Computer Simulation of Electric Curing of In-Situ Reinforced Concrete Structures

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Abstract. The paper presents the results of computer simulation of electric curing of in-situ reinforced concrete columns using the ELCUT Pro 6.3 software. The purpose of this work is to solve the thermodynamic problem of electric curing under freezing temperatures. A block of a monolithic residence building under construction (Tomsk, Russia) is assumed as a basis. The importance of this research arises from the need to provide the temperature conditions for concrete curing and strength gain in winter. The initial parameters are introduced in the ELCUT Pro with the WinConcret add-in for the built structures. As a result, the rod electrode spacing is determined to provide a uniform distribution of temperature fields over the structure cross-section. The time of isothermal concrete heating and the concrete strength are identified depending on the outside temperature. Rationale is prepared for the mold insulation for in-situ reinforced concrete columns, depending on the outside temperature. Based on the ELCUT Pro simulation, the electric curing technique is proposed for reinforced concrete columns at freezing temperatures. This technique is deployed in on-site conditions.

1. Introduction
In Russia, on-site concreting operations are performed both in summer and winter. The temperature conditions necessary for the concrete strength gain in winter represent a topical problem in the construction field. Under freezing temperatures, in-situ reinforced concrete structures undergo heating by using various methods. Electric curing leads among artificial heating methods used in winter concreting. Heating of concrete with an electric current utilizes the principle of converting electrical energy into heat energy [1–5]. The preliminary temperature calculation and its successive control are important for winter concreting, since the concrete heat treatment conditions significantly affect the strength of a structure [6, 7]. The preliminary calculation of curing temperature is therefore indispensable for a high-quality cast-in-situ structure. The use of an electric current for concrete heating is based on the Joule-Lenz law [1].

In order to analyze the electric curing conditions of concrete structures, a large amount of parameters must be set, such as the cement type and grade, its content in concrete, the modulus of concrete surface, the mold material and thickness, the initial concrete temperature, the concrete strength by the end of the heat treatment, outside temperature, wind speed and direction, curing conditions, the type of electrodes, etc.

Thus, in hand calculating the main parameters of electric curing, a mechanical engineer needs to consider many factors to make the right decisions. Moreover, different temperatures observed at the
edges of the structure are not taken into account. The temperature field nonuniformity over the cross-section of the structure also is not considered, especially during the first hours of electric curing [8]. All this can cause serious errors in the electric curing design.

As is already known, in manufacturing concrete structures, the temperature gradients have a significant effect on curing mechanisms [9–22]. The heat and mass transfer processes are the main factors that affect concrete curing [17, 23].

Many Russian researchers are currently involved in the implementation of computer simulation methods to identify the temperature and strength gain conditions for concrete, but their exploratory studies are not systematized [6, 8, 11, 24–27].

This problem can be solved by the finite element method (FEM) of simulating thermal fields using the ELCUT Pro 6.3 software (the license agreement of 26.06.2018 with the software company “Tor”, Saint-Petersburg, Russia). The ELCUT Pro is provided with modules for concrete curing calculations, namely: the alternating-current module, transient heat conduction module, and elastic stress and strain module. However, the ELCUT Pro lacks additional functions for calculating concrete heating and curing, so it comes with the WinConcret add-in [8].

This software is used to calculate the temperature fields in the plane section of the structures to be concreted, thereby solving a stationary problem for estimation of the initial conditions. Next, a number of non-stationary problems are solved at a given integration step and the temperature field calculations. The ELCUT Pro allows a user to select heating energy sources, materials and climatic conditions for winter concreting. The WinConcret add-in is used to measure the cement hydration heat. The latter is defined by the function of time and temperature. The problem solution is presented by the temperature field diagrams obtained at different stages of electric curing. The ELCUT Pro assists in constructing diagrams of the temperature conditions for concrete curing and strength gain [27, 28].

The purpose of this work is a computer simulation of the thermodynamic problem of electric curing of in-situ reinforced concrete column under freezing temperatures [27].

2. Materials and methods
A block of a monolithic residence building under construction (Tomsk, Russia) given in figure 1, was assumed as a basis for the proposed concreting technique of the load bearing structures.

Figure 1. Plan view of load bearing structures in a monolithic residence building block under construction in Tomsk.
In accordance with the design project, the load bearing structures in this block were made of heavy concrete B25. The thickness of the monolithic bearing walls was 200 and 250 mm. The in-situ reinforced concrete columns had 400×400, 250×800 and 250×1200 mm transverse profiles and the constant cross-section over the height.

The in-situ reinforced concrete column 3100 mm high with the transverse profile of 250×800 mm was investigated. Its modulus of the concrete surface was 10.82 m\(^{-1}\). This is schematically shown in figure 2.

![Figure 2. Transverse profile of the in-situ reinforced concrete column.](image)

The authors were challenged to identify the rod electrode spacing in the structure, the time of isothermal concrete heating at different outside temperatures and also made recommendations on how to provide the uniform temperature distribution in the structural section at low outside temperatures.

To achieve the objectives, the column design model was created using the ELCUT Pro 6.3 software with adherence to the geometry and physical properties of the materials. The finite element division of the column was achieved automatically with FE meshing, which is illustrated in figure 3.

![Figure 3. FEM of the in-situ reinforced concrete column.](image)

The proposed FEM employs thermodynamic properties of the materials and their physical parameters. The initial parameters include heavy concrete B25; a laminboard mold 18 mm thick; the thermal source, which is the electrode rod with a diameter of 6 mm; slag wool insulation 50 mm thick.

The initial conditions include 5 and 10 °C temperature of the concrete mix, the outside temperature range from −5 to −25 °C with a 5 °C interval, a 15 m/s wind velocity (convection coefficient is 48 W/(m\(^2\)°C)), and 65 V operating voltage.

The parameters of the materials are as follows. Reinforcement: 58 W/(m\(^2\)°C) thermal conductivity, 0.48 kJ/kg·°C specific heat capacity, 7850 kg/m\(^3\) density. Concrete: 1.86 W/m·°C thermal conductivity, 0.84 kJ/kg·°C specific heat capacity, 2400 kg/m\(^3\) density. Mold: 0.17 W/(m\(^2\)°C) thermal conductivity,
2.52 kJ/kg·°C specific heat capacity, 600 kg/m³ density. Slag wool: 0.049 W/(m·°C) thermal conductivity, 0.76 kJ/kg·°C specific heat capacity, 50 kg/m³ density.

Using the WinConcret add-in, the FE model of the concrete column is divided into blocks as presented in figure 4. Each block is numbered and has the temperature and strength of its own.

![Figure 4. FEM of the in-situ reinforced concrete column divided into blocks with the WinConcret.](image)

Blocks 3, 4, 5 and 6 are not shown in this figure because they locate near the joint between the reinforcement and the mold and have a small size.

In order to simulate the electric curing of concrete, it is first of all necessary to determine the electrode spacing. We suggest two variants depicted in figure 5.

![Figure 5. Schematic of rod electrode arrangement: a – variant 1, b – variant 2.](image)

3. Results

As a result of the ELCUT Pro simulation of electric curing at different electrode spacing, the temperature fields obtained are presented in figures 6 and 7. One can see that the electrode arrangement by variant 2 provides more uniform distribution of the temperature fields over the column section. The time of isothermal heating is 18 hours at −10 °C outside temperature.

The main results for the analysis and selection of the best arrangement of the rod electrodes are summarized in table 1.
Figure 6. Temperature field in reinforced concrete column after 18 h isothermal heating (variant 1).

Figure 7. Temperature field in reinforced concrete column after 18 h isothermal heating (variant 2).

Table 1. Data on the arrangement variants for rod electrodes.

| Arrangements | Concrete temperature after 18-h isothermal heating (°C) | Concrete strength after electric curing (%) |
|---------------|--------------------------------------------------------|---------------------------------------------|
|               | Block 1 | Block 11 | Block 19 | Block 28 | Block 1 | Block 11 | Block 19 | Block 28 |
| Variant 1     | 42.4    | 51.8     | 48.1     | 51.1     | 37.6    | 46.2     | 41.0     | 44.2     |
| Variant 2     | 52.2    | 64.9     | 81.3     | 71.0     | 44.4    | 54.9     | 65.9     | 58.5     |

*Per cent of design strength.

4. Discussion

According to table 1, variant 2 is more preferable for electric curing of the concrete column, because the temperature distribution inside the column is more uniform than at the arrangement by variant 1. Also, during the same time of isothermal heating, the concrete strength gain at the electrode arrangement by variant 2 is higher than by variant 1. Further ELCUT Pro simulation of electric curing utilizes variant 2.

The time of concrete isothermal heating and the outside temperature should be considered during electric curing. In the case of the incorrectly set heating time, the concrete column may freeze or overheat, which will negatively affect its ultimate strength. The ELCUT Pro simulation of the concrete heat treatment allows these parameters to be taken into consideration.

The time of isothermal heating was obtained at different outside temperatures, namely −5, −10, −15, −20 and −25 °C. It was found that at −5 °C, the time of isothermal heating was 16 hours, while at −10,
–15 and –20 °C, it was 18 hours. In this case, at –5, –10 and –15 °C, the initial concrete temperature must be not lower 5 °C, while at –20 °C, it must be not below 10 °C.

The temperature field distribution over the column cross-section is presented in figures 8–11 for the outside temperature of –5, –10, –15 and –20 °C.

Figure 8. Temperature field in reinforced concrete column after 16 h isothermal heating at –5 °C outside temperature.

Figure 9. Temperature field in reinforced concrete column after 18 h isothermal heating at –10 °C outside temperature.

Figure 10. Temperature field in reinforced concrete column after 18 h isothermal heating at –15 °C outside temperature.
Figure 11. Temperature field in reinforced concrete column after 18 h isothermal heating at −20 °C outside temperature.

The strength gain values are given in table 2 for the respective blocks of the in-situ reinforced concrete column.

**Table 2. Strength gain values obtained at different outside temperatures.**

| Outside temperature (°C) | Concrete strength after electric curing (%)<sup>a</sup> |
|--------------------------|------------------------------------------------------|
|                          | Block 1  | Block 11 | Block 19 | Block 28 |
| −5                       | 45.0     | 54.9     | 65.2     | 58.2     |
| −10                      | 45.1     | 55.5     | 66.3     | 59.2     |
| −15                      | 41.1     | 52.1     | 63.8     | 56.2     |
| −20                      | 38.9     | 50.6     | 63.1     | 55.0     |

<sup>a</sup> Per cent of design strength.

According to table 2, during a certain time of isothermal heating at different outside temperatures, the concrete gains the critical strength in all the blocks, at which neither its strength nor other parameters reduce during subsequent curing after defrosting.

Table 3 shows that at the outside temperature of −25 °C and after 18-hour isothermal heating, the concrete gains the critical strength. The time increase of isothermal heating is not appropriate, since it is not economically viable. Therefore, we introduce the parameter of the perimetric insulation of the structure using a slag wool roll 500 mm thick.

**Table 3. Strength gain values at −25 °C outside temperature.**

| Insulation   | Heating time (h) | Concrete strength after electric curing (%)<sup>a</sup> |
|--------------|------------------|------------------------------------------------------|
|              |                  | Block 1  | Block 11 | Block 19 | Block 28 |
| No slag wool | 18               | 34.7     | 47.0     | 60.3     | 51.8     |
| Slag wool    | 11               | 55.3     | 59.9     | 64.7     | 60.5     |

<sup>a</sup> Per cent of design strength.

The temperature field distribution presented in figures 12 and 13 is simulated for the concrete columns with and without the slag wool insulation. As a result, the insulation provides more uniform temperature and strength distribution over the column section and reduces the time of electric curing by ~1.5 times.
Based on the results of the ELCUT Pro simulation, we accepted the rod electrode spacing and the time of isothermal heating as shown in tables 4 and 5. In accordance with the Construction Rule 70.13330.2012, the stripping strength of concrete was assumed to be not less than 70% of its design strength.

**Table 4.** Arrangement of rod electrodes in in-situ reinforced concrete columns.

| Column cross-section (mm) | Arrangement of rod electrodes | Electrode parameters | Number of electrodes |
|---------------------------|-------------------------------|----------------------|----------------------|
| 400×400                   | ![Diagram](image1.png)       | $d=6\text{ mm}$, $l=3000\text{ mm}$ | 2                    |

**Figure 12.** Temperature field in reinforced concrete column without insulation after 18 h electric curing at $–25^\circ\text{C}$ outside temperature.

**Figure 13.** Temperature field in insulated reinforced concrete column after 11 h electric curing at $–25^\circ\text{C}$ outside temperature.
Table 5. Isothermal heating time of in-situ reinforced concrete columns.

| Column sizes (mm) | Isothermal heating time (h) |
|-------------------|----------------------------|
|                   | Outside temperature (°C)   |
|                   | -5 | -10 | -15 | -20 | -25 |
| 400×400           | 16.0 | 16.0 | 16.0 | 16.0 | 18.0 |
| 250×800           | 16.0 | 18.0 | 18.0 | 18.0 | 11.0 |
| 250×1200          | 20.0 | 22.0 | 24.0 | 12.0 | 12.0 |

The perimetric heat insulation of the mold should be provided for the concrete columns at the following outside temperatures. In the temperature range from −5 to −25 °C for a 400×400 mm column; at −25 °C for a 250×800 mm column and in the range from −20 to −25 °C for a 250×1200 mm column.

The temperature of the concrete mix by the beginning of heating should be as follows. For a 400×400 mm column: 5 °C (in the range from 0 to −25 °C of outside temperature); for a 250×800 mm column: 5 °C and 10 °C (in the range from 0 to −20 °C and at −25 °C outside temperature, respectively); and for a 250×1200 mm column: 5 °C and 10 °C (in the range from 0 to −10 °C and from −15 to −25 °C of outside temperature, respectively).

5. Conclusions

Based on the results, it can be concluded that the hand calculation of the main parameters of the concrete electric curing did not allow considering the temperature difference at the column sides and the nonuniformity of the temperature field over the structure cross-section, especially during the first hours of the heating process.

This paper has clearly shown that the ELCUT Pro with the WinConcret add-in provided more precise calculation of the electric curing parameters. The ELCUT Pro allowed estimating the temperature fields and the strength gain in different column blocks.

The obtained parameters included the electrode spacing, the time of electric curing depending on the outside temperature, and the concrete strength after electric curing. Recommendations were given on electric curing of the concrete columns at low outside temperatures.

Using the computer simulation, the electric curing technique was proposed for the load bearing vertical structures in a monolithic residence building under construction in Tomsk. This technique was developed with regard to engineering and technological solutions oriented towards the improvement and optimization of electric curing with the use of rod electrodes, increase in the production rates and minimization of labor costs.
6. References

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