Structure formation of UHPC with metal fiber exposed to high temperature curing

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Abstract: the paper reveals the possibility of using the almost impermeable structure of ultra-high-performance concrete (UHPC) for heat treatment at temperatures above 100 °C as an alternative to autoclaving, while achieving similar physical and mechanical characteristics.

1. Introduction

Ultra-high performance concrete is a relatively new composite material containing steel fiber, the main features of which are high strength, durability, ability to withstand high bending and tearing loads. The main task in the design of the UHPC composition is the rational selection of micro-aggregates, taking into account the particle size distribution, which ensures a high density of the cement matrix [1, 2]. The introduction of various combinations of steel fiber allowed significantly increasing the impact resistance and wearing resistance of structures, which allowed to actively introducing the material into the field of infrastructure construction [3] Particular attention is paid to the heat treatment of finished products. Since its composition contains up to 25% (by weight) of amorphous silica fume [4], the maximum fineness of the fine aggregate usually does not exceed 600 μm, which indicates a high specific surface and a larger contact area between the aggregate and cement matrix. As a result of this, pozzolanic reactions increase the content of the C – S – H phase in the contact zone and improve it, have a significant effect on the compressive strength [5, 6]. Therefore, after the heat treatment, it is possible to stably observe the increase in strength, which is explained by the intensification of pozzolanic reactions [7, 8, and 9]. However, an increase in the temperature of heat treatment above 100 °C requires the use of an autoclave [10]. The hypothesis of this study is that it is possible to use the almost impermeable structure of ultra-high-performance concrete for heat treatment at temperatures above 100 °C as an alternative to autoclave curing, while achieving similar physical and mechanical characteristics.

2. Material and methods

2.1. Curing regimes

The following curing regimes were determined for the experiment:

- steam curing at 90 ± 2 °C for 24 hours (excluding heating / cooling time);
- oven curing at 150 °C ± 10 °C for 8 hours;
- oven curing at of 250 °C ± 10 °C for 8 hours;

Tests are conducted on samples with and without containing steel fiber at the age of 3, 7 and 28 days. Samples without steel fibers are used as controls to determine the quality of the cement matrix. The final compositions are shown in table 2.
2.2. Raw materials

In this study used commercially available materials: Portland cement CEM I 42.5 N, manufactured by Teploozerskcement JSC, MKU-85 silica fume, Silverbond EW 20 quartz powder. Fine silica sand with a bifurcation composition (60% - fraction of 350 μm - 630 μm / 40% - fraction of 150 μm - 350 μm) was chosen as a fine aggregate. Polycarboxylate-based superplasticizer additive - MasterPolyHeed 3043. Characteristics of the materials are given in table 1.

| Material      | Blaine fineness (g / cm³) | Density, (kg / m³) | Bulk density, (kg / m³) |
|---------------|---------------------------|--------------------|-------------------------|
| CEM I 42.5 N  | 2 800                     | 3 100              | 1 200                   |
| Quartz sand   | -                         | 2 630              | 1 540                   |
| Silica fume   | 22 350                    | 2 210              | 310                     |
| Silica flour  | 4,000                     | 2.650              | 850                     |
| Silver bond EW20                     |                      |                    |                         |

Table 2. Mix proportion of the UHPC (Mass).

| CEM I 42.5 N | Quartz sand | Quartz fume | Silica powder | W/C | SP (water solution) | SF * |
|--------------|-------------|-------------|---------------|-----|---------------------|------|
| 1            | 1.15        | 0.25        | 0.25          | 0.23| 0.03                | 0.2  |
| 1            | 1.15        | 0.25        | 0.25          | 0.23| 0.03                | -    |

* steel fiber, dosage by volume.

In this experiment we used brass steel fiber (HCSF LV) from high-carbon wire 15 mm long and 0.3 mm thick (l / b = 50), tensile strength not less than 2 900 MPa. The volumetric dosage of fiber as part of UHPC is 2%.

2.3. Specimens preparation

The starting components — silica sand, silica fume and quartz powder — are pre-mixed in a mixer until a homogeneous mixture is obtained for 3 minutes. In the resulting mixture gradually 70% of all mixing water with SP is added. At low speed (140 rpm) stirring is performed for 3 minutes. The prepared cement sample and the remaining 30% of mixing water are added to the resulting solution gradually, within 1 minute. The mixture is stirred for 3-5 minutes. In tests requiring the addition of fiber, its introduction is carried out gradually immediately after cement. The last 30-40 seconds of mixing are carried out at high speed.

2.4. Flexural strength and compressive strength

Testing of samples for physical and mechanical characteristics was carried out on beam samples with dimensions of 40 mm x 40 mm x 160 mm in accordance with GOST 30744-2001. “Cements. Test Methods Using Polyfractional Sand”.

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3. Results and interpretation

**Figure 1.** Effect of curing regime on the compressive strength (without SF).

**Figure 2.** Effect of curing regime on the compressive strength (with SF).

The highest compressive strengths of 149 and 229 MPa (Fig. 1 and 2) were obtain for samples held at a temperature of 250 °C ± 10 °C. Next are samples cured at a temperature of 150 °C ± 10 °C; their compressive strength was 137 and 184 MPa. The compressive strength of 170-176 MPa was shown by samples aged for 28 days under normal conditions. Strength close to normal hardening was shown by samples after steam curing, but in this series it turned out to be slightly lower and amounted to 167 MPa.

Samples that underwent intensive heat treatment at a temperature of 250 °C ± 10 °C on the 3rd day of hardening, could not withstand internal stresses, were either partially damaged or critically destroyed.
The presence of fiber did not significantly increase the resistance to tensile stress of the samples at this age. The average weight loss for samples for the third day during heat treatment of 150 °C - 250 °C is higher than for 7 d and 28 d. 3.4% versus 1.9% and 1.2%, respectively. Fig. 1 shows that on day 3, due to moisture loss, hydration stopped and the samples showed strength similar to the control samples at the same age. A visual comparison between the samples on day 3 and day 7 is shown in Figure 3. It can be seen that an impenetrable structure is not formed at an early age.

![Figure 3](image1.png)

**Figure 3.** Comparison between samples cured at temperature 150 °C ± 10 °C for 3 days (left) and 7 days (right).

On day 7, we see a significant increase in compressive strength for samples hardening at 150 °C and 250 °C with respect to 28 daily strengths: from 8% to 18% for samples without fiber, and up to 25% for samples with fiber.

![Figure 4](image2.png)

**Figure 4.** Effect of curing regime on the flexural strength (without SF).
Figure 5. Effect of curing regime on the flexural strength (without SF).

The flexural strength after heat treatment at 150-250 °C ranged from 35 MPa to 40 MPa for samples with steel fiber. Strength close to each other was shown by samples aged under normal conditions and steam curing - 25-30 MPa (Fig. 4 and 5). The best results for the flexural strength of the cement matrix can be observed in samples whose hardening occurred under normal conditions - 12.5 MPa - 13.5 MPa. Among the samples subjected to heat treatment, there is no significant difference in strength, and the result is in the range of 10.5 MPa - 11.5 MPa.

Samples obtained by steam curing were additionally subjected to heat treatment in an oven at a temperature of 250 °C, to compare the two methods. The experimental results are shown on fig. 6 and 7.

Figure 6. Comparison of compressive strength between steam curing and oven curing at 250 °C.
For samples containing steel fiber, one can observe an increase in the mechanical strength in relation to samples subjected to steam curing, which amounted to 36.5% and 35.4% under compression and flexural, respectively. The increase in strength without steel fiber is insignificant and amounts to 8.3% and 5.9%.

4. Conclusions

Based on this experimental investigation, the following conclusions can be drawn:

1. The high-density and practically impermeable structure of ultra-high performance concrete allows the use of non-steam conditions with temperatures above 100 °C, while obtaining a significant increase in strength.
2. The improving of the contact zone, due to the intensification of pozzolanic reactions and the formation of new hydration products, allows you to stably obtain strength indicators that are superior to those obtained with conventional heat treatment methods.
3. Heat treatment over 100 °C has a significant effect on the growth of strength in samples containing steel fiber, which can reach up to 25% with respect to normal hardening.

Further studies are planned of UHPC with intensive heat treatment in the following areas:

1) Optimization of the composition of ultra-high-performance concrete in order to increase its tensile strength to use higher heat treatment modes;
2) Investigation of the effect of significant hardening of the structural matrix from steel fiber after exposure to high temperatures.

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