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New research methods of electro-corrosion processes in concrete structures

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Abstract. The paths of electric currents flowing through sleepers and traditional methods of corrosion under the influence of leakage currents are analysed. Based on the results of this analysis, a new method of studying the processes occurring in concrete under the influence of electrical potentials is proposed for comparative studies of the electro-corrosion behaviour of sleepers and other structures with steel and composite reinforcement. The method involves the application of electric potentials, constant or pulsating unidirectional, to the sleeper models and the study of samples extracted from the models using nanoindentation. By means of nanoindentation it is possible to obtain the values of the micromechanical properties of the cement paste, the modulus of elasticity *E* and the hardness *H*, which depend on the degree of its electromigration leaching. It is experimentally proved that due to electromigration leaching, *E* and *H* decrease, starting from the face of the model, for which a negative potential is applied. The values of unleached and maximally leached cement paste with W/C = 0.35, which is characteristic of concrete sleepers, are determined. It is found that the nature of these dependencies and, consequently, the intensity of electro-corrosion processes in concrete, depends on the nature of the applied electrical potential (constant or pulsating unidirectional) and the type of reinforcement (steel or composite).

1 Introduction

Reinforced concrete and wooden sleepers are the main types of sub-rail foundations on the world's railways. Compared to wooden sleepers, reinforced concrete sleepers are not subject to biological damage and wear out to a lesser extent in the sub-rail area, and therefore they have a longer service life (durability). Reinforced concrete sleepers provide more reliable track stability due to their greater weight and the strength of the rail fasteners, which is why they are preferred for sections with higher load and speed, as well as for jointless track. However, reinforced concrete sleepers have a number of drawbacks. Their greater weight requires more powerful mechanization equipment and higher energy consumption for track laying and maintenance. Sleepers have a high electrical conductivity, which in wet weather, especially with worn insulation parts and microcracks in concrete, leads to an increase in traction current losses on AC or DC electrified railway sections (figure 1). The presence of reinforcement at the ends of sleepers due to the manufacturing technology also affects the current flow paths. Constant leakage currents cause electro-corrosion processes in metal parts, reinforcement and even concrete of sleepers and metal and reinforced concrete structures located in the path of leakage currents.

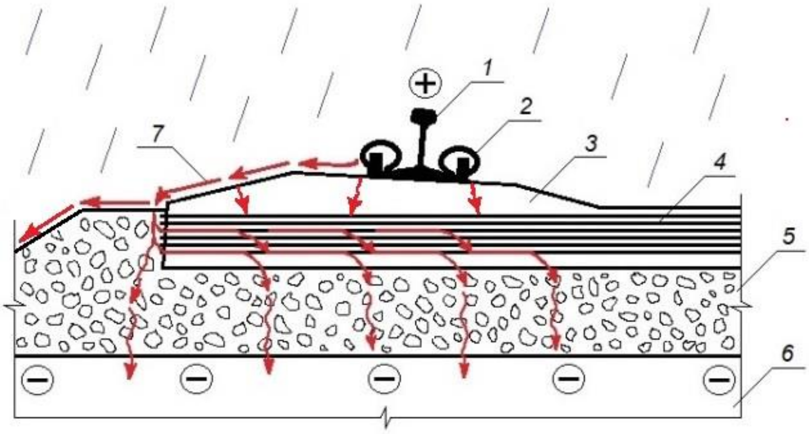


Figure 1. Diagram of leakage current flowing through sleeper and ballast in wet weather [1]: *1* – rail; *2* – rail fastener; *3* – concrete of the sleeper; *4* – reinforcement wire; *5* – ballast; *6* – roadbed; *7* – leakage current

Earlier, the authors have proposed to lay sleepers with composite reinforcement made of basalt or glass fibres bonded with epoxy resin for DC electrified sections. It is assumed that replacement of steel reinforcement in concrete sleepers with composite reinforcement will increase their electrical resistance, reduce leakage currents (in particular, traction current losses), eliminate corrosion processes associated with the flow of electric current and the influence of aggressive media, reduce the requirements for crack resistance of sleepers, and reduce the prestressing forces of the reinforcement. Most of these characteristics of sleepers with steel and composite reinforcement can be compared using standard or conventional testing methods. However, there are no standard methods for assessing electro-corrosion processes in concrete, so the development of new original research methods that can be used to compare the effects of electric currents on concrete and reinforcement is an urgent task.

This work was carried out by the Ukrainian State University of Railway Transport together with the University of the West of Scotland as part of work package III Railway sleepers of the grant research project "Integrated rail freight optimization in Ukraine: Railway sleepers, rolling stock and logistics" (UUK and UK-Ukraine R&I twinning grant , Project #11150).

2 An analytical review of studies of electro-corrosion processes in reinforced concrete structures

It is known that metal structures and reinforcement of reinforced concrete structures undergo electro-corrosion under the influence of direct currents [2, 3], in particular, leakage currents from the rail tracks of DC electrified railways [1, 4]. Electro-corrosion damage is also observed in steel fibre concrete [5].

Study [1] and other works of the authors demonstrate that constant or pulsating unidirectional electrical potential triggers corrosion processes in concrete, thus intensifying various known types of corrosion, which depends on the ion transfer processes, i.e., leaching (figure 2, a), internal corrosion due to an alkali-silica reaction (figure 2, b), etc. These processes result in significant gradients of concrete properties in structures. Study [6] shows that electric potentials accelerate leaching due to the ion transfer and lead to the formation of property gradients.

Various theoretical and experimental methods are used to study electro-corrosion processes including the finite element method [7, 8]. However, these methods are mainly used to study the electro-corrosion of reinforcement. In [9] and other works, the authors investigate the corrosive effect of electric current on concrete by determining the change in the density and strength of concrete, electrical measurements, pH-metry, optical and electron microscopy, X-ray phase analysis, and infrared spectroscopy. These methods are not necessarily accurate, but they are independent and complementary.

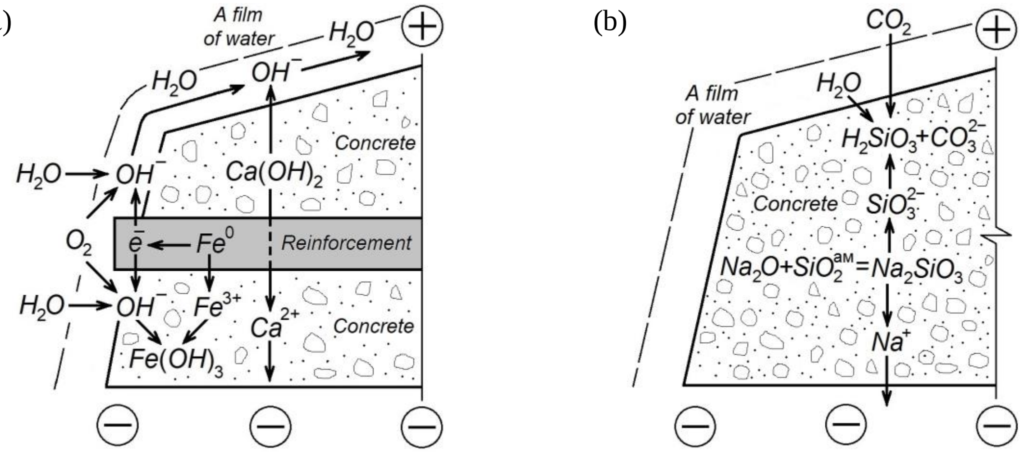


Figure 2. Diagram of current flowing through concrete and steel reinforcement of sleepers and corrosion processes [1]: (a) – current flowing through concrete and reinforcement and electro-corrosion of reinforcement; (b) – intensified corrosion of concrete due to ASR

In [10], a correlation is revealed between the *Ca*/*Si* ratio and the micromechanical properties of the cement paste and it has been proposed to use this correlation to study the effects of leaching. Thus, the nanoindentation method is used to determine the micromechanical properties. We believe that this method, as an independent one, will well complement the known methods for studying electro-corrosion processes in concrete and significantly increase the reliability of research results.

Consequently, the purpose of the work is to develop a methodology for studying electro-corrosion processes in concrete to compare their intensity in structures with steel and composite reinforcement.

Research tasks:

1) to substantiate of the method of research of electrocorrosion processes using nanoindentation;

2) to investigate the relationship between the micromechanical properties of cement paste and the degree of its electrocorrosive damage, which is electromigratory leaching;

3) to determine the micromechanical properties of the original and leached cement paste

3 Development of research methods

In order to study electro-corrosion processes in sleepers with composite and steel wire reinforcement, an original research method is developed using models that present the operating conditions for sleepers in an electrified track (figure 1). The models are samples of cement-sand mortar or cement stone 1 (figure 3) with bundle of steel wire *2* or composite rod *3*. The models are formed in cylinders of dielectric material *4*, in which the ends of reinforcement go through their walls. The gaps between the cylinder holes and the reinforcement are sealed with silicone sealant. The models are placed in container of dielectric material *6*, filled with water or a solution of electrolyte (sodium chloride). The cylinder above the sample is also filled with water or sodium hydroxide solution, respectively. Electrodes *7* are placed above and below the sample: positive on top, negative on the bottom.

The models are exposed to an electric potential, constant and pulsating, in the mode that simulates rolling stock passing on the track section relative to a section of the overhead line. The control models are in the same media without electrical exposure. After exposure to various aggressive impacts, the models are cut into specimens and their sections on lower, near-reinforcement and upper zones are examined. The depth of chloride penetration is determined by direct measurement on the section after treatment with a silver nitrate solution, and the depth of neutralisation through leaching is determined by a phenolphthalein solution.

(a) (b)

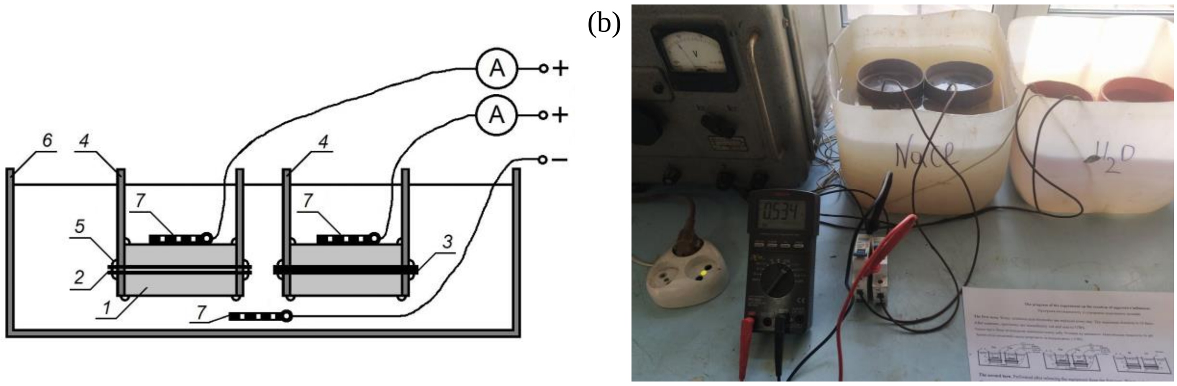


Figure 3. Experimental installation with sleeper models with steel wire and composite reinforcement for the study of electro-corrosion processes: *a* – schematic diagram; *b* - general view

The change in the properties of cement stone along the height of the model is determined by the nanoindentation method. To do this, samples of 20×20×20 mm are cut out of different areas of the models and immersed in a vacuum-impregnated epoxy resin cylinder. After the epoxy has cured, the upper face of the samples is smoothed with a diamond disc and polished to a roughness size of 0.25 µm. The finished samples are shown in figure 4.

(a) (b)

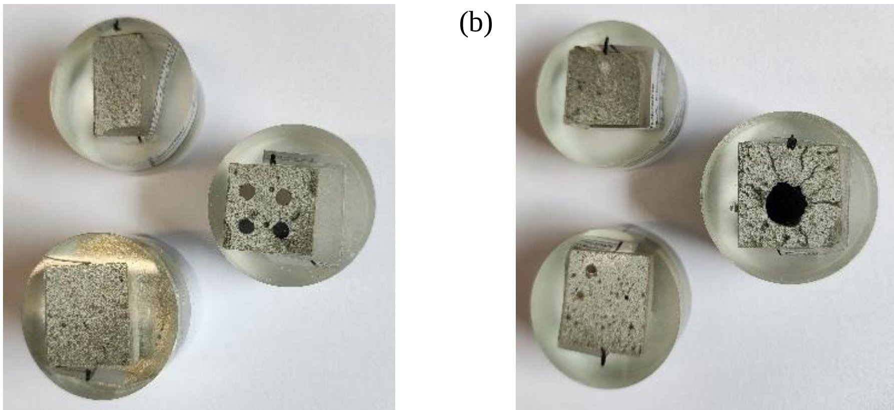
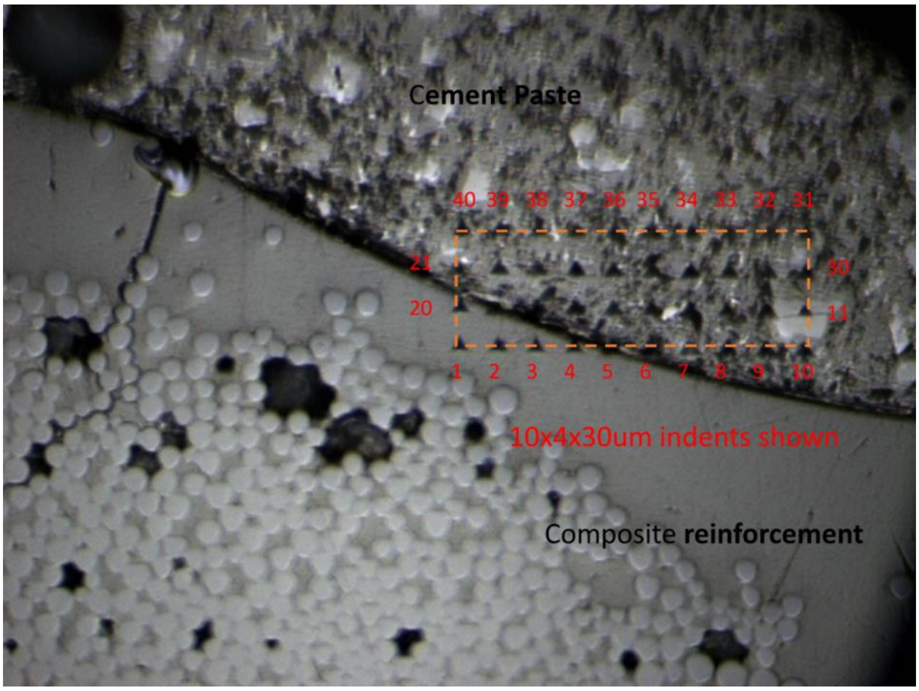


Figure 4. Specimens prepared for nanoindentation: (a) – from models with steel wire reinforcement; (b) – from models with composite reinforcement

Nanoindentation is performed using an Agilent G200 Nano Indenter® equipped with a Berkovich diamond indenter tip. The device presses the indenter into the surface of the sample and measures the force and depth of indentation at different points (figure 5). By the values of force and depth, the software of the device determines the micromechanical properties, the modulus of elasticity *M* in GPa and the hardness *H* in MPa. Measurements are carried out in zones located at different distances *h* from the edge of the sample, which corresponds to the lower face of the model (figure 3). In each zone, 30–40 measurements are made and the average value for each zone is calculated. Based on the results of measurements, graphs of the dependence of *M* and *H* on the distance *h* are plotted. By the nature of these graphs, conclusions are drawn about the gradients of the micromechanical properties of the cement paste, and therefore, about the influence of the electric potential on electro-corrosion processes. The reinforcement zone is also examined (figure 5)



M, GPa	0	30	60	90	120	150	180	210	240	270
90	29.5	29.5	25.7	24.2	26.9	14.6	29	26.3	23.3	26.1
60	50.8	36.7	20.9	36.6	29.5	22.7	38.8	32.1	49.2	31.2
30	5.2	9.4	18.6	28.9	23	25.3	26.9	44	37.5	100.8
0	5.3	5	5.3	5.5	14.2	27	5.8	22.7	35.4	24.9

H, MPa	0	30	60	90	120	150	180	210	240	270
90	0.91	1.19	0.99	0.78	0.83	0.39	1.17	1.08	0.82	0.75
60	5.13	1.53	0.68	1.19	0.94	0.93	1.46	1.69	2.39	1.11
30	0.35	0.73	0.73	1.32	0.9	0.92	1	1.93	1.56	8.06
0	0.35	0.32	0.37	0.37	0.66	1.21	0.39	0.88	1.42	0.69

Figure 5. A specimen from a model with a composite reinforcement after exposure to a direct potential: indentation area (zone) with associated *M* and *H* properties maps

4 Results and discussion

The effect of the nanoindentation method, created according to the diagram of figure 3, on cement paste with W/C = 0.35 in sleeper models with steel wire and composite reinforcement of electric potentials, has been studied at:
- direct 38 V for 96 hours in the aquatic environment;
- pulsating (15 min. on, 10 min. off) unidirectional 38 V for 160 hours in aqueous environment (96 hours direct electrical exposure).

The cement paste layer of the model has been studied from its lower face to the reinforcement. Graphs of the dependence of the elasticity modulus *M* and the hardness *H* of the surface of the samples from these models on the distance from the lower face of the models are shown in figure 6.

As can be seen from the graphs (figure 6), electrical influences led to the formation of gradients of micromechanical properties of the cement paste, caused by the transport of Ca^{2+} cations and the decomposition of $Ca(OH)_2$ and calcium hydrosilicates. In the depth of the models, where leaching does not cause tangible impact, the modulus of elasticity *M* is 27–33 GPa, and the microhardness *H* is 1.2–1.4 MPa. Near the lower face, where the number of Ca^{2+} ions is maximum, *M* and *H* decrease to 15–20 GPa and 0.8–1 MPa, respectively.

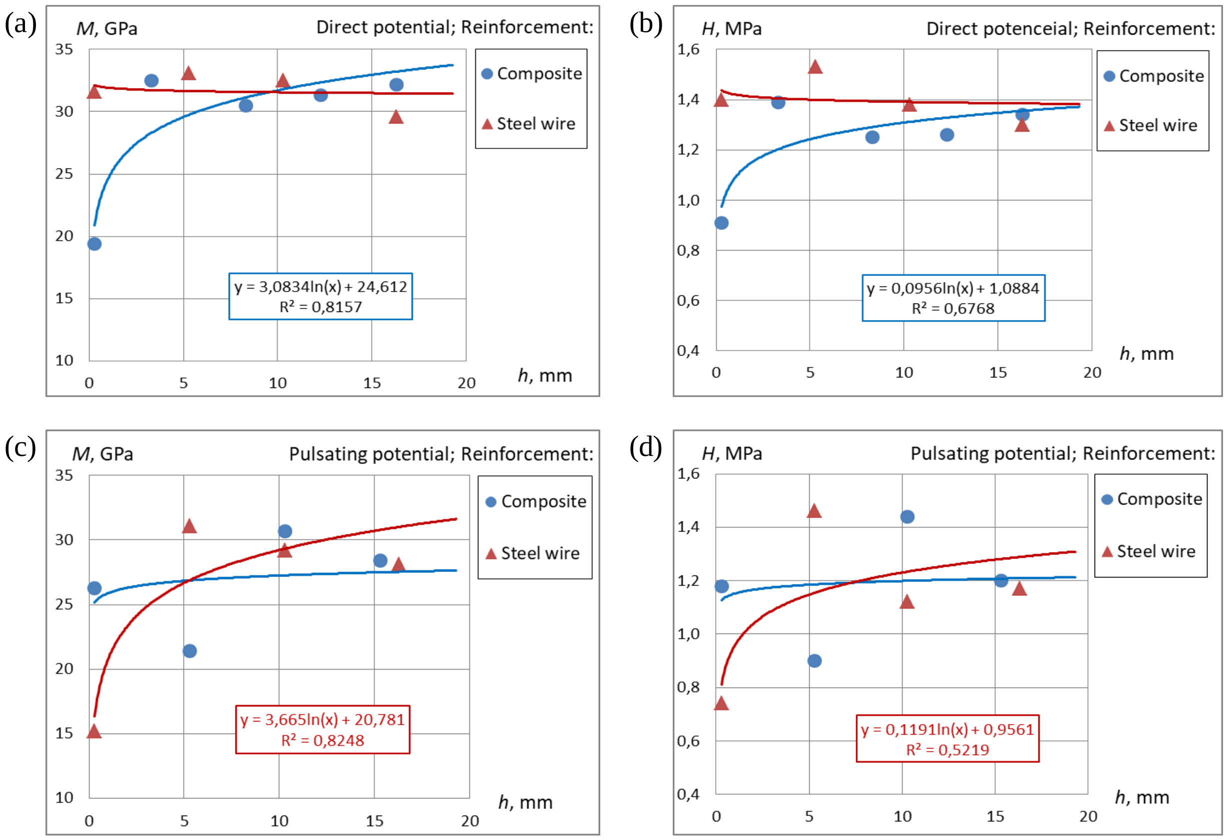


Figure 6. The dependence of the elasticity modulus *M* (a, c) and the hardness *H* (b, d) of cement paste on the distance *h* from the bottom face (negative potential) according to the results of nanoindentation after exposure to direct potential (a, b) and pulsating unidirectional potential (c, d)

From the graphs of figure 6 also shows that the effects of constant and pulsating potentials on the specified layer of cement paste of the model with steel and composite reinforcement are different:

1) under the influence of a constant potential in the model with steel reinforcement, there is almost no change in micromechanical properties – *M* and *H* along the entire height of the sample are about 32 GPa and 1.4 MPa, respectively;

2) under the influence of a constant potential in the model with composite reinforcement *M* increases from 20 to 34 GPa and *H* – from 1 to 1.4 MPa along the sample height, the change is well described by a logarithmic equation with a correlation coefficient of 0.82–0.9;

3) under the influence of a constant potential in the model with steel reinforcement *M* increases from 15 to 32 GPa, and *H* – from 0.8 to 1.3 MPa along the sample height, the change is well described by a logarithmic equation with a correlation coefficient of 0.72–0.9; and

4) under the influence of a pulsating unidirectional potential in the model with composite reinforcement, there is almost no change in micromechanical properties – *M* and *H* are about 26 GPa and 1.2 MPa, respectively, along the entire height of the sample.

Thus, under the influence of a constant potential in the model with steel reinforcement, electro-corrosion processes in the cement paste do not occur, obviously due to the fact that current leaks through the reinforcement extensions (figure 1; 3, a). In the model with composite reinforcement, in which current does not leak through the reinforcement, it runs through the cement paste, and the electro-corrosion processes in the cement paste are intense.

Under the influence of a pulsating unidirectional potential in the model with steel reinforcement, despite the current leaks from the reinforcement extensions, electro-corrosion processes in the cement paste are intense, obviously due to the polarization and de-polarization of the reinforcement and the cement paste layer between the reinforcement and the lower face. In the model with composite reinforcement, on the contrary, electro-corrosion processes in the cement paste are almost not observed, possibly due to the fact that the reinforcement is not polarized and the thickness of the cement paste layer is doubled.

5. Conclusions

Thus, a new informative method for studying electro-corrosion processes in concrete structures, in particular, railway sleepers, under the influence of leakage currents is substantiated; it includes the creation of these electrical influences on models and the study of models by nanoindentation. Nanoindentation makes it possible to obtain the values of the micromechanical properties of the cement paste, the modulus of elasticity *M* and the hardness *H*, which depend on the degree of its electromigration leaching.

It is experimentally established that as a result of electromigration leaching, *M* and *H* decrease, starting from the face of the model, on which a negative potential is applied during exposure. The maximum values of *M* and *H* are in the depth of the model, and their dependencies on the distance from the specified face are well described by logarithmic equations. The unleached cement paste of concrete sleepers with $W/C = 0.35$ is characterized by M = 27–33 GPa and H = 1.2–1.4 MPa. As a result of electromigration leaching, *M* and *H* are reduced to 15–20 GPa and 0.8-1 MPa, respectively.

It is also proved that the nature of these dependencies and, consequently, the intensity of electro-corrosion processes in concrete, depends on the nature of the applied electrical potential (constant or pulsating unidirectional) and the type of reinforcement (steel or composite).

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