when using high-strength concrete instead of conventional.

However, despite of the best strength, thermal and economic properties of high-strength concrete, it is still does not find wide application because of the stereotype of its high cost. In the nearest future, this bias should go away under the pressure of unbiased calculations and accelerated construction rates providing a wide field of activity for the use of high-strength concrete.

We are grateful to the laboratories of the Institute of Civil Engineering from Peter the Great St. Petersburg Polytechnic University which provided all equipment and materials and helped to conduct the experiments.

References

1. O.M. Smirnova, Magazine of Civil Engineering **6**, 12-22 (2016)
2. C. Gu, G. Ye, W. Sun, Science China Technological Sciences **58**, 587-599 (2015)
3. M. M. Batdalov, H. N Maiev., D. K. S. S. G. K. Batayev, Earthquake-resistant construction. Safety of structures **1**, 45-47 (2013)
4. A.N. Ponomarev , Magazine of Civil Engineering **6**, 25-33 (2009)
5. O. N. Pertseva, S.G. Nikolsky, Magazine of Civil Engineering 47, 71-76 (2014
6. S. G. Nikol'skii, O. N. Pertseva, V. I. Ivanov, Magazine of Civil Engineering **60**, 7-19 (2015)
7. E. E. Koryakina, V. N. Aksenov , Modern science-intensive technologies **2**, 23-26 (2016)
8. S. G. Nikolsky, T. S. Nikolskaya , Proceedings of the III MK "Popular concrete scince", ed. by M. Skipski. SPb.: OOO "Stroybeton", 35-44 (2009)
9. State Standart 31914-2012 High-strength heavy-weight and fine-grane concretes for situ-casting structures. Rules for control and quality assessment
10. EN 1992 Eurocode 2. Design of concrete structures.
11. S.A. Memon, Renewable Sustainable Energy Rev. **31**, 870-906 (2014)
12. G. Barrios, G. Huelsz, R. Rechtman, J. Rojas, Energy and Buildings **43**, 219-223 (2011)
13. J. Zemitis, A. Borodinecs, M. Frolova , Energy and Buildings 127, 884-891 (2016)
14. A. Keyvanfar, A. Shafaghat, M. Z. A. Majid, H. B. Lamit, M. W. Hussin, K. N. B Ali, A. D. Saad , Journal of Renewable and Sustainable Energy Reviews **39**, 277-293 (2014)
15. T.A. Musorina, O.S. Gamayunova, M.R. Petrichenko, Herald of MGSU **12**, 1269-1277 (2017)
16. S.V. Kornienko, N.I. Vatin, M.R. Petrichenko, A.S. Gorshkov, Construction of Unique Buildings and Structures **6**, 19-33 (2015)
17. B. Nagy, S. G. Nehme, D. Szagri, Energy Procedia **78**, 2742-2747 (2015)
18. Z. Mitraka, E. Diamantakis, N. Chrysoulakis, E. A. Castro, R. S. Jose, A. Gonzalez, I. Blecic, Sustainability **6**, 7982-8006 (2014)
19. M. Petrichenko, N. Vatin, D. Nemova, N. Kharkov, A. Korsun, Appl. Mech. Mater. **672-674**, 1903-1908 (2014)
20. N. Vatin, M. Petrichenko, D. Nemova, Appl. Mech. Mater. **633-634**, 1007-1012 (2014)
21. T.A. Hezhev, A.V. Zhurtov, A.S. Tsipinov, S.V. Klyuev, Magazine of Civil Engineering **4,** 181–194 (2018)
22. M. R. Petrichenko, Examples of fundamental and applied research of the XXV international scientific-practical conference 31-35 (2016)
23. M. Petrichenko, A. Ostrovaia, E. Statsenko, Appl. Mech. Mater. **725-726**, 87-92 (2015)
24. A. Gracia, L. F. Cabeza, Energy and Buildings **103**, 414-419 (2015)
25. B. Akturk, N. Yuzer, N. Kabay, International Scholarly and Scientific Research & Innovation **8**, 859-864 (2014)
26. C. Balocco, Energy and Buildings **34**, 469-475 (2002)
27. A.A. Minea, Int. J. Heat. Mass. Tran. **68**, 78-84 (2014)
28. N.I. Gamajunov, S.N. Gamajunov, Vestnik TvGTU **22**, 46-54 (2012)
29. A.V. Rosca, I. Pop, Int. J. Heat. Mass. Tran. **60**, 355-364 (2013)

30. R. Fuliotto, F. Cambuli, N. Mandas, N. Bacchin, G. Manara, Q. Chen, Energy and Buildings **42**, 23-28 (2010)

31. S.V. Klyuev, A.V. Klyuev, T.A. Khezhev, Yu.V. Pucharenko, Journal of Engineering and Applied Sciences **13 (8 SI),** 6407-6412 (2018)

32. S.V. Klyuev, T.A. Khezhev, Yu.V. Pukharenko, A.V. Klyuev, Materials Science Forum **931,** 598-602 (2018)

33. L.P. Churilov, Yu.I.Stroev, S.A. Varzin, Teoriya i Praktika Fizicheskoy Kultury (2014)

34. S.A. Varzin, , O.E. Piskun, , N.N. Petrova, Teoriya i Praktika Fizicheskoy Kultury (2014)