Rapid direct electric heating of fresh concrete

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Abstract. Direct electric curing as a volume-heating method can provide fairly uniform temperature field at high heating rates. However, most of the current research focuses on reproduction of general form of temperature curve used in conventional techniques, i.e. at low heating rates. This paper evaluates the effect of rapid direct electric heating of fresh concrete on temperature variation, compressive strength and energy consumption. Samples subjected to rapid electric heating to 50, 60 and 70⁰C in 10 minutes were insulated, kept for 13 hours, demolded and tested for compressive strength. According to measurements in three points saved every 30 seconds, the temperature field remains uniformly over the cycle. The ratio of energy consumption and the resulting strength allows to select the most optimal mode for a particular case. It has been determined that an increase in temperature of 10 ⁰C leads to an increase in strength by 4% (for the considered composition). Results derived from this study confirm the effectiveness of applying rapid electric heating of fresh concrete for precast concrete production.

1. Introduction
Thermal curing, applied for acceleration of concrete solidification is inalienable and crucial stage of precast concrete production, especially in time limit conditions. There are a number of methods of its implementation currently known.

Steam curing (SC) is one of its most widespread types used in precast plants to achieve high temperature cycles while ensuring abundant moisture supply [1-3]. Although reliable and relatively easy to control, SC has poor energy efficiency (700 MJ/m³). A more effective method, applied predominantly in Russia, is accelerated curing in gas combustion products. The average energy consumption of this method is much lower (400 MJ/m³), which makes the procedure cheaper. However, it cannot provide high humidity as with steam curing, which has a less favorable effect on the quality of the final product [4]. This way is more suitable for light-weight concrete.

Another alternative way to improve energy efficiency and provide favorable conditions for hardening is by using direct electric heating methods. Their effectiveness lies in the fact that first the concrete is heated, and then part of the heat is transferred to the equipment, the casing and the ambient. Direct electric curing (DEC) is the widespread approach in this field. There are many DEC studies to date, including steel fiber concrete, reinforced concrete, and ash-based concrete [1, 5, 6, 7]. This method has proved itself as one of the most energy efficient [8]. However, the potential for improving the energy efficiency of direct curing methods has not yet been fully realized. Achieving lower energy consumption is possible through the use of rapid direct electric heating of fresh concrete (RDEHFC). Despite the fact that this method was proposed in the 60s, it was not applied in precast concrete plants. DEHFC used
mainly on building sites for heating of in-situ structures, particularly in winter. Average specific energy consumption with the use of RDEHFC during accelerated curing of in-situ structures is 50 kWh (180 MJ). It also should be taken into account that this characteristic was obtained for building sites under unfavorable conditions of unstable ambient temperature and weather conditions, for structures of different types, and their imperfect heat insulation. Conditions and the strategy of manufacture of precast concrete are mostly free of the above-mentioned drawbacks, which is a prerequisite for the achievement of much smaller specific electric energy consumption in the case of implementation of the suggested method to precast plants procedures. The essence of the method lies in the rapid heating of fresh concrete (5-10 minutes) and its re-compaction. The product is then insulated and cooled slowly without additional heating.

The aim of this paper is to evaluate the effect of rapid direct electric heating on temperature variation, compressive strength, energy consumption and also to determine the most optimal heating mode for considered concrete composition.

2. Equipment and experimental plan
To fill the samples, a polyamide mold was used, containing three samples with dimensions of 100×100×100 mm. Electrodes on opposite sides of the mold and baffles between the samples are made of steel (Figure 1).

![Figure 1. Mold for casting the samples: scheme (a) and photo (b) - main text](image)

Figure 2 shows a simplified diagram of the applied system. Energy is supplied in pulses from isolating transformer by means of proportional–integral–derivative (PID) controller. The electricity meter is used to estimate the energy consumption per heating cycle. Amperemeter and voltmeter are used for electric resistance monitoring (An increase in electrical resistance indicates the beginning of concrete setting. In this case, re-compaction required by experimental conditions is impossible). Temperature sensors (resistance thermometers), a data acquisition system (DAQ) and a computer were used for the measuring and recording the temperature. Glass tubes were used to isolate the sensors from the electric field. The gap between the sensor and the tube was filled with a thermal-conductive liquid.

For the experiment, grade B25 concrete (according to Russian Standard) was used. More detailed information on the composition is presented in Table 1.

After pouring the mixture, it was compacted. Then the fresh concrete was heated to a predetermined temperature in 10 minutes and compacted again. After disconnecting from the energy source the mold was insulated with a film and covered with a heat-insulating casing. Over the next 13
hours the samples were kept without additional heat introduction, after which they were demolded and tested for compressive strength. Throughout all stages, the temperature of each sample was measured and recorded every 30 seconds. 27 samples were heated and examined. The experiments were carried out in a room with a temperature of 20 °C.

Table 1. Mixture composition.

| Component | Type               | Content, kg/m³ |
|-----------|--------------------|----------------|
| Cement    | CEMI 42.5 B        | 350            |
| Sand      | 2-2.5 mm           | 810            |
| Gravel    | 5-20 mm            | 1100           |
| Water     |                    | 158            |

3. Results and discussion

After pouring and compacting the mixture and insulating the product there is little cooling of concrete (as a result of heat transfer between liquid phase and less heated aggregates), then temperature rise again to maximal, then a very slow natural cooling of the structure occurs, which is comparable to isothermal phase with conventional methods. This dependence is observed at all values of the heating temperature (Figure 3). In general, the curing cycle is divided into three stages: \( \tau_1 \) – heating phase (10 min), \( \tau_2 \) – Isothermal phase without additional heat source (13 h), \( \tau_3 \) – natural cooling phase (3 h). The heat rapidly introduced in fresh concrete leads to intensification of cement exotherm and other physicochemical processes. Due to this phenomena, the high temperature of concrete preserves for a long time. Regarding temperature field, both during heating and during isothermal phase, the temperature distribution between the samples is almost uniform (Figure 4). In the considered range, with increasing temperature, a slight increase in strength is observed. Conversely, energy consumption increases significantly. Thus, an increase in temperature of 10 °C leads to an increase in strength by 4% and energy consumption by 42%.

Figure 2. System diagram.
Figure 3. Average temperature variation of specimens heated to 50, 60 and 70 °C.

Figure 4. Variation and distribution of temperature when concrete is heated to 50 °C.

By comparing energy consumption and the obtained compressive strength, the most optimal heating temperature for a particular composition can be selected (Table 2). It should be noted that even at the lowest heating temperature strength of 88 % was obtained. Typically, the handling strength is 70%. Thus, if the reusability of the mold is one per a day, then the most optimal temperature will be 50 °C.
Table 2. Data for experiment.

| Experiment maximum temperature, °C | Energy supplied, kWh | Average compressive strength, MPa | Percentage of expected strength, % |
|-----------------------------------|----------------------|-----------------------------------|----------------------------------|
| 50                                | 0.07                 | 28.83                             | 88                               |
| 60                                | 0.10                 | 30.06                             | 92                               |
| 70                                | 0.13                 | 31.97                             | 96                               |

4. Conclusion

Long-term temperature preserving effect inherent in this approach is main feature and the reason of its feasibility in factory conditions. In comparison with the conventional techniques, described in [1, 2], RDEHFC provides a more uniform temperature field in the bulk of the structure. It should also be noted that the implementation of the thermal curing process according to the approaches proposed in [5, 6] requires the operation of thermal and auxiliary equipment throughout the entire cycle. The use of RDEHFC implies the operation of the specified equipment only at the heating stage (for a 10-15 minutes), which leads to additional costs reduction. Since the experiments considered the composition used for the manufacture of precast concrete well rings, the results can be applied in practice.

References

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