1. Introduction

Many experimental works have shown the feasibility of using special prepared binders to reduce the emission of ions from soil, and immobilize metals migration from waste deposits. Clay-cement slurries are mixtures containing in their compositions clinker binder and clay minerals, in this case they were Belchatów and Koniecpol clays. After hydration process mixtures they create flexible and tight structures that are used, among others, as a barriers immobilizing the spread of pollution. The tests have shown that in the case of amphoteric metals, it is possible to accumulate almost 100% of the contamination using clay-cement suspensions. An attempt was also made to explain the mechanisms of ion retention in arises structures. The article presents three probable mechanism of amphoteric ions binding, the first is retention in the clay minerals interlayer spaces, the second is entrapment in CSH type phases formed during hydration. Last possibility is formation of some new silicate structures.

2. Materials and Methods

The various samples of clay-cement binders were prepared using as a base two different types of the mineral compounds, the first one was Koniecpol clay and the second one was Belchatów clay, and the third type of samples the waste ashes were used. In this preparation as a filler the medium mesh size sand was imputed. Samples contain also 1% wt of sodium silicate (waterglass), that is added to the clay-cement hydrobarriers to control the hydration process (Zhang et al. 2008, Wang et al. 2017, Bashir et al. 2011).
and comparison study, the samples with high concentration of sodium silicate and the samples without it were tested.

Amount and type of the compounds in the samples are presented in the Table 1, as well as the pH values for that type of mixtures. The pH index of the samples is stable and characteristic for clay-cement mixtures. The acronyms of the samples indicate respectively, the type of additive used (P25 – ash, K – Koniecpol clay, B – Belchatów clay) and then content of cement and water glass.

The slurry mixes were spiked with various amphoteric hydroxides of metals that are considered as a harmful after Minister of Environment act „Standards for soil and earth quality” publicized in 2001. For the purposes of this research, there elements were chosen: Lead II Zinc (II) and Chromium (III). The standards for the those elements contents are show in Table 2.

The hydroxides of those elements were added to the slurry mixtures in the quantity exceed twice the standards for its concentration in the soil, with the parameters as follows:

- Lead – 2000 mg/kg
- Zinc – 40 mg/kg
- Chromium – 1600 mg/kg

On account of slurry high pH factor, the hydroxides started dissolve and created aqua soluble complex ions such as: $[\text{Cr(OH)}_4]^{-3}$, $[\text{Zn(OH)}_4]^{2-}$, $[\text{Pb(OH)}_4]^{2-}$. In this state investigated compounds should be successfully inhibited in clay-cement slurry.

The samples were saturated with distilled water and extraction was allowed to occur for 48h. The samples were placed in special cylinders and forced to flow by them distilled water, under constant pressure. The hydraulic gradient was generated by compressed air at stabilized pressure. Compressed air displaced distilled water from the tank which through a sample in the measuring chamber water flowed into the filtrate container. The samples were filtered under the pressure of 1 atm to obtain 100 ml of extract. The filtrate was subjected to analytical test. The filtration system has been shown on figure 1.

3. Results and Discussion

The physical and chemical characteristics of effluents are presented in Table 3 and 4 and concentration of metals cations are show the Figure 2. The trace amounts of the metal ions were observed in the samples. The percentage of the

| Sample  | Sample mass [g] | Sodium silicate [g] | cement [g] | soil [g] | pH    |
|---------|----------------|---------------------|------------|----------|-------|
| P25.50.0| 106.3          | 0                   | 53.2       | 53.2     | 13.03 |
| P25.50.1| 109.2          | 1.09                | 54.6       | 54.6     | 13.29 |
| P25.50.2| 105.6          | 2.11                | 52.8       | 52.8     | 13.44 |
| P25.60.0| 106.5          | 0                   | 63.9       | 42.6     | 13.27 |
| P25.60.1| 102.8          | 1.03                | 61.7       | 41.1     | 13.48 |
| P25.60.2| 108.1          | 2.16                | 64.9       | 43.2     | 13.48 |
| P25.70.0| 105.6          | 0                   | 73.9       | 31.7     | 13.37 |
| P25.70.1| 100.3          | 2.01                | 70.2       | 30.1     | 13.54 |
| P25.70.2| 109.2          | 2.18                | 76.4       | 32.8     | 13.25 |
| K.50.0  | 107.0          | 0                   | 53.5       | 53.5     | 13.25 |
| K.50.1  | 103.1          | 1.03                | 51.5       | 51.5     | 13.34 |
| K.50.2  | 105.4          | 2.11                | 52.7       | 52.7     | 13.34 |
| K.60.0  | 108.5          | 0                   | 65.1       | 43.4     | 13.15 |
| K.60.1  | 109.2          | 1.09                | 65.5       | 43.7     | 13.58 |
| K.60.2  | 106.7          | 2.13                | 64.0       | 42.7     | 13.43 |
| K.70.0  | 108.0          | 0                   | 75.6       | 32.4     | 13.48 |
| K.70.1  | 106.1          | 1.06                | 74.3       | 31.8     | 13.37 |
| K.70.2  | 101.8          | 2.04                | 71.3       | 30.5     | 13.54 |
| B.50.0  | 107.6          | 0                   | 53.8       | 53.8     | 13.43 |
| B.50.1  | 102.3          | 1.02                | 51.2       | 51.2     | 13.25 |
| B.50.2  | 105.1          | 2.10                | 52.6       | 52.5     | 13.34 |
| B.60.0  | 104.3          | 0                   | 62.6       | 41.7     | 13.15 |
| B.60.1  | 108.2          | 1.08                | 64.9       | 43.3     | 13.23 |
| B.60.2  | 105.6          | 2.11                | 63.4       | 42.2     | 13.58 |
| B.70.0  | 107.5          | 0                   | 75.3       | 32.2     | 13.25 |
| B.70.1  | 106.3          | 1.06                | 74.4       | 31.9     | 13.15 |
| B.70.2  | 102.8          | 2.06                | 71.9       | 30.8     | 13.23 |
leaching of this ions to the soil is very low, therefore it is not significant for the study of cement-clay slurry as the hydroisolation barriers.

Figure 2. below, show the relationship between cation charge and concentrations of elements in effluent after washing. The higher concentration value of chromium ions can be caused by different ions migration mechanism. The maximum concentration is 0.45 mg/L which is considered as trace quality.

The results show negative dependence between cations leaching and the compositions of slurry mixtures samples. The data show no relation between ions migrations and the percentage of sodium silicate in the composition of binder. The observation was made that the type of materials (like clays or ashes) used in binder’s composition should not affect the accumulation of harmful elements.

3.1. The mechanizm of ion immobilisation

A characteristic feature of clay-cement binders is that throughout the entire bonding area they behave like viscoplastic fluids and there is no rigid crystal structure created e.g. characteristic for concrete. Thanks to this, the connection of the linker phases contained in the material and fine dispersion Clay fractions ensure high tightness and harmful substances retention capacity.

The impact of foreign ions Pb²⁺, Zn²⁺, Cr³⁺ within the structure of clay cement mixtures was investigated, and there is most likely three possibilities, of ion immobilization:
- interlayer position in clays,
- intermolecular bonds in cement
- or ash or arising different structure.

In the light of these facts, the fundamental understanding of clay-cement mixtures chemistry remains as an important issue.

Ion exchange in clays is dependent on the crystalline structure of the mineral and on the chemical composition of any solution in contact with the mineral. The structures of clay minerals are briefly described to provide a background for the discussion of their ion-exchange reactions. Ion exchange in these minerals is a reversible chemical reaction that takes place between ions held near a mineral surface by unbalanced electrical charges within the mineral framework and ions in a solution in contact with the mineral. Generally the excess charge on the mineral is negative, and it attracts cations

Tab. 2. The standards for the contents of metals in the different type of soils
Tab. 2. Zawartości normowe metali w różnych typach gruntów

| Lp | pollution | type A | type B | type C |
|----|-----------|--------|--------|--------|
|    |           |        | Depth [m] |        |
|    |           |        | 0-0,03 | 0,3-15,0 | >15 | 0-2 | 2-15 |
|    |           |        | up to | below | up to | below | up to | below |
|    |           |        | 1x10⁻⁷ | 1x10⁻⁷ | 1x10⁻⁷ | 1x10⁻⁷ |
| 1  | Chromium  | 50     | 150   | 150   | 190   | 150   | 380   | 500   | 150   | 800   |
| 2  | Zinc      | 1      | 4     | 5     | 6     | 4     | 10    | 15    | 6     | 20    |
| 3  | Lead      | 50     | 100   | 100   | 200   | 100   | 200   | 600   | 200   | 1000  |

Fig. 1. Filtration set
Rys. 1. Zestaw filtracyjny
from the solution to neutralize this charge. The chemical reactions in ion exchange follow the law of mass action, but the reactions are restricted by the number of exchange sites on the mineral and by the strength of the bonding of the exchangeable cations to the mineral surface.

In this experiment two samples were added clay agent, the first one Koniecpol clay, which is multiminerals (contains also sand, and anthem types of clays), but more than 50% is vermiculite – smektyte type. Second was Belchatów Clay, monomineral montmoryllonite – beidellite type. Each clay mineral has a range of exchange capacities because of differences in structure and in chemical composition, but in this case both of them are 2:1 and expanding structure which means that they can exchange cations. The ranges (in milliequivalents per 100 grams) are; montmorillonite, 70–100; ilite, 10–40; vermiculite, 100–150 (Pardo et al. 2018, Esaifan et al. 2019). In the available space between individual interlayer there are exchangeable cations and water molecules. When introducing different types of cations, it becomes possible that this space is naturally inaccessible, and interchangeable cations are not replaceable. Model of structure is shown on figure 3. In interchangeable cation position may substitute zinc, lead or chromium, and because of charge and ionic radius chromium will be privileged.

The samples were filtered under the same pressure, but eluent was nitrogen V acid because solubility of arising salts, for example zinc, or lead chlorides are unsoluble. The concentration was 10% wt quite low, because of undesiderable corrosion. As you may notice, again have higher concentration value of chromium ions be caused by different ions migration mechanisms, and cation charge. Lead and zinc still very low. And finally we can observe, samples with water glass addition, inhibits more elements than samples without it. Results are included in table 4 and on figure 4, and demonstrate the effective immobilization of amphoteric ions.

Second possibility by immobilizing ions are intermolecular bonds in cement and ash. In the assumption cement and ash have similar hydration possibilities. The samples were mixed before the hydration process, so the phenomenon of ion retention was considered taking into account the non-hydrated phases. Of course, after mixing with water and solidifying the samples, the clinker phases go into CSH gels, and proper immobilization already occurs in hydrated minerals. There are a few clinker phases such as follows: alite C₃S, be-

| Sample | Pb²⁺ [mg/l] | Zn²⁺ [mg/l] | Cr³⁺ [mg/l] |
|--------|------------|------------|------------|
| P25.50.0 | 0.083 | 0.0033 | 0.433 |
| P25.50.1 | 0.071 | 0.0027 | 0.333 |
| P25.50.2 | 0.071 | 0.0076 | 0.322 |
| P25.60.0 | 0.073 | 0.0029 | 0.286 |
| P25.60.1 | 0.068 | 0.0012 | 0.296 |
| P25.60.2 | 0.067 | 0.0087 | 0.222 |
| P25.70.0 | 0.047 | 0.0031 | 0.271 |
| P25.70.1 | 0.038 | 0.0045 | 0.231 |
| P25.70.2 | 0.053 | 0.0012 | 0.246 |
| K.50.0 | 0.135 | 0.0045 | 0.377 |
| K.50.1 | 0.081 | 0.0023 | 0.361 |
| K.50.2 | 0.083 | 0.0031 | 0.343 |
| K.60.0 | 0.085 | 0.0022 | 0.327 |
| K.60.1 | 0.056 | 0.0056 | 0.276 |
| K.60.2 | 0.066 | 0.0037 | 0.273 |
| K.70.0 | 0.082 | 0.0045 | 0.254 |
| K.70.1 | 0.077 | 0.0023 | 0.241 |
| K.70.2 | 0.079 | 0.0029 | 0.268 |
| B.50.0 | 0.048 | 0.0031 | 0.453 |
| B.50.1 | 0.045 | 0.0045 | 0.439 |
| B.50.2 | 0.068 | 0.0012 | 0.376 |
| B.60.0 | 0.057 | 0.0026 | 0.365 |
| B.60.1 | 0.051 | 0.0045 | 0.329 |
| B.60.2 | 0.031 | 0.0070 | 0.366 |
| B.70.0 | 0.042 | 0.0045 | 0.361 |
| B.70.1 | 0.015 | 0.0023 | 0.275 |
| B.70.2 | 0.063 | 0.0026 | 0.243 |
lite C$_2$S, C$_4$AF and C$_3$A. There is about 65% alite in clinker, so other phases were skipped. Structure of alite is very interesting, tricalcium silicate C$_3$S has structure with isolated [SiO$_4$] which are connected by Ca-O polyhedra. The approximate chemical formula is 3CaO·SiO$_2$ (C$_3$S in cement chemist notation), but in fact the structure is different, alite exhibits a complex polymorphism depending on impurities. Picture shows pure alite monoclinic mineral structure but alite found in clinker is a solid solution with a highly defective structure. Oxygen atoms are present in two different coordinations – in Si tetraedres, and in Ca – octaedres coordinated by 6 calcium ions. And for that reason, cations can be built-in the structure during hydration process (Horst et al 2015). The influence of individual ions on the structure of C$_3$S has been extensively studied in past decades (Zhang et al. 2011). The higher crystal symmetry is achieved without substituted ions. By defining a quantity called structure different factor D, in which the structural parameters such as radius, electronegativity, coordination number of the substituent ion were taken into account with relation to Ca$^{2+}$. Table 5 shown the relation between chemical structure parameters of investigated ions Pb$^{2+}$, Zn$^{2+}$, Cr$^{3+}$, and their substitution patterns and abilities to unstabilize alite crystals. Absolute value of D factor greater than or equal 0.2 destabilized structure. Conclusion is that alite structure immobilize amphoteric metals but lead could be dangerous for stable structure.

$$D = \frac{Z \cdot \Delta \chi \cdot (R_{Ca^{2+}} - R)}{R_{Ca^{2+}}}$$

D – structure different factor – related to calcium.

And in following formula:

$$Z$$ – ion charge,

$$\Delta \chi$$ – electronegativity difference between ion and calcium,

$$R$$ – ion radius,

$$R_{Ca^{2+}}$$ – calcium cation radius.

Absolute value of D factor greater than or equal 0.2 destabilized structure. These results indicate that alite structure immobilize amphoteric metals but lead could be dangerous for stable.

### 3.2. Quality precipitation of silicates of the selected amphoteric metal cations.

![Fig. 2. Amfoteric metals water condition leaching test](image1)

![Rys. 2. Wymywalność metali amfotercznych w warunkach wodnych](image2)

![Fig. 3. Clay mineral 2:1 type structure](image3)

![Rys. 3. Struktura mineralu lastego typu 2:1](image4)
Fig. 4. Amphoteric metals low pH condition leaching test  
Rys. 4. Wymywalność metali amfoterycznych w warunkach niskiego pH

Fig. 5. SEM and EDS analysis of sample with 25% ash content  
Rys. 5. SEM i EDS próbki zawierającej 25% popiołu

Fig. 6. SEM and EDS analysis of sample based on Koniecpol clay  
Rys. 6. SEM i EDS próbki zawierającej il Koniecpol

Fig. 7. SEM and EDS analysis of sample based on Belchatów clay  
Rys. 8. SEM i EDS próbki zawierającej il Belchatów

| Ionic radius [pm] | Pb^{2+} | Zn^{2+} | Cr^{3+} |
|------------------|---------|---------|---------|
| Coordination number | 4       | 4       | 6       |
| Electronegativity | 1,87    | 1,65    | 1,66    |
| Substitution pattern | Pb→Ca | Zn→Ca | Cr→Ca/Al |
| D factor | -1,32 | 0,328 | 0,7 |
The experiment was carried to confirm the redirection about the possibility that certain amphoteric metal cations may precipitate as insoluble and stable salts in strong alkaline solution. To each solution of soluble salts of the selected metal cations, the sodium silicate was added, to observe if the precipitate will form. The experiment was conducted in the following conditions.

- the concentration of 20% of the following salts PbNO₃, ZnCl₂ and CrCl₃
- the sodium silicate Mk = 2,5
- reagents in the proportion 1:1

To accelerate the rate of reaction the samples were put in the laboratory drier at 80 degree Celsius. All samples formed the insoluble precipitant as follows:

- monohydrate lead II silicate PbO∙SiO₂∙H₂O (white crystals)
- monohydrate zinc II silicate ZnO∙SiO₂∙H₂O (blue opalescent gelatinous precipitate)
- monohydrate chromium III silicate Cr₂O₃ ∙SiO₂∙H₂O (pale green crystals)

Additional validation of creating unsoluble chemical bounds were obtained by SEM images with EDS analysis (figure 5–7). The EDS analysis shows that transition metals content is significantly increased, while the contents of impurity elements (Zn, Cr, Pb). These metals are immobilized in cement phases (long tiny crystals).

4. Conclusions

1. Clay cement mixtures retain amphoteric metals
   - part as interchangable cations in clay minerals structures
   - part as cations substitute during the formation of the alite phase
   - and some form new structures by reaction with waterglass
2. The mechanism of cation retention depends on the quantitative composition of the mixture, but inhibition in the structure of the alite is the strongest
3. Chromium has an affinity for clay minerals, in case of ion radius, charge and negative D factor value – confirmation by acid leaching
4. Indirect conclusion – complexes ion have weaker bonds than the hydration reaction

Conflict of interests: The author declares no conflict of interest.

| Sample HNO₃ | Pb²⁺ [mg/l] | Zn²⁺ [mg/l] | Cr³⁺ [mg/l] |
|-------------|-------------|-------------|-------------|
| P25.50.0    | 0,007       | 0,006       | 0,0076      |
| P25.50.1    | 0,007       | 0,007       | 0,0063      |
| P25.50.2    | 0,007       | 0,007       | 0,0067      |
| P25.60.0    | 0,006       | 0,006       | 0,0049      |
| P25.60.1    | 0,007       | 0,007       | 0,0042      |
| P25.60.2    | 0,007       | 0,005       | 0,0087      |
| P25.70.0    | 0,007       | 0,007       | 0,0071      |
| P25.70.1    | 0,008       | 0,008       | 0,0085      |
| P25.70.2    | 0,003       | 0,003       | 0,0072      |
| K.50.0      | 3,54        | 0,005       | 377,8       |
| K.50.1      | 3,38        | 0,003       | 261,4       |
| K.50.2      | 3,28        | 0,001       | 143,4       |
| K.60.0      | 3,09        | 0,002       | 227,8       |
| K.60.1      | 2,96        | 0,006       | 176,1       |
| K.60.2      | 2,72        | 0,007       | 73,3        |
| K.70.0      | 2,08        | 0,005       | 254,0       |
| K.70.1      | 1,78        | 0,003       | 141,4       |
| K.70.2      | 1,08        | 0,009       | 68,1        |
| B.50.0      | 6,05        | 0,001       | 753,5       |
| B.50.1      | 5,45        | 0,005       | 439,4       |
| B.50.2      | 5,07        | 0,002       | 376,0       |
| B.60.0      | 5,06        | 0,006       | 665,1       |
| B.60.1      | 4,75        | 0,005       | 329,3       |
| B.60.2      | 4,03        | 0,007       | 366,0       |
| B.70.0      | 4,04        | 0,005       | 471,8       |
| B.70.1      | 4,02        | 0,003       | 275,3       |
| B.70.2      | 3,06        | 0,006       | 243,1       |
| Number | Reference                                                                                     |
|--------|-----------------------------------------------------------------------------------------------|
| 1      | Andersen S. Ødegård S., Hans M. Seip 1994 Background levels of heavy metals in Polish forest soils Ecological Engineering, Volume 3, Issue 3, pp 245-253 |
| 2      | Andreola F., Barbieri L., Corradi A., Lancellotti I., Manfredini T., 2001 The possibility to recycle solid residues of the municipal waste incineration into a ceramic tile body. J Mater Sci 36:4869–4873. doi: 10.1023/A:1011823901409 |
| 3      | Bashir MJ, Aziz HA, Yusoff MS 2011 New sequential treatment for mature landfill leachate by cationic/anionic and anionic/cationic processes: optimization and comparative study. J Hazard Mater vol 186 pp 92–102 |
| 4      | Boghetich G., Liberti L., Notarincola M., Palma M., Petruzelli D. 2005 Chloride extraction for quality improvement of municipal solid waste incinerator ash for the concrete industry. Waste Manag Res 23:57–61. doi: 10.1177/0734242X05051017 |
| 5      | Chibuike G. U., Obiora S. C. 2014 Heavy Metal Polluted Soils: Effect on Plants and Bioremediation Methods Applied and Environmental Soil Science Article ID 752708, http://dx.doi.org/10.1155/2014/752708 |
| 6      | Collivignarelli, M.C., Abbà, A., Sorlini, S. et al. 2017 Evaluation of concrete production with solid residues obtained from fluidized-bed incineration of MSW-derived solid recovered fuel (SRF) J Mater Cycles Waste Manag 19: 1374. https://doi.org/10.1007/s10163-016-0523-y |
| 7      | Dalton J.L., Gardner K.H., Seager T.P., Weimer M.I., Spear J.C.M., Magee B.J. 2004 Properties of Portland cement made from contaminated sediments. Resour Conserv Recycl vol 41 pp 227–241 |
| 8      | Esaifan M., LN. Warr, G. Grathoff, T. Meyer, MT Schafmeister, A. Kurt, H. 2019. Testrich Synthesis of Hydroxy-Sodalite/Cancrinite Zeolites from Calcite-Bearing Kaolin for the Removal of Heavy Metal Ions in Aqueous Media, Minerals, vol 9(8), pp 484; |
| 9      | Horst ML, Wensheng Z. 2015 Research review of cement clinker chemistry, Cement and Concrete Research vol 78 pp 24–37 |
| 10     | Izak P., Wójcik L., Slowikowski D., 2015 Rheology of soil binder dispersions Materiały Ceramiczne = Ceramic Materials / Polskie Towarzystwo Ceramiczne, Kraków ; vol 67 pp 158-163 |
| 11     | Kasmi, A., Abriak, NE., Benzerzour, M. et al. 2017. Environmental impact and mechanical behavior study of experimental road made with river sediments: recycling of river sediments in road construction J Mater Cycles Waste Manag 19: 1405. https://doi.org/10.1007/s10163-016-0529-5 |
| 12     | Korotenko E., Hendrych J., Mašín P., Solidification of Sludge from Waste Water Treatment, Inżynieria Mineralna – Journal of the Polish Mineral Engineering Society, No 1(41), p. 103–110, DOI: 10.29227/IM-2018-01-17 |
| 13     | Lafhaj Z., Samara M., Agostini F., Boucard L., Skoczylas F., Depelsenaire G. 2007 Polluted river sediments from the North region of France: treatment with Novosol process and valorization in clay bricks. Constr Build Mater vol 148 pp 606–612 |
| 14     | Malviya, R., Chaudhary, R. J. 2006 8: 78. https://doi.org/10.1007/s10163-005-0139-0 Evaluation of leaching characteristics and environmental compatibility of solidified/stabilized industrial waste Mater Cycles Waste Manag |
| 15     | Monteiro RCC, Figueiredo CF, Alendouro MS, Ferro MC, Davim EJR, Fernandes MHV 2008 Characterization of MSWI bottom ashes towards utilization as glass raw material. Waste Manag 28(7):1119–1125. doi: 10.1016/j.wasman.2007.05.004 |
| 16     | Pardo L., Cecilia JA, Lopez-Moreno C., Hernandez V., Pozo M., Bentabol JM, Franco F. 2018 Influence of the Structural and Experimental Surfaces Modifications of 2:1 Clay Minerals on the Adsorption Properties of Methylene Blue Minerals, vol 8(3), pp 359; https://doi.org/10.3390/min8080359 |
| 17     | Prawo ochrony środowiska (Dz.U. Nr 62, poz. 627) http://prawo.sejm.gov.pl/isap.nsf/DocDetails.jsp?id=W-DU20010620627 |
| 18     | Seip H. M., Pawalski L., Sullivan T., 1994 Environmental degradation due to heavy metals and acidifying deposition — A Polish-Scandinavian workshop Ecological Engineering Volume 3, Issue 3, pp 205-206 |
| 19     | Spence W. P., Kultermann E. 2017 Construction Materials, Methods and Techniques CENGAGE Learning |
| 20     | Stempkowska A., Wójcik L., Izak P., Staszewska M., Mastalska-Popławska J., 2018 Investigation of post-industrial pollutions’ immobilization in an hydraulic self-solidifying clay-cement binder IOP Conference Series: Materials Science and Engineering vol. 427 pp 1–10 |
| 21     | Stempkowska A., Izak P., Mastalska-Popławska J., 2017 Selected elements cations exchange in acidic medium on sorbents surface based on modified brown coal Gospodarka Surowcami Mineralnymi = Mineral Resources Management ; vol. 33 iss. 1, pp. 139–149. |
22. Stempkowska A., Wójcik Ł., Izak P., 2011 Pseudothixotropic properties of clay-cement slurries Materiały Ceramiczne = Ceramic Materials / Polskie Towarzystwo Ceramiczne, Kraków, vol 6, pp. 278–282

23. Varshney, S., Jain, P., Srivastava, S. J 2017 Application of ameliorated wood pulp to recover Cd(II), Pb(II), and Ni(II) from e-waste, Mater Cycles Waste Manag https://doi.org/10.1007/s10163-016-0539-3

24. Wang L. K., Yung-Tse Hung, Shammas N. K. 2010 Handbook of Advanced Industrial and Hazardous Wastes Treatment, CRC Press

25. Wang, D., Liu, D., Tao, L. et al. 2017 The impact on the effects of leachate concentrates recirculation for different fill age waste, J Mater Cycles Waste Manag https://doi.org/10.1007/s10163-016-0508-x

26. Wójcik Ł., Izak P., Kuś R., 2009 The influence of composition changes on properties of clay-cement binders Materiały Ceramiczne = Ceramic Materials / Polskie Towarzystwo Ceramiczne, Kraków, Vol 61, pp 27-30

27. Wójcik Ł., Izak P., Mastalska-Popławska J., Gajek M., 2015 Clay-cement suspensions - rheological and functional properties Journal of Physics. Conference Series, vol. 790, pp 1–7.

28. Wuana R. A., Okieimen F. E. 2011, Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation I SRN Ecology Article ID 402647, http://dx.doi.org/10.5402/2011/402647

29. Zhang W., Ren X., Ouyang S., 2011 Development on ion substitution effect on the crystal structure and properties of tricalcium silikat Journal of Chinese. Ceramic Society vol 39 pp1666-1672

30. Zhang, H., He, PJ., Shao, LM. et al. 2008 Leaching behavior of heavy metals from municipal solid waste incineration bottom ash and its geochemical modeling, J Mater Cycles Waste Manag https://doi.org/10.1007/s10163-007-0191

31. Zmijowa D., Koliba M., Raclavski K 2018 Human Health Risk Assessment of Heavy Metals Bound on Particulate Matter Inżynieria Mineralna Wyd. Polskiego Towarzystwa Przeróbki Kopalń, z. 1(41), s. 93–98, DOI: 10.29227/IM-2018-01-15

Mechanizm immobilizacji kationów metali amfoterycznych w mieszaninach ilowo-cementowych
W artykule przedstawiono możliwości zastosowania specjalnie przygotowanych spoiw w celu unieruchomienia migracji metali amfoterycznych. Sposób cementowo-ilowe to mieszaniki zawierające w swoich składach spoiwo klinkierowe i minerały ilaste, w tym przypadku były to gliny Bełchatów i Koniecpol. Po procesie hydratacji mieszanik te tworzą elastyczne i szczelne struktury, które są wykorzystywane m.in. jako bariery unieruchamiającerozprzestrzelenie się zanieczyszczeń. Testy wykazały, że w przypadku metali amfoterycznych możliwa jest prawie 100% akumulacja zanieczyszczeń w strukturze zawiesin iłowo-cementowych. Podjęto również próby wyjaśnienia mechanizmów zatrzymywania jonów w powstałych strukturach. W artykule przedstawiono trzy prawdopodobne mechanizmy wiązania jonów amfoterycznych, pierwszy to retencja w przestrzeniach międzywarstwowych minerałów ilastych, drugi to uwięzienie w fazach typu CSH powstałych podczas hydratacji. Ostatnią możliwością jest tworzenie nowych struktur krzemiannych.

Słowa kluczowe: jony amfoteryczne, zanieczyszczenie metalami, mieszanki gliny z cementem, hydratacja
