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Thermal stresses at the early stage of the hardening of steel-fiber reinforced concrete

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Abstract. The article studies the influence of steel fiber on the change in temperature stresses in concrete at an early hardening stage. When hardening concrete is exposed to heat treatment, its volume and, consequently, density change. Under certain circumstances, this can lead to its structural damage and, ultimately, to a decrease in its physical and mechanical properties at the design age. Such structural damage of concrete can appear even at the earliest hardening stage, before the formation of the elastic properties of the material. When testing concretes subjected to heating, we recorded the development of temperature deformations and assessed their plastic viscosity. To determine the temperature stresses, we proposed a method based on the Kelvin-Voigt rheological model. Studies have shown that the presence of steel fibers in concrete leads to a decrease in the deformations of concrete during heat treatment. To assess the thermal stresses arising at the early stage of hardening, we derived an analytical dependence, taking into account the viscosity of the hardening concrete. During the experiments, we obtained values for the viscosity of steel-fiber reinforced concrete depending on its fiber content. The results showed that, without changing its density, steel-fiber reinforced concrete can take significantly higher thermal stresses than unreinforced concrete at the early hardening stages. With an increase in the temperature, the change in the thermal stresses, depending on the fiber content, begins to have a more pronounced non-linear nature. We also showed that before a certain structural strength is reached, there are no thermal stresses in steel-fiber reinforced concrete due to the steel-fiber induced redistribution of temperature forces throughout the volume of concrete.

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1. Introduction

The formation of a favorable thermally stressed state of concrete during hardening is the basis for ensuring the quality of monolithic structures.

The problem of the thermo-stressed state of concrete structures has been most fully explored for dams, since such massive structures may have large temperature differences over the cross-section [1–3]. The temperature differences between the core and the peripheral zones of structures are caused by the exothermic hydration reaction given the relatively low thermal conductivity of concrete. Heat treatment of concrete is not used in such structures, since a large amount of heat is already released during the hydration process. On the contrary, the technologies limiting the temperature of concrete are used in massive structures.

Non-massive concrete structures are heated in low air temperature conditions or to accelerate hardening. When concrete is exposed to heat treatment, its volume constantly changes. Such deformations indicate a change in the density of the material, and, consequently, a degree of structural damage during its heat treatment [4]. Such structural damage negatively affect its physical and mechanical properties at the age of 28 days.

It is possible to create conditions to minimize grad*t* over the cross-section of concrete [5–7], but it is impossible to influence the continuity of the temperature change function when concrete is heated. With the largest construction size of 2 m and a permissible grad*t* of 0.1 °C/cm, there will be a temperature drop over the cross-section of concrete of up to 20 °C, while heating this structure from 10 to 50 °C will ultimately lead to a temperature difference at the same point already at 40 °C [8] show that the maximum increase in the deformations of concrete occurs when it is heated and directly depends on the temperature elevation rate. Taking into account that the structure of concrete is formed in its initial hardening period, the effect of such deformations on the properties of concrete at the design age is fundamental.

Most studies assess thermal stresses through Hooke's law, considering the deformation of concrete at the elastic stage, when it already has a certain value of the elastic modulus [9–11]. The minimum time before concrete can be considered as an elastic material is 6 hours [12]. Data on the formation of elastic properties in 12 hours [13], and some works mention not the holding time, but about the concrete strength of 22–30 % [4, 10, 14]. By this time, concrete is already able to take some stress values without changing its structure (volume). Even at early hardening stages, the physical and mechanical properties of steel-fiber reinforced concrete are higher than for standard concrete [15], therefore, it can take higher thermal stresses.

To get an idea of the order of magnitudes of the thermal stresses when standard concrete is heated at the elastic stage, [4] gives an example, which demonstrates stresses of about 2942 kPa. A similar value (3138 kPa) was obtained in [16].

The physical and mechanical properties of concrete directly depend on its density, which is formed during the compaction of concrete mixtures. Starting from the time when the concrete mixture was compacted and until the beginning of the elastic stage (as mentioned, at least 6 hours), temperature effects can lead to irreversible plastic deformations which reduce the density of the material and lead to a worsening of its design characteristics. However, in severe climatic conditions, it is impossible to keep concrete in the formwork for 6 hours without temperature variation and it may freeze over this time period with negative consequences [17].

During the heat treatment of concrete, thermal stresses may occur, however, they are almost unlikely [18]. This is primarily explained by the low structural strength of fresh concrete and the zero elasticity modulus. Nevertheless, according to such models as Kelvin-Voigt or Maxwell, stresses arise in elastic and viscoelastic materials. Steel-fiber concrete mixtures have a significantly higher structural strength than standard concretes due to the formation of a spatial frame using steel fiber [19]. When the geometric characteristics of the fiber change, such a frame can pass from a free-flowing to a bound state.

A fundamentally important task is to identify the possible participation of reinforcement in absorbing thermal stresses and ensuring crack resistance of structures [20]. The solution to this problem resulted in the amendment in 1987 of SNIP III-15-76 in terms of clarifying the maximum permissible temperature differences between the concrete surface and the environment during stripping. Notably, steel fiber fully or partially plays the role of reinforcement in steel-fiber concrete structures.

We consider below the distribution of thermal stresses over time in heated steel-fiber reinforced concrete at its early hardening stage. These studies are of important scientific interest since they cover the initial period of the formation of the steel fiber reinforced concrete structure.

The main purpose of the study is to determine the influence of steel fiber on the change in temperature stresses in concrete at its early hardening stage.

To achieve this purpose, the authors carried out several tests of concretes subjected to heating, as a result of which they recorded the development of temperature deformations and assessed their plastic viscosity. To determine the temperature stresses, they proposed a method based on the Kelvin-Voigt rheological model.

2. Methods

The experiments were carried out on concrete prisms of 300×100×100 mm. The concrete used in the experiments (per 1 m^3 of concrete) had the following composition: cement – 450 kg, sand – 890 kg, crushed stone – 800 kg, water-cement ratio – 0.4, superplasticizer – 0.25 % of the cement mass. We used fibers cut from a Fibrex steel sheet with a nominal diameter of 0.67 mm and a length of 40 mm.

We determined the rheological characteristics of the concrete mixtures using a technical viscometer [21] installed on a vibrating platform.

To assess temperature deformations, we used two ICh-0.01 dial gauges located at a distance of 75 mm from the ends of the prism (Fig. 1). Plastic washers with a diameter of 20 mm and a thickness of 2 mm were placed under the indicator feet. The averaged values of the readings of the two indicators were taken as the calculated temperature deformations.

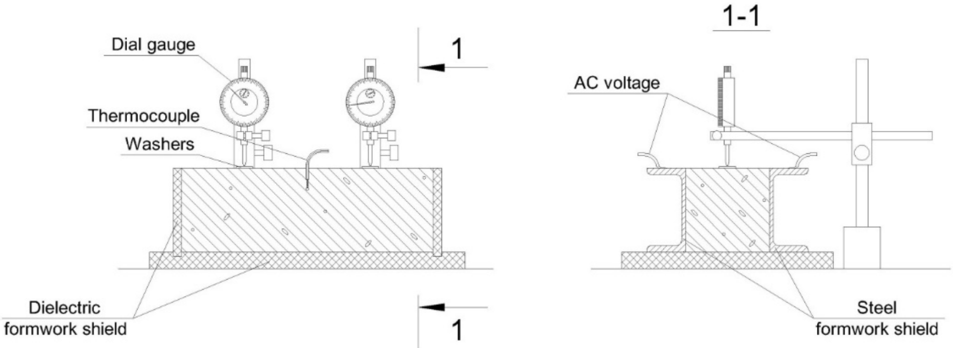

Figure 1. The experimental setup.

The concrete was heated by the AC passing through the concrete sample from two electrodes (from the channel steel), which are also the longitudinal elements of the formwork. The temperature was determined using a chromel-alumel thermocouple located at a depth of 25 mm from the surface of the prism in the middle of the indicators. All the formwork elements are rigid (with a thickness of at least 10 mm for the vertical elements and 20 mm for the horizontal base), so that their shape does not change during the temperature deformations of the concrete.

The initial concrete temperature was 18 °C. The heating rate was 5 °C/min and was regulated by a laboratory transformer by changing the voltage of the electric current. For convenience, the time when the concrete temperature was 20 °C was taken as the zero reading. Such a high heating rate forms the shock nature of the temperature influence on the hardening concrete and allows us to simulate the most negative consequences of its structural changes. Due to the small mass of the sample (the modulus of the sample surface is 47 m^{-1}) and the close arrangement of the electrodes (100 mm), there is almost no significant temperature gradient over the cross-section of concrete at such a heating rate. This allows us to assume that concrete deformations in the experiment are mainly caused by the temperature changes in time but not in space.

3. Results and Discussion

The results of the experiments for the assessment of temperature deformations are summarized in Table 1 and shown in Fig. 2.

Table 1. Values of sample deformations during heating

Heating time, min	Concrete temperature, °C	Relative concrete deformations ($*10^{-3}$) at the fiber content, %			
		0	0.5	1	1.5
0	20	0	0	0	0
1	25	0.2	0	0	0
2	30	1.4	0.6	0	0
3	35	3.4	2.4	0.8	0.2
4	40	5.9	4.5	2.4	1.2
5	45	8.9	7.3	4.4	2.2
6	50	12.8	11.0	7.4	3.7
7	55	17.4	15.1	11.1	5.2
8	60	23.4	20.2	16.6	7.2
9	65	32.1	28.0	22.6	9.9
10	70	44.1	37.9	31.1	12.7

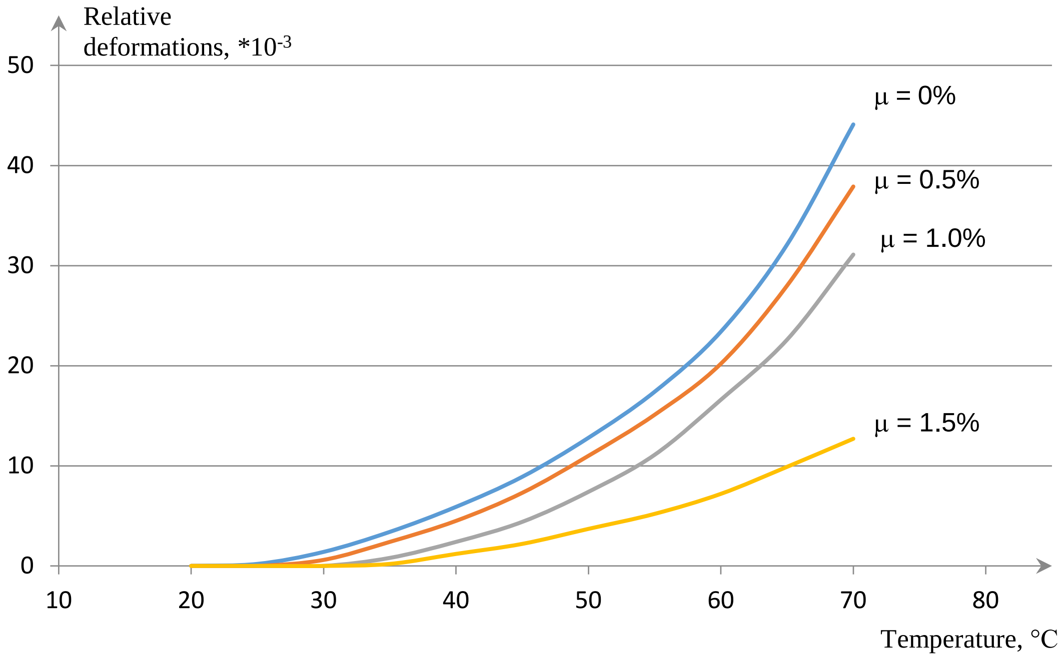

Figure 2. Growing deformations of the samples with a change in their temperature.

Table 1 and Fig. 2 show that the risk of developing unacceptable concrete deformations can be reduced by regulating the content of steel fiber, limiting the heating rate and the maximum concrete temperature.

To assess thermal stresses during heating, we consider fresh concrete according to the Kelvin-Voigt model, as a viscoelastic material. The stresses in such material are

$$\sigma = \sigma_{elas} + \sigma_{vis} = E\varepsilon + \eta\dot{\varepsilon}, \tag{1}$$

where η is plastic viscosity; E is concrete elasticity modulus; $\varepsilon, \dot{\varepsilon}$ are relative concrete deformations and rate of relative concrete deformations, respectively.

Taking into account that at the initial moment of concrete hardening its elasticity modulus is 0, we can write formula (1) in differential form:

$$\sigma = \eta\frac{d\varepsilon}{d\tau}. \tag{2}$$

By analogy with the known formula for calculating temperature deformations in an elastic body [4]:

$$\sigma_t = \frac{\alpha E \Delta t}{1-\nu},$$

where α is the coefficient of linear thermal expansion of concrete; ν is Poisson's ratio of concrete (at an early stage of curing it can be taken to be 0.15), formula (2) can be written as follows:

$$\sigma_t = \sum\frac{\alpha\frac{\eta}{\tau_i}\Delta t_i}{1-\nu}. \tag{3}$$

Here, Δt_i is the change in the concrete temperature (°C) over time τ_i (seconds).

The plastic viscosity for a technical viscometer can be determined by [22]:

$$\eta = 91.79k\tau_a = [\text{kPa}\cdot\text{sec}], \tag{4}$$

where k is the constant of the device (for the technical viscometer used in the research k = 0.45); τ_a is the time for leveling the concrete mixtures in the inner and outer cylinders of the technical viscometer, sec.

Taking into account formula (4) and considering that $\varepsilon = \alpha \Delta t,$ formula (3) can be written as follows

$$\sigma_t = \sum \Delta \varepsilon_i \frac{91.97 k \tau_a}{\Delta \tau_i (1 - \nu)}. \quad (5)$$

Formula (5) replaces the integration with the summation of the values of the deformation rates at separate time intervals.

The coefficient of the linear thermal expansion of concrete (α) changes depending on the percentage of steel-fiber reinforcement [23].

In formula (5), the plastic viscosity of concrete (the numerator) is assumed constant over time since the tests showed that it changes insignificantly during 10 minute heating, which is in line with [24]. The obtained values of time τ_a are:

- for the fiber-free concrete mixture = 2 seconds,
- for the concrete mixture with 0.5 % fiber = 7 seconds,
- for the concrete mixture with 1.0 % fiber = 18 seconds,
- for the concrete mixture with 1.5 % fiber = 32 seconds.

The results using formula (5) with the data from Table 1 are shown in Table 2.

Table 2. Changes of the thermal stresses in concrete during heating

Heating time, min	Thermal stresses (kPa) at the following percentage of fiber reinforcement			
	0	0.5	1.0	1.5
1	0.324	–	–	–
2	2.265	3.403	–	–
3	5.502	13.602	11.660	5.188
4	9.552	25.517	34.990	31.097
5	14.416	41.384	64.145	57.016
6	20.731	62.360	107.883	95.889
7	28.184	85.612	161.820	134.773
8	37.903	114.522	241.999	186.601
9	51.995	158.740	329.474	256.581
10	71.432	214.874	453.391	329.150

An increase in the mechanical stresses in structures is proportional to the increase in the rigidity of the material. This is attributable to the elasticity modulus in elastic structures, and plastic viscosity in viscous materials. That is, with an increase in viscosity (the content of fiber), the thermal stresses arising in concrete increase, which is confirmed by the data in Table 2. We can see that the stress values at the same temperature increase with an increase in the percentage of fiber reinforcement from 0 to 1 %.

This can be explained by the fact that the heating process is accompanied by the appearance of excess pressure in the vapor-air medium of concrete, which leads to the separation of solid concrete particles and a decrease in its density. During the heat and mass transfer process, moisture moves from more stressed capillaries to less stressed ones. That is, during such moisture migration, the latter acts as a damper, reducing and leveling the thermal stresses in concrete due to their redistribution. Due to friction and mechanical linkage, the fiber additionally restrains the separation of the concrete mixture components, thereby maintaining the density and strength of the material. This fiber behavior is observed in hardened and fresh concrete [25]. This contributes to an increase in the thermal stresses taken without significant deformations.

The reverse trend appears in concrete with a steel-fiber reinforcement of over 1 %: the thermal stresses begin to decrease. This can be explained by the fact that while the viscosity growth rate slows with an increase in the content of fiber [26], due to the larger number of fibers per unit volume, it better restrains concrete deformations. With an increase in the concrete temperature, the change in the thermal stresses depending on the fiber content begins to have a more pronounced nonlinear nature (Fig. 3). At a temperature of 40 °C, the changes in the thermal stresses with an increase in the fiber reinforcement percentage can be described with a second-degree polynomial, while at temperatures of 55 and 70 °C they are described by a third-degree polynomial. Such nonlinearity is caused by the low growth rate of the relative deformations in concrete with a 1.5 % fiber reinforcement compared to the consistently high growth rate of such deformations with fiber content of up to 1 %. This phenomenon is clearly observed in the temperature range from 40 to 70 °C.

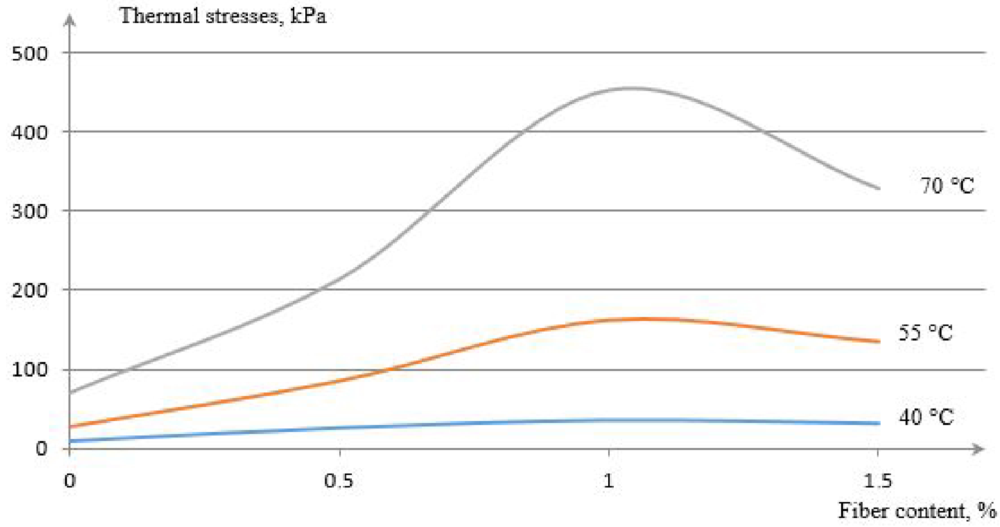

Figure 3. The change in the thermal stresses with an increase in the fiber reinforcement percentage.

This allows us to understand why zero deformations in standard concrete are retained only when it is heated from 18 to 20 °C, while in steel fiber reinforced concretes with a fiber content of 1–1.5 %, they are retained when it is heated to 30 °C. In fact, the temperature of 20 °C is the limit of the viscous capabilities of fresh concrete to move moisture from stressed capillaries to less stressed ones without the appearance of thermal stresses. 30 °C is the structural strength limit of viscoelastic concrete when thermal stresses do not arise due to the redistribution of temperature forces throughout the volume of concrete because of the use of steel fiber. Thus, at this heating rate, stresses will arise in steel fiber reinforced concrete with 1 % and 1.5 % reinforcement when it is heated by 12 °C, and in ordinary concrete by 2 °C.

4. Conclusion

1. In the viscous state of hardening concrete, thermal stresses are an order of magnitude less than in the elastic state. While at the elastic stage they can be about 2942 kPa, in the viscous state they are 71.4–453.4 kPa. Nevertheless, even such low stresses should not be ignored, since they arise during the most crucial period of the formation of a concrete structure.

2. Even during the early hardening stage, steel-fiber reinforced concrete can take 3–6 times higher thermal stresses than standard concrete of the same age. This is connected with the preservation of the concrete density during heating because the fiber restrains the separation of the components of concrete.

3. With an increase in the temperature of concrete, the change in the thermal stresses depending on the fiber content begins to have a more pronounced nonlinear nature which is preconditioned by the low growth rate of the relative deformations of steel-fiber reinforced concrete with a high reinforcement percentage at the concrete temperatures above 40 °C.

4. At the early hardening stage, thermal stresses in standard concrete arise when it is heated by 2 °C, and they arise in steel-fiber reinforced concrete with a reinforcement 1 % or more only when it is heated by 12 °C (from 18 to 30 °C), which is connected with the redistribution of temperature forces throughout the volume of concrete because of the use of fiber.

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