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CONTROL SYSTEM OF PARAMETERS OF ELECTRICAL CURING OF CAST-IN-SITU REINFORCED CONCRETE STRUCTURES

Stepan V.Leontev, Andrey A. Taleyko

Perm National Research Polytechnic University, Perm, RUSSIA

Abstract: At the moment in house-building industry cases of increase of efficiency of cast-in-situ concrete structures electrical curing are insufficiently studied. Development and implementation of control systems of parameters of electrical curing can be solve of current concerns. Development sequence of this control system included: collection of initial data; development of virtual model of considered structures, using ELCUT; analysis of rate of simulation parameters, depend on ambient conditions; fixation of values of simulation parameters; development of mathematical model of correlation between transformer voltage and temperatures of concrete, ambient air and time of electrical curing; development and description of circuit diagram of proposed control system.

The control system, developed by the authors, can be the basis for creation of automated complex of electrical curing of cast-in-situ reinforced concrete structures. Application of this system will significantly allow to decrease electricity consumption and labor costs, connected with electrical curing of structures

Keywords: parameters of electrical curing, control of parameters of curing, winter concreting, cast-in-situ reinforced concrete structures, simulation of curing conditions

СИСТЕМА УПРАВЛЕНИЯ ПАРАМЕТРАМИ ЭЛЕКТРОПРОГРЕВА ЖЕЛЕЗОБЕТОННЫХ МОНОЛИТНЫХ КОНСТРУКЦИЙ

С.В. Леонтьев, А.А. Талейко

Пермский национальный исследовательский политехнический университет, г. Пермь, РОССИЯ

Аннотация: В статье представлены результаты разработки системы управления параметрами электропрогрева монолитных железобетонных конструкций. Последовательность разработки включала в себя следующие этапы: сбор исходных данных; построение виртуальной модели конструкций в программе Elcut; анализ динамики изменения параметров модели в зависимости от внешних факторов; фиксация числовых значений параметров модели; построение математической модели зависимости выходного напряжения трансформатора от температур бетона, окружающей среды и времени электропрогрева; разработка и описание принципиальной схемы функционирования предложенной системы управления.

Разработанная авторами система управления может послужить основой при создании автоматизированного комплекса электропрогрева монолитных железобетонных конструкций, применение которого позволит значительно снизить энергопотребление и трудозатраты связанные с их электропрогревом.

Ключевые слова: электропрогрев бетона, управление параметрами тепловой обработки, зимнее бетонирование, монолитные железобетонные конструкции, моделирование условий прогрева

INTRODUCTION

At present the main technology, used in the construction of buildings and structures, is cast-in-situ construction technology. One of the undeniable advantages of this technology is the high pace of construction-and-assembling operations [1-3].
But, also the rate of concrete strength gain is the main constraint for construction activities rate, that's why it is impossible to do without the intensification of this process at the construction site, especially in conditions of cold weather. This concern is too relevant for Russia, so cold weather conditions are in the most area of country from 3 to 10 month. It is established by normative documents, that cold weather concreting can be applied at temperature up to -40 °C. However, in practice the rational field of application of cold weather concreting is not lower temperature than (-15) – (-20) °C [4-7].
In case of erection of cast-in-situ structures of residential and public buildings (slabs, walls, column etc., which have module of cooling surface about 4-10) electrical curing with heating wires is one of the most widespread methods of temperature and humidity intensification of concrete strength gain. Insulated heating wires with constant step are installed to mesh reinforcement, and stay subsequently inside the structure body [8, 9].
However, advantages of this method of electrical curing have some concerns, solve of which is so important for striving for quality improvement and increase of rate of construction [10, 11]. One of these is problem of concrete strength gain in conditions of cold weather and also rational use of energy consumed [12-15].
Regardless of apparent simplicity and efficiency of concrete electrical curing, there are concerns in practice such as: significant unjustified overspending of electricity consumed for heating of reinforce concrete structures in winter, associated with constant parameters of electrical curing, that is independent of ambient conditions; lack of a unified methodology of calculation of transformer voltage according to variable curing factors. Existing solutions of electrical heating are standard and do not take into account a lot of factors such as: structure type, temperature of ambient air, curing time [16, 17].
The solve of this concern is development of efficient control system of parameters of electrical curing of reinforce cast-in-situ structure, which would consider the factors mentioned above. Control system were developed by the example of standard elements of cast-in-situ framework such as walls, columns and slabs. These structures are thin-walled, therefore, special attention is required for thermal regime in the cold weather condition [18-20].

MATERIALS AND METHODS

Mathematical model of correlation of transformer voltage on concrete temperature, ambient air temperature and curing time were based on considered control system. Sequence of development of control system of electrical curing parameters for thin-walled reinforced concrete structures can be presented as follows:
1. Collection of initial data for developing of model (geometric size of structure and formwork, thermal parameters of materials, parameters of ambient conditions, parameters of concrete curing);
2. Development of virtual model of considered structures with variable parameters of ambient conditions and concrete electrical curing, using ELCUT software package, which is used for temperature field creating for different physical processes. ELCUT is universal domestic software product of two-dimensional simulation. The field development is realized with finite element method [21, 22];
A lot of studies of Russian researchers [21-23] were devoted to the use of ELCUT software package for simulation of concrete curing. Tuo Shi et al. [11-14] investigated the correlation of computer model of concrete curing, created with ANSYS software package, and experimental data of temperature distribution. The authors found that simulation data was in good agreement with the measured results;

3. Analysis of concrete rate of temperature across cross-section of explored cast-in-situ structures (temperature of ambient conditions, parameters of transformer work, scheme of heating wires layout, time). Determination of structures temperature at the different periods of time. Collecting temperature data for developing of mathematical model;
4. The mathematical model development of considered process for each type of structures, using temperature data of computer simulation. Mathematical model was created with use of mathematical methods of complex experiment planning and statistical data manipulation, using STATISTICA software package.
5. Transition from temperature of reinforced concrete structure in current time to transformer voltage. Development and description of control system of reinforced concrete structure curing parameters.
6. Development and description of principal scheme of the proposed control system.
In the first phase data was collected for each type of structures, used during development of virtual model of concrete curing. Initial data for considered structures are presented in table 1.
"ПНСВ" wires with diameter of current carrying 1,2 mm were chosen as the heat source.
In the second phase virtual models of heating of structures of wall, column and slab were created with ELCUT, based on initial data.
ELCUT is an integrated interactive system of programs, which allows to solve different field problems, including temperature fields

Table 1. Initial data

No.	Parameter	Unit	Value
1	Size of concrete structures	mm	
1.1	Column section		600x300
1.2	Wall thickness		200
1.3	Slab thickness		200
2	Concrete grade	-	B25
3	Cement content (use for evaluation of concrete liberation of heat during hydration)	kg/m^3	350
4	Range of ambient temperature	˚C	-30…-10
5	Wind speed	m/s	5
6	Temperature of as-placed concrete	˚C	10
7	Temperature of isothermal concrete curing	˚C	50
8	Curing period	days	3
9	Thermal conductivity of materials	W/(m·°C)	
9.1	Concrete		1.51
9.2	"Dornit" (insulating cover)		0.029
9.3	Form plywood		0.12
9.4	Steel reinforcement		58
10	Specific heat capacity of materials	J/(kg·K)	
10.1	Concrete		840
10.2	"Dornit" (insulating cover)		1340
10.3	Form plywood		2300
10.4	Steel reinforcement		482
11	Density of materials	kg/m^3	
11.1	Concrete		2400
11.2	"Dornit" (insulating cover)		29
11.3	Form plywood		600
11.4	Steel reinforcement		7850

(stationary and nonstationary heat transfer problem).

ELCUT allows to solve two-dimensional boundary-value problem of mathematical physics, which described by partial differential equation of elliptic type regarding the scalar or single-component vector function (potential), and also analysis problem of strain-stress state of solid (plane-stresses, plane-deformations, axially symmetric loads), including problems of building of temperature fields. [22].

At this study stationary and nonstationary heat transfer problems in linear statement have been solved. Following heat conduction equation is used during solving of heat transfer problem in described statement (1):

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) = -q - c\rho \frac{\partial T}{\partial t} \qquad (1)$$

where, T – temperature; t – time; λ_{xy} – components of the thermal conductivity tensor; q – specific power of heat liberation, in the linear formulation of problem - constant; c – specific heat capacity, in the linear formulation of problem – constant; ρ – density.

In stationary problem the last addend at the right is zero. All parameters of equation in the linear statement are constant within each of blocks of model.

The solution of problem can be divided into following phases.

- Building of geometrical models of structures (Fig. 1), using CAD program, uploading to DXF and import to ELCUT.

Assigning of materials blocks markers and setting of their properties according to initial data.

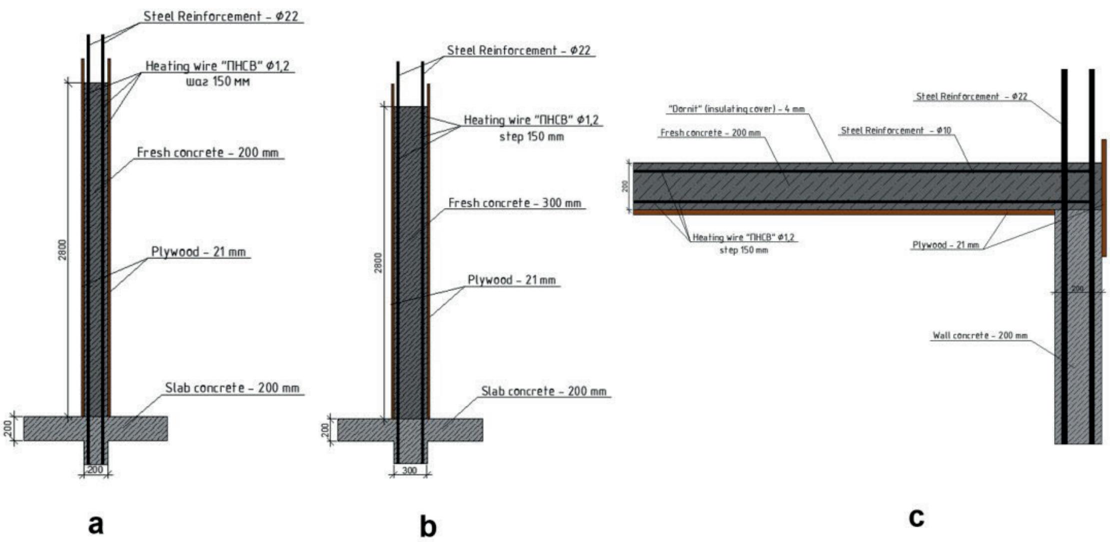
- Assigning of edges markers to set boundary conditions of convections (in the interface of structure and ambient air) and to set initial temperature of concrete, surface of reinforcement and hard concrete of existed structures (only for stationary problem).
- Assigning of apexes markers to set specific electrical loading on the wire.

During development of model liberation of heat of concrete was considered with setting of bulk thermal-power density as follows (2) [8]:

$$Q = Z \cdot qmax \cdot (1 - (0.04 * (t/3600) + 1) * \exp(-0.04 * (t/3600)))/((t + 1)/3600)/36 \qquad (2)$$

where, Z – cement content, kg/m^3; q_{max} – maximal heat liberation of cement, kJ/kg (for PC400 the value is 335 kJ/kg); t – ELCUT variable of time.

After setting of all markers and their properties stationary heat transfer problem was solved to set initial conditions of heating. Next, on the base of previous result the main nonstationary



<u>Figure 1.</u> Geometric models of explored structures: a) wall; b) column; c) slab

heat transfer problem was solved for the 48th hours period of time with integration step of 2 hours.

Described problems were solved for different temperatures of ambient air (-10, -20, -30 °C) and different specific electrical loadings on the wire (30, 40, 50 W/m) [23].

Additionally, nonstationary heat transfer problem was solved, which simulate structure cooling under the condition, that supply voltage was stopped after 48 hours of heating. Initial conditions for this problem were result of previous nonstationary problem at the time of 48 hours.

RESULTS AND DISCUSSIONS

Based on obtained solution the rate of change of average temperature of concrete was analyzed, and also temperature values were determined in different times. The results for wall are presented in tables 2.

Then, based on the temperature data mathematical model of concrete heating was built, using STATISTICA. In result, following equations were found, relating temperature of structure with specific electrical loading on the wire and temperature of ambient air, of form (3):

Table 2. Average temperature of wall

No.	Specific electrical loading, W/m	Temperature of ambient air, °C	Temperature of concrete structure, °C												
			Heating, h									Cooling, h			
			0	6	12	18	24	30	36	42	48	54	60	66	72
1	30	-10	10.0	14.9	18.8	21.9	24.4	26.3	27.9	29.0	29.9	16.5	7.6	2.4	-0.6
2	40	-10	10.0	19.1	25.8	30.7	34.4	37.0	39.0	40.6	41.6	24.0	12.5	5.6	1.5
3	50	-10	10.0	23.1	32.6	39.2	44.0	47.4	49.9	51.8	53.0	31.4	17.3	8.7	3.5
4	30	-20	10.0	11.8	13.5	15.0	16.5	17.8	18.9	19.9	20.5	6.6	-2.3	-7.5	-10.5
5	40	-20	10.0	15.9	20.2	23.6	26.2	28.3	29.9	31.1	31.9	14.2	2.7	-4.3	-8.4
6	50	-20	10.0	19.9	27.0	32.1	35.9	38.7	40.7	42.3	43.3	21.6	7.4	-1.2	-6.4
7	30	-30	10.0	8.6	7.9	7.9	8.4	9.0	9.8	10.4	10.9	-3.1	-12.1	-17.4	-20.5
8	40	-30	10.0	12.7	14.6	16.4	18.0	19.5	20.6	21.6	22.3	4.5	-7.2	-14.2	-18.3
9	50	-30	10.0	16.7	21.4	24.9	27.7	29.9	31.5	32.8	33.7	11.9	-2.3	-11.1	-16.3

Table 3. Coefficients of the equations for model of wall heating

t, час	a_0	a_1	a_{11}	a_2	a_{22}	a_{12}	a_{122}	a_{112}	a_{1122}
0-6	4.68	0.46	-0.007	0.3	-0.0002	0.0002	0	0	0
6-12	-3.8	1.04	-0.004	0	0	0	0.0007	-0.0004	-0.000008
12-18	-2.3	1.12	-0.003	0.34	-0.006	0.016	0	0	-0.000003
18-24	-6	1.435	-0.006	0.007	-0.013	0.04	0.0006	-0.004	-0.000008
24-30	-3	1.36	-0.04	0.0355	-0.01	0.02	0.0005	-0.003	-0.000005
30-36	4.1	1.07	0.0005	1.17	0.01	-0.016	-0.0006	0.0002	0.000008
36-42	-6.7	1.7	-0.06	-0.05	-0.02	0.05	0.0009	-0.005	-0.00001
42-48	-3.2	1.54	-0.004	0.24	-0.01	0.03	0.0007	-0.0004	-0.000007
48-54	5.3	0.7	0.0005	1.24	0.005	-0.01	-0.0002	0.0001	0.000002
54-60	7.4	0.25	0.03	1.7	0.02	-0.04	-0.001	0.0005	0.00001
60-66	2.1	0.35	-0.0005	0.99	0	0	0	0	0
66-72	1.4	0.29	-0.001	0.84	-0.005	0.007	0.0002	-0.00007	-0.000002

$$T_{str} = a_0 + a_1 p + a_{11} p^2 + a_2 T_{ext} + a_{22} T_{ext}^2 + a_{12} p T_{ext} + a_{122} p T_{ext}^2 + a_{112} p^2 T_{ext} + a_{1122} p^2 \mathrm{T}_{ext}^2 \quad (3)$$

where, Tstr – temperature of structure, °C; p – specific electrical loading, W/m; Text – temperature of ambient air, °C.

Coefficients of these equations for structure of wall are presented in table 3.

To use obtained equations for determination of necessary electrical loading, it is needed to find temperature of ambient air and specified temperature of structure at a given time. For this purpose, determination of thermal regime for each type of structure is further found.

Based on data from МДС 12-48.2009 rates of heating and cooling of cast-in-situ reinforced concrete structures depend on module of surface (Ms). For columns and walls with module of surface 4-6 m^{-1} the rate of heating must not exceed 6 °C per hour and rate of cooling – 3 °C per hour. But for slabs with module of surface 7-10 m-1 the rate of heating must not exceed 10 °C per hour and rate of cooling – 5 °C per hour.

According to МДС 12-48.2009 temperature of isothermal concrete curing was 50 °C. Thermal regime was chosen based on data of rate of heating and cooling and also that concrete would gain 70% of project strength at the end of isothermal curing [24, 25]. According to this, thermal regime can be presented as follows (Fig. 2).

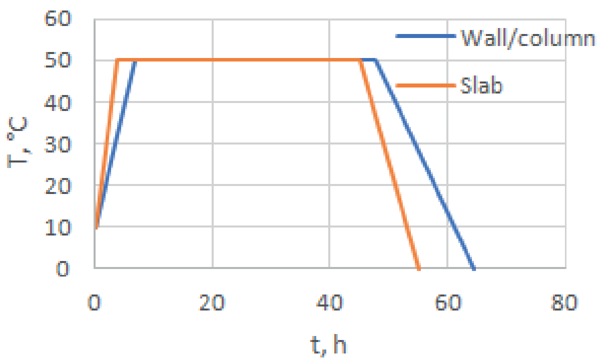


Figure 2. Operation of structure heating

According to the above, to find specified electrical loading on the wire, it needs to solve the equation with specified temperature of structure (according to the graph) and with current temperature of ambient air. Herewith, it is necessary to select equation, which meet the current period of time.

For example, it needs to find electrical loading on the wire at the time of 10 h with temperature of ambient air -15 °C for heating of wall. Specified temperature of structure at this time will be 50 °C. Then, solving the equation (4):

$$T_{str} = -3.8 + 1.04p - 0.004p^2 + 0.0007pT_{ext}^2 - 0.0004p^2 T_{ext} - 0.000008p^2 T_{ext}^2 \quad (4)$$

for p, we find p=45 W/m.

In the Fig. 3 the data of specified electrical loading on the wire are shown for temperature of ambient air -15 °C for heating of wall.

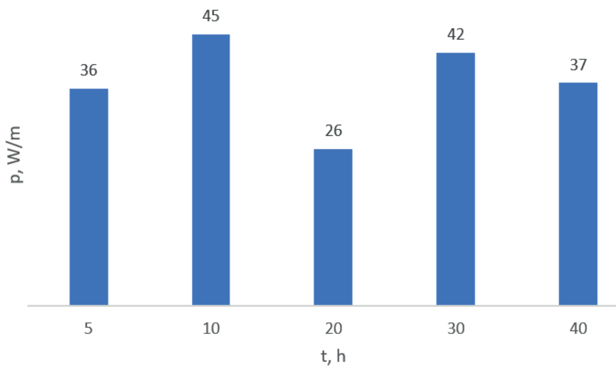


Figure 3. Specific electrical loading during heating of wall

Mathematical model of described control system of electrical heating of reinforced concrete structures based on algorithm noted above. Control of thermal regime of structure is realized with voltage variation on the wire, that’s why it needs to transit from electrical loading on the wire to transformer voltage.

In the Fig. 4 the circuit diagram of control system of electrical curing of cast-in-situ reinforced concrete structures is shown.

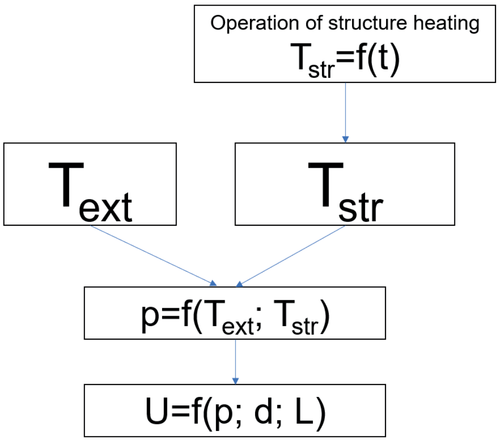


Figure 4. Circuit diagram of governing system of voltage on the wire (T_{ext} – temperature of ambient air, °C; T_{str} – permissible temperature of structure, °C; t - time, h; p – specific electrical loading, W/m; U – voltage on the wire, V; d – diameter of current carrying wire, mm; L – length of wire, m)

Transition from calculated specific electrical loading on the wire to voltage is realized with well-known equation [10] (5):

$$P = \frac{U^2 S}{L \rho_t} \tag{5}$$

from which it follows (6):

$$U = \frac{2L}{d}\sqrt{\frac{p\rho_t}{\pi}} \tag{6}$$

where P – effective power, realized by the wire, W; U – voltage, V; S – cross sectional area of current carrying wire, m^2; L – length of wire, m; ρ_t – electrical resistivity of the current carrying wire at a given temperature, Ω·м; d – diameter of current carrying wire, mm; p – specific electrical loading, W/m.

For calculations it was accepted: L= 30 m, ρ_t = $10 \cdot 10^{-8}$ Ω·m (for steel), d = 1.2 mm

Thus, the transformer voltage at the different time for heating of wall is presented in Fig. 5.

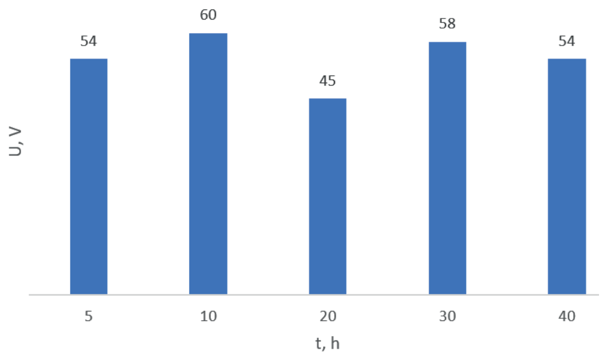


Figure 5. Voltage on the wire from different curing period

This voltage values will be set on the transformer, after the system, based on temperature detector data, has performed operation described above and transfer data to control assembly. The temperature detectors are installed inside structure and on the surface of structure.

The control system of cast-in-situ reinforced concrete structure heating with heating wire can be presented as "black box" model (Fig. 6). Input parameter is transformer voltage (U) and output parameters are divided into uncontrollable (temperature of ambient air (T_{ext}), wind speed (v_{wind})) and controllable (temperature of concrete of structure (T_{str}), time of isothermal curing (t_{isoth})).

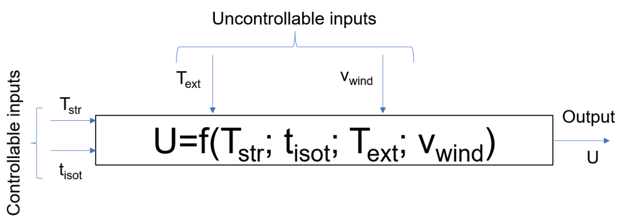


Figure 6. Circuit diagram of governing system of concrete heating

Content and type of cement, having accelerator admixtures and whether or not thermal insulation of structure during concrete curing, diameter, resistance and length of wire can also be attributed to input parameters. However, described parameters with their constant values can be considered into the numerical model, because construction method for each of building company is constant. That's why the controlled input can be considered only that was described above.

It is also necessary to point out natural limitations of parameters values (table 4).

Thus, finding equations together with thermal regime of concrete curing can be used for building of automated control system of heating of reinforced concrete structure with heating wire. And in doing so, thermal regime can be presented as equation, witch correlate specified concrete temperature with curing time, considering noted limits.

CONCLUSION

Thus, it needs to note that at this time there are some unsolved problems of electrical curing of cast-in-situ reinforced concrete structures and it needs optimization and improvement. Development and implementation of control system of parameters of electrical curing can be solves of this concern.

The control system developed by the authors can be basis for creation of automated system of electrical heating of cast-in-situ reinforced concrete structures. Maintenance of optimal thermal regime of concrete curing will be task of developed system depending on different internal factors such as temperature of ambient air, rate of surface cooling, time of concrete curing, type and parameters of heating wire etc.

Application of such automated control systems of electrical curing will facilitate reduction of labor cost and provide optimal curing conditions for concrete strength gain. It also will facilitate to save electricity through reduction of wire voltage depending on time of concrete curing and temperature of ambient air.

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Table 4. Limits of some concrete curing parameters

Parameters	Limits	Limit definitions
p	≤40 W/m	Temperature of wire exceeds 100°C during high loading, that leads to structural damage of concrete and decrease of its strength. In addition, insulation of wire can be damaged, and short circuit on reinforcement will able to occur
U	{55, 65, 75, 85, 95}, V	Discrete voltage level (depends on transformer type)
T_{str}	≤ (70-80) °C	It due to structurization and strength gain processes of concrete

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Stepan V. Leontev - Ph.D. in Engineering Science, senior lecturer of department of Construction Engineering and Materials Science, Perm National Research Polytechnic University; Russia, 614010, Perm, ul. Kuibyshev, 109; phone +73422198352, e-mail: n1306cl@yandex.ru.

Леонтьев Степан Васильевич - к.т.н., доцент кафедры «Строительный инжиниринг и материаловедение» Пермского национального исследовательского политехнического университета; Россия, 614010, г. Пермь, ул. Куйбышева, 109; тел. +73422198352, e-mail: n1306cl@yandex.ru

Andrey A. Taleyko - student of department of Construction Engineering and Materials Science, Perm National Research Polytechnic University; Russia, 614010, Perm, ul. Kuibyshev, 109; phone +73422198352, e-mail: taleyko.99@mail.ru

Талейко Андрей Алексеевич - студент (магистрант) кафедры «Строительный инжиниринг и материаловедение» Пермского национального исследовательского политехнического университета; Россия 614010, г. Пермь, ул. Куйбышева, 109; тел. +73422198352, e-mail: taleyko.99@mail.ru