Influence of curing temperature on the mechanical properties of high-performance concrete

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Abstract. As part of the research focused on high-performance concrete (HPC) at our workplace, the impact of temperature curing on compression strength of HPC has been investigated. Four sets of samples (100 x 100 x 100 mm cubes, 30 samples in each set) were produced with the same mix design. Each set was cured with a different temperature: 20°C (reference samples), 50°C and 80°C (high and very high temperature curing) and 10°C (simulation of concreting in winter conditions). The curing was always carried out in a water bath with a given temperature during the whole time of maturing of the samples. Samples were tested in 1, 3, 7, 14 and 28 days of age. In each time step, three cubes were tested for compression strength and three cubes for tensile splitting strength. The results of the primary research are the time records of the increase of both strengths.

1. Introduction

Cement hydration is a chemical reaction in which heat is released. The elevated temperature influences the hydration rate, the development of the hydration heat, and the C-S-H gel structure [1]. The elevated temperature is exhibited mostly in the initial stages of hydration, especially during the first three days [2]. According to the standards, the curing temperature is 20°C; at the temperature of 30°C, growth rate of compressive strength is accelerated during the first few days. On the other hand, reducing the curing temperature to 10°C leads to a significant deceleration of hydration, as well as to a slow increase of compressive strength during the first days.

At elevated temperature a large amount of hydrates has not enough time for ideal growth, what may cause loss of final strength (at age of 28 days). This phenomenon is known as the "crossover effect" [2, 3, 4].
Figure 1. Crossover effect for low curing temperature and high curing temperature of concrete [2].

To avoid this effect, temperature of 70°C is considered safe maximum limit in wet environment, and 85°C in dry environment [5]. High curing temperature favourably affects behaviour of pozzolanic active additives as fly-ash and microsilica. During heating, their hydrating effect grows, what increases density of cement paste and consequently strength of concrete [6, 7].

In the treatment with high temperature a delayed ettringite formation may occur. In fact, it is an internal sulphate attack, in which monosulfate reacts with gypsum and the reaction product is ettringite. Ettringite is characterised by high hydration rate, at which increases its volume by up to 270% [8].

The ettringite crystal sizes are also temperature-dependent; the conventional crystals formed at a temperature of 25°C are smaller than crystals created at crystallisation around 60°C [6]. The recrystallization of ettringite takes place several days after the heat treatment, when the cement paste has already hardened, and recrystallization disturbs its structure. This is a fundamental difference against the ettringite crystals, which are created several hours after beginning of hydration. At this moment, the cement paste is still soft and therefore creating of ettringite crystals does not cause mechanical disturbance of the structure. At this stage, ettringite is in the form of a stable monosulfate and contributes to the initial increase in strength.

Delayed ettringite formation can be reduced by addition of fine pozzolanic admixtures, which, practically, are in all HPC recipes. If pozzolanic admixtures are used, the temperature treatment may reach 80°C without delayed formation of ettringite [9].

2. Experimental methods
The investigation of HPC behaviour at temperature treatment was performed on cubes of size 100 x 100 x 100 mm. The recipe shown in a table 1 was used during the whole experiment. Four sets of specimens were elaborated with the recipe, each set with 30 specimens. Half of specimens was used for compressive strength testing, the other half for tensile tests. Testing was performed at 1, 3, 7, 14 and 28 days.

Curing of specimens was always performed in water environment with temperature 10°C, 20°C, 50°C and 80°C with this procedure: after placing of fresh concrete in moulds the specimens rested 2 hours, and then they were immersed in water bath including the steel mould. The water had already been preheated to required temperature. The water level did not overtop the top edge of the mould.
The specimens were cured for 24 hours. After this time the specimens were demoulded, and first specimens were tested in compression and tensile. The rest of specimens were again immersed in water basin and the water level was raised to sink the whole specimens including the upper surface.

The temperature of water treatment was not changed during maturing of specimens. The authors are aware of the low efficiency of temperature treatment after 3 days of specimen age [10], however the presented results represent the pilot investigations, and for simplification the temperature remained constant during the whole experiment.

No enhancement of mechanical properties was expected for specimens treated in water with 10°C compared to reference specimens treated in 20°C. Curing with this temperature should only serve for better understanding relation of temperature and mechanical properties.

### Table 1. Composition of the mixture.

| Compound         | Specification | Dosage [kg/m³] |
|------------------|---------------|----------------|
| Cement           | CEM I 42,5    | 650            |
| Water            |               | 175            |
| w/b              |               | 0.22           |
| Aggregate 0/4    | Basalt        | 780            |
| Aggregate 4/8    | Basalt        | 478            |
| Aggregate 8/16   | Basalt        | 360            |
| Microsilica      | Stachesil S   | 80             |
| Plasticizer      | Stachement    | 29             |

### 3. Results

#### 3.1. Compressive strength

The main reference parameter was compressive strength, which was measured always on three cubes with dimensions 100 x 100 x 100 mm. Presented result is an average value from three measurements. The specimens were strained by constantly increasing load of rate 8 kN/s [11]. Results are depicted in figure 2.
Set of specimens treated at 80°C had the highest compressive strength (86.3 MPa) at age one day, but at age of three days the compressive strength was only 94.0 MPa, what is lower than compressive strength of reference specimens. The increase of compressive strength stopped at age 7 days for the specimens treated by temperature 80°C and the final compressive strength was by 32% lower than reference specimens’ strength. The authors are aware that 80°C is quite high temperature, but they based their investigations on precedent research [9], which showed that in case of application of latent hydraulic admixtures this temperature is acceptable. Presented investigations do not prove this theory.

3.2. Tensile splitting strength
The other investigated parameter was tensile splitting strength, which was also measured on cubes with dimensions 100 x 100 x 100 mm. Results depicted in figure 3 are the arithmetic average of three measurements. The specimens were loaded with constantly increasing load with 0,96 kN/s [12].
The samples that have been subjected to thermal curing reached lower splitting tensile strength than the samples that have been cured at standard room temperature (20°C). This is in accordance with another results from literature. It has been observed that the ratio between compressive and tensile strength can be changed from 1:10 up to 1:20 by thermal curing. The increase of the ratio depends mainly on thermal gradient [13].

Results of studies confirm our observations of effect of elevated temperature on compressive strength. The paper [14] came to similar conclusions as our team regarding measurement of compressive strength of specimens treated in different temperatures: “Comparison of the results for the same mixture at different curing conditions shows that, although higher temperatures improve the initial strength development, the value at a later stage, 14 or 28 days, seems to be penalized.” Measuring of tensile strength of specimens cured at different temperatures is not in the focus of interest in the studies.

Several studies focused in investigation of autogenous shrinkage. The papers state that curing temperature affects autogenous shrinkage. Paper [15] concludes that the autogenous shrinkage of HPC increased with the increase of curing temperature. Since the decrease of tensile strength is directly linked to higher shrinkage, this may considered as a confirmation of our conclusions.

On the other hand, various other studies [16, 17, 18] show that undoubted conclusions on effect of temperature curing on autogenous shrinkage and consequently on tensile strength cannot be drawn.

4. Conclusions
The following conclusions can be drawn based on the obtained results:
- The positive effect of temperature treatment on the rate of compressive strength increase in the initial phase of concrete maturing has been demonstrated.
- Therewithal, an assumption was confirmed that temperature treatment may accelerate increase of compressive strength, not the final value of compressive strength. Compressive strength of reference specimens at age 28 days was 142.6 MPa and specimens cured in water of temperature 50°C had 28 days compressive strength 146.5 MPa.
The presented results show that ideal curing temperature to achieve high short-term compressive strengths is 50°C. At this temperature, the compressive strength increased by about 30% within first 7 days, then the differences in the compressive strength between the samples treated in 50°C water and the reference samples decreased, and at the age of 28 days, the strengths were practically identical.

Temperature treatment in 10°C was only a complement of the research. A slower increase of the compressive strength compared to the reference samples was expected. Likewise, the reference samples reached higher values of compressive strength at the age 28 days.

Tensile strengths testing of investigated type of high-performance concrete confirmed assumption that heat treatment results in decrease of tensile strength. Highest tensile strength was reached for reference specimens. It was by 15% higher compared to specimens cured in 50°C and 80°C. Clear general conclusion on influence of temperature treatment on tensile strength apparently cannot be made. This phenomenon is unsystematic and varies for different types of cement composites and their composition.

Tensile strength of specimens treated in 10°C reached half the value of reference specimens, what is also unpredicted result.

Based on the results of the research, the authors recommend to use thermal curing with maximum temperature of 70°C for the given mixture.

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