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Article *in* Materials Science Forum · August 2019

DOI: 10.4028/www.scientific.net/MSF.968.50

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Materials Science Forum
ISSN: 1662-9752, Vol. 968, pp 50-60
doi:10.4028/www.scientific.net/MSF.968.50

Submitted: 2019-04-29
Accepted: 2019-05-29

The Influence of Storage Conditions on the Electric Conductivity of Concrete

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Keywords: electric resistance of the concrete, capillary-&-porous structure, sleepers, electrified railway

Abstract. Theoretical and experimental investigations of the influence of concrete moisture, its age, holding conditions after its thermal moisture treatment and other factors on the specific electric resistance of the concrete of a C32/40 grade used for reinforced concrete sleepers have been carried out. The obtained research data allowed us to specify holding modes and the duration of them and these enable the generation of objective information on the specific electric resistance of the concrete used for the sleepers during their operation.

Introduction

The railway track rails are the components of the electric circuits of the signaling currents that flow in alarm, interlocking and blocking systems (AIB) and also the traction current that arise on electrified railway sections. To provide a reliable operation of those circuits the rails must be electrically isolated from each other and from the earth. Usually it can be done using the insulating parts of intermediate rail fastenings. However, such factors as aging, wearing, and the obstruction of rubber and polymer insulating parts result in an abrupt drop of the electric resistance of isolation especially in wet weather and as a consequence in malfunction of AIB systems, and inadmissible loss of the traction current due to its drainage to the earth including the electric corrosion of metal and reinforced concrete structures caused by leakage currents. Therefore, the concretes of rail bases, in particular the sleepers, the ballastless base, are supposed to be stable when exposed to mechanical effects and even highly functional concretes are used for this purpose [1] and these should also contribute to the electrical isolation of the rails from each other and from the earth.

Lately, the authors developed and enacted the national standard DSTU B V2.6-209:2016 "Preliminary Strained Reinforced Concrete Sleepers for the Railways with the Tracks of 1520 and 1435 mm. Technical Specifications". It was done to standardize for the first time in Ukraine the value of specific electric resistance of the concrete for reinforced concrete sleepers that should not be less than 100 Ohm·m, specifying the control procedure of it and the measurement procedure using reference specimens.

However, the manufacturers of reinforced concrete sleepers state the cases of incompliance of this value with the standard value according to the output inspection data of it. The standard value can be attained at a later time of hardening when the sleepers will be already in operation. A previous analysis showed that it is conditioned first of all by the fact that electric resistance measurement methods were developed when the reference specimens of concrete were stored on the shelves in the premises of the plant laboratory or at the molding shop. According to the current legislation, the specimens are kept today in moist cabinets at a temperature of 20 ± 2 °C and a relative air humidity φ of at least 95 % during 28 days. It conditions the topicality of the investigation of the influence that specimen storage conditions have on the specific electric conductivity of concrete and allows us to specify the procedure of its control and measurement methods using the obtained research data.

Analytical review of the literature data and the theoretical investigation of the factors that affect the electric resistance of concrete

The electric resistance of concrete depends on the influence of moisture, capillary-&-porous structure, temperature, availability of electrolyte admixtures and long-term factors [2-7]. The concrete is simultaneously the polydispersed system and capillary-&-porous body therefore the electric resistance of it is formed by the electric resistance of solid and liquid phases. The electric resistance of the solid phase of concrete is defined by the electric resistance of the aggregates and the cement stone [2, 5-7]. The rock forming minerals of rocks that are used as the aggregates are the dielectrics. As a rule, the electric resistance of rocks is lower than that of their minerals due to the content of moisture and admixtures [2, 6, 7], the defects and availability of interfaces between the minerals [4]. A specific electric resistance of the rocks is in the range of $1 \cdot 10^4$ to $1 \cdot 10^{10}$ Ohm·m [2].

The cement stone is also a dispersed system that consists of incompletely hydrated clinker particles (clinker relicts) and mineral admixtures and also crystallohydrate and gel products of cement hydration. The specific electric resistance of clinker minerals is as follows: C_3S - $1.2 \cdot 10^6$ Ohm·m, C_2S - $1.5 \cdot 10^7$ Ohm·m, C_3A - $6.0 \cdot 10^5$ Ohm·m, C_4AF - $6.4 \cdot 10^5$ Ohm·m [3]. The specific electric resistance of crystallohydrates is in the range of $1 \cdot 10^4$ to $5 \cdot 10^7$ Ohm·m [3] and it is much higher than the resistance of hydrosilicate gel that contains the major portion of bound water due to a larger specific surface.

The water contained in the pores and capillaries of the cement stone and concrete is the saturated solution of $Ca(OH)_2$ with the concentration of 0.02 mole/l that is a porous electrolyte. This solution is the conductor of the 2nd kind and Ca^{2+} and OH^- ions of it act as electric current carriers.

Its electric conductivity and electric resistance are defined by the concentration of those ions and by the temperature [4, 7]. The values of specific electric resistance that were defined experimentally are as follows: for the saturated solution of $Ca(OH)_2$ it is 1.25 Ohm·m [2]; for the liquid phase C_3S after the 7 days of hydration it is 1.2 Ohm·m [8] and for the cement stone water extracts it is 1.23 Ohm·m.

With the exposure of concrete to CO_2 and other acid gases the solution neutralization occurs, i.e. Ca^{2+} and OH^- ions are bound to form $CaCO_3$ and H_2O, accordingly and pH is reduced. However, cement hydration products, in particular portlandite $Ca(OH)_2$ and potassium hydrosilicates are stable in the environment of the saturated solution of $Ca(OH)_2$ [10], and when the pH is reduced to 11 and lower these are decomposed and the solution is replenished by Ca^{2+} and OH^- ions [8]. Therefore, the cement stone and the concrete are able to maintain rather high value of pH and a high concentration of $Ca^{2+}$and OH^- ions for a long time actually until the complete neutralization of $Ca(OH)_2$.

A porous space of the cement stone contains gel pores with the cross section of up to 10 nm, the microcapillaries of 0.1 to 1µm and noncapillary pores of more than 1 µm [10-12]. Double electric layers (DEL) [13] are formed on the walls of those pores and capillaries at the phase interfaces that consist of 75 % of calcium hydrosilicate [10] with negative potential-defining ions and the Ca^{2+} ion concentration in these DELs in particular of counter ions is one order of magnitude higher than that in the solution volume. Therefore, in these pores and capillaries the influence of DELs on the electric conductivity and electric resistance should be anticipated according to the portion occupied by the DEL in the pore cross-section and the smaller the pore size the greater the influence is. The thickness of the dense portion of DEL is insignificant; it corresponds to the radius of counter ion. Counter ions are strongly bound in it by the potential-determining ions of hard surface and their participation in electric conductivity can be neglected.

The thickness of the diffusion portion of DEL δ depends on the concentration of electrolyte in the solution volume c [13, 14]:

$$\delta = \frac{1}{zF}\sqrt{\frac{\varepsilon\varepsilon_0 RT}{2c}}, \tag{1}$$

where z is the valence of the counter ion in the DEL, for Ca^{2+} it is equal to 2; F is the Faraday number, $9.65\cdot10^4$ C/mole; ε is the relative dielectric permeability; ε_0 is the electric constant , $8.85\cdot10^{-12}$ F·m; R is the universal gas constant, 8.31 J/(mole·K); T is the temperature, 293 K.

By substituting these values into (1) we obtain the thickness of the diffusion portion of DEL for the pores and capillaries of cement stone:

$$\delta = \frac{1}{2\cdot 9.65\cdot 10^4}\cdot\sqrt{\frac{81\cdot 8.85\cdot 10^{-12}\cdot 8.31\cdot 293}{2\cdot 20}} = 1.1\cdot 10^{-9}[m] = 1.1[nm].$$

Fig. 1 *a* gives the calculated dependence of the share of x that falls to the diffusion portion of DEL of thick $\delta = 1.1$ nm in the cross-section of the cylindrical pore or the capillary on the diameter of this pore. Fig. 1 *a* shows that the share of the diffusion portions of DEL in the cross-section x of noncapillary pores and the microcappilaries [10] is insignificant and it makes 5 to 40 % for the microcapillaries and it exceeds 40 % for gel pores. However, in spite of a high concentration of the counter ions of Ca^{2+} due to their proximity to the hard surface the mobility of those ions is limited at a surface normal to a greater extent and at a tangent to the surface to a less extent in comparison to the ions present in the porous electrolyte volume [3]. Therefore, we can assume that these do not affect the electric conductivity due to low strength values of the external electric field or insignificant potential difference. Hence, the free (physically bound) water (i.e. the electrolyte) of the porous space has an effect on the electric conductivity and the electric resistance of the cement stone and concrete. It is manifested by the influence of moisture on the specific electric resistance ρ of concrete.

Fig. 1 *b* gives the experimental dependence of the specific electric resistance of concrete with the compression strength of 20MPa on its moisture W at a temperature of 10 °C, according to the experimental data [2]. This dependence is well-approximated by the exponential equation. Fig. 1 *b* shows that at W lower than 1.5 % at which actually all the water is physically-& -chemically bound in the DEL ρ is increased to the values exceeding $1\cdot10^4$ Ohm·m, peculiar for the rocks -the aggregates.

The concrete age has an essential influence on the electric resistance of it. Fig. 2 *a* gives the diagrams of the dependence of specific electric resistance ρ of the water-saturated concrete with the compression strength of 50 and 30 MPa on its age τ, according to the experimental data [3]. Fig. 2 *a* shows that with advancing age the specific electric resistance of concrete is increased and at an age of more than 1 or 1.5 months it attains 100 Ohm·m even in the water-saturated state and at an age of 2 years it attains 280 Ohm·m for the concrete strength of 30 MPa and 430 Ohm·m for 50 MPa. It was established in [3] that the electric resistance and the concrete frost -resistance are interrelated and the alternating freezing and thawing have an effect on the electric resistance of concrete. In addition, the electric resistance of concrete specimens with the frost-resistance grade of F100 was reduced from 2.8 to 0.4 kOhm after 100 cycles, as for F200 it was reduces from 3.3 to 0.7 kOhm after 200 cycles and for the grade higher than F200 it was reduces from 3.6 to 1.6 kOhm after 200 cycles. The loss in strength for these specimens was within 2.5 %.

The polarization phenomena, in particular the forced polarization [15] also have an effect on the actual electric resistance of the cement stone. It was established in [15] that the passage of direct current through cube specimens with the edge of 10 mm made of the cement and sand (1:2.5) solution with the water-to-cement ratio W/C=0.5 at the age of 35 days results in the potential difference opposite to the externally applied U that increases the measured electric resistance of concrete. This potential difference, i.e. the forced polarization potential is increased with an increase in the value of U and it is detected by the intermediate measurement after the removal of external potential U (Fig. 2 *b*). Fig. 2 *b* shows that after the application and removal of the external potential of $U = 100$, U_{fp} immediately exceeds the value of 3 V, however it is dropped to 1.2 V approximately after 3 minutes.

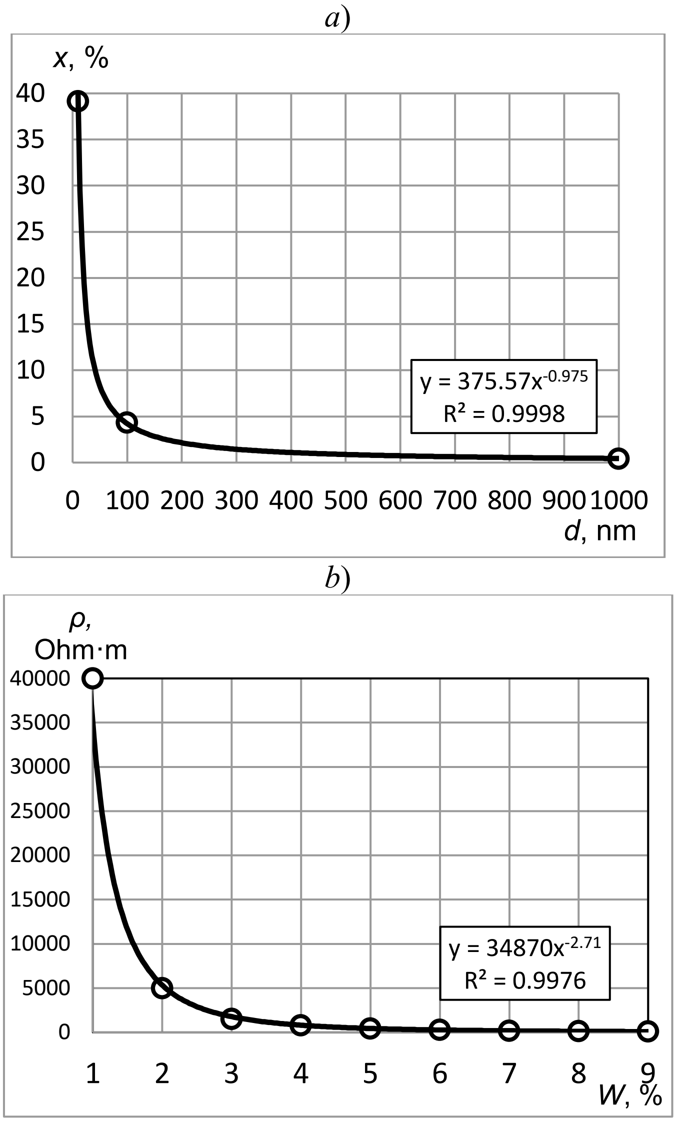

Fig. 1 Dependence of the share x that falls to the diffusion portion of DEL in the cross-section of the cylindrical pore or the capillary on the diameter of that pore d (*a*) and the specific electric resistance ρ of the concrete with the compression strength of 20 MPa on its moisture W at a temperature of 10 °C, according to the experimental data [2] (*b*)

In [3, 16] a mechanism of the forced polarization is explained by the DEL polarization around dispersed particles under the influence of external electric field and a slow reset after the termination of this influence. This polarization occurs due to the electromigration transfer of counter ions in the DEL in the appropriate direction of electric field and the reset occurs due to their back transfer by diffusion [16-18]. It is mentioned in [14, 16] that the main contribution to the forced polarization of the cement stone is made by sufficiently long capillaries not by dispersed particles.

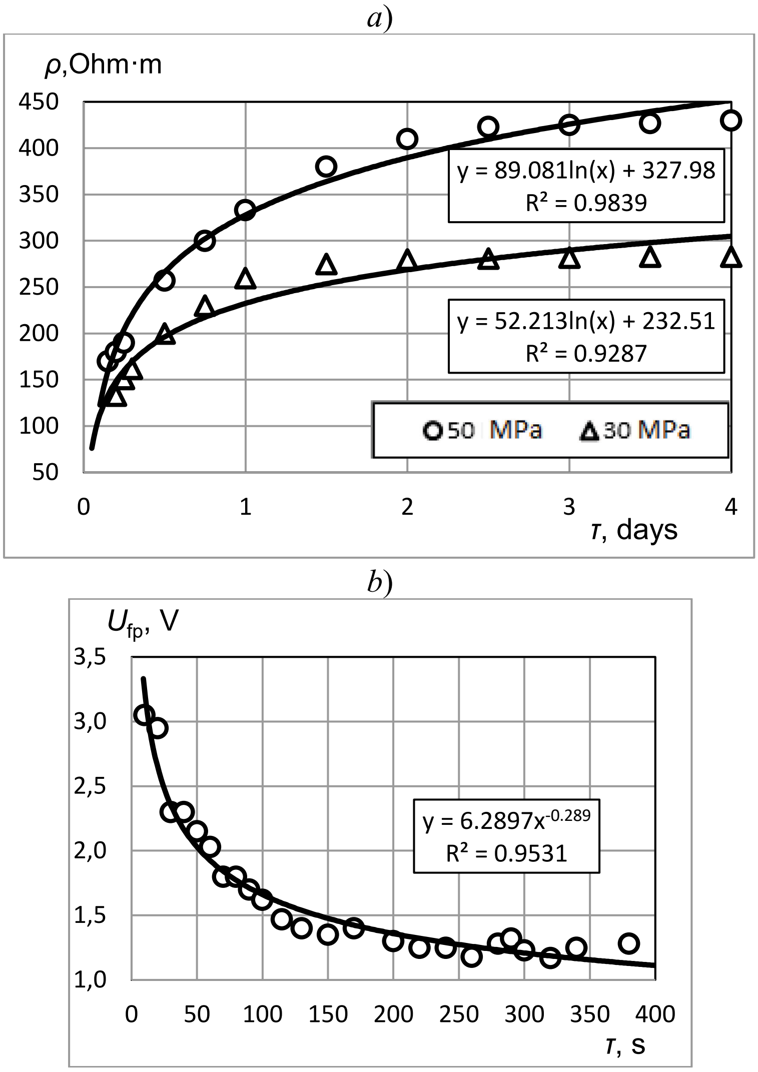

Fig. 2 Dependence of the specific electric resistance ρ of the water-saturated concrete at the compression strength of 50 (*1*) and 30 (*2*) MPa on the age of concrete τ according to the experimental data [3] (*a*) and the residual potential of forced polarization U_{fp} on the time t after the disconnection of externally applied potential difference of 100 V [15] *(b)*

On the grounds of above, the influence of forced polarization on the electric resistance of concrete and reinforced concrete structures was substantiated in [4, 13] and the equations were proposed for their electric conductivity J and the resistance R_{s} in which these are complex values consisting of active electric resistance R and the capacitance component ωC, conditioned exactly by the polarization:

$$J = \omega \cdot C + \frac{1}{R}; \quad R_s = \frac{1}{\omega \cdot C + 1/R}, \tag{2}$$

where ω is the current frequency or in the analyzed case it is the period of one-time measurement of the influence.

Hence, the electric resistance of concrete is influenced by its moisture, age, compression strength and frost resistance including the number of alternating freezing and thawing cycles and polarization phenomena. The specific electric resistance of concrete exceeding 100 Ohm·m is provided after 1 month at the moisture content within 8 %. Polarization phenomena can affect the electric resistance measurement data therefore the measurements should be taken prior to the stabilization of instrument readings. All these effects must be verified experimentally.

Methods of Experimental Investigations

The investigations were carried out using the cube specimens with the edge size of l = 100 mm made of the cement provided by five production storehouses:

Grade C32/40 for the sleepers with the cement consumption of 440 and 410 kg/m^3;

Grade C32/40 for contact network supports;

Grade C20/25 for floor plates and fence plates.

The specimens were subjected to thermal-moisture treatment together with the structures and afterwards these were held in the moist cabinet. The investigations were started for different specimen series taking into consideration their initial age of 3, 11 and 22 days. The specimens were held under different temperature-moisture conditions:

- t = 0-20 °C, φ= 10-90 % (outside, in the ambient air);
- t = 11-14 °C, φ= 76 % (inside, in the premises);
- t = 16-18 °C, φ= 70-80 % (inside);
- t = 20±2 °C, φ= 95-100 % (in the moist cabinet);
- t = 60-70 °C, φ= 70-80 % (inside in the contact with the heat source);
- t = 400 °C (in the drying cabinet).

Starting from the indicated date the mass m of each specimen was measured every twenty-four hours with the accuracy of 0.5 g and their electric resistance R was measured as well.

Based on the measurement data of the mass of specimens for each day i a change in their mass Δm and the moisture W_m was defined:

$$\Delta m = (m_i - m_0)\cdot 100 / m_0 \ [\%]; \tag{3}$$

$$W_m = (m_i - m_n)\cdot 100/m_n \ [\%], \tag{4}$$

where m_n is the mass of the specimen that was dried to a permanent mass at a temperature of 400 °C.

The electric resistance of each specimen R was measured between its opposite edges that were vertical during the molding according to the scheme given in Fig. 3 *a*. The measurements were taken using special electrodes (Fig. 3 *b*) and the digital multimeter Sanwa PC 510. Special electrodes were manufactured from the sponge *2* with the diameter d = 30 mm and the thickness of 10 to 15 mm that side with the copper plate *3* of the same diameter and of 1 to 2 mm thick to which the conductor *5* was soldered that was connected to the multimeter. The sponge was impregnated with the saturated solution of copper sulfate $CuSO_4\cdot 5H_2O$ by the method of immersion into the solution. To prepare 100 ml of the saturated solution the cup was filled with copper sulfate in the amount of 35.6 g with the addition of distilled water in the amount of 100 ml and these were mixed using the glass stick to provide a complete dissolution.

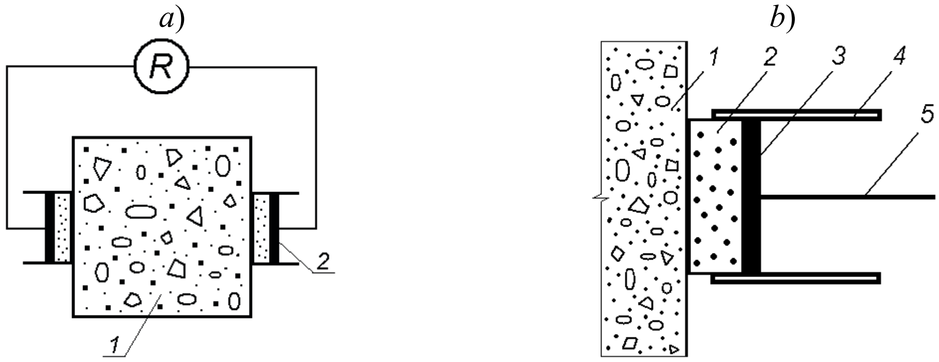

Fig. 3 Measurements of the electric resistance of concrete: *a* is the measurement scheme; *1* is the concrete specimen; *2* is the special measurement electrode; *b* is the scheme of the special measurement electrode: *1* is the concrete specimen surface; *2* is the sponge impregnated with the copper sulfate solution; *3* is the copper plate, *4* is the polymer tube; *5* is the conductor

Any digital multimeter that meets the requirements can be used: in particular if it allows us to take DC measurements; manually switch over the ranges; if it has a high input electric resistance not lower than 10 MOhm; the measurement range not higher than 10 Ohm and not lower than 10 MOhm; the resolution of at least 1 Ohm and the error within 2%.

Prior to taking the measurements, the specimen faces intended for the measurements were degreased to remove lubricant debris. During the measurement, copper sulfate -saturated electrodes were tightly and continuously pressed to specimen faces prior to taking the readings. The electrodes were subjected to the repeated impregnation after every 2 or 3 measurements. The measurements were taken in the DC mode and the measurement range was switched over manually. To switch over to another mode the electrodes were separated from the specimen and on completion of the switching these were pressed again to the surface after 1 minute. The readings were taken after 10 s following the measuring circuit closure (the contacting of electrodes). After the readings were taken the polarity was changed (by changing electrode places) and the readings were taken again. If a negative value was obtained, its absolute value was adopted.

A minimum value of the two values measured with the opposite polarity was taken as a unit value of the electric resistance of the specimen. The arithmetical mean value of the electric resistance of the all specimens of an R series was taken as the electric resistance of the series of specimens. The specific electric resistance of the concrete specimen was derived from the formula:

$$\rho = R\cdot\pi\cdot d^2/4l = R\cdot\pi\cdot 0.03^2/(4\cdot 0.1) = 7.065\cdot 10^{-3}\cdot R \text{ [Ohm}\cdot\text{m]}. \quad (5)$$

The measurement data were used to construct the diagrams - of dependence of the specific electric resistance ρ and the concrete mass loss Δm on the specimen holding time t and of dependence of the specific electric resistance ρ on mass loss Δm and the moisture W.

Experimental Investigation Data

Fig.4 gives the diagrams of dependence of specific electric resistance ρ of the sleeper concrete of a grade C32/40 on the concrete age τ for different storage conditions, in particular temperature t and a relative air humidity φ. To attain the given age of 3, 11 and 22 days the specimens subjected to the thermal moisture treatment were stored in the moist cabinet at t = 20±2°C and φ = 95-100 %. Fig. 4 shows that these dependences are well-approximated by polynomial equations. After the storage in the moist cabinet the specific electric resistance of test specimens exceeded 50 Ohm·m independently of its age. All the storage modes under outside and inside conditions showed an increase in ρ to the value of 100 Ohm·m:

- for the initial age of concrete of 3 days at a temperature of 16 to 18°C it took 27 days, and at 60 to 70 °C it took 3 days to attain this value;
- for the initial age of concrete of 11 days at a temperature of 0 to 20°C it took 15 days;
- for the initial age of concrete of 21 days at a temperature of 16 to 18°C it took 10 days, and at 60 to 70°C it took 3 days.

Fig.5 gives the diagrams of the dependence of the specific electric resistance ρ of concrete on the mass loss Δm of the specimens (on the state in which these were removed from the moist cabinet) and on the moisture W at different storage temperatures. It can be seen from Fig. 5 *a*, that the dependence of ρ on Δm is well-approximated by exponential equations. The rate of an increase in the electric resistance depends on the storage mode. The specific electric resistance of 100 Ohm·m is attained at m = 0.3-0.53 %.

Fig.5, *b* shows that the dependence of specific electric resistance ρ of concrete on its moisture W is well-approximated by exponential equations. The specific electric resistance of 100 Ohm·m is provided when the concrete moisture content W is within 5.3 to 5.4 %.

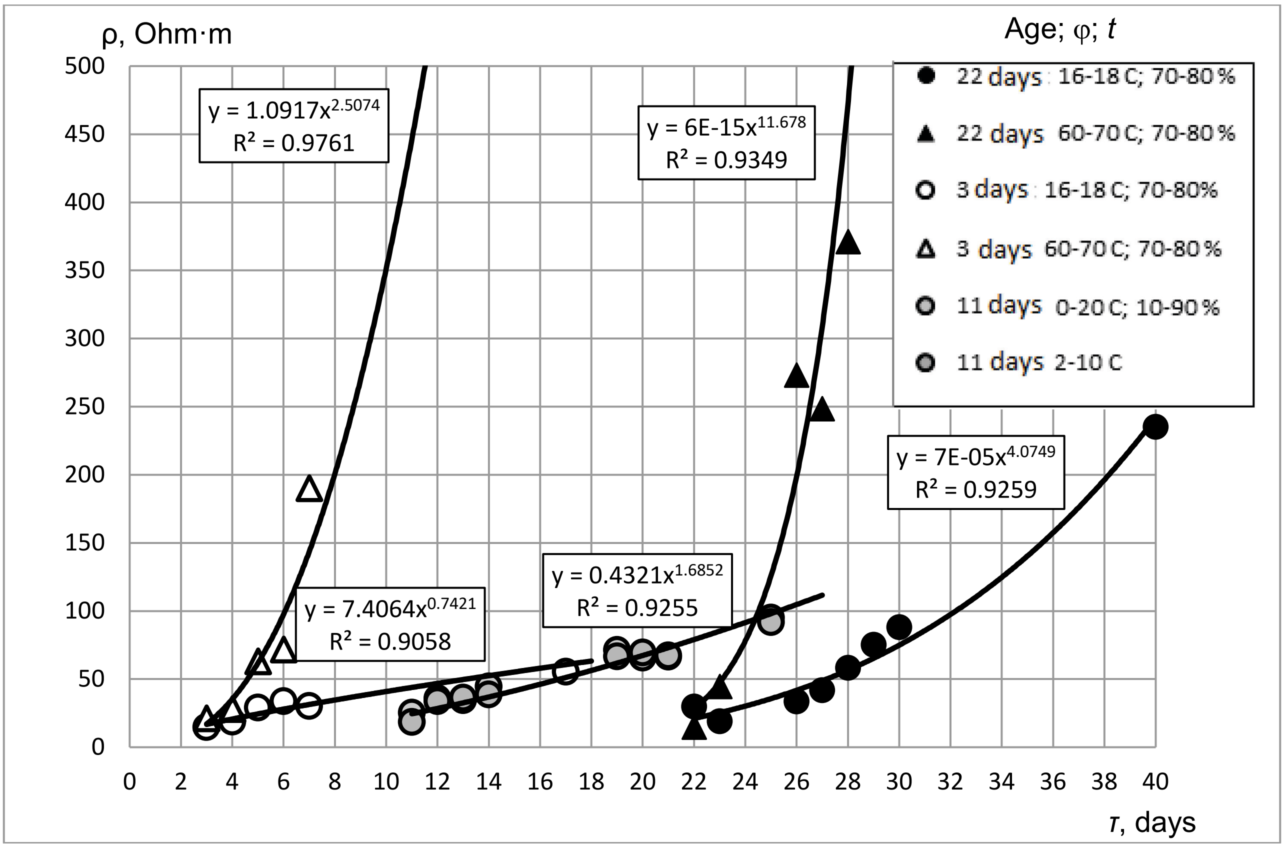

Fig. 4 Dependence of the specific electric resistance ρ of the concrete on its age τ at different storage temperatures t and relative air humidity φ. All the specimens were stored at $t = 20\pm2$°C and $\varphi = 95$ to100 % to attain the age of 3, 11, 22 days

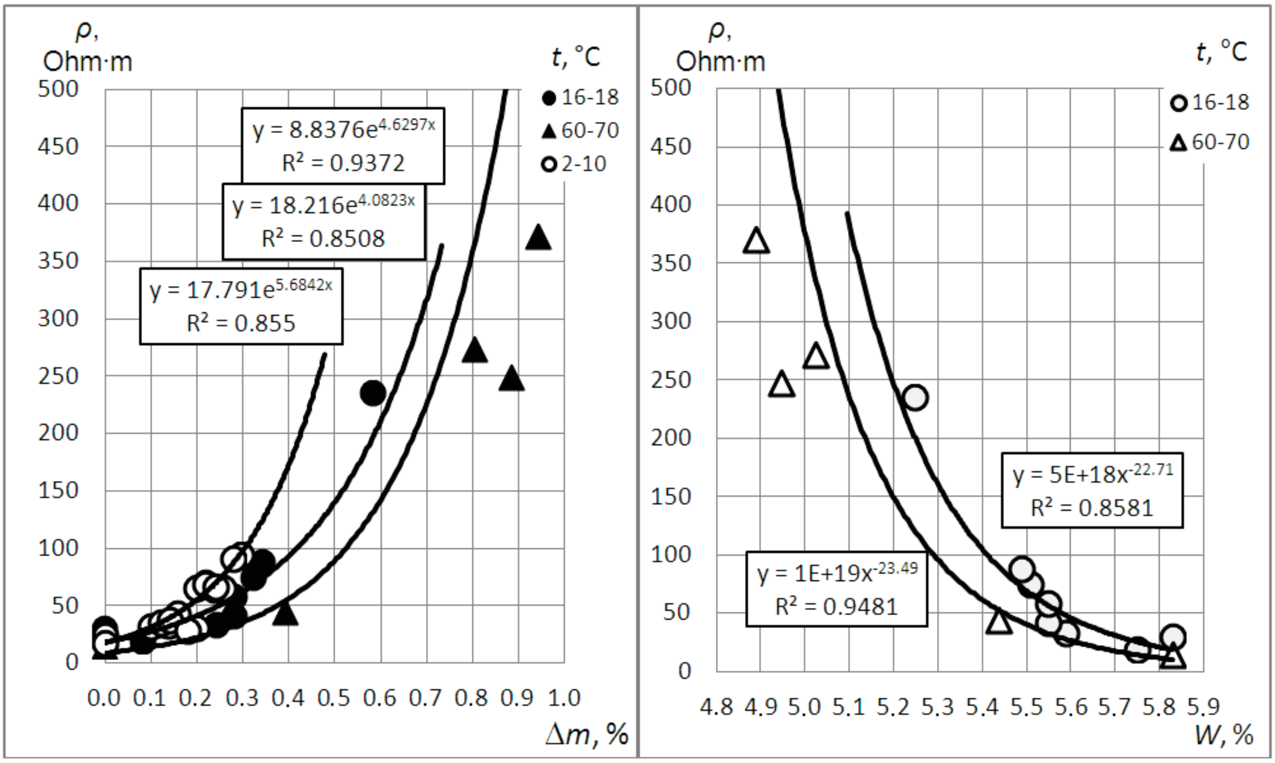
a) *b*)

Fig. 5 Dependence of the specific electric resistance ρ of the concrete on the mass loss Δm (*a*) of the specimens during their storage (on the state in which these were removed from the moist cabinet) and on the moisture W (*b*) at different storage temperatures t

Fig. 6 gives the kinetics of a change in the mass Δm of the concrete specimens of C32/40 and C20/25 grades during their storage in the given mode (starting from the state in which these were removed from the moist cabinet) and in their specific electric resistance ρ. It can be seen from Fig. 6 that the storage of specimens at a relative air humidity exceeding 95 % resulted in no mass reduction and / or an increased electric resistance of the concrete, but on the contrary it provided the increase of the mass of specimens by 0.4 % and a certain drop in the electric resistance. A decrease in the relative air humidity to 70-80 % resulted in a fast decrease in the mass of specimens and in an increase of the specific electric resistance of the concrete. It took 5 days for the specific electric resistance to attain the value of 100 Ohm·m.

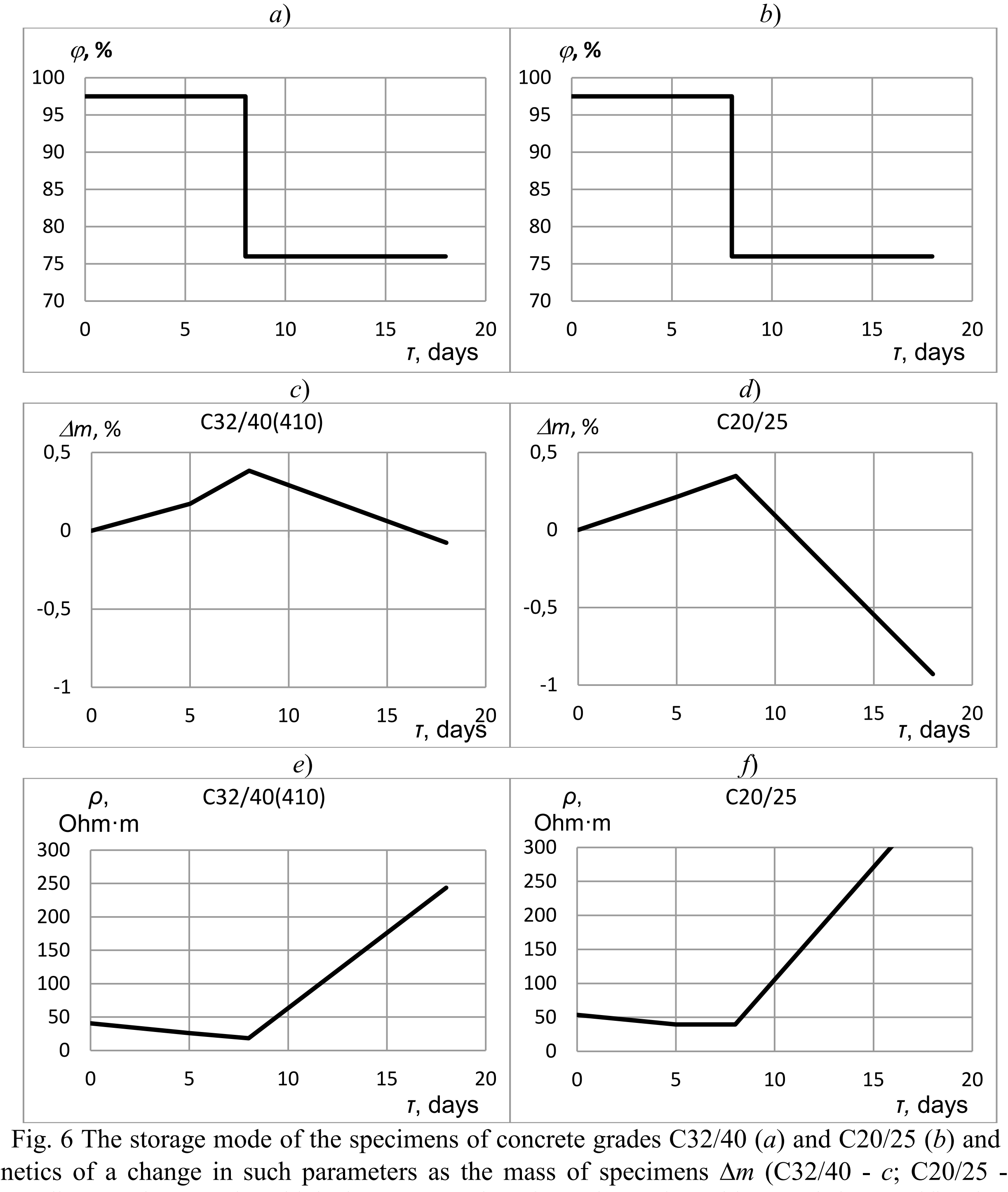

Fig. 6 The storage mode of the specimens of concrete grades C32/40 (*a*) and C20/25 (*b*) and the kinetics of a change in such parameters as the mass of specimens Δm (C32/40 - *c*; C20/25 - *d*) depending on the state in which these were taken from the moist cabinet and the specific electric resistance ρ (C32/40 - *e*; C20/25 - *f*) of concrete during their storage (depending on time τ)

Research Data Summarization and Discussion

The analytical review of literature sources and theoretical investigations showed that the electric resistance of concrete as the polydisperse system and capillary-&-porous body is formed by the electric resistance of the solid phase in the range of $1\cdot10^4$ to $1\cdot10^{10}$ Ohm·m and that of the liquid phase represented by the saturated solution of $Ca(OH)_2$ (porous electrolyte) of 1.2-1.25 Ohm·m.

The pore electrolyte is the conductor of the second kind in which Ca^{2+} and OH^- ions act as electric current carriers. In the noncapillary pores and in the macrocapillaries (whose size varies in the range of 1 and 0.1-1µm, accordingly) of concrete actually all the water is physically bound, and in the microcapillaries (10 to 100nm) and gel pores (less than 10nm) the content of physically bound water makes up 60 to 95 % and less than 60 %, accordingly. Physically bound water ions are incorporated into the composition of double electric layers, in particular in their diffusion portion of approximately 1.1 nm thick. These ions are sluggish and their influence on the electric conductivity can be neglected. Hence, the electric resistance of concrete is mainly defined by physically bound water contained in the noncapillary pores and in the macrocapillaries.

The electric resistance of concrete is subjected to the effect of its moisture, age (crystallineness degree of the hydration and neutralization products of $Ca(OH)_2$), water-cement ratio (compression strength and frost-resistance), availability of free electrolyte admixtures and the salts of a different origin (for example from the aggregates,) and also destructive effects (the number of alternating freezing and thawing cycles, etc). The specific electric resistance ρ of concrete over 100 Ohm·m is provided at the age of over 1 month at the moisture W within 8 %. At W less than 1.5 % when actually all the water is physically and chemically bound in the DEL, ρ is increased to the values that exceed $1\cdot10^4$ Ohm·m and are peculiar for the aggregates, clinker minerals and the crystallohydrates.

Due to alternating freezing and thawing cycles ρ is decreased and for the concretes of a frost-resistant grade, in particular F200 and lower it drops below 100 Om·m. We believe that it happens due to the formation of the combined spatial system of cracks that are not critical for the compression strength (its loss is in the range of 2 to 5 %) but these have a strong effect on ρ due to the watering.

The storage of concrete specimens of C32/40 and C20/25 grades at φ over 95 % resulted in the specimen mass buildup by 0.4 % and a certain decrease in ρ. A decrease in φ to 70-80 % provided a fast decrease of the mass of specimens and an increase in ρ that attained 100 Ohm·m after 5 days.

Hence, at the age of one month and the moisture within 8 % in the absence of the influence of electrolyte admixtures that failed to bind to form hydrates or the salts of other origin and /or in the absence of an ample quantity of alternating freezing and thawing cycles the specific electric resistance of the concrete of a C32/40 grade used for reinforced concrete sleepers should attain the value over 100 Ohm·m. Therefore, the speeding up of the processes of attainment of an appropriate ρ value at the concrete age less than 1 month through the holding mode for its final check won’t provide the operation of the track-placed sleepers whose specific electric resistance is less than 100 Ohm·m.

As consequence of the investigations carried out we managed to specify the holding conditions of concrete specimens before the measurement of their specific electric resistance. The measurements of the electric resistance of concrete specimens should be taken after their holding in air-dry conditions at relative air humidity within 75 % and the air temperature not lower than +18°C at least during 7 days.

Conclusions

The obtained theoretical and experimental investigation data allowed us to establish the influence of the concrete moisture, age, holding conditions after the thermal moisture treatment and other factors on the specific electric resistance of the concrete of a C32/40 grade used for the reinforced concrete sleepers. As consequence of the research done, we specified the mode and the holding time that allow us to obtain objective data on the specific electric resistance of the concrete used for the sleepers that is measured during their operation.

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