Hydraulic and Civil Engineering Technology VIII
M. Yang et al. (Eds.)
© 2023 The Authors.
This article is published online with Open Access by IOS Press and distributed under the terms of the Creative Commons Attribution Non-Commercial License 4.0 (CC BY-NC 4.0).
doi:10.3233/ATDE230772

## Concrete Protection from Sulfate Aggression by Coating Based on Zeolite-Like Binders

# Pavlo KRYVENKO<sup>a,1</sup>, Igor RUDENKO<sup>a</sup>, Oleksandr KONSTANTYNOVSKYI<sup>a</sup>, Danutė VAIČIUKYNIENĖ<sup>b</sup>

 <sup>a</sup>Scientific Research Institute for Binders and Materials, Kyiv National University of Construction and Architecture, 03037 Povitroflotskyi Avenue, 31, Kyiv, Ukraine.
 <sup>b</sup> Faculty of Civil Engineering and Architecture, Kaunas University of Technology, Studentu st. 48, LT-51367 Kaunas, Lithuania

**Abstract.** The article is dedicated to concrete protection, exploited in sulfate mediums. Protective surface coating based on based on zeolite-like binder was proposed as a mean to restrict  $SO_4^{2^-}$  ions transport in concrete. It was demonstrated that the coating with a 3 mm thickness provides total protection of concrete. The ions transport in concrete depending on cation of sulfate medium lowers in the row  $(NH_4)_2 SO_4 > Na_2 SO_4 > Mg SO_4$ . The simulation of coating work was realized by adding the specified salts in zeolite-like binder. pH value decreasing of water extracts during binder hydration while applicated 2.5 % Mg SO\_4 is evidence of higher crystallinity of zeolite-like hydroalumino silicates, containing sulfate, with including of  $Mg^{2+}$  ions equal to  $Ca^{2+}$  ions. While the content of  $(NH_4)_2 SO_4$  was rised up to 5.0 %, minor pH was fixed due to declined synthes of other zeolite-like minerals. The absence of  $Na_2SO_4 (0.5...2.5 \%)$ . Thus, the limitation of  $SO_4^{2^-}$  ions transport in the coating is due to their binding in zeolite-like minerals with advanced crystallinity in the appearance of  $Na^+$ ,  $NH_4^+$ , and  $Mg^{2+}$  sulfate cations.

Keywords. Zeolite-like binder, concrete, sulfate aggression, protective coating, ions transport, corrosion

### 1. Introduction

The durability of concrete is one of the main requirement in building production. Operating conditions determine the construction durability. Engineering constructions in chemical and energy industries, seaports, bridge foundations, tunnels, etc. undergo the most destructive influence [1-3]. Sewage systems and drainage systems of bridges and mega-cities are exploited in aggressive conditions [4]. Still, nearly, 75 % of concrete constructions undergo the destructive influence of aggressive mediums [5].

Sulfate mediums are among the most aggressive that causes steel reinforcement corrosion. This is because of the presence of sulfates in almost all natural and sewage waters [6]. The penetration of sulfate ions in concrete is determined by cation in sulfate

<sup>&</sup>lt;sup>1</sup> Pavlo KRYVENKO, Corresponding author, Scientific Research Institute for Binders and Materials, Kyiv National University of Construction and Architecture, 03037 Povitroflotskyi Avenue, 31, Kyiv, Ukraine; E-mail: pavlo.kryvenko@gmail.com.

salt [7]. Sulfate ions do not determine steel reinforcement depassivation but cause the formation of hydrogen sulfide ( $H_2S$ ), which catalyzes the oxidation (carbonation) of hydrates. This effect is accompanied by lower pH values of pore water as the main factor for the stability of passive film on the surface of steel reinforcement [8].

The modern demands for advanced consistency of fresh concretes are realized on the practice. Thus, the disturbance of the reinforcement passive state can be determined by changes in concrete especially in aggressive mediums. Thus, the limitation of sulfate ions transport in concretes, obtained from advanced consistency of fresh mixes and exploited in sulfate mediums, is an actual problem [9].

Limitation of sulfate ions transport in concrete structures can be achieved due to their binding by hydrated phases of cements. Hydro silicate C–S–H and hydro aluminosilicate C–A–S–H gel-liked phases of Portland cement are characterized by chemical adsorption [10]. Sulfate-ions can be also chemically binded due to the participation of tricalcium aluminate (C<sub>3</sub>A) and fourcalcium alumoferrite in the formation of AFm phases (Al<sub>2</sub>O<sub>3</sub>-Fe<sub>2</sub>O<sub>3</sub>-mono), which can include different anions [11].

The durability of reinforcement concrete structures can be increased due to the application of cements containing ground blast furnace slags (further, GBFS). Such cements conform to the modern tendencies in construction engineering [12, 13]. Their ecological profits are caused by less emission of  $CO_2$  due to the use of waste products [14]. Formation of *AFm* phases can be enhanced due to GBFS in cement in view of higher Al<sub>2</sub>O<sub>3</sub> content [15]. *AFm* phases are characterized by advanced binding capacity if compare with calcium hydro silicates [16].

Alkali-activated slag cements (further, AASCs) are the most perspective ones to ensure the durability of reinforced concrete, which undergo sulfate aggression [17, 18]. The ecological benefits of AASCs are caused not only by the reduction of  $CO_2$  emission but also by the possibility of using radioactive wastes and manufacturing waters [19] in safe building materials.  $SO_4^{2-}$  ions are bound in AASCs by hydro silicate C–S–H and hydro aluminosilicate C–A–S–H gels as well as by alkaline hydro aluminosilicates, which are analogs of natural zeolites [17, 20]. The mean to restrict aggressive ions in pore water due to binding by *AFm* phases and natural zeolite in AASC was developed [21, 22, 23].

Advanced densification of structure due to surfactants is also known for minimization of  $SO_4^{2^-}$  ions transport in concrete. Nowadays the most effective waterreducing surfactants for Portland cement systems are polyesters [24]. However, increasing slag in cement leads to minor effectiveness of specified surfactants [25] and to its total loss in the case of AASC [26]. The principles for the choice of surfactants and complex admixtures based on them were proposed: plasticizers [27], for control the setting times [28], for mitigation of drying shrinkage [29], for control of freeze/thaw resistance [30] etc.

Specified means for limitation of  $SO4^{2-}$  ions transport in reinforced concrete structure should be taken into account and used comprehensively while building of constructions. However, protective coatings, which prevent penetration of aggressive ions in concrete and ensure a passive state of steel reinforcement, are used for the protection of already constructed structures. There are different types of protective coatings: for covering of concrete surface; for sealing the surface with densification of porous structure; and for impregnating [31]. For instance, water solutions of chlorides, nitrates, and sulfates of alkaline-earth metals ( $Mg^{2+}$ ,  $Zn^{2+}$ ,  $Mn^{2+}$ ,  $Cu^{2+}$ ,  $Ni^{2+}$ ) which can bind free alkali in insoluble compounds, ensure densification and advanced impermeability can be used in AASC's concretes [32].

Inorganic protective coatings, based on zeolite-like binders, for the prevention of aggressive ions transport in concrete and ensuring the passive state of steel reinforcement, are known [33]. Protective coatings based on zeolite-like binder with advanced durability in different exploitation conditions and the due formation of analogs of natural zeolites and feldspathoids were proposed [17, 34]. High performances, water resistance and durability of protective coatings based on such binder with formula (0.8Na<sub>2</sub>O+0.2K<sub>2</sub>O)·Al<sub>2</sub>O<sub>3</sub>·4.5SiO<sub>2</sub>·nH<sub>2</sub>O are provided due to formation of zeolite-like hydrated phases as sodium and potassium heulandite (Na<sub>5</sub>Si<sub>27</sub>Al<sub>9</sub>O<sub>72</sub>·26H<sub>2</sub>O and K<sub>5</sub>Si<sub>27</sub>Al<sub>9</sub>O<sub>72</sub>·24H<sub>2</sub>O agreeably). phillipsite (1.5Al<sub>3</sub>Si<sub>5</sub>O<sub>16</sub>·6H<sub>2</sub>O), chabazite (Ca, Na<sub>2</sub>, K<sub>2</sub>)<sub>2</sub>(Al<sub>2</sub>Si<sub>4</sub>O<sub>12</sub>)<sub>2</sub>·12H<sub>2</sub>O) and faujasite (Ca, Na<sub>2</sub>, Mg)<sub>3.5</sub>(Si<sub>17</sub>Al<sub>7</sub>O<sub>48</sub>)·32(H<sub>2</sub>O). Oxide ratios in the zeolite-like binder should be  $SiO_2/Al_2O = 4.5$  and  $R_2O/Al_2O_3 = 1.0$  to ensure the necessary direction in structure formation [35].

It can be predicted that, while the interaction of the mentioned coating with sulfate mediums, zeolite-like minerals will bind  $SO_4^{2-}$  ions and ensure their less penetration in protected concrete.

Thus, this research aimed to investigate the restriction  $SO_4^{2-}$ -ions transport in concrete by protective coating based on zeolite-like binder.

#### 2. Raw Materials and Testing Techniques

Zeolite-like binder with formula (0.8 Na<sub>2</sub>O+0.2 K<sub>2</sub>O)·Al<sub>2</sub>O<sub>3</sub>·4.5SiO<sub>2</sub>·nH<sub>2</sub>O was used in protective coating.

Aluminosilicate components of the binder were presented by:

- metakaolin (Ukraine) (by mass, %:  $SiO_2 - 53.67$ , CaO - 0.27,  $Fe_2O_3 - 0.77$ ,  $Al_2O_3 - 43.61$ ,  $Na_2O - 0.25$ ; loss on ignition - 0.50 %), specific surface= 800 m<sup>2</sup>/kg (by Blaine);

- tripoli powder (Ukraine) (by mass, %:  $SiO_2 - 88.40$ , CaO - 0.86,  $Al_2O_3 - 6.40$ ,  $TiO_2 - 2.10$ ,  $Fe_2O_3 - 3.25$ ,  $Na_2O - 0.69$ , MgO - 0.98,  $SO_3 - 0.40$ ; ignition loss - 0.20 %), specific surface= 800 m<sup>2</sup>/kg (by Blaine);

- fly-ash (Ukraine) (by mass, %: SiO<sub>2</sub> – 50.94, CaO – 2.86, Al<sub>2</sub>O<sub>3</sub> – 24.56, TiO<sub>2</sub> – 0.94, MgO – 1.98, Fe<sub>2</sub>O<sub>3</sub> – 13.25, SO<sub>3</sub> – 0.40, Na<sub>2</sub>O – 0.69; ignition loss – 1.64 %), fr.  $\leq$  0.16 mm.

The alkaline component of the binder is presented by sodium water glass, modulus  $M_s= 2.8$ , density= 1430 kg/m<sup>3</sup>.

Quartz sands, fr. 0...0.315 Ta 0.315...0.63 mm, were used as fillers.

Complex additive, consisting of  $Na_3PO_4$  12H<sub>2</sub>O (according to CAS No 7601-54-9) and Na gluconate (acc.to CAS 527-07-1), was used to ensure consistency and workability retention time of fresh mortar.

Carboxymethyl cellulose («Gabrosa HV» AkzoNobel, Netherlands) for the waterretaining capacity of fresh mortar was used.

Liquid and dry constituents of alkali-activated aluminosilicate coating were prepared separately. Liquid constituent (alkaline solution) consists of sodium water glass and water. Dry state constituent consists of all components of the binder. Liquid and dry constituents were mixed in a mixer Hobart type.

Protective coating was covered on the side surfaces of fine concrete specimens 40x40x160 mm (Portland cement:sand – 1:3, W/C ratio= 0.5).

The effectiveness of protective coating was evaluated by the penetration depth of sulfate-ions from aggressive mediums in structure.

The coatings were covered on the surfaces of concrete specimens providing different thickness of layer (1...3 mm) and stored during 28 d at t=  $20 \pm 2$  °C and R.H. =  $95 \pm 5$  %. Then the specimens, both protected and unprotected ones, were located vertically in water (the reference specimens) and aggressive water solutions of Na, Mg, and NH<sub>4</sub> sulfates (concentration – 30000 mg/l by SO<sub>4</sub><sup>2-</sup> ions). The exposure class of aggressive mediums was XA3 according to EN 206-1.

After 360 d in aggressive solutions, the specimens were sliced to determine the penetration of sulfates from aggressive mediums. The penetration depth of SO<sub>3</sub> groups, by mean of an electronic microscope with a microanalyzer, was defined.

The exploitation of protective coating in sulfate mediums was simulated by adding of specified salts in an zeolite-like binder. Changes in the pH values of water extracts, taken from the binder modified by sulfates during the early four hours of hydration, were investigated. Measurements were realized by mean of the laboratory apparatus «EZODO PL-700AL» for analysis of water parameters.

Microprobe analysis was carried out by electronic microscope with microanalyzer REMMA 102-02.

## 3. Results and Discussions

The influence of the aggressive medium on the penetration depth of sulfate-ions in structure is shown (figure 1). Penetration of sulfate-ions in unprotected concrete was 5.8...7.6 mm depending on cation whilst in protected one was 0.1...1.5 mm depending on the thickness of coating.



Figure 1. Penetration of sulfates in concrete within 360 d.

The coating with a thickness of 1 mm determines penetration depth in the limits of 1.3...1.5 mm. According to microprobe analysis, increasing the thickness of coating up to 3 mm ensures ions transport in concrete structure is impossible. Thus, sulfate content at a depth of 1 mm for unprotected concrete was 4.0 % by SO<sub>3</sub> (figure 2 a) while for protected by 3 mm coating it was 0.0 % (figure 2 b).

According to the results, penetration of protected concrete regarding sulfate-ions decreases in row (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>>Na<sub>2</sub>SO<sub>4</sub>>MgSO<sub>4</sub> that is caused by different chemical activity of cation.

The binding of  $SO_4^{2-}$ ,  $NH_4^+$ ,  $Mg^{2+}$  ions in structure of zeolite-like phases while the interaction of sulfate mediums with protective coating was confirmed by the changes of pH of water extracts (figure 3).



Figure 2. Microprobe analysis of the unprotected (a) the protected concrete (coating 3.00 mm) (b) concrete specimen after storing during 360 d in a solution of sodium sulfate

Thus, 2.5 % of MgSO<sub>4</sub> defines a decrease in pH values compared with the reference zeolite-like binder (figure 3 a). This is evidence of intensified hydration of the binder and crystallization of zeolite-like hydroaluminosilicates at normal temperature. Mg<sup>2</sup> ions equal to Ca<sup>2+</sup> ions participate in the formation of the mentioned hydrates with the binding of sulfate-ions. The admixture of  $(NH_4)_2SO_4$  causes decreased pH values while its content is 5.0 % already. That is evidence of the same direction in structure formation but delayed because of the lesser concentration of alkaline-earth metals and the formation of another type of zeolite-like minerals. The admixture of Na<sub>2</sub>SO<sub>4</sub> almost doesn't change the intensity of structure formation because of no cation exchange, which is confirmed by the stability of pH values while concentration ranges from 0.5 % to 2.5 % (figure 3 b).



Figure 3. Influence of MgSO<sub>4</sub> (a) and Na<sub>2</sub>SO<sub>4</sub> (b) on pH values of water extracts from zeolite-like binder.

The resistance of protective coatings, based on the binder, can be explained by the formation of zeolite-like phases containing SO42-, NH4+, and Mg2+ ions. Thus, exchange of  $OH^{-}$  anions to  $SO_4^{2-}$  anions causes the formation of such minerals as  $Na_6Ca_2[(CO_3)_2|Al_6Si_6O_{24}] \cdot 2H_2O_{4}$ cancrinite biachellaite (Ca, Na.  $K_{8}(A_{16}S_{16}O_{24})(SO_{4})_{2}(OH)_{0.5} \cdot H_{2}O$ , franzinite  $(Na,K)_{6}Ca_{2}(A_{16}S_{16}O_{24})(SO_{4})_{2} \cdot 0.5H_{2}O$  etc. In one's turn, exchange of  $Na^+$  cations by  $NH_4^+$  and  $Mg^{2+}$  cations can lead to formation of ammonium-heulandite  $[(NH_4)_2 Ca]_2Al_4Si_{14}O_3 \cdot 12H_2O_1$ , ammonium-chabazite [(NH<sub>4</sub>)<sub>2</sub>Ca]Al<sub>2</sub>Si<sub>4</sub>O<sub>12</sub>·12H<sub>2</sub>O, ammonium-thomsonite (Na, NH<sub>4</sub>)Ca<sub>2</sub>[Al<sub>5</sub>Si<sub>5</sub>O<sub>20</sub>]·6H<sub>2</sub>O, Mg-faujasite  $(Mg, Na_2, Ca)_{3.5}[Al_7Si_{17}O_{48}] \cdot 32H_2O,$ Mg-chabazite  $(Mg_{0.7})$ K<sub>0.5</sub>Ca<sub>0.5</sub>Na<sub>0.1</sub>][Al<sub>3</sub>Si<sub>9</sub>O<sub>24</sub>]·10H<sub>2</sub>O and Mg-ferrierite (Mg, Na<sub>2</sub>, K<sub>2</sub>, Ca)<sub>3-5</sub>Mg[Al<sub>5-7</sub>Si<sub>27,5-</sub> 31 O72]·18H2O [20].

According to electron microscopy, restriction of  $SO_4^{2-}$  ions transport is caused not only by their binding by zeolite-like phase but also due to advanced crystallinity of structure in the presence of  $Mg^{2+}$ ,  $NH_4^+$ , and  $Na^+$  cations (figures 4).



Figure 4. SEM images of zeolite-like binder: the reference (a) and modified by 2.5 % of magnesium (b) after hardening during 180 d.

An application of the investigated coatings was realized while the reconstruction of Kyivo-Pechers'ka Lavra (Kyiv) for protection of foundation, which undergo influence of sulfates according to exposure class XA3 (figure 5). As provided by inspection, the state of coatings (strengthening, absence of cracks, no traces of leakage or extraneous inclusions etc.) and their performances (adhesion) comply the mandatory requirements [36, 37].



Figure 5. The surface of foundation concrete: (a) - without covering; (b) - protected by the coating

## 4. Conclusion

1. Restriction of sulfate-ions transport to protect the concrete from high sulfate aggression is possible due to covering by protective coating based on zeolite-like binder.

2. Total protection of concrete in the absence of traces of  $SO_4^2$  ions transport can be ensured by 3 mm of the coating. Transport properties of concrete, regarding sulfates, decrease in the row  $(NH_4)_2 SO_4 > Na_2SO_4 > MgSO_4$ , explained by the chemical activity of cation in these salts.

3. Less  $SO_4^{2-}$  ions transport is caused both by their binding in zeolite-like phases with additional increasing crystallinity in the presence of Na<sup>+</sup>, NH<sup>4+</sup>, and Mg<sup>2+</sup> cations and by their occluding in the already formed structure of the protective coating.

#### Acknowledgments

Authors would like to acknowledge the contribution of the Research Council of Lithuania and the Ministry of Education and Science of Ukraine project "Solutions to reduce aggressive ions  $SO_4^{2-}$  and Cl<sup>-</sup> during transport in Portland cement concrete with steel reinforcement in hydraulic structures", project code S-LU-22-7. The authors also express their gratitude to the Ministry of Education and Science of Ukraine for financial support of this research that is carried out within the budgetary financing of topics with registration No 0123U101831, No 0123U101832, and implementation period 2023 - 2026.

#### References

- Chen Y, Zhang Z and Li D. Aging treatment implementation strategy for instrumentation and control equipment in nuclear power plants based on preventive replacement. Nuclear Technology. 2018; 204(3): 378-385.
- [2] Val DV and Stewart MG. Life-cycle cost analysis of reinforced concrete structures in marine environments. Struct. Saf. 2003; 25 (4): 343–362.
- [3] Zhang Z, Gong R, Zhang H and He W. The sustainability performance of reinforced concrete structures in tunnel lining induced by long-term coastal environment. Sustainability. 2020; 12: 3946.
- [4] Scrivener K and De Belie N. Bacteriogenic sulfuric acid attack of cementitious materials in sewage systems. In: Alexander, M., Bertron, A., De Belie, N. (eds) Performance of cement-based materials in aggressive aqueous environments. RILEM State-of-the-Art Reports. 2013; 10: 305–318.
- [5] Rodrigues R, Gaboreau S, Gance J, Ignatiadis I and Betelu S. Corrosion of reinforced steel in concrete and its control: an overview. Journal of Steel Structures & Construction. 2017; 03(01): 1000124.
- [6] Liu G, Zhang Y, Ni Z and Ran Huang. Influence of sulfate salt type on passive film of steel in simulated concrete pore solution. Construction and Building Materials. 2019; 223: 352–359.
- [7] Kyrychok V. Alkaline aluminosilicate binders with increased sulphate resistance and coatings based on them for the protection of concrete. Ph.D. thesis (Eng), Kyiv National University of Construction and Architecture, 2018.
- [8] Poursaee A. 2 Corrosion of steel in concrete structures. Corrosion of steel in concrete structures. 2016; 19-33.
- [9] Michel A, Otieno M, Stang H and Geiker MR. Propagation of steel corrosion in concrete: experimental and numerical investigations. Cement and Concrete Composites. 2016; 70: 171–182.
- [10] Saillio M, Baroghel-Bouny V and Barberon F. Chloride binding in sound and carbonated cementitious materials with various types of binder. Construction and Building Materials. 2014; 68; 82–91.
- [11] Plugin AA, Borziak OS, Pluhin OA, Kostuk TA and Plugin DA. Hydration products that provide waterrepellency for portland cement-based waterproofing compositions and their identification by physical and chemical methods. Lecture Notes in Civil Engineering. 2020; 100: 328–335.
- [12] Sanytsky M, Usherov-Marshak A, Kropyvnytska T and Heviuk I. Performance of multicomponent portland cements containing granulated blast furnace slag, zeolite and limestone. Cement, Wapno, Beton. 2020; 25(5): 416–427 (2020).
- [13] Kostyuk T, Vinnichenko V, Plugin A, Borziak O and Iefimenko A. Physicochemical studies of the structure of energy-saving compositions based on slags. IOP Conference Series: Materials Science and Engineering. 2021; 1021(1): 012016.
- [14] Kropyvnytska T, Sanytsky M, Heviuk I and Kripka L. Study of the properties of low-carbon portlandcomposite cements CEM II/C-M. In Proceedings of EcoComfort 2022; Blikharskyy, Z., Ed.; Lecture Notes in Civil Engineering; Springer International Publishing: Cham. 2023; 290; 230–237.
- [15] Maes M, Gruyaert E and De Belie N. Resistance of concrete with blast-furnace slag against chlorides, investigated by comparing chloride profiles after migration and diffusion. Materials and Structures. 2013; 46: 89–103.
- [16] Wan X, Cui Y, Jin Z and Gao L. Chloride transport and related influencing factors of alkali-activated materials: a review. Materials 2023; 16: 3979.
- [17] Provis JL and van Deventer JSJ (eds.). Alkali-Activated Materials: State-of-the-Art Report. Rilem TC 224-AAM. Springer/RILEM. 2014.

- [18] Krivenko P, Petropavlovskyi O, Kovalchuk O, Rudenko I and Konstantynovskyi O. Enhancement of alkali-activated slag cement concretes crack resistance for mitigation of steel reinforcement corrosion. E3S Web of Conferences. 2020; 166: 06001.
- [19] Kochetov G, Prikhna T, Kovalchuk O and Samchenko D. Research of the treatment of depleted nickelplating electrolytes by the ferritization method. Eastern-European Journal of Enterprise Technologies. 2018; 3(6-93): 52–60.
- [20] Akimkhan AM. Structural and ion-exchange properties of natural zeolite. in Ion Exchange Technologies, edited by Ayben Kilislioğlu (IntechOpen, 2012).
- [21] Krivenko P, Rudenko I and Konstantynovskyi O. Design of slag cement, activated by Na(K) salts of strong acids, for concrete reinforced with steel fittings. Eastern-European Journal of Enterprise Technologies. 2020. 6 (6 - 108): 26–40.
- [22] Krivenko P, Rudenko I, Konstantynovskyi O and Boiko O. Prevention of steel reinforcement corrosion in alkali-activated slag cement concrete mixed with seawater. E3S Web of Conferences. 2021; 280: 07004.
- [23] Kryvenko P, Rudenko I, Konstantynovskyi O and D. Vaičiukynienė. Mitigation of corrosion initiated by Cl- and SO42--ions in blast furnace cement concrete mixed with sea water. Materials. 2022; 15(9): 3003.
- [24] Batrakov VG. Modified concretes. Theory and practice, 2-d ed (Tehnoproekt, Moscow, 1998). 768.
- [25] Nikiforov OP. High-density concrete based on slag-containing binders with complex modifiers (Porogi, Dnipropetrovsk, 1996). 232.
- [26] Palacios M and Puertas F. Effect of superplasticizer and shrinkage-reducing admixtures on alkaliactivated slag pastes and mortars. Cement and Concrete Research. 2005; 35: 1358–1367.
- [27] Krivenko P, Gots V, Petropavlovskyi O, Rudenko I and Konstantynovskyi O. Comparison of influence of surfactants on the thermokinetic characteristics of alkali-activated slag cement. Eastern-European Journal of Enterprise Technologies. 2021; 6 (6-114): 6–15.
- [28] Kryvenko P, Rudenko I, Kovalchuk O, Gelevera O and Konstantynovskyi O. Influence of dosage and modulus on soluble sodium silicate for early strength development of alkali-activated slag cements. Minerals. 2023; 13: 1164.
- [29] Krivenko P, Gots V, Petropavlovskyi O, Rudenko I, Konstantynovskyi O and Kovalchuk A. Complex shrinkage-reducing additives for alkali activated slag cement fine concrete. Solid State Phenomena. 2021; 321: 165–170.
- [30] Krivenko P, Rudenko I and Konstantynovskyi O. Effect of technological factors on freeze-thaw resistance of alkali-activated slag cement concrete in NaCl solution. AIP Conference Proceedings; 2023; 2684: 040011.
- [31] Zhang Z and Wang H. 22-Alkali-activated cements for protective coating of OPC concrete. in Handbook of alkali-activated cements, mortars and concretes; edited by F. Pacheco-Torgal, J. A. Labrincha, C. Leonelli, A. Palomo, P. Chindaprasirt. Woodhead Publishing, 2015: 605–626.
- [32] Cherniavskyi VL. Adaptation of abiotic systems: concrete and reinforcement concrete (DNURT, Dnipropetrovsk, 2008; 412.
- [33] Rong XP, Wang Z, Xing X and Zhao L. Review on the adhesion of geopolymer coatings. ACS Omega. 2021; 6(8): 5108-5112.
- [34] Krivenko P, Guzii S, Rudenko I and Konstantynovskyi O. Intumescent fireproof coatings based on zeolite-like cement matrices. CE/Papers. 2023; 6 (5): 923-929.
- [35] Kryvenko P, Rudenko I, Konstantynovsky O and Vaičiukynienė D. Feasibility of incorporating SO42-ions in zeolite-like matrices based on alkaline aluminosilicate binders. Construction and Building Materials. 2023; 391: 131878.
- [36] DSTU B V.2.6-145:2010. Protection of concrete and reinforced concrete structures from corrosion. National standart of Ukraine.
- [37] DSTU B V.2.6-186:2010. Guidelines for the protection of building constructions from corrosion. National Standart of Ukraine.