Structural and Temperature Effects on Electrical Resistivity of Concrete During Its Hardening and Strengthening

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Abstract. The presented work describes the research findings related to the impact of temperature and structural effects on electrical resistivity of concrete during its hardening. The methodology is based on formulation and implementation of the concept of concrete iso-strength (iso-structural) condition. The experimental data analysis under the iso-strength conditions within the temperature range: 283–313 K allows to suggest that the state of electrically conductive phase - structured water consecutively transforms from liquid to quasi-solid. The ability is shown of separating the temperature and structural effects and their impact on the value and the nature of electrical resistivity in the process of concrete hardening. The temperature impact on the resistivity changes in the hardening' process. Upon reaching a certain strength’ value, corresponding to a sufficiently high level of structure development, the temperature coefficient of electrical resistivity changes its sign: it changes from a negative to a positive area.

Introduction

The nature of hardening and strengthening of Cement-Concrete Compositions (hereinafter: CCC) is complicated and in many cases even controversial. On the one hand, the hardening is a result of the joint development and interaction (in terms of thermodynamics) of chemical and structural transformations [1]. On the other hand, it is necessary to take into consideration the following facts:

Chemical reactions of hydration and hydrolysis of mineral cementitious materials are evolving at the atomic-molecular level in strict quantitative (stoichiometric) ratios,

Structure formation is a result of the reaction products' interaction at the level of particles and aggregates, evolving in indeterminate quantitative ratios.

Moreover, the hardening is a sequence of the material's transformations from one structural state into another. Every structural state differs from the previous one by the level of structural development and a new combination of structural and mechanical properties.

The initial state of any CCC (compaction structure) is a coagulation structure with the dominating viscous-plastic properties that are practically degenerating by the finish of setting (FS). Upon completion of setting processes, the formation starts of a crystallization capillary-porous structure with dominating elastic properties, i.e., strengthening.

The nature of strengthening is actually the development and interaction of two alternative processes:

On the one hand, the amount of the solid phase in the volume of the material increases, as well as the level of the interaction between the solid-phase elements of the structure,

However, on the other hand, the structure defectiveness evolves at the same time—it's general porosity is formed and increased.

The evolved pores and capillary are filled with liquid and gas (water steam), which makes the strengthening mechanism more difficult and controversial.

The CCC liquid phase is a full-fledged factor of the structure formation process, and it has the remarkable properties as follows [2]:

Physical moisture always exists in the thermodynamic equilibrium with the solid surfaces on which it is adsorbed (or by which it is adsorbed).
Therefore, the physical moisture state appropriately reacts to all the structural changes (formation of new solid surfaces, formation of pores and capillaries etc.) in the process of CCC hardening.

Besides, the structured physical water—pore solution is the sole electrically conductive phase in all the hardening process stages. This is exactly why the electrical resistivity method has been effectively used for over 90 years for solving the problems of research and development and technological monitoring of CCC hardening (Y. Schimizu 1928 [3]). Recently, considerable attention has been paid to CCC hardening problems [4 - 8], including those present specifically at the construction sites [9,10].

Subsequently, it should be noted that the temperature rise intensifies the chemical and structural transformations during the hardening of mineral cementitious materials and concrete. In particular, further to the rule of J.H. van’t Hoff (1884) [11], the rates of the chemical reactions get 2-4 times greater per every 10 °C (°K). In addition, the temperature change makes an impact on new formations' surface morphology and area.

Besides, the electrical resistance/resistivity directly reacts to CCC temperature change [12 - 15]. This aspect must also be considered while solving the research and development problems and technological tasks.

### CCC Structure Formation and Electrically Conductive Properties

Naturally all the solid-phase CCC components are effective dielectrics. Thus, the electrical resistance of pure siliceous sand is $10^{14}$ - $10^{16}$ Ohm, granite - $10^{10}$ - $10^{11}$ Ohm etc. The only electrically conductive CCC component on all hardening stages is the physical water. Therefore, the term “electrical resistivity of cement paste, mortar or concrete” actually relates not to all the multicomponent and heterogeneous composition but rather solely to the pore solution - structured physical water.

The moisture mass balance of any CCC in thermodynamically closed system is the sum of the masses of the chemically bound $m_{ch}$ and physical (structural) $m_{ph}$ components. In its return, the value $m_{ph}$ is summed up out of the strongly bound $m_{sb}$ and capillary $m_{cap}$ component. Strongly bound water includes the adsorption layers water, as well the gel water which – non-evaporable water, according to T. Powers [16, 17], does not get involved in the hydration reaction of the clinker minerals.

Then the moisture mass balance will be given as follows:

$$m = m_{ch} + m_{ph} = m_{ch} + m_{sb} + m_{cap}.$$  \hspace{1cm} (1)

It should be assumed that the electric current is mainly transferred by the capillary water. The electrical conductivity of thin layers of the adsorption strongly bonded water is minimal or even equal to zero [18].

The hardening of all CCC is substantially a non-stationary process, in which all the material structural properties are constantly modified: from the initial state – the viscous-flow or viscous-plastic mix state up to the final state – that of artificial stone with the dominating elastic properties. The electrically conductive properties of the hardening CCC are appropriately changed.

In general, the electrical conductivity $\sigma$ (ohm$^{-1}$ m$^{-1}$) or electrical resistivity $\rho$ (ohm m) of the porous material’ may be defined from the Nernst-Einstein equation as follows:

$$\sigma = \frac{1}{\rho} = D \frac{(zF)^2 c_i}{RT},$$

where $D_i$ - diffusion coefficient (cm$^2$ s$^{-1}$), $z_i$ - ionic valence, $F = 9.648 \cdot 10^4$ (C mol$^{-1}$) - Faraday constant, $R = 8314$ (J mol$^{-1}$ K$^{-1}$) - universal gas constant, $T$ - absolute temperature (°K), $c_i$ - the concentration of the $i^{th}$ ion in the pore solution (mol·cm$^{-3}$).
Expressing the diffusion coefficient out of the Einstein-Smoluchowski equation,

\[
D_i = \frac{RT}{6\pi r N_A \eta},
\]  

(3)

we will determine the electrical resistivity through the viscosity \( \eta \) and concentration \( c_i \)

\[
\rho = \frac{1}{\sigma} = \frac{\eta}{(zF)^2 c_i},
\]

(4)

where \( \eta \) - dynamic viscosity of electrically conductive phase (Pa \( \cdot \) s), \( r \) - ion radius (m), \( N_A = 6.022 \cdot 10^{23} \) (mol\(^{-1}\)) - Avogadro’s number.

In Eq. 4 only the viscosity of the pore solution and the concentration of the dissociated ions are time-varying values. Subsequently, \( \eta(\tau) \) and \( c_i(\tau) \) particularly determine the electrical resistivity change’s value and nature in the process of hardening, i.e.

\[
\rho(\tau) = \frac{1}{\sigma(\tau)} = \frac{\eta(\tau)}{c_i(\tau)} \text{const},
\]

(5)

where \( \tau \) - time.

The temperature \( T \) is implicitly present in this relation: during the hardening temperature change, the liquid viscosity and chemical reaction rates appropriately change.

The structured liquid viscosity – of the pore solution – is directly determined by the capillary-porous structure development’ level and properties. The less is the pore and capillary size, the greater the \( \eta \) value.

It should be noted that the chemical \( c_i \), the structural \( \eta \) and the temperature \( T \) factors have a different impact on the electrical resistivity value and nature:

On the one hand,

Development of the chemical reaction of hydration and hydrolysis of clinker minerals stipulates an increase in the conductive phase (pore solution) ionization degree \( (c \rightarrow \text{max}) \), and the electrical resistivity decreases \( (\rho \rightarrow \text{min}) \).

The increase in the hardening temperature reduces the pore solution viscosity \( (\eta \rightarrow \text{min}) \), and accordingly the mobility of the dissociated ions increases and the electrical resistivity decrease \( (\rho \rightarrow \text{min}) \).

On the other hand, during the CCC hardening process, the size of the pores, capillaries, holes etc., i.e. the cross-sectional areas of the current flow channels decrease, and as a result, the electrically conductive phase (pore solution) viscosity increases \( (\eta \rightarrow \text{max}) \); the mobility of ions decreases, and the electrical resistivity increases \( (\rho \rightarrow \text{max}) \).

Subsequently, the value \( \rho \) measured in the process of concrete hardening is the sum of three components differently influencing the electrical resistivity change value and regularities

\[
\rho = -\rho(c_i) - \rho(T) + \rho(\eta).
\]

(6)

The character of curve \( \rho = f(\tau) \) during 28 days of ordinary dense concrete hardening reveals that only on the initial stage (Fig. 1a): from the moment of formation of the concrete compaction structure \( (\tau = 0) \) up to completion of setting \( (\tau = FS) \) and beginning of crystallization strengthening \( (\tau = ICrStr) \) the electrical resistivity changes in a non-monotonic manner. Non-monotonicity is stipulated by the simultaneous development and interaction of chemical, temperature and structural factors. Further on, \( \rho \) consistently grows during 28 days (Fig. 1b).
Thus, during the crystallization strengthening of CCC, the capillary porosity formation and development have a major effect on the $\rho$ change (increase).

![Figure 1. Typical curve of change of electrical resistivity during the hardening of concrete by constant temperature: $a$ – during the first 24 hours, $b$ – during 28 days.](image)

**Experimental Research and Preliminary Analysis of Results**

In order to examine the concrete hardening and strengthening regularities, special research has been carried out. Using the concrete composition (kg/m$^3$): Cement CEM I 42.5N = 279, Water = 195, Sand = 679, Coarse = 1193, (without chemical additives), standard sample 10-cm edge size cubes were made. Samples stayed in the thermostatic chamber and were hardening within 168 hours (7 days) at the constant temperatures: 283, 293, 303, 313, 323 and 333 K. The compressive strength was measured at the ages of 1, 2, 3, 4 and 7 days (Fig. 2a). All the concrete mixture components were held, prior to mixing, at the specific constant temperatures within 24 hours.

The concrete hardening process control was carried out, based on Contect-8 measurement system. The container type cylindrical sensors [19,20] were located near standard cubical samples in the same chamber. The exposed samples surfaces were protected from evaporation (however they were not sealed). The measurements of the electrical resistivity were carried out continuously with a 6-minute interval within 7 days (Fig. 2b).

The temperature increase accelerates the hardening processes, though it does not improves the forming structure properties. In a fast initial hydration “...products of poorer physical structure, probably more porous...” are generated [21 – p. 318]. The changes are also possible in chemical and mineral composition of the reaction product. Thus, during the process of hardening of alumina cement at $t > 40^\circ$C instead of $CAH_{10}$ the less active $C_3AH_6$ is formed [22].

However, the high temperature negative influence on the concrete strengthening is shown at later ($\tau > 7$ days) hardening time [23, 24]. Therefore, in our case, the strengthening curves within the $S = \rho(\tau)$ temperature range $T = 283 – 333$ K are practically parallel to one another and are uniformly located in the graph plane $S – \tau$ (Fig. 2a).

The stable growth of all the curves clearly shows $\rho = f(\tau)$ the dominating impact of the structure factor on the electrical resistivity value. Indeed, as mentioned above, the pore solution – electrolyte temperature rise should reduce the value $\rho$ (see for example [25]). Therefore, the ranging of the kinetic curves observed in Fig. 2b

$$\rho_{283} = f(\tau) > \rho_{293} = f(\tau) > \rho_{303} = f(\tau) > \rho_{313} = f(\tau) > \rho_{323} = f(\tau) > \rho_{333} = f(\tau)$$

is mainly stipulated by intensification of the capillary-porous structure formation due to the hardening temperature rise.

Kinetic curves $\rho = f(\tau)$ in Fig. 2b are clearly divided into two groups. The hardening at low and medium temperatures $T = 283 – 313$ K is characterized by the monotonous increase $\rho$ in
time. However, during increase in the hardening temperature up to \( T = 323 - 333 ^{\circ} \text{K} \) the value of electrical resistivity significantly increases, while the curves obtain a rising pattern. It should be assumed that the hardening temperature increase \( T > 313 ^{\circ} \text{K} \) triggers the additional concrete dehydration, since the molds with hardening samples were not sealed. The dehydration stipulates significant decrease in the layer thickness of the electrically conductive phase, and as a result, disproportionally high increase in \( \rho \).

![Figure 2. Strengthening (a) and concrete electrical resistivity change (b) in the process of hardening within the temperature range of 283 - 333 \(^{\circ}\text{K}\).](image)

Therefore the experimental data analysis (Fig. 2) will be carried out only within the range of low and medium temperatures \( T = 283 - 313 ^{\circ} \text{K} \). Fig. 3 shows the diagram “Strength – Electrical Resistivity” plotted with the experimental data Fig. 2.

![Figure 3. “Strength – Electrical Resistivity” diagram.](image)

It is obvious that the dependencies \( S - \rho \) approximate by the linear relations with high correlation ratios \( (0.970 \leq R \leq 0.991) \). Along with this, the aggregate of test points for all the considered temperatures may be described by one logarithmic equation \( S = 12.489(\ln \rho) - 56.612 \). Besides, the correlation lines \( S(T) = a \rho + b \) have a common intersection point with the coordinates \( \sim (16.0 \text{MPa} - 335 \text{ohm*m}) \). This clearly shows that single-composition concrete hardening at
different temperatures undergoes a certain intermediate state with equal structural-mechanical properties.

**Structural and Temperature Effects during the Concrete Hardening**

It was stated above that the impact of temperature on the electrical resistivity of the hardened concrete with the constant structural properties had been thoroughly examined [1,5,12-15,25]. A far bigger challenge is the monitoring of the concrete hardening under the significant properties change $\rho$.

Fig. 2b shows that at each $T_i = const$ (i = 283, 293, 303, 313 K) the electrical resistivity consistently and monotonously grows in time. Only at the initial hardening stage ($\tau \leq FS$), the resistivity changes in a non-monotonous manner (Fig. 1a). At this stage, the chemical (pore solution ionization), temperature (exotherm) and structural (on the coagulative level) factors evolve simultaneously and have a mutual effect on one another.

It follows therefore that the stable growth of the electrical resistivity of concrete hardening at a constant temperature is mainly determined, upon the completion of the setting processes ($\tau = ICrStr FS > FS$), by the capillary-porous structure formation.

Therefore, in order to evaluate the influence of temperature and structural effects on the regularities of specific electrical resistivity changes, an analysis should be performed under isotherm and isostructural conditions.

As to isotherm conditions ($T = const$), the matter is entirely clear and straightforward. The concrete hardening at a constant temperature is a rather easy implementable process (see. Fig. 1 and 2b). Short-term – until finish of setting – temperature increase at 1 – 2 °C (°K) resulted from hydration and hydrolysis exothermic effects (see Fig. 1a) does not have a significant effect on the nature of further hardening and strengthening (important to stress, that at construction sites, the hardening processes of concrete and reinforced concrete elements of large volume or large cement amount are developing in non-isothermal conditions).

The term “isostructural conditions” requires further clarification.

Generally, structure is a way of elements organizing and nature of interactions between them [26]. In real physical systems there are spatial and temporal structures.

In hardening CCC:

Spatial Structure is a configuration of solid particles ordered by energy interactions,

Temporal Structure evolves during formation of those interactions as a transition “from Being to Becoming”, according to I. Prigogine concept [27].

The main structural parameter of the CCC is porosity: “The structural differences between the unequal types of paste made from the same cement are primarily due to the difference in capillary porosity.” [28]. However, the capillary-porous structure properties are defined not only by total porosity value $P$, but mainly by the distribution of the pores by sizes, relation between the volumes of interconnecting and closed pores, etc

The structural porosity directly determines the value of the concrete main constructive and exploitation property – its compressive strength [29,30]

$$S = -\frac{1}{k} \ln \frac{P}{P_0},$$

where $S$ - compressive strength (MPa), $P_0$ - porosity at zero strength being close by value to $\kappa$ 0.6; $k$ - constant equal to 2.6 $10^{-5}$ (1/MPa).

On the other hand, according to the “gel - space” concept [16,17,28], the strength is the result of development of the complex physical - chemical process: formation, aging and stiffening of the cement gel with its subsequent crystallization.
\[ S = S_0 \left( \frac{V_g}{V_g + V_{sc}} \right)^n = S_0 P_{\text{pow}}^n, \]  

where \( S_0 \) - material’ strength at \( P=0 \) (in this case all the pores and capillaries are filled with the cement gel), \( P_{\text{pow}} \) - Powers’ porosity, \( n \) - the index of the power, whereas its value changes within the range of 2.5 – 3.7.

During CCC hardening process, the average sizes of pores, capillaries etc. decrease. As a result, the structured pore solution’ viscosity consistently grows along with the gain in strength. Consequently, there is proportionality \( \eta \propto S \). Therefore the pattern of the concrete electrical resistivity change (Eq. 5) should comply with the strengthening regularities thereof.

Thus, the strength is a common, integral property determining the hardening concrete structure state. Accordingly the equal strength values of the same concrete composition's hardening at different temperatures \( (S = S(T) = \text{const}) \) define the iso-structural state.

Further on, the strengthening of concrete may be considered as a consequence of discrete structural states, each of which is characterized by a specific strength value. Under iso-strength (iso-structural) conditions the controlled concrete element is a electric conductor with constant structural-mechanical properties, for which the interrelation “Electrical Resistivity – Temperature” at \( S = \text{const} \) is defined by the linear dependency

\[ \rho = aT + b, \]

where \( a \) - temperature coefficient of electrical resistivity (ohm m K\(^{-1}\)).

The term “constant structural-mechanical properties” is usually applied to hardened concrete at age > 28 days. It is generally accepted that at this age the hardening processes of CCC were almost completed, and the basic properties of the material: porosity, strength etc. practically did not change (change very slowly), i.e. \( P_{28} = \text{const} \) and \( S_{28} = \text{const} \). However, this provision can be extended to any intermediate state of hardening CCC, i.e. measure and record the values of porosity and strength of concrete \( P_i = \text{const} \) and \( S_i = \text{const} \) at the age of \( \tau = 1,2,3... \) days.

Fig. 4 shows the family of iso-strength line \( \rho = f(T) \) within the temperature range of 283 – 313 K. The values \( \rho(T) \) for the temperatures 283, 293, 303 and 313 K are obtained by calculation according to the equations of trend dependencies of the experimental data \( (\rho - S)_T = \text{const} \) (Fig. 3) with an increment \( S(T) = 1 \text{ MPa}^a \). Each line \( \rho = f(T) \) defines the temperature effect value in the concrete fixed structural state at \( S_i = \text{const} \) \( (i = 5,6,7,...,23) \).

The linearity of iso-strength (iso-structural) lines \( \rho = f(T) \) (Fig. 4) clearly complies with the outcomes obtained by various authors with respect to the hardened concrete with the constant structural characteristics [8,25,31].

\(^a\) Concrete initial calculated strength assumed to be equal to \( S = 5 \text{ MPa} \). This complies with ASTM C-1074 standard regulations establishing the capability of implementing “Maturity” method only upon completion of concrete setting (or after gaining the concrete strength \( S \geq 4 \text{ MPa} \).

In particular, the slope angle of each iso-strength line \( \rho = f(T) \) under \( S_i = \text{const} \) in Fig. 4 is the temperature coefficient of the electrical resistivity \( a \) (Eq. 9)

\[ \left( \frac{\partial \rho}{\partial T} \right)_{S_i} = a, \]

\[ \text{(10)} \]

Coefficient \( a \) determine the change value \( \rho \) (ohm m) per 1 K within the hardening temperature range from 283 to 313 K.

It is necessary to note the key issue.

In the concrete strength range \( 5 \leq S \leq 23 \text{ MPa} \) all the lines have the negative slope about the axis \( T \), and coefficient \( a < 0 \). This means that when the hardening’ temperature rises the electrical
resistivity of the pore solution reduces, which is common for the electrolytes [32]. And this is a logical result, since in the concrete structure only the liquid phase – the pore solution – conducts an electric current.

As the strength grows the temperature impact on the value $\rho$ falls, and the slope angles gradually decrease. The decreasing of the line slope angles $\rho = f(T)$ as the strength grows is in compliance with the results received by [25] for the hardened concrete with various W/C-ratio (i.e. various strengths, according to the law of D. Abrams [33]). It is clear that if this tendency stays the iso-strength lines will have to become ascending about the $T$-axis.

With the strength of $S \approx 23.5 \text{ MPa}$, the straight line $\rho = f(T)$ is parallel to the $T$-axis, i.e. in this structural state the electrical resistivity is independent of temperature: $\rho = \text{const}$ and $a = 0$.

But further ($S \geq 23.5 \text{ MPa}$) iso-strength lines $\rho = f(T)$ acquire an ascending character.

This means that as a result of the development of the concrete’ structure, the average liquid adsorption layer thickness will reach this value (around $(15-30) \times 10^{-10} \text{ m}$ [28]), whereas the solid surface influence on the structured water characteristics will become dominating. In these layers the liquid even gets the elastic properties having the measured shearing modulus and flow limit [34].

Therefore, at $S \geq 23.5 \text{ MPa}$, the structured pore solution’ electrical resistivity should increase with the temperature increasing, which is common for the solid bodies.

**Discussion**

Thus, variations in the temperature coefficient of the electric resistivity (Eq. 10) across the strength scale of the concrete first develop in the negative region, and then in the positive region (Fig. 5). Change sign $\mp a$ is
the result of evolution of the pore solution properties, or more precisely, from an increase in its interaction with the solid surfaces of the forming capillary-porous structure. Analysis of the curve $a = \phi(S)$ allows us to estimate the influence of structural and temperature effects on the nature of the change in electrical resistivity.

At the initial stage of hardening at low strength values ($5 \leq S \leq 10$ MPa) the temperature coefficient decreases almost linearly with a small intensity of $-0.024 \text{ ohm} \cdot \text{m} / \text{K}$ per 1 MPa. At this stage the capillary-porous structure is just beginning to form. The intensity of the interaction of the electrically conductive pore solution with solid surfaces is still small, and the solution behaves like a typical electrolyte. This is confirmed by the maximal negative coefficient values $a$: an increase in the hardening temperature of the concrete causes a significant decrease in electrical resistivity.

In the range of strength $10 \leq S \leq 23$ MPa, the electrolytic properties of the pore solution gradually disappear. This is evidenced by a significant decrease in the temperature coefficient $a \rightarrow 0$ with an average intensity of $-0.161 \text{ ohm} \cdot \text{m} / \text{K}$ per 1 MPa.

After the concrete reaches 23.5 MPa strength, the properties of the pore solution change abruptly. Now with increasing temperature $\rho \rightarrow \text{max}$ (Fig. 4), and the temperature coefficient becomes positive: $a > 0$. The intensity of the change increases by an order of magnitude: $2.91 \text{ ohm} \cdot \text{m} / \text{K}$ per 1 MPa. This means that thin, strongly bound layers of the pore solution lose their electrolytic properties, and the electrically conductive phase goes into a quasi-solid state. As a result of these effects’ development, the impact of temperature on the change in electrical resistivity is significantly enhanced.

![Figure 5. The changes in the temperature coefficient $a^*$ depending on the strength within the temperature range of 283 – 313 K.](image)

A similar curve $a = \phi(S)$ was obtained by us as a result of processing the experimental data presented in Fig. 4 in [25] (Fig. 6). In this work the temperature effect on the concrete electrical resistivity with various W/C-ratio 0.37, 0.42, 0.47 and 0.57 was studied. Concrete samples were initially cured at 21 °C for 54 days over water; next they were placed over a saturated salt solution at 75% RH for an additional 14 days. The samples then were exposed to a series of different temperatures, and electrical resistivity was measured at 1 kHz.

The concretes with various W/C-ratio are distinguished by the size and nature of porosity, and naturally, in strength, according to Abrams law [33]. Therefore, a decreasing of W / C from 0.57 down to 0.37 (Fig. 6) can be viewed as a process for modeling the formation of a capillary-porous structure and strengthening of concrete. This specifically explains the similar temperature coefficient $a$ change nature when strengthening concrete in the hardening process (Fig. 5) and during lessening the hardened concrete W/C-ratio (Fig. 6).
Far greater coefficient values in Fig. 6, in comparison with our data (Fig. 5), are caused, apparently, firstly, by different degrees of saturation of the structure with the pore solution, and secondly, differences in the pore solution electrolyte characteristics.

So, in the case we are considering, the concrete hardening process during 7 days (Fig. 5), the physical moisture mass constantly decreases, and so does the thickness of layers $h \to \text{min}$. In the thin layers of the strongly bound pore solution the dissociated ions have low mobility. Therefore the temperature change effect on the electrical resistivity value is relative small.

![Figure 6. The change of the temperature coefficient $\theta$ depending on W/C-ratio within the temperature range of $10 - 25 \, ^\circ\text{C} (283 - 298 \, ^\circ\text{K})$: processing of [25] experimental dates.](image)

At the same time, in the experiment [25], with prolonged (68 days) curing of hardened concrete (Fig. 6), first, in water vapor and then in salt water vapor, the structure is saturated to a state of equilibrium moisture. The absorbed water is the capillary bulk water with a high concentration of the conductive ions. This proves by rather low electrical resistivity values: even at minimal temperature of $10 \, ^\circ\text{C} (283 \, ^\circ\text{K}) \quad \rho = 268 \, \text{ohm m}$ for W/C = 0.37 и $\rho = 338 \, \text{ohm m}$ for W/C = 0.57. Under these conditions the ions have high mobility and therefore, the temperature changes have a significant effect on the electrical resistivity value.

**Summary**

The implementation of the iso-strength (iso-structural) concept allows to understand the physical nature of electrical resistivity’ changes in the concrete’ hardening process. In addition, it becomes possible of quantification of the temperature and structural effects influence on $\rho$ values changes.

Within the low and medium temperature range (283 – 313 $^\circ\text{K}$) the iso-strength dependencies $\rho = f(T)$ have strictly linear nature. However, in the concrete hardening process the line slope angles $\rho - T$ with respect to axis $T$ consistently decrease. It is obvious that as the capillary-porous structure evolves, the pore solution's layer thickness decreases. Accordingly, the intensity of the solution interaction with the solid surfaces increases. As a result, the electrical conductive properties of a structured liquid gradually approach those of the solid phase.

It has been determined, that the temperature impact on the electrical resistivity changes significantly in the process of concrete hardening. Upon reaching a certain strength’ value, corresponding to a sufficiently high level of structure development, the temperature coefficient of electrical resistivity changes its sign: it changes from a negative to a positive area.

This conclusion is confirmed by the processing of experimental data of Hope et al. [25]: The similar tendency of the change dependency $\rho = f(T)$ is also observed in the course of decreasing W/C-ratios of concrete.
Therefore, the results of the analysis of the development and interaction of the structural and temperature effects permit us:

Qualitatively—to discern the action of both factors in the process of hardening and strengthening of the concrete,

Quantitatively—to assess the effect of these factors on the magnitude and the nature of the change in the electric resistivity

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