



Leaching behaviour of magnesium phosphate cements containing high quantities of heavy metals

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ABSTRACT

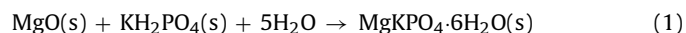
Stabilization/solidification (S/S) is one of the most employed techniques for treating liquid wastes containing heavy metals. Magnesium potassium phosphate cements have been used in recent years as stabilizing agents with positive results. However, little information is available about the retention of the metals by magnesium potassium phosphate cements matrices with the exception of the results of compliance tests. In this work, several pastes were prepared by reaction between low grade MgO and KH_2PO_4 in the presence of different heavy metal nitrate solutions (containing Cd(II), Cr(III), Cu(II), Ni(II), Pb(II) or Zn(II)). In all cases, the initial metal content of the dissolution was 25 g dm^{-3} and the oxide–phosphate ratio of the pastes was (50:50) in weight. Four different leaching tests were conducted on magnesium potassium phosphate cement pastes: simple batch test (EN 12457-2), equilibrium leaching test, availability test (NEN 7371) and acid neutralization capacity test (ANC). The metal leachate concentration was determined by means of ICP-MS. The stabilization of metals was successful in all cases, although the immobilizing system shows a better behaviour for Pb(II) and Cr(III) under acidic or neutral conditions.

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1. Introduction

Surface treatment industries generate exhausted baths with a high content of heavy metals. Magnesium potassium phosphate cements are used for stabilization/solidification (S/S) of different wastes, mainly mixed wastes and low-level nuclear wastes [1–3]. Magnesium potassium phosphate cements also have been utilized for rapid repair of pavements [4], although magnesium ammonium phosphate cements were traditionally employed for such purpose [5]. Magnesium phosphate cements, like many other types of cement, are obtained by mixing some reagents with water at room temperature. However, their structure and properties are similar to the ones of ceramic materials. For this reason, they are also called chemically bonded phosphate ceramics or CBPC [6].

The main reaction product of magnesium potassium cements is magnesium potassium phosphate hexahydrate or k-struvite ($\text{MgKPO}_4 \cdot 6\text{H}_2\text{O}$), according to the reaction below [1]:



Abbreviations: ANC, acid neutralization capacity; CBPC, chemically bonded phosphate ceramics; XRD, X-ray diffraction; ELT, equilibrium leaching test; ICP-MS, inductively coupled plasma-mass spectrometry; L/S, liquid-to-solid ratio ($\text{dm}^3 \text{ kg}^{-1}$); LR, level of retention; S/S, stabilization/solidification; TCLP, toxicity characteristic leaching procedure; W/S, water-to-solid ratio ($\text{dm}^3 \text{ kg}^{-1}$).

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K-struvite is obtained by an acid–base reaction between magnesia and potassium dihydrogen phosphate in the presence of water. Once water is added to a powder mix of magnesia and phosphate, phosphate dissolves in water and produces an acid dissolution. Later, phosphate reacts with magnesia and k-struvite is obtained. With time, in the presence of water, a more stable compound is formed, cattite ($(\text{Mg}_3(\text{PO}_4)_2 \cdot 22\text{H}_2\text{O})$ [7] which will later convert into bobierrite ($\text{Mg}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$) [8]. Bobierrite has also been observed in magnesium potassium phosphate cements [9].

Few studies are known about the behaviour of magnesium potassium phosphate cements regarding the retention of heavy metals. For example, wastes from contaminated soils containing Cd, Cr or Pb at concentrations between 1044 and 2457 mg dm^{-3} were stabilized using magnesium phosphate cements. Metal leachate concentrations after TCLP test ranged between 0.03 and 0.2 mg dm^{-3} [10]. In another study on the immobilization of metal nitrates (of Cr, Cd or Ni) with a load of 70% in weight, initial metal concentrations ranged from 360 mg dm^{-3} to 610 mg dm^{-3} . Leachate concentrations ranged between 0.01 mg dm^{-3} and 0.05 mg dm^{-3} for different metals [11]. The same authors also stabilized Pu-contaminated fly ashes containing contaminants like Cr(III), Ni or Pb at initial concentrations between 4860 mg dm^{-3} and 8600 mg dm^{-3} , with leachate concentrations ranging between 0.01 mg dm^{-3} and 0.10 mg dm^{-3} [12]. For simulated wastes containing Cd, Cr, Pb or Zn at concentrations between 0.91 mg dm^{-3} and 373 mg dm^{-3} , leachate concentrations ranged between 0.01 mg dm^{-3} and

0.05 mg dm⁻³ [13]. Other authors used magnesium potassium phosphate cements with K₂S for the stabilization of wastes with a Hg²⁺ content between 281.8 mg dm⁻³ and 572.7 mg dm⁻³. Leachate concentrations after the TCLP test ranged between 1.6 mg dm⁻³ and 16.12 mg dm⁻³ [14].

Despite providing promising results, the studies in the literature focus on the stabilization/solidification (S/S) of wastes containing relatively low quantities of heavy metals. Moreover, most works use the TCLP (Toxicity Characteristic Leaching Procedure) [15]. However, the TCLP test has come to unfavourable criticism because of its limitations for simulating different disposal conditions of the waste [16]. On the other hand, little information is available on modelling of the release of heavy metals from magnesium potassium phosphate cements, even though the release of heavy metals from Portland cement has been widely modelled [16,17].

The aim of the present work was to study the retention of high quantities of heavy metals, such as Cd(II), Cr(III), Cu(II), Ni(II), Pb(II) or Zn(II), by magnesium potassium phosphate cement matrices. Four leaching tests were used, with the purpose of having a more complete vision of the matrix behaviour under different environmental conditions. Single batch test (EN 12457-2) allowed assessing whether a waste could be considered hazardous or not. Equilibrium leaching test intended to reach chemical equilibrium conditions. Availability test (NEN 7371) evaluated the potential leachability of a contaminant under the usual disposal conditions. Acid neutralization capacity test allowed studying the role of phosphates and oxides/hydroxides on the retention of heavy metals. In addition, leachate heavy metal concentration at a given pH was modelled using the geochemical code Visual MINTEQ [26]. Equilibrium geochemical models attempts to simulate the influence of pH on metal solubility. They are usually employed for predicting metal concentrations from leaching tests at a given pH.

2. Materials and methods

2.1. Materials

Low grade calcined magnesia was employed from the air filters of the electric furnaces used for the calcination of magnesite by the company Magnesitas Navarras S.A. (Zubiri, Spain). Calcined magnesia contains a 70% of MgO and other oxides such as CaO, SiO₂, Fe₂O₃, Al₂O₃ or SO₃ in different proportions below 7.5% [18]. KH₂PO₄ extra pure was obtained from Scharlau (Sentmenat, Spain). Different dissolutions of Cd(NO₃)₂·4H₂O, Cr(NO₃)₃·9H₂O, Cu(NO₃)₂·3H₂O, Ni(NO₃)₂·6H₂O, Pb(NO₃)₂, or Zn(NO₃)₂·6H₂O at a concentration of 25 g dm⁻³ of each heavy metal were used as surrogate wastes. Salts of heavy metals were also obtained from Scharlau.

2.2. Preparation of samples

The pastes were obtained by mixing magnesia powder with potassium dihydrogen phosphate powder (50% in weight of each component with respect to the total solid content) and adding a dissolution of a metal nitrate at two different water-to-solid ratios (W/S): 0.4 and 0.5 dm³ kg⁻¹. The mixture was stirred by a magnetic stirrer for 30 min. Afterwards it was poured into cylindrical moulds of 30 mm diameter and 60 mm length. The samples were cured for 3 weeks inside polypropylene containers at the laboratory conditions (25 ± 2 °C and 50 ± 5% relative humidity).

2.3. Leaching tests

Different leaching tests such as simple batch test (EN 12457-2), equilibrium leaching test, availability test (NEN 7371) and acid neutralization capacity test (ANC) were performed in this study.

The purpose of the simple batch tests is to provide acceptance criteria for wastes in a controlled site. In this paper, the European simple batch leaching test EN 12457-2 [19] was conducted. It consisted of a single extraction with a liquid-to-solid ratio (L/S) of 10 dm³ kg⁻¹. The material was previously crushed at a size <4 mm. Contact time was 1 day. The samples were stirred using a rotative stirrer with a speed of 2 ± 0.2 rpm.

Although single batch tests are widely used, they have limitations based on technical considerations such as leaching kinetics [20], as the short contact time may not assure chemical equilibrium conditions for all the components in the system. In this work, in order to enhance the chemical equilibrium conditions, an equilibrium leaching test [21] was conducted. Deionized water was employed as leaching agent. Liquid-to-solid ratio (L/S) was 4 dm³ kg⁻¹ and particle size was <150 μm. Contact time between the pastes and the leachant was 7 days. The samples were stirred by a rotative stirrer with a speed of 10 ± 0.5 rpm.

Availability tests allow determining the potential leachability of a contaminant under the usual disposal conditions. The availability test defined by the Dutch standard NEN 7371 [22] was employed in this work. It consisted of two successive extractions with HNO₃ diluted with deionized water. Leachate pH in the first extraction was 7 ± 0.5. The liquid-to-solid (L/S) ratio was 50 dm³ kg⁻¹. Leachate pH in the second extraction was 4 ± 0.5 also with a liquid-to-solid ratio (L/S) of 50 dm³ kg⁻¹. Particle size was <125 μm. Contact time was 3 h for each extraction. Speed of the rotative stirrer was 10 ± 0.5 rpm. According to the standard, the two dissolutions were mixed and the concentration of the different components was determined.

Acid neutralization capacity is a very important parameter in the disposal of stabilized wastes. A great value of acid neutralization capacity assures the chemical fixation of contaminants in a basic system which will be resistant to the acid leaching conditions [23,24]. Thus, the more acid equivalents a material neutralizes, the more effective it is for the reduction of the mobility of metals, as most of the metallic species become more soluble as pH decreases. The pH values of minimum leaching for most metals range between 8 and 10. The acid neutralization capacity leaching test also allows identifying the sensibility of a material to small pH changes. Moreover, it is a base for comparing international leaching tests as well as for the geochemical modelling of species. The acidity may reach the disposal environment of a waste by means of acid rain, organic matter degradation or reactions with atmospheric carbon dioxide [25]. In the present work, 12 parallel extractions with nitric acid at different concentrations ranging between 0 equivalents of H⁺ per kilogram of waste and 22 equivalents of H⁺ per kilogram of waste were carried out. Liquid-to-solid ratio (L/S) was 10 dm³ kg⁻¹. A particle size below 150 μm was employed. Contact time was 2 days according to Environment Canada [26], with the intention to reach chemical equilibrium conditions. A rotative stirrer was used with a speed of 10 ± 0.5 rpm.

In all the leaching tests, the leachates were filtered with cellulose filters of porus diameter 0.45 μm prior to analysis.

2.4. Methods of analysis

The analysis of the metal concentrations in the leachates was carried out by means of an ICP-MS Elan 6000 from Perkin Elmer. Metal concentrations were determined in mg dm⁻³. Afterwards, they were converted into concentrations in mg kg⁻¹, in order to compare them with the limits defined by current laws.

$$C_1 = C_2 (L/S) \quad (2)$$

where: C₁ is the concentration in mg kg⁻¹, C₂ is the concentration in mg dm⁻³, and L/S is the liquid-to-solid ratio in dm³ kg⁻¹

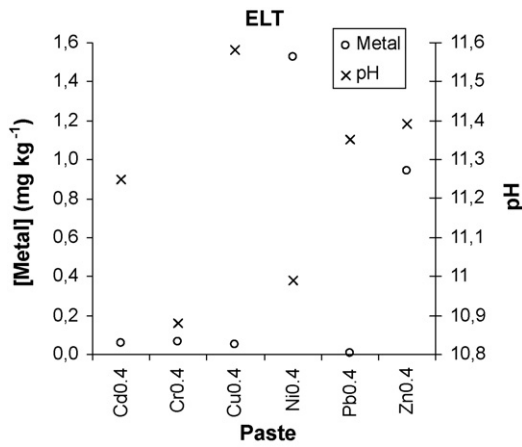


Fig. 1. Equilibrium leaching test (ELT). Cd²⁺, Cr³⁺, Cu²⁺, Ni²⁺, Pb²⁺ or Zn²⁺ leachate concentration of pastes Cd0.4, Cr0.4, Cu0.4, Ni0.4, Pb0.4 or Zn0.4 respectively. Leachate pH.

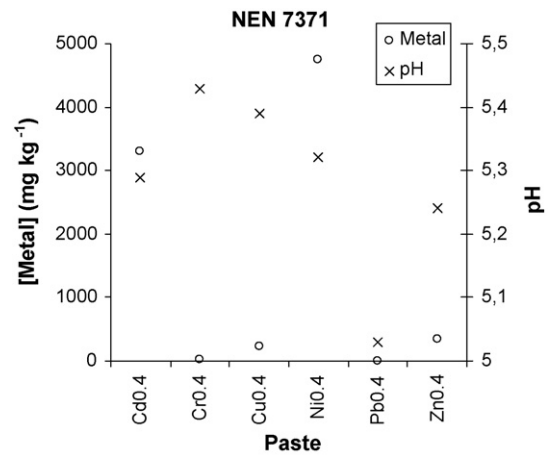


Fig. 2. Availability test (NEN 7371). Cd²⁺, Cr³⁺, Cu²⁺, Ni²⁺, Pb²⁺ or Zn²⁺ leachate concentration of pastes Cd0.4, Cr0.4, Cu0.4, Ni0.4, Pb0.4 or Zn0.4 respectively. Leachate pH.

Liquid-to-solid ratios employed in this paper are the following: 10 dm³ kg⁻¹ (EN 12457-2 and Acid Neutralization Capacity), 4 dm³ kg⁻¹ (equilibrium leaching test) or 100 dm³ kg⁻¹ (availability test NEN 7371).

Levels of retention were calculated as follows:

$$LR(\%) = \frac{Q_0 - Q_f}{Q_0} 100 \quad (3)$$

where: LR is the level of retention (%), Q_0 is the initial quantity of metal in a sample (g), and Q_f is the final quantity of metal in the leachate (g)

pH measurements were done with a pH-meter with temperature compensation from CRISON, model GLP 22.

2.5. Modelling

In order to describe the solubility behaviour of heavy metals in Stabilized/Solidified (S/S) galvanic wastes, the system was modelled using the geochemical code Visual MINTEQ [27]. Visual MINTEQ is a mechanistic model based on MINTEQA2, previously developed by the US EPA. It is a chemical equilibrium model for the calculation of metal speciation and solubility equilibria. It includes a thermodynamic database with different species in aqueous and solid forms. In this work, the standard database of the code was used, with the addition of k-struvite, MgKPO₄·6H₂O.

3. Results and discussion

3.1. Test EN 12457-2

For the single batch test, two different water-to-solid (W/S) ratios were tested according to preliminary results obtained in previous studies. The obtained metal concentrations in leachates were compared with criteria defined by the European Union for waste disposal in landfill [28] (Table 1).

Taking into account the heavy metal leachate concentration, all the stabilized wastes containing Ni(II), Pb(II), Cu(II) and Zn(II) could be disposed of in a landfill site class I (for inert wastes), if the remainder admission criteria were also accomplished. Some of the stabilized wastes containing Cd(II) and Cr(III) should be disposed of in a landfill site class II (for not hazardous wastes), although their leachate concentrations are only slightly higher than the acceptance criteria for a landfill site class I.

Heavy metal leachate concentrations are similar to those previously published on stabilization/solidification (S/S) of wastes using magnesium potassium phosphate cements [10–13]. All levels of retention were higher than 99.9%, showing the excellent retention properties of magnesium potassium phosphate cements for the stabilization/solidification (S/S) of wastes containing high quantities of heavy metals.

As a general trend, the higher the water-to-solid ratio (W/S) of the paste, the lower the leachate pH. The reasons for this are that pastes prepared with a higher proportion of water will contain with time more bohierrite Mg₃(PO₄)₂·8H₂O [9]. Thus, the higher the

Table 1

Simple batch test (EN 12457-2). Leachate heavy metal concentration (mg kg⁻¹) of stabilized wastes and comparison with acceptance criteria (mg kg⁻¹).

Paste	Leachate pH	Leachate metal concentration (mg kg ⁻¹)	Leaching limit values (EN 12457-2, L/S = 10 dm ³ kg ⁻¹)		
			Landfill CI-inert (mg kg ⁻¹)	Landfill CII-not hazardous (mg kg ⁻¹)	Landfill CIII-hazardous (mg kg ⁻¹)
Cd0.4	11.5	0.08	0.04	1	5
Cd0.5	11.4	0.04	0.04	1	5
Cr0.4	10.6	0.41	0.5	10	70
Cr0.5	10.4	0.54	0.5	10	70
Cu0.4	11.5	0.02	2	50	100
Cu0.5	11.0	<0.02	2	50	100
Ni0.4	11.4	0.12	0.4	10	40
Ni0.5	10.9	0.18	0.4	10	40
Pb0.4	11.7	0.12	0.5	10	50
Pb0.5	11.6	0.02	0.5	10	50
Zn0.4	11.0	0.11	4	50	200
Zn0.5	11.0	<0.10	4	50	200

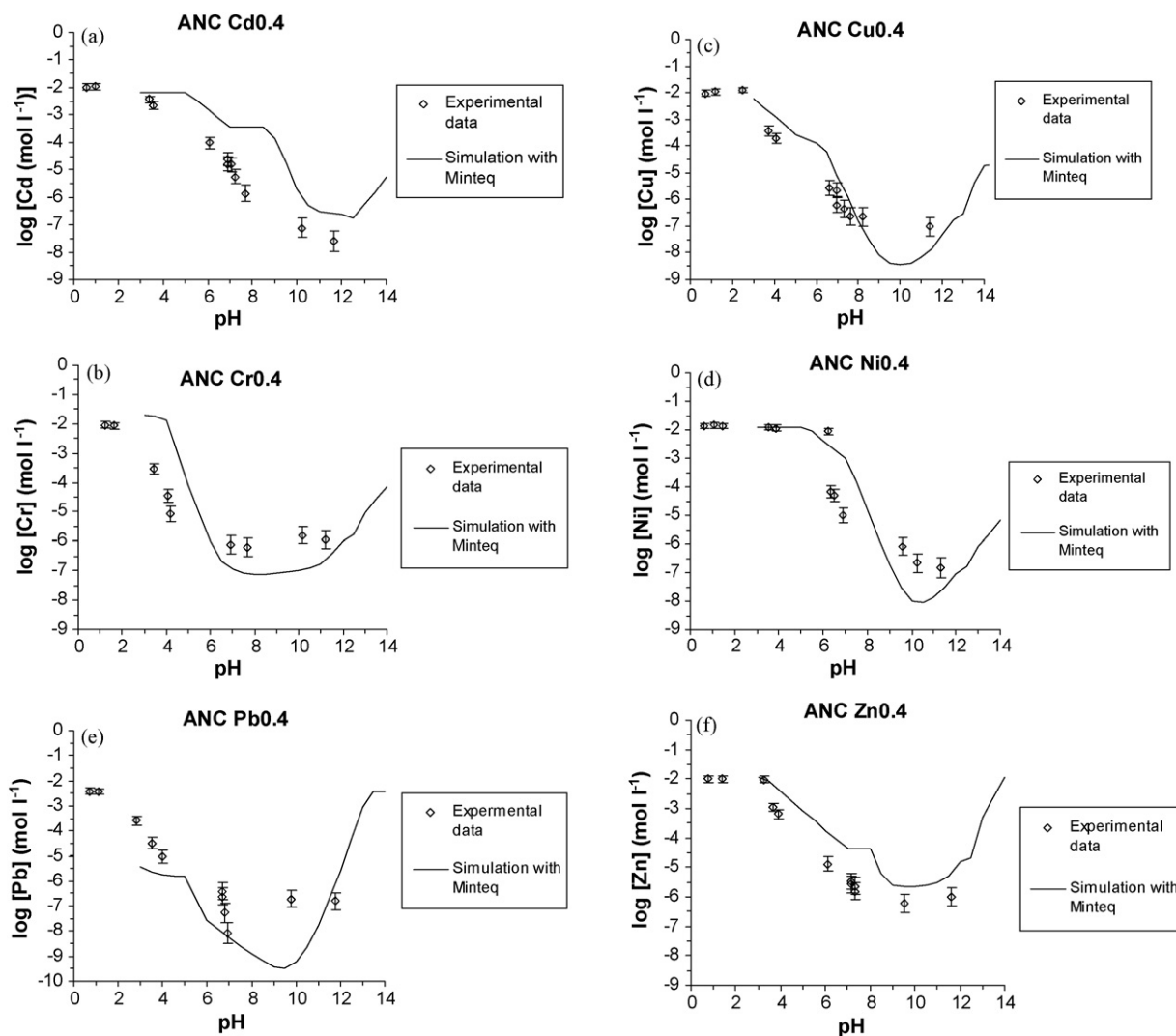
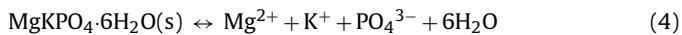


Fig. 3. Acid neutralization capacity test (ANC). Leachate heavy metal concentration (mol l^{-1}) and simulated heavy metal concentration (mol l^{-1}) of: (a) paste Cd0.4, (b) paste Cr0.4, (c) paste Cu0.4, (d) paste Ni0.4, (e) paste Pb0.4, (f) paste Zn0.4.

quantity of bobierite formed, the lower the quantity of k-struvite remaining in the paste. During the leaching test, the most soluble phases of the matrix, such as k-struvite, will mainly dissociate. Dissociation of k-struvite will produce Mg^{2+} , PO_4^{3-} and K^+ in dissolution (Eq. (4)), although some magnesium oxide will also dissolve (Eq. (5)). Phosphate anion will do a hydrolysis reaction (Eq. (6)).



A lower initial k-struvite content of the paste will not favour the hydrolysis reaction of phosphate. This will reduce the leachate pH and also the precipitation of $\text{Mg}(\text{OH})_2$. For this reason, the $\text{Mg}(\text{II})$ concentration in the leachate will increase. In addition, less phosphate will remain in the leachate because less k-struvite will have dissociated. Thus, a higher water-to-solid ratio (W/S) of the paste (and therefore, a lower k-struvite content) implies a lower leachate pH, according to the hydrolysis reaction of phosphate (Eq. (6)).

On the other hand, if a paste has a higher water-to-solid ratio (W/S), it also contains a higher quantity of heavy metal. When the paste, for example containing Ni, is subjected to a leaching test, the presence of more Ni^{2+} cations in dissolution enhances the forma-

tion of the corresponding hydroxide (Eq. (7)). Therefore, leachate pH will decrease.



Thus, if the pastes contain more water they also contain more heavy metal. This favours a lower leachate pH.

3.2. Equilibrium leaching test

As the results of the single batch test showed few differences regarding leachate metal concentration, a more detailed study was carried out on pastes obtained with a water-to-solid ratio (W/S) of $0.4 \text{ dm}^3 \text{ kg}^{-1}$. In Fig. 1, heavy metal leachate concentrations for the equilibrium leaching test are summarized.

Although all pH values are contained within a range of 1 pH unit, final leachate pH values are slightly different for the different pastes studied. This is due to a different acidic behaviour of each metallic cation in solution as well as the different molar concentrations of metallic cations in the cement pastes.

Comparing the results in Table 1 (simple batch test) with the results in Fig. 1 (equilibrium leaching test) for each one of the pastes reveals similar concentrations in both tests as a general trend. However, for pastes Ni0.4 and Zn0.4 heavy metal leachate

concentrations in the equilibrium leaching test are about ten times higher than heavy metal concentrations in the simple batch test. This suggests that when the pastes contain Ni or Zn the contact time of the simple batch test (1 day) is insufficient for reaching chemical equilibrium conditions. Levels of retention for Ni(II) and Zn(II) were lower than for the other metals, but always higher than 99.7%.

3.3. Availability test

Fig. 2 shows the leachate concentrations and pH values of all the samples studied.

The leachate pH for all the pastes was similar, around 5.2 (the final leachant was a mix of a pH 7 dissolution with a pH 4 dissolution in all cases). The heavy metals leachate concentration was lower than 50 mg dm^{-3} (5000 mg kg^{-1}) in all cases, although the test is conducted under acidic (pH 4) or neutral conditions (pH 7). In the simple batch test and equilibrium test, the leachant employed was deionized water. Therefore, throughout the test an alkaline pH was reached. In the availability test, Ni(II), Cd(II), Cu(II) and Zn(II) leachate concentrations were higher than the respective leachate concentrations in the simple batch test or in the equilibrium test. On the contrary, Pb(II) and Cr(III) leachate concentrations in the availability test (with neutral and acidic conditions) were only slightly higher than the leachate concentrations obtained in the simple batch test or in the equilibrium test. Pb(II) leachate concentration for paste Pb0.4 is markedly low, 0.01 mg dm^{-3} (1 mg kg^{-1}) while Cr(III) concentration for paste Cr0.4 was only 0.3 mg dm^{-3} (30 mg kg^{-1}). This could be explained because of the formation of stable chemical species like metal oxides or phosphates which would be present at low pH values in the case of Pb(II) and Cr(III). The level of retention was higher than 99% for Pb(II) and Cr(III), higher than 95% for Cu(II) and Zn(II) and lower than 60% for Cd(II) and Ni(II). This shows that the retention of Ni(II) and Cd(II) by the matrix is poor at neutral or acidic conditions.

In order to detect the metal oxides and phosphates that would be responsible for the stabilization of metals by the magnesium potassium phosphate cements, XRD analyses were performed to pastes Cd0.4, Cr0.4, Cu0.4, Ni0.4, Pb0.4 and Zn0.4. Only nickel hydroxide ($\text{Ni}(\text{OH})_2$ or teophrastite) was detected in paste Ni0.4, probably because the concentrations of other compounds were below the detection limit of the XRD technique. The corresponding diffractogram of paste Ni0.4 was shown in another paper [9]. Other researchers have found the phosphate PbHPO_4 in magnesium phosphate cements [29].

3.4. Acid neutralization capacity test (ANC)

In Fig. 3, the heavy metal leachate concentrations (in mol l^{-1}) are presented as a function of pH and compared with the equilibrium model.

The experimental results follow the same trend as the model. Fig. 3a shows the solubility curve for Cd(II), which has two parts: the left one corresponds to the solubility of a phosphate and the right one corresponds to the solubility of a hydroxide. According to the Visual MINTEQ model, the distribution of Cd(II) species shows $\text{Cd}_3(\text{PO}_4)_2$ (s) at pH values ranging from 5 to 8, while at higher pH values Cd(II) would be mainly found as $\text{Cd}(\text{OH})_2$ (s). Fig. 3b corresponds to the solubility curve of Cr(III). In this case, according to Visual MINTEQ, for pH 5 or higher the curve corresponds to the solubility of Cr_2O_3 (s). The solubility curve of Cu(II) (Fig. 3c) shows two parts: for pH values from 3 to 5 most Cu(II) would be found as $\text{Cu}_3(\text{PO}_4)_2$. For higher pH values, there would be tenorite (CuO), according to the model. For Ni(II) (Fig. 3d), a small area corresponding to the solubility of $\text{Ni}_3(\text{PO}_4)_2$ is shown for pH values between 5 and 6; at higher pH values teophrastite ($\text{Ni}(\text{OH})_2$) would

be formed [9]. For Pb (II) (Fig. 3e) the geochemical code Visual MINTEQ shows the formation of the phosphates PbHPO_4 (s) and $\text{Pb}_3(\text{PO}_4)_2$ at pH ranging from pH 3 to pH 5 and the phosphates $\text{Pb}_3(\text{PO}_4)_2$ and hydroxypyromorphite ($\text{Pb}_5(\text{PO}_4)_3\text{OH}$) from pH 5 to 7. For higher pH values, Pb would be found as $\text{Pb}(\text{OH})_2$. Finally, for Zn(II) (Fig. 3f), the corresponding phosphate $\text{Zn}_3(\text{PO}_4)_2 \cdot 4\text{H}_2\text{O}$ will be formed between pH 3 and pH 7. The corresponding hydroxide $\text{Zn}(\text{OH})_2$ (zincite) would be found from pH 8 to pH 14. Thus, most of the theoretical solubility curves of heavy metals stabilized with magnesium potassium phosphate cements present two parts: for high pH values the curve fits in with the solubility curve of the corresponding oxide/hydroxide while for low pH values the metal solubility is lower than that of the oxide/hydroxide and would fit in with the solubility curve of a metal phosphate.

4. Conclusions

This study showed that the short term heavy metal retention by magnesium potassium phosphate cements is very effective, especially regarding Ni(II), Pb(II), Cu(II) and Zn(II), when compared with the disposal criteria under the current regulations. When more aggressive leaching agents such as nitric acid are employed, the release of Pb(II) and Cr(III) is especially low under acidic or neutral conditions. This is probably due to the formation of compounds such as PbHPO_4 , $\text{Pb}_3(\text{PO}_4)_2$ or Cr_2O_3 , which are very insoluble in a wide range of pH. On the other hand, the experimental results of the acid neutralization test carried out with leaching agents of different acidity show the same trend as the simulated results obtained with the Visual MINTEQ geochemical code. At neutral and basic pH, the phase which controls solubility of heavy metals is the corresponding oxide/hydroxide, while at acid pH the solubility is mainly controlled by the corresponding phosphates.

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Glossary

Chemically bonded phosphate ceramics: All inorganic materials that are consolidated into a hard mass by chemical reactions and not by sintering. They include magnesium phosphate ceramics.

Magnesium phosphate cements: Cements obtained by mixing magnesium oxide with either phosphoric acid or an acidic phosphate. They include magnesium potassium phosphate ceramics and magnesium ammonium phosphate ceramics among others. Magnesium phosphate cements are also called magnesium phosphate ceramics.

Magnesium potassium phosphate cements: Magnesium phosphate cements obtained by mixing magnesium oxide with potassium dihydrogen phosphate in the presence of water.

Water-to-solid ratio (W/S ratio): The weight of liquid compared to the weight of total solid in the formulation of a cement paste (e.g. $\text{dm}^3 \text{kg}^{-1}$).

Liquid-to-solid ratio (L/S ratio): The amount of a leaching solution in contact with the amount of waste tested (e.g. $\text{dm}^3 \text{kg}^{-1}$).