Magnesium Potassium Phosphate Cement for Encapsulation of Ash from Burning Radioactively Contaminated Wood

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When wood from Chornobyl radioactively contaminated forests is burned in the Incinerator created in the Chornobyl zone under support of the European Commission, ash with a high content of Cs radionuclides is formed. Recently, magnesium potassium phosphate cements (MKPC) have been proposed as an effective alternative to Portland cement-based protective matrices. In this work, MKPC compositions were optimized for laboratory-scale encapsulation of inactive model ash, used as surrogate of the radioactive ash. The influence of the MgO/KH2PO4 ratio and the amount of added model ash on the temperature and setting time of the MKPC paste were determined. The compressive strength after 28 days of MKPC curing without ash was 22.7 MPa. After adding 20 wt.% model ash, the compressive strength of the MKPC matrix was 34.5 MPa, 40 % model ash was 23.4 MPa and 60 % model ash was 8.3 MPa. Thus, the accepted amount of the added ash that does not initiate the essential strength decrease of the MKPC matrix is 40 %. X-ray diffraction analysis of the MKPC matrix with 40 % model ash shows the presence of the main phase – K-struvite MgKPO4·6H2O. In addition to K-struvite, there are peaks of unreacted MgO and compounds such as calcite CaCO3, quartz SiO2, and potassium chloride KCl, which are parts of the model ash. It has been shown that ash components such as hydroxyapatite Ca(PO4)2(OH) and calcium oxyphosphate Ca3(PO4)2O are involved in the formation reaction of phosphate cement and it contributes to increasing of the permissible amount of ash encapsulated into the MKPC matrix. SEM images of MKPC samples demonstrate a dense structure with well-connected ash particles. The leaching behavior of the MKPC matrices and their thermal stability were also assessed using immersion tests and thermogravimetric analysis, respectively.
The Cs leaching rate of $1.2 \times 10^{-4}$ g/cm$^2$·day from the MKPC matrix containing 40 % MA is lower than the rates typical for cement waste forms. The obtained results demonstrate the possibility of using new magnesium-potassium phosphate cement as a matrix for the encapsulation of ash from the combustion of radioactively contaminated wood in the Chornobyl zone.

Keywords: ash from wood burning, magnesium potassium phosphate cement, encapsulation, matrix, strength, structure, leaching.

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Introduction

After the Chornobyl accident, forests were one of the main natural ecosystems that were contaminated as a result of radioactive fallout. The main problem regarding long-term radioactive contamination of the forest environment and forest products is $^{137}$Cs due to its 30-year half-life. Other radionuclides, such as $^{60}$Sr and plutonium isotopes, have a limited distribution in forested areas, with the exception of small areas in and around the Chornobyl exclusion zone [1].

Consequently, fires in the contaminated forests of the Chornobyl zone pose a great danger, as a result of which radioactive combustion products of radioactively contaminated wood enter the air. Reducing the risk of fires in the region and preventing radioactive contamination by burning products can be achieved by reducing the volume of dry forest in the Chornobyl exclusion zone. For this purpose, in 2015, with the financial support of the European Commission, an experimental installation Incinerator was built. The experimental installation Incinerator is designed for burning radioactively contaminated wood (which belongs to the category of radioactive waste) harvested in the 30-km exclusion zone [2].

Thermal energy produced by burning wood is used to power existing heat supply systems for various facilities in the Chornobyl exclusion zone, including the city of Chornobyl.

After burning radioactively contaminated wood in the Incinerator installation, ash is formed containing radionuclides with increased concentration. Radioactive ash resulting from the operation of the Incinerator installation is unsuitable for long-term storage, much less final disposal, due to its tendency to disperse and its inability to contain the spread of radionuclides into the environment. The first step to ensure reliable insulation of radioactively contaminated ash is to encapsulate it into a protective matrix.

Encapsulation into a cement matrix is one of the most common methods for conditioning low- and intermediate-level radioactive waste. In many ways, cementing has become widely used due to the availability and low cost of technological equipment, starting materials and the relative simplicity of technological processes. The main disadvantages of the cementation method using Portland cement include low strength of cement matrices, low waste content, high water permeability and low chemical resistance.

Recently, the use of magnesium potassium phosphate cement (MKPC) as a matrix material for the encapsulation of radioactive waste has been proposed and successfully tested. MKPC is defined as a ceramic cement that has properties characteristic of both ceramics and hydraulic cements. The microstructure of MKPC is similar to ceramics, with a strongly pronounced crystalline structure, however, unlike ceramics, MKPC is formed at room temperature and uses water to initiate chemical reactions followed by hardening of the material, which is similar to the manufacture of hydraulic cements [3]. Unlike Portland cement, which typically has a pH of about 12, the final pH of MKPC is neutral, making it inert to the additives used to make various phosphate composites.

A significant part of the research on the immobilization of various types of radioactive waste in the MKPC matrix was performed at the Argonne National Laboratory, USA [4]–[7]. Currently, research is being carried out on the use of MKPC as a matrix for the immobilization of high-salt radioactive solutions [8]–[11], radioactive concrete waste generated during the decommissioning of nuclear power plants [12], waste of reactive metals such as uranium and aluminum [13]–[15] and other radioactive waste.

The development of a protective MKPC matrix for encapsulation ash from burning radioactively contaminated wood in the Chornobyl zone is the main goal of this work. Ash obtained by pyrolytic treatment of pine wood at a temperature of 650 °C for 3 hours was used as a model ash (MA). The resulting MKPC matrix was characterized by X-ray diffraction (XRD), structural analysis (SEM), thermogravimetric analysis (DTA/TGA), compressive strength and leaching testing. The behavior of cesium was examined during the leaching test of the MKPC matrix with encapsulated MA, saturated with a CsNO$_3$ solution.
Materials and Methods

Magnesium oxide MgO with purity 97%, particle size < 200 µm, (Alchem, Ukraine), potassium dihydrogen phosphate KH₂PO₄ with purity 98%, particle size < 630 µm, (Israel) and distilled water were used as raw materials for the production of MKPC. Boric acid H₃BO₃ with purity 99%, (Alchem, Ukraine) was used as a reaction retarder. Cesium (nonradioactive) from cesium nitrate CsNO₃ was used as ^137Cs surrogate for the MA.

Heat treatment of MgO powder was carried out in air in an electric furnace Nabertherm P310 (Germany) at a temperature of 1300 °C for 1 hour.

The setting time of MKPC pastes was measured using the Vicat needle test. The phase composition of the materials was studied by XRD analysis (DRON-4-07 Cu Kα with a nickel filter to attenuate the Kβ component of characteristic radiation). The ICDD PDF-2 diffraction database (2004) was used for phases identification.

Differential thermal and thermogravimetric analyses (DTA/TG) were carried out on an SDT Q600 V20.9 Build 20 thermal analyzer for determination of the processes that took place during heating of MKPC samples in the temperature range of 20–1000 °C and heating rate 20 °C/min.

The microstructure of MKPC samples was studied using a Jeol JSM 6700F scanning electron microscope (Japan). The concentration of cesium in the leachate was determined by inductively coupled plasma atomic emission spectroscopy ICP-OES (iCAP 6300 Duo spectrometer from Thermo Scientific Corporation, USA).

MA was produced by pyrolytic treatment of pine wood at a temperature of 650 °C for 3 hours. MA was added to the prepared CsNO₃ aqueous solution (1 % CsNO₃) and kept for 7 days for saturation at room temperature. After drying, the MA powder was sieved through a 200-µm sieve and subsequently used for experiments. The appearance of the MA powder is presented in Figure 1. Using X-ray phase analysis, it was established that the main phases of MA are: calcite CaCO₃, quartz SiO₂, hydroxyapatite Ca₅(PO₄)₃(OH), calcium oxyphosphate Ca₄(PO₄)₂O and potassium chloride KCl (Figure 2).

The MKPC samples with the addition of MA were prepared according to the scheme presented in Figure 3. Dry components (MgO, KH₂PO₄ and MA) were mixed in a Pulverisette 6 planetary monomill (Germany): container (200 ml) and stainless steel balls, rotation speed 200 rpm, time 10 minutes. Next, boric acid (2 % of MgO + KH₂PO₄), used as a retarder, was dissolved in distilled water and a mixture of dry components was added to this solution and finally mixed for 2 minutes until a homogeneous paste was obtained.
The resulting paste was poured into plastic molds. The samples were stored in the molds for 24 hours, then removed and kept under closed conditions (to prevent excessive drying) until compressive strength (7, 14 and 28 days) and leaching tests (after 28 days of curing) were carried out.

**Results and Discussion**

As it is known, the setting time and the temperature of the paste, as well as the structure, density, strength and other physicochemical properties of the solid MKPC product are influenced by the ratio of MgO to KH$_2$PO$_4$ (M/P), water content and the presence of reaction retarder [16]–[20]. Thus, an increase in the water content in the mixture leads to a decrease in compressive and bending strength, which is typical for conventional cements [21].

In the case of manufacturing MKPC samples with a stoichiometric ratio $M/P = 1/3.37$ and a water to compressive and bending strength, which is typical water content in the mixture leads to a decrease in the reaction retarder [16]–[20]. Thus, an increase in the water content in the mixture leads to a decrease in compressive and bending strength, which is typical for conventional cements [21].

In the case of manufacturing MKPC samples with a stoichiometric ratio $M/P = 1/3.0$, swelling decreases (Figure 4a). The swelling of MKPC is probably due to the presence of residual KH$_2$PO$_4$ in the pores of the material and, in the presence of water, subsequent precipitation of products causing swelling. Swelling creates significant loads on the structure of the material, which leads to cracking or even destruction of samples [22].

With an increase in the amount of MgO relative to KH$_2$PO$_4$ (M/P = 1/3.0), swelling decreases (Figure 4b) and it is not observed at M/P = 1/2.5. The amount of water was increased to $w/c = 0.38$ at M/P = 1/2.5 to ensure acceptable workability of the MKPC paste.

The samples obtained after hardening of the MKPC (M/P = 1/2.5) with MA content from 0 to 60 wt. % are presented in Figure 5. With an increase in the amount of MA to 60 %, the amount of water was also increased to $w/c = 0.45$. Upon visual inspection, no visible defects were found on the surface of the samples. The influence of the M/P ratio and the amount of added MA on the temperature and setting time of the MKPC paste (total weight of dry components $\sim 25$ g) are presented in the graphs (Figures 6, 7).

In the temperature curves of the MKPC paste with 40 % MA, two distinct exothermic peaks are observed for all M/P values (Figure 6a). With an increase in the amount of MgO relative to KH$_2$PO$_4$, the second temperature maximum shifts towards shorter times and at the same time its value increases to 72.6 °C (M/P = 1/1.5). The position of the first maximum is observed at 6 minutes and its value is practically unchanged at 42–44 °C for all M/P ratios.

The appearance of two temperature maxima probably exists, along with the exothermic reaction of MKPC formation, due to the dissolution of KH$_2$PO$_4$ in water with the absorption of heat [23]. Therefore, at a certain point in time, the overall temperature will drop and a region with lower temperature will appear between two temperature maxima. With an increase in the proportion of MgO and, accordingly, with a decrease in the proportion of KH$_2$PO$_4$, the length of this section and the value of its minimum decrease.

With an increase in the proportion of MgO, the setting time of MKPC paste decreases from 38 minutes for $M/P = 1/3.37$ to 20 minutes for $M/P = 1/1.5$ (Figure 6b). This is due to a corresponding increase in the specific surface area of the MgO powder and, as a consequence, acceleration of the formation reaction of MKPC.

The effect of addition MA from 0 to 80 wt.% on the temperature of the MKPC paste ($M/P = 1/2.5$) is presented in Figure 7a. With an increase in the amount of MA, a decrease in the first and an increase in the second temperature maximum are observed. The time for the second appeared maximum is also reduced from 56 minutes (0 % MA) to 16 minutes (80 % MA).

MA contains a sufficient amount of calcium (Figure 2), which will participate in the reaction to produce MKPC. Consequently, with an increase in the amount of MA, a reduction in the time of appearance of the second maximum occurs due to a decrease in the number of K$^+$ ions relative to the sum of Mg$^{2+}$ and Ca$^{2+}$ ions, just as with an increase in the M/P ratio (Figure 6a).

With an increase in the amount of MA to 40 %, the setting time increases from 8 to 28 minutes and decreases to 20 and 14 minutes with the addition of 60 and 80 % MA, respectively (Figure 7b). After addition MA (up to 40 %), the ionization rate of KH$_2$PO$_4$ slows down due to the general ionic effect [24] caused by the ionization of phosphate-containing compounds present in the ash. A decrease in the rate of K$^+$ formation, in turn, leads to a slowdown in the formation of K-struvite, since K$^+$ is one of the main forming ions for K-struvite structure. It is also believed that delayed setting of the MKPC paste may occur due to the dilution effect of ash, similar to both the much higher w/c ratio and the addition of fly ash or ground granulated blast furnace slag [25].

However, a further increase in the added MA to 60 and 80 % leads to a decrease in the setting time of the MKPC paste. As the amount of ash increases, the amount of calcium will also increase, which in turn can lead to the formation of calcium phosphate compounds. Calcium phosphates are good binders by nature [26]. It should be taken into account that CaO can react more easily with KH$_2$PO$_4$ than calcined MgO, and as a result, the setting time of the cement paste will be reduced.

Thus, based on the performed analysis, it was determined that MKPC paste ($M/P = 1/2.5$, $w/c = 0.42$) with 40 % of added MA has the longest setting time of 28 minutes.
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Figure 4 – Appearance of MKPC samples in forms with M/P ratio: a – 1/3.37, b – 1/3.0

Figure 5 – Appearance of MKPC samples with MA content in the range from 0 to 60%

Figure 6 – Effect of the M/P ratio on the temperature (a) and setting time (b) of MKPC paste

Figure 7 – The influence of the amount of added MA on the temperature (a) and setting time (b) of MKPC paste
An increase in the amount of MA simultaneously reduces the content of magnesium-potassium phosphate cement, as a binder, in the MKPC matrix. This leads to the fact that MKPC is not able to bind all unreacted MA particles, and the compressive strength of the samples decreases. A decrease of compressive strength by 63% occurs when the amount of MA increases to 60%, that's why the accepted amount of the added MA in MKPC matrix is 40%.

Analysis of the diffraction patterns of the MKPC matrix with 40 and 60% MA (Figure 8) shows the presence of the main phase – K-struvite MgKPO₄·6H₂O. In addition to K-struvite, there are peaks of unreacted MgO and compounds such as calcite CaCO₃, quartz SiO₂ and potassium chloride KCl, which are parts of the MA (Figure 2). The absence of hydroxyapatite Ca₅(PO₄)₃(OH) and calcium oxyphosphate Ca₄(PO₄)₂O, also included in the composition of the MA, can be explained by the fact that these compounds are participated in the formation reaction of both calcium-containing K-struvite Mgₙ₋₅Ca₅KPO₄·6H₂O and new calcium phosphate compounds. Apparently new calcium phosphate compounds form as amorphous phases, as evidenced by a small "halo" located in the diffraction patterns in the angle range of 25–35°.

The obtained MKPC (M/P = 1/2.5) samples after curing for 7, 14 and 28 days were tested for compressive strength. Table 1 shows data on the density (ρ) and compressive strength (σ_{compr}) of MKPC samples with different amounts of added ash: MPC-A0 (0 % MA), MPC-A20 (20 % MA), MPC-A40 (40 % MA) and MPC-A60 (60 % MA). As can be seen, the density of the MKPC samples decreases with an increase in the amount of MA. The best compressive strength of 34.5 MPa after 28 days of curing is characteristic of samples with 20% MA. With an increase in the amount of MA to 40% , the compressive strength decreases to 23.4 MPa, and with 60% MA it significantly decreases to 8.3 MPa. Thus, the MKPC matrix is accepted to the general technical requirements for cemented radioactive waste (σ_{compr} ≥ 4.9 MPa) [27].

The mass ratio of binder materials and MA is crucial for the formation of a compact microstructure and, accordingly, the strength properties of the MKPC matrix. In process of matrix manufacturing, part of the added MA reacts and takes part in obtaining the MKPC. The other unreacted portion acts as reinforcing fine particles coated with MKPC. Therefore, with the encapsulation of 20% MA, an increase of strength by more than 50% is observed compared to MKPC without MA. The addition of 40% MA leads to a slight increase in compressive strength.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Addition MA, %</th>
<th>w/c</th>
<th>ρ, g/cm³</th>
<th>σ_{compr}, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPC-A0</td>
<td>0</td>
<td>0.38</td>
<td>1.77</td>
<td>16.2</td>
</tr>
<tr>
<td>MPC-A20</td>
<td>20</td>
<td>0.41</td>
<td>1.75</td>
<td>25.8</td>
</tr>
<tr>
<td>MPC-A40</td>
<td>40</td>
<td>0.42</td>
<td>1.73</td>
<td>17.2</td>
</tr>
<tr>
<td>MPC-A60</td>
<td>60</td>
<td>0.45</td>
<td>1.68</td>
<td>6.5</td>
</tr>
</tbody>
</table>

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Analysis of the diffraction patterns of the MKPC matrix with 40 and 60% MA (Figure 8) shows the presence of the main phase – K-struvite MgKPO₄·6H₂O. In addition to K-struvite, there are peaks of unreacted MgO and compounds such as calcite CaCO₃, quartz SiO₂ and potassium chloride KCl, which are parts of the MA (Figure 2). The absence of hydroxyapatite Ca₅(PO₄)₃(OH) and calcium oxyphosphate Ca₄(PO₄)₂O, also included in the composition of the MA, can be explained by the fact that these compounds are participated in the formation reaction of both calcium-containing K-struvite Mgₙ₋₅Ca₅KPO₄·6H₂O and new calcium phosphate compounds. Apparently new calcium phosphate compounds form as amorphous phases, as evidenced by a small "halo" located in the diffraction patterns in the angle range of 25–35°.

![XRD patterns of MKPC matrix with MA: a – 40 %, b – 60 %](image-url)
With an increase in the amount of MA from 40 to 60%, there is a noticeable decrease in unreacted MgO from 6.9 to 1.6% and an increase in CaCO₃ from 5.6 to 10.5%. The amount of K-struvite, quartz and potassium chloride calculated by the Rietveld method remains practically unchanged. The lattice parameters of K-struvite increase slightly due to the partial replacement of Mg²⁺ by Ca²⁺. K-struvite lattice parameters: a = 6.874, b = 6.161, and c = 11.089, and with 40% MA: a = 6.881, b = 6.170 and c = 11.108 Å.

Considering that the MA contains a large number of different compounds, the resulting MKPC with the encapsulated MA is characterized by a complex and heterogeneous microstructure. The microstructure of the MKPC matrix was studied using SEM, and the concentration of elements was analyzed using energy-dispersive X-ray spectroscopy (EDS). SEM microphotographs of cleavage of MKPC samples with 40% MA are shown in Figure 9. Microstructure images show that there are remains of wood with a characteristic fibrous structure, tightly bound by the MKPC matrix.

Data on the chemical composition of the MKPC matrix, determined using EDS analysis, confirm the presence of the main phase – K-struvite (Figure 10, Table 2). A significant difference in the chemical composition of different sections of the resulting material was also discovered due to the presence of other phases, including in the amorphous state.

In Figure 10, the MKPC material of areas 1, 3, 4 and 5 mainly includes elements such as Mg, K and P. These areas are K-struvite. The material from site 2 contains Mg, K and P, but also Si and Ca and lesser amounts of Al and Cl, indicating the presence of several phases at this site. The particle in area 6 is an aluminum-potassium silicate and consists mainly of K, Si and Al. As can be seen, this particle is tightly bound to the MKPC matrix (Figure 10). The formation of auxiliary phases of calcium phosphosilicates formed in MKPC with the addition of MA is confirmed by the EDS analysis data of area 7.

The data of DTA/TG analysis of the obtained MKPCs both with and without MA are shown in Figure 11. The DTA curve of MKPC without MA shows a significant endothermic peak at ~125 °C, which is defined as the characteristic dehydration temperature of K-struvite (Figure 11a). Dehydration of K-struvite occurs in accordance with the following reaction [28]:

\[
\text{MgKPO}_4\cdot6\text{H}_2\text{O} \rightarrow \text{MgKPO}_4 + 6\text{H}_2\text{O}up
\]

This process is accompanied by significant mass loss, namely the removal of water, starting at ~60 °C and ending at ~350 °C. That is, the loss of H₂O molecules from the K-struvite structure occurs gradually depending on the temperature within one peak. At a temperature of ~350 °C, the total mass loss is 33.5% of the initial mass and does not change with a subsequent increase in temperature.

DTA curves of MKPC with 40 and 60% MA also have endothermic peaks at slightly lower temperatures of 110–115 °C (Figure 11b, c). In the temperature range 20–350 °C, the mass decreases due to dehydration of K-struvite by 30 and 25% with 40 and 60% MA, respectively. This can be explained by the fact that the addition of MA results in the formation of MKPC material with a lower proportion of K-struvite compared to MKPC without MA. With a further increase in temperature to 1000 °C, an increase in mass loss is observed by 5% in the case of adding 40% MA and by 8% – 60% MA. With an increase in the amount of ash, the mass loss in the temperature range 350–1000 °C also increases, which is likely due to the decomposition primarily of CaCO₃, which is part of the MA.

In general, the resulting MKPC matrices demonstrate good thermal stability at high temperatures. The total mass loss of MKPC at a temperature of 1000 °C without MA is 33.5%, and with the addition of 40 and 60% MA – 35 and 33%, respectively.

One of the main parameters characterizing the corrosion resistance of matrices for radioactive waste is the rate of leaching of radionuclides and matrix elements. The mass loss of samples per unit surface area over a certain period of leaching is often used [29], especially for rapid assessment corrosion resistance during leaching. Leaching was carried out in Teflon containers at a constant temperature of 25 °C for 7, 14, 21 and 28 days.

The results of the analysis of mass loss during leaching of MKPC samples with different amounts of MA are shown in Figure 12. The corrosion resistance of MKPC without and with the encapsulation of 20% MA is almost the same. With an increase in the amount of MA to 40%, an increase in mass loss occurs. And at 60% MA, a more significant increase in mass loss is observed. Moreover, after 21 days of leaching, a slowdown in mass loss is observed in all MKPC samples.

Taking into account the results of strength and leaching tests, we can conclude that an increase in the amount of MA to 60 wt.% leads to a more significant deterioration in the strength and corrosion properties of the MKPC matrix. Therefore, it should be considered that 40% of the MA is the optimal “loading” of the MKPC matrix. It should also be noted that, the maximum setting time (28 minutes) of the MKPC paste is observed with the encapsulation of 40% MA.

The leaching rate of Cs from MKPC sample with 40% MA (Figure 13) was calculated using the standard formula [29] and the results of the concentration of stable Cs in the leachate measured by atomic emission spectroscopy with inductively coupled plasma ICP-OES. The leaching rate of Cs on the 28th day of leaching was 1.2x10⁻¹ g/cm²·day, which is lower than that accepted as one of the main indicators of the quality of cement compounds, namely the leaching rate for ¹³⁷Cs (10⁻³ g/cm²·day) [27].
Figure 9 – SEM image of a cleavage of a MKPC sample with 40 % MA

Figure 10 – SEM image of the MKPC sample (40 % MA) with designated areas for EDS analysis (No. 1–7)

Table 2 – Concentration of elements according to EDS analysis (areas No. 1–7) in terms of oxides

<table>
<thead>
<tr>
<th>N</th>
<th>Na₂O</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>P₂O₅</th>
<th>SO₃</th>
<th>Cl</th>
<th>K₂O</th>
<th>CaO</th>
<th>Cr₂O₃</th>
<th>FeO</th>
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<td>0.40</td>
<td>3.62</td>
<td>46.61</td>
<td>0.44</td>
<td>0.26</td>
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<td>0.07</td>
<td>0.00</td>
<td>100.00</td>
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<td>33.52</td>
<td>0.00</td>
<td>0.00</td>
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Magnesium Potassium Phosphate Cement for Encapsulation of Ash from Burning Radioactively Contaminated Wood

In this work, laboratory-scale encapsulation of a model as a surrogate of radioactive ash into MKPC was carried out. Effective binding of MA particles by the MKPC matrix was confirmed by microscopic studies. X-ray phase analysis confirmed the presence of the main phase of K-struvite MgKPO₄·6H₂O in the composition of the MKPC matrix. Problems with swelling of MKPC samples were solved with determining the optimal ratios of MgO to KH₂PO₄ and water to the cement mixture. Up to 40% of MA was successfully encapsulated into the MKPC matrix without deteriorating its strength properties. Also considering the results of Cs leaching, it is obvious that MKPC matrix with 40% MA exceeds the generally accepted criteria for the waste forms based on a cement matrix.

The obtained results confirm the promising properties of the new MKPC for encapsulation ash from the burning of radioactively contaminated wood in the Chornobyl zone.
References

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Магній-калій-фосфатний цемент для інкапсуляції золи від спалювання радіоактивно забрудненої деревини

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Під час спалювання деревини з радіоактивно забруднених лісів на установці Інсинератор, створений в Чорнобильській зоні за підтримки Єврокомісії, утворюється зола з високим вмістом радіонуклідів Cs. Неодноразово магній-калій-фосфатні цементи (далі – МКФЦ) були запропоновані як ефективна альтернатива захисним матрицям на основі портландцементу. У цій статті склад МКФЦ було оптимізовано для лабораторної інкапсуляції неактивної модельної золи, яка використовувалася як імітатор радіоактивної золи. Визначено вплив співвідношення MgO/KH₂PO₄ та кількості доданої модельної золи на температуру та час туговування МКФЦ пасті. Міцність на стиск після 28 діб туговування МКФЦ без золи становила 22,7 МПа. Після додавання 20 мас.% модельної золи міцність на стиск МКФЦ матриці становила 34,5 МПа, 40 % МЗ – 23,4 МПа і 60 % МА – 8,3 МПа. Отже, допустима кількість доданої золи, яка істотно не знижує міцність МКФЦ матриці, становить 40 %.

Рентгеноструктурний аналіз МКФЦ матриці з 40 % модельної золи показує наявність основної фази – К-струвіту MgKPO₄·6H₂O. Окрім K-струвіту, є піки непрореагованого MgO та таких сполук, як кальцит CaCO₃, кварц SiO₂ та хлорид калію KCl, які є більшою кількістю золи.

SEM зображення MKФЦ зразків демонструють щільну структуру з добре зв’язаними частинками золи. Також оцінювали поведінку MKФЦ матриць під час вилуговування та їх термічну стабільність за допомогою ікерсійних випробувань і термогравіметричного аналізу, відповідно. Швидкість вилуговування Cs 1,2×10⁻⁴ г/см²·добу з матриці МКФЦ, що містить 40 % модельної золи, нижча показників, характерних для цементних форм відходів. Отримані результати свідчать про можливість використання нового МКФЦ як матриці для інкапсуляції золи від спалювання радіоактивно забрудненої деревини в Чорнобильській зоні.

Ключові слова: зола від спалювання деревини, магній-калій-фосфатний цемент, інкапсуляція, матриця, міцність, структура, вилуговування.

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