

A study of the products of ferritization processing of galvanic waste: sludge and spent process solutions is carried out. As a result of experiments on dynamic leaching of heavy metal ions, the immobilization properties of the sludge, obtained at different process parameters of ferritization are determined. It is shown that the level of immobilization of heavy metals in ferrite sludge after leaching is 99.96 wt % and in the sludge of traditional wastewater neutralization <97.83 wt %. The studies determine the possibility of reliable utilization of ferritized galvanic waste – introduction into the charge to produce alkaline cements. It is found that the main crystalline phases in the structure of alkaline cements with ferrite sludge are calcite, quartz and heavy metal ferrites. In addition, jelly-like formations are found, which are further capable of crystallization. Such formations reliably bind heavy metals in the chemical structure of cement. It is found that when using up to 10 wt % of ferrite sludge in the total weight of cement, the compressive strength of artificial stone reaches 40 MPa, which meets the requirements of the current standard. The chemical stability of the alkali cement matrix using ferrite sludge is confirmed by the study of leaching of heavy metals for one day in neutral, alkaline and acidic media. It is shown that the degree of immobilization of heavy metal ions in cement with a ferrite sludge content of 30 wt % is >99.98 %. In addition, the concentrations of heavy metal ions during leaching meet the national and international standards for their MPC in drinking water and soil. This approach will allow solving the problem of utilization of hazardous galvanic waste and production of general construction materials

Keywords: *galvanic waste, ferritization, alkaline cements, heavy metals, sludge, leaching, electromagnetic pulses*

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1. Introduction

The functioning of production cycles of enterprises of instrument-making, chemical, machine-building and other industries is accompanied by the formation of industrial waste. The volume of this waste is constantly growing every year, while the rate of processing and disposal is incomparably low. As a result, millions of tons of various industrial wastes have been accumulated that need to be recycled and disposed of.

The most environmentally hazardous industrial waste includes metal-containing galvanic waste in the form of pasty sludge [1]. Such waste is generated by reactant wastewater treatment or disposal of working solutions containing heavy metal ions. After neutralization, galvanic sludge has a class III hazard, it contains sparingly soluble hydroxides of

heavy metals (nickel, copper, zinc, chromium, cadmium), and sludge itself exhibits alkaline properties [2]. High density of galvanic sludge at industrial sites and placement in large areas of the urban zone allow assessing them as a source of high man-made impact on the environment [3]. When such sludge is stored on an open surface, metal ions due to the easy dissolution of hydroxides are leached from storage sites into soil and water bodies under the influence of atmospheric precipitation. Therefore, improper storage of such sludge causes irreparable damage to the entire ecosystem.

Processing of galvanic sludge with subsequent disposal in special landfills is too complicated and unprofitable. Thus, the task is to develop effective methods of utilization of waste containing heavy metals as the last final stage of electroplating production. Difficulties in sludge utilization are associated with the following characteristics: high humidity (90–95 %),

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DEVELOPMENT OF TECHNOLOGY OF UTILIZATION OF PRODUCTS OF FERRITIZATION PROCESSING OF GALVANIC WASTE IN THE COMPOSITION OF ALKALINE CEMENTS

G. Kochetov

Doctor of Technical Sciences, Professor
Department of Chemistry*

E-mail: gkochetov@gmail.com

O. Kovalchuk

PhD, Senior Researcher

V. D. Glukhovskii Scientific Research Institute for
Binders and Materials*

E-mail: kovalchuk.oyu@gmail.com

D. Samchenko

PhD, Senior Researcher

Scientific Research Part*

E-mail: sama30071988@gmail.com

*Kyiv National University of

Construction and Architecture

Povitroflotskyi ave., 31, Kyiv, Ukraine, 03037

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complexity, variable composition, large volume, instability of some compounds. Also, when storing galvanic sludge, in addition to environmental damage, a large amount of valuable raw materials is lost. Reuse of materials extracted from the sludge, on the contrary, allows saving significant amounts of natural resources and reducing the burden on the ecosystem [4]. So, research and technologies are being actively developed all over the world, which provide for resource-saving processing and utilization of electroplating waste.

Therefore, to solve the above problems, further development and implementation of environmentally friendly, low-waste and energy-saving technologies that allow efficient sludge utilization and the creation of closed-loop water recirculation systems in production are relevant.

2. Literature review and problem statement

The biggest environmental problem of modern galvanic production is the reliable disposal of toxic sludge formed as a result of reactant wastewater treatment. As a rule, neutralization sludge at general treatment facilities of industrial enterprises contains a mixture of different heavy metals, so the ways of disposal of such sludge are extremely limited [2]. An option to overcome these difficulties is to organize a certain electroplating line at local treatment facilities [3]. Then the treatment process is much easier to control, because the neutralization sludge contains compounds of only one heavy metal.

Leaching of toxic heavy metal compounds from hydroxide sludge leads to their dangerous spread in the environment. Given this, there is a need to develop reliable methods for processing galvanic waste. Known methods of neutralization of hydroxide sludge are associated with their use as additives in the production of various materials: concrete [5], expanded clay [6], asphalt [7], Portland cement [8], bricks and ceramics [9]. It is also possible to produce pigments and catalysts from them [10]. A significant drawback of these technologies is the inevitable leaching of heavy metal ions from these materials into the environment [11].

In [12], the results of studies on the extraction of valuable heavy metal compounds from galvanic sludge by dissolving them in sulfuric acid are presented. However, when applying this method, the issues related to the use of chemically hazardous acid and the subsequent production of commercial products remain unresolved [13].

An option to overcome these difficulties may be sludge processing by ferritization. This approach is used in [14], which examines the possibility of chemical stabilization of sludges in the formation of low-toxic ferrites of heavy metals – compounds of class IV hazard. They can be stored in open areas without the risk of environmental pollution. The ferritization process involves the transformation of compounds of ferrous and ferric iron and other heavy metals during the oxidation of the reaction mixture with air oxygen. In addition, this method provides a high degree of extraction of heavy metal ions from liquid industrial waste [15].

It is found that the processing of industrial wastewater and galvanic sludge by ferritization is carried out at temperatures above 60 °C and lasts more than an hour [14]. Given that the thermal method of process activation is quite energy- and resource-intensive, an alternative can be energy-saving electromagnetic pulse (EMP) activation of the reaction mixture [16].

Compared to the traditional reagent method of sludge processing [2], the possibilities of utilization of ferritization sludges are significantly expanded. They can be used in the production of soft magnetic high-frequency materials [17], ferromagnetic fabrics [18], as well as radio-absorbing coatings [19], in which the requirements for the ferrite material structure are strictly regulated. The direct use of ferrite sludge in the production of alkaline cements is also promising [20]. Previous studies have shown that such cements are resistant to aggressive media and have a significant range of unique performance properties. Alkaline cements reliably fix radioactive and heavy metals in their structure not only at the physical but also at the chemical level [21]. In [22], the possibility of adding ferrite sludge in the range of 5.5 to 7.5 wt % (content of the metal ferrite phase in the sludge $\geq 90\%$) in alkaline cements as a filler is shown. The deviation of the strength of the obtained alkaline cements from standard analogues does not exceed 5 %.

However, in [22], the issues concerning the stability of ferrite sludge under different environmental conditions remained unresolved. That is why the study of the degree of leaching of heavy metals from ferrite sludge contributes to the development of their environmentally friendly utilization, as well as energy and resource saving in galvanic production.

All this allows us to assert the reliability and safety of processing toxic galvanic sludge by ferritization with the subsequent use of processing products in the matrix of alkaline cements. With such sludge utilization, there is a fundamental possibility to fix oxide compounds of heavy metals in the cement structure not only at the physical but also at the chemical level. This method of galvanic waste utilization will allow saving valuable raw materials and using toxic galvanic sludge as a commercial product.

3. The aim and objectives of the study

The aim of the work is to determine the effect of ferrite sludge as products of galvanic waste processing on the immobilization properties of alkaline cements. This will make it possible to develop a new technology of toxic waste disposal.

To achieve the aim, the following objectives were set:

- to investigate the chemical stability of sludges obtained under different process parameters of ferritization, as a result of studying the ability to leach heavy metal ions from them;
- to study the possibility of introducing ferrite sludge into the charge for the preparation of alkaline cement and to determine the immobilization properties of the obtained material;
- to study the structural and physical-mechanical properties of alkaline cements using ferrite sludge.

4. Materials and methods of the study of products of galvanic waste ferritization as a part of alkaline cements

Samples of ferrite sludge obtained in processing galvanic waste by ferritization according to the method given in [23] were used for the study. Ferritization was carried out in laboratory installations with thermal at a temperature of 75 °C and electromagnetic pulse (EMP) activation of the pro-

cess at 18 °C [16, 23] with the following parameters: total concentration of heavy metal ions $C_{\Sigma}=6.41\div 14.23$ g/dm³; ratio of concentrations of iron ions to the total concentration of heavy metal ions in the solution $[Fe^{tot}]/\Sigma Me$ ($[Ni^{2+}] + [Cu^{2+}] + [Zn^{2+}]$) $Z=2\div 6$; pH=8.5÷10.5; process duration $\tau=25$ min; air bubbling rate of the mixture $v=0.075$ m³/h.

The ion content in the studied sludge samples is presented in Table 1. Phase composition: heavy metal ferrites Fe₂(Fe,Ni,Cu,Zn)O₄, iron-nickel oxyhydroxide (FeNi)O(OH) and sodium sulfate Na₂SO₄. These phases have ferromagnetic properties and a spinel-like crystal lattice.

The chemical stability of ferrite sludge was determined by leaching heavy metal ions in a neutral medium, according to the requirements of EN 12457 –1:2002 Part 1. Leaching was carried out for 1 day in a dynamic mode, which occurs under the influence of precipitation on landfill sludge. To do this, an installation for mixing sludge samples with a leaching eluate with a speed of 9 rpm was used, shown in Fig. 1.

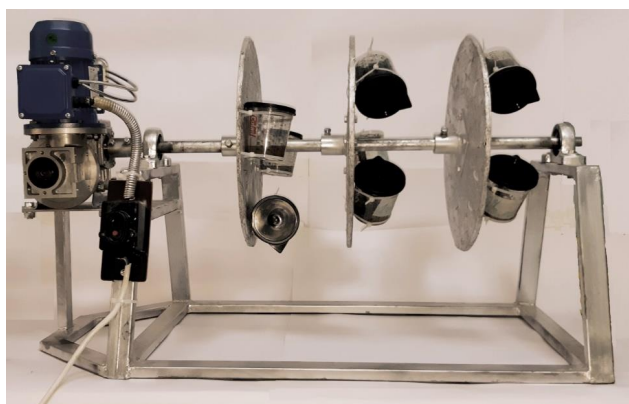


Fig. 1. Installation for studying dynamic leaching of heavy metal ions

A sample of ferrite sludge with a total mass M_W corresponding to 0.175 kg±0.005 kg of dry mass M_D was used for the study. The sample was placed in a 0.5 dm³ polypropylene bottle. Then the required volume of leacher L was added, set during the extraction process by the liquid/solid ratio $(L/S)=2$ dm³/kg±2 % and calculated by the formula (1). The relative leaching value of heavy metal ions (A) in mg per kg of sludge is determined by the formula (2):

$$L = \left(2 - \frac{MC}{100} \right) \cdot M_D, \tag{1}$$

$$A = C_{tot} \cdot \left[\left(\frac{L}{M_D} \right) + \left(\frac{MC}{100} \right) \right], \tag{2}$$

where L is the volume of the leacher, dm³, MC is the moisture content factor, %, MD is the mass of dry matter in the sludge sample, kg, A is the amount of leached component, mg/kg, C_{tot} is the residual component concentration in the eluate, mg/dm³.

For grinding ferrite sludge samples, an EB 50×40 – L jaw crusher (Germany) was used, for sieving – sieves with a nominal size of 4 mm. The pH of the eluate was monitored by a pH-150 meter (Belarus). The process of sludge weighing was carried out on the “AXIS” AD100 series 3 accuracy class analytical scales (Poland). Distilled water with pH=6.0 and electrical conductivity <5 μS/cm was used in the studies.

The residual concentrations of heavy metal ions (iron, nickel, copper and zinc) after leaching heavy metals in the eluate were determined on a DR 3900 spectrophotometer (Hach, USA).

To study the leaching of heavy metal ions from samples of alkaline cements with ferrite sludge, 2×2×2 cm cubes were formed. After the cement samples gained strength characteristics for 28 days under normal conditions at a humidity of 95 %±5 % and a temperature of 20 °C±2 °C, they were crushed in the jaw crusher. Leaching of heavy metals from the obtained cement was carried out at a temperature of (20±5) °C for 1 day in distilled water at pH=6.0, as well as in acidic (pH=3.5) and alkaline media (pH=11.5). To create acidic and alkaline media, the required amount of reagent grade nitric acid and sodium hydroxide, respectively, was added to the water.

As raw materials for the production of alkaline cements, granulated blast furnace slag of the PJSC “Dnieper Metallurgical Plant”, Kamyanske (Ukraine) according to DSTU B B.2.7-302: 2014, ground to a specific surface area of 450 m²/kg (according to Blaine) and lime factor of 1.11 was used. Soda ash and sodium metasilicate pentahydrate (TU 6–18–161–82) were used as an alkaline component of the charge. Physico-mechanical tests of alkaline cement were performed according to DSTU B B.2.7–187:200.

Structural analysis of dried alkaline cement powders was performed by stepwise powder diffraction with Cu – K α radiation on an Ultima IV diffractometer (Rigaku, Japan). The survey was carried out in the angle range of 2 θ 6–70° with a scanning step of 0.05° and exposure time of 2 s. A REMMA-101A scanning electron microscope-analyzer (SEIMI, Ukraine) was used to study the microstructure of sludge samples.

Table 1

Ion content in ferrite sludge (wt %)

Z(Fe/Me)	pH	Method of activation of the ferritization process											
		Electromagnetic pulse (EMI)						Thermal					
		Fe ²⁺	Ni ²⁺	Cu ²⁺	Zn ²⁺	Na ⁺	SO ₄ ²⁻	Fe ²⁺	Ni ²⁺	Cu ²⁺	Zn ²⁺	Na ⁺	SO ₄ ²⁻
2/1	10.5	55.1	14.9	8.2	4.4	5.6	11.8	56.4	15.3	8.5	4.6	4.8	10.4
4/1	8.5	63.9	8.6	4.7	2.6	6.4	13.8	66.7	8.9	4.9	2.7	5.4	11.4
	9.5	67.3	9.1	5.0	2.7	5.1	10.8	68.4	9.3	5.2	2.8	4.5	9.8
	10.5	71.4	9.7	5.4	2.9	3.4	7.2	70.7	9.6	5.3	2.9	3.7	7.8
6/1	10.5	70.3	6.5	3.5	1.9	5.7	12.2	74.9	6.8	3.7	2.0	4.0	8.6

5. Results of studies of the properties of alkaline cements using ferrite sludge

5.1. Study of the chemical stability of ferrite sludge obtained under various process parameters of ferritization

The study of leaching of heavy metal ions from ferrite sludge allows determining the chemical stability of these materials. Leaching of heavy metal ions from sludge (Fig. 2, 3) depends on the parameters and activation method of the galvanic waste treatment process. Analyzing the data of Fig. 2, it should be noted that the lowest concentration values of metal ions when they are leached from ferritization sludge were obtained with pH=10.5 and different activation methods. In addition, the concentrations of metal ions during leaching meet the requirements of DSanPiN (state sanitary regulations and norms) 2.2.7.029–99 and Directive 86/278/EU regarding their MPC in soil. This indicates a reliable fixation of these toxic metals in the composition of ferrite formations with a reverse spinel structure. Exceeding these standards during leaching nickel and copper ions is observed for

sludge obtained at pH=8.5. In addition, as can be seen from the diagrams in Fig. 2, with increasing pH of the ferritization reaction mixture, leaching of heavy metal ions from sludge decreases when using both methods of activation. Compared to the conventional thermal method, electromagnetic pulse activation of the ferritization process leads to an increase in the concentrations of iron, copper and zinc ions leached from the sludge. However, the difference in these values is insignificant and lies in the range of 0.1–0.9 mg/kg. Another trend is observed in the leaching of nickel ions: their concentration is approximately 2 times higher with the thermal activation method in the entire investigated pH range.

As shown in Fig. 3, the lowest values of leaching of heavy metal ions are observed during the ferritization process with Z=4/1 and pH=10.5. The concentration values of these ions are in the range of 0.20–0.83 mg/kg. With a significant increase in the concentration of iron ions in the solution (Z=6/1), the leaching of heavy metal ions, although reaching maximum values, remains within the requirements of DSanPiN 2.2.7.029–99 and Directive 86/278/EU.

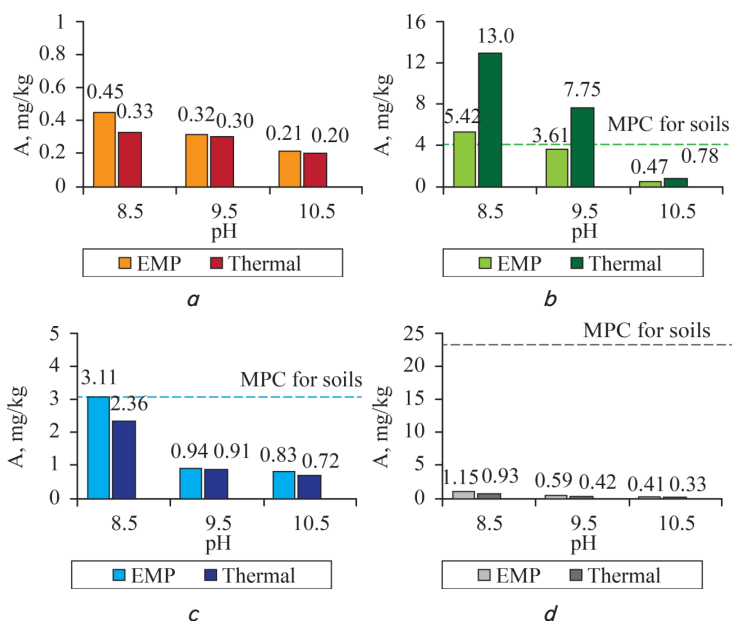


Fig. 2. Leaching of heavy metals (A) from the sludge obtained by EMP and thermal methods of activation of the ferritization process and different pH values of the initial reaction mixture: a – Fe^{tot}; b – Ni²⁺; c – Cu²⁺; d – Zn²⁺

Table 2

Determination of chemical stability of ferrite sludge in the alkaline cement matrix

pH of the initial eluate	Sludge content in cement, wt %	Ion concentration during leaching							
		Fe ^{tot}		Ni ²⁺		Cu ²⁺		Zn ²⁺	
		A, mg/kg	C _{tot} , mg/dm ³	A, mg/kg	C _{tot} , mg/dm ³	A, mg/kg	C _{tot} , mg/dm ³	A, mg/kg	C _{tot} , mg/dm ³
3.5	10	not found	not found	not found	not found	0.08	0.03	not found	not found
	20	not found	not found	0.34	0.16	0.18	0.08	not found	not found
	30	0.18	0.08	0.44	0.21	0.30	0.14	not found	not found
6.6	10	not found	not found	not found	not found	not found	not found	not found	not found
	20	not found	not found	not found	not found	0.08	0.03	not found	not found
	30	not found	not found	not found	not found	0.20	0.09	not found	not found
11.5	10	not found	not found	not found	not found	not found	not found	not found	not found
	20	not found	not found	not found	not found	0.14	0.06	not found	not found
	30	not found	not found	not found	not found	0.24	0.11	not found	not found

Note: not found – the values of metal concentrations beyond the sensitivity threshold of the device: Fe^{tot} – <0.1; Ni²⁺ – <0.05; Cu²⁺ – <0.01; Zn²⁺ – <0.01 mg/dm³

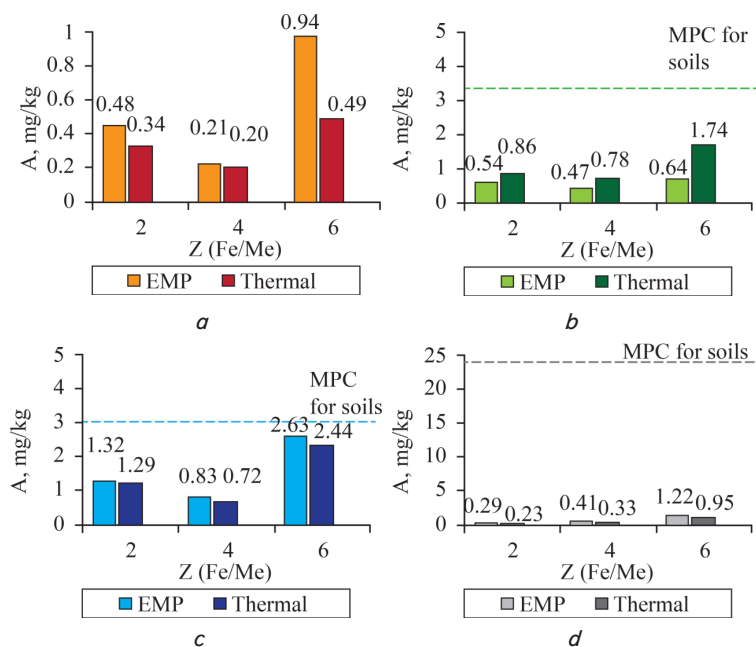


Fig. 3. Leaching of heavy metals (A) from the sludge obtained by EMP and thermal methods of activation of the ferritization process and different values of Z: a – Fe^{tot}; b – Ni²⁺; c – Cu²⁺; d – Zn²⁺

5. 2. Study of leaching of heavy metal ions from the alkaline cement matrix using ferrite sludge

To study the possibility of reliable immobilization of heavy metals, the ferrite sludge obtained at Z=4/1 and pH=10.5 by the electromagnetic pulse activation method was used as a component of alkaline hybrid cements. Ferrite sludge in an amount of 10 to 30 % by weight of cement was added to the charge for making cement. The results of the study of leaching heavy metal ions are presented in Table 2. Concentrations of heavy metals are given in mg/kg (A) and mg/dm³ (C_{tot}) to compare them with MPC in soil and drinking water, respectively.

As can be seen from Table 2, the leaching of metal ions depends on the pH of the medium, as well as the amount of ferrite sludge in the cement. It should be noted that in all series of experiments, the residual concentrations of heavy metals during leaching meet the requirements of DSaNPiN 2.2.7.029–99 and Directive 86/278/EU on their MPC in soil. The effect of acidic medium on the resulting cement should be noted. Concentrations of iron, nickel and copper ions during leaching in the acidic medium are higher than in neutral and alkaline. However, their concentration in the eluate is lower than the MPC of these ions in the soil. At pH values of 6.6 and 11.5, slight leaching of only copper ions was found in the sludge samples at a ferritization sludge content of 20 and 30 wt % in cement.

In addition, the residual concentrations of heavy metals in the eluate meet the requirements of drinking water quality standards (Table 3).

Table 2 shows a reliable chemical fixation of the above heavy metals in the composition of alkaline cements, only in an amount not exceeding 10 wt %. In the case of the introduction of ferrite sludge into cement composition in the amount of 20 and 30 wt %, as well as in the conditions of leaching in an acidic medium, there is an excess of MPC standards of nickel ions for drinking water.

5. 3. Study of structural and physical-mechanical properties of alkaline cements using ferrite sludge

The composition and performance properties of the obtained cements are given in Table 4.

Analyzing the data in Table 4, it can be assumed that the introduction of more than 10 wt % of ferrite sludge significantly impairs the strength characteristics of the material by 15 % compared to alkaline cement without additives.

To justify a significant loss of strength characteristics of cement at 30 wt % of ferrite sludge, we consider it appropriate to determine the qualitative and quantitative phase composition of hydration products presented in Fig. 4 and Table 5.

The results of the studies showed that the content of crystalline ferrite phases in the composition of the identified formations in the cement is 17.6 %, while the content of ferrite components in the original non-hydrated mixture was 27.0 %. This suggests that the remaining 9.4 % of ferrites were bound and incorporated into the structure of jelly-like X-ray amorphous compounds.

The presence of a significant number of jelly-like formations is confirmed by electron microscopy (Fig. 5).

Table 3

Norms and standards of drinking water quality

Metal ions	Norms and standards for drinking water, mg/dm ³		
	Ukraine (DSaNPiN 2.2.4-171-10)	European Union (EU Directive 98/83)	USA (NPDWR EPA)
Fe ^{tot}	0.2	0.2	0.3
Ni ²⁺	0.02	0.02	not rated
Cu ²⁺	1.0	2	1.3
Zn ²⁺	1.0	not rated	5.0

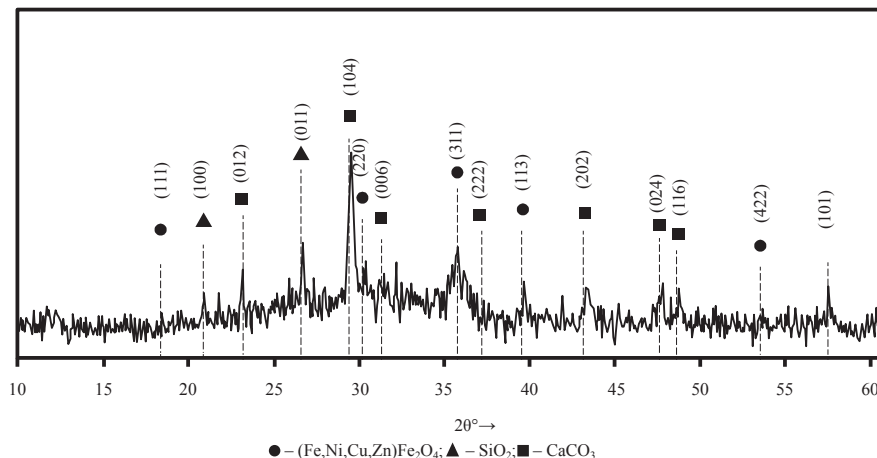


Fig. 4. Diffractogram of a sample of artificial stone based on alkaline cement with the addition of 30 wt % of ferrite sludge

Table 4

Composition and performance properties of alkaline cement paste using ferrite sludge

Com- position No.	Cement composition, wt %				Compressive strength, R_{comp} , MPa, after, days		
	Sludge	Metasili- cate	Soda ash	Ferrite sludge	3	7	28
1	95	3	2	–	13.4	31.1	41.3
2	85.5	2.7	1.8	10	0.7	5.0	35.0
3	76	2.4	1.6	20	0.5	4.1	25.0
4	66.5	2.1	1.4	30	–	2.0	12.5

Table 5

Quantitative phase composition of alkaline cement using 30 wt % of ferrite sludge

No.	Identified phase	Chemical formula	Mass fraction of phase, %
1	calcium carbonate	$CaCO_3$	71.9
2	metal ferrite	$(Fe, Ni, Cu, Zn) Fe_2O_4$	17.6
3	silicon dioxide	SiO_2	10.5

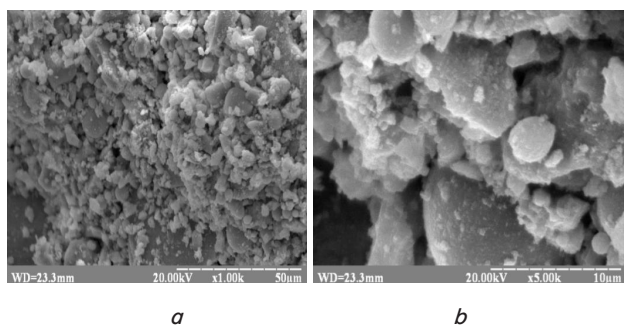


Fig. 5. Microphotographs of the chipped surface of the artificial cement stone using 30 wt % of ferrite sludge, magnification: $a - \times 1,000$, $b - \times 5,000$

Fig. 5 shows that the surface of the material is fine-grained. At high magnification, aggregates are observed in the cement matrix, which may belong to ferrite compounds.

6. Discussion of the results of utilization of galvanic waste processing products in alkaline cements

The results of leaching of heavy metals from sludge obtained under different ferritization conditions showed a reliable fixation of these heavy metals in the composition of formations with a reverse spinel structure. It is noted that the leaching of heavy metals increases with decreasing pH of the ferritization process from 10.5 to 8.5 (Fig. 2), which is obviously due to a decrease in the number of crystalline ferrite phases in the sludge. It can be assumed that the increase in the leaching of nickel ions is associated with an increase in the content of the nickel limonite $(FeNi)O(OH)$ phase. Since this phase is unstable in an aqueous solution [24], its content determines the degree of leaching of nickel ions. It is found that the sludge obtained by the electromagnetic pulse method of activation and the following ferritization parameters: $C_2=10.41 \text{ g/dm}^3$; $Z=4/1$, $pH=10.5$ is characterized by a high degree of immobilization of heavy metals of 99.96 % unlike galvanic sludge, in which this value is less than 97.8 % (Fig. 2, 3).

It is advisable to use chemically stable products of ferritization of galvanic waste in the charge to produce alkaline cements. It is found that with the introduction of up to 10 wt % of ferrite sludge, the strength of artificial stone reaches 40 MPa under normal curing conditions and is not inferior to traditional analogues of general construction purposes. When introducing 30 wt % of sludge in cement, there is a loss of strength characteristics of the material within 50 % (Table 4). As shown by the analysis of previous studies [22], when introducing 5.5 to 7.5 wt % of ferrite sludge as a filler to alkaline cements, the strength is stabilized to 43 MPa. Such a strength of the material corresponds to the composition of the comparison cement (without ferrite sludge). It is found that when introducing 27 wt % of ferrite sludge in the mixture, the content of crystalline ferrite phases in the cement is 17.6 wt %, and the rest were bound and incorporated into the structure in the form of amorphous compounds (Table 5). This assumption is confirmed by the absence of crystalline formations of sodium and calcium hydrosilicates in the cement composition and corresponds to the well-known nature of the processes of structure formation of alkaline cements. Comparison of the obtained results on the microstructure of artificial cement stone (Fig. 5) with the literature data [20] confirms the presence of a jelly-like matrix of weakly crystallized formations.

The study of leaching of heavy metal ions makes it possible to determine the immobilization properties of artificial stone based on alkaline cement using ferrite sludge under the action of an aggressive medium. It is proved that the degree of immobilization of heavy metals at a ferrite sludge content of 30 wt % in cement even during leaching in the acidic medium is 99.98 % (Table 2). The results of the studies based on previous results [22] indicate that heavy metals are bound at the chemical level, entering the structure of formations of the resulting materials, which ensures their reliable fixation. Obviously, heavy metals are included in the structure of submicrocrystalline formations of alkaline cements, which is confirmed by very low leaching rates of these metals from the matrix. Such jelly-like (submicrocrystalline) formations are the basis for further recrystallization into zeolite structures.

Thus, the studies suggested the use of alkaline cements as matrices for the utilization of galvanic waste processing products. The use of up to 10 wt % of alkaline cements allows utilizing galvanic waste processing products without significant loss of operational properties, as confirmed by the experiments. The results of the studies on leaching heavy metals meet the requirements of DSaNPiN 2.2.4-171-10, EU Directive 98/83 and USA NPDWR EPA, regarding their MPC in drinking water and soil. It should be noted that with the use of such cements it is possible to obtain environmentally friendly materials for general construction purposes, which are not inferior to traditional analogues in terms of operational indicators. But, as the study showed, the introduction of more than 30 wt % of ferrite sludge in the matrix of alkaline cements significantly impairs the immobilization and operational properties of the obtained material.

In the future, we consider it appropriate to investigate the possibility of increasing the strength properties of alkaline cements with a ferrite sludge content of more than 30 wt % to the values of traditional analogues.

7. Conclusions

1. Rational parameters of toxic waste processing by ferritization are determined: total concentration of heavy metal

ions – 10.41 g/dm³; ratio of the concentrations of iron ions to the total concentration of other heavy metal ions in the solution $[Fe^{tot}]/\Sigma Me ([Ni^{2+}]+[Cu^{2+}]+[Zn^{2+}]) - 4$; the pH of the reaction mixture – 10.5 with thermal and electromagnetic pulse activation methods. High immobilization properties of ferrite sludge in relation to heavy metals were confirmed (immobilization level after leaching is 99.96 wt % in contrast to hydroxide galvanic sludge <97.83 %). This indicates the environmental safety of the obtained materials.

2. The environmental safety of alkaline cements with the use of ferritization sludge by leaching heavy metal ions in a neutral, alkaline and acidic medium is studied. It is shown that the degree of immobilization of heavy metals in cement with a ferrite sludge content of 30 wt % is more than 99.98 %, which meets the requirements of DSaNPiN 2.2.4-171-10, EU Directive 98/83 and USA NPDWR EPA on MPC of heavy metal ions in drinking water and soil.

3. The mineralogical composition of alkaline cements using ferrite sludge is determined. It is shown that the main crystalline phases are calcite, quartz and metal ferrites. Compositions of alkaline cements using galvanic waste processing products are proposed. It is found that when using up to 10 % of ferrite sludge of the total weight of cement, the strength of artificial stone reaches the value of 40 MPa after 28 days of curing under normal conditions. In addition, the presence of jelly-like formations in the alkaline cement matrix, which are further capable of recrystallization into zeolite-like phases, is determined. Such a composition of formations provides reliable attraction of heavy metal ions to the chemical structure of the resulting material.

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