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ORIGINAL PAPER

Electrokinetic decontamination of heavy metals in construction materials: contribution of the different parameters to the global efficiency

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Abstract To discriminate between the relative weights of each factor involved in the global process of an electrokinetic treatment for remediation, mortar and brick contaminated with Cs, Sr, Co, Cd and Cu were submitted to electrokinetic treatments with different enhancing electrolytes (distilled water, Na_2-EDTA, oxalic acid and citric acid), and the efficiency was analysed in function of the parameters involved in the process. The data obtained in this research, a matrix including 40 cases, have been correlated for the decontamination percentage in function of the key variables of the treatment, and the best correlation found, able to explain a variance of the 78.5% of the data, was a non linear exponential grow regression. An order in the weight of the contributions has been established that, from bigger to smaller contribution, is: constants of chelation equilibriums > precipitation as hydroxide constants > zeta potential > conductivity of the catholyte > pH catholyte > diffusion coefficient > pH of the material.

Keywords Electrokinetic decontamination · Relative weight · Contribution of parameters · Construction materials · Zeta potential · Heavy metals · Enhancing electrolytes · Mortar · Brick

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1 Introduction

In the past years, decontamination of construction materials has become a subject of great interest, mainly related to radioactive elements, finding in the literature trials with different types of treatments [1–11]. Among the different treatments, only few studies on electrokinetic treatments to decontaminate concrete have been found [6–12]. The electrokinetic treatment for remediation of construction materials is based on the direct application of an electrical field to the contaminated porous materials, being the final efficiency in function of the solubility of the contaminants and their transport through the electrodes that depends on several factors related to the properties of the material, the contaminants and the specific experimental parameters.

When performing an electrokinetic treatment by applying an electrical field to a monolithic porous construction material in order to decontaminate it, the following processes take place [13, 14]: Electrodic processes, Electromigration, Diffusion, Electroosmosis, Joule effect and also associated solid/liquid interactions as sorption and desorption of species.

Concerning the electrodic reactions, for hydrolysis of water in both compartments as the only process considered, according to Faraday's law, each 96486 C of current passed imply the formation of one equivalent of OH^- and H^+ at the cathode and anode, respectively. This implies a progressive acidification of the anolyte and alcalinisation of the catholyte. On the other hand, upon application of the electrical field, the ions in the pore solution of the materials will move towards the electrode charged with an opposite sign to that each ion exhibits, traversing the monolith material, in order to carry the electricity passing through the cell. This phenomenon is known as electromigration. Thus, every ion takes part in the migration process in a proportion known as their “transport or transference number”. In addition, diffusion will take place simultaneously to the electromigration movement and the final result will depend on the relative importance of both movements (voltage drop applied).

Concerning the electrokinetic effects, when two phases are placed in contact, there develops, in general, a difference in potential between them. As a consequence, the region between two adjoining phases is marked by a separation of electric charges, so that near to or on the surface of one phase, there is an excess of charge of one sign, and the balancing charge is distributed through the adjoining surface regions of the other phase. When one of these phases is caused to move tangentially past the second phase, it takes place a number of phenomena which are grouped under the generic name of “electrokinetic effects”. When the solid remains stationary and the liquid moves in response to an applied electrical field, this is called electro-osmosis [15]. This is the case of a monolithic material when submitted to an external electrical field. The direction of the flux of water will depend on the sign of the charged walls of the pores.

Finally, the Joule effect is defined as the increase in heat, resulting from the passage of a current through a conductor.

Therefore, as a consequence of all these processes, there are changes in the concentration of every species in the aqueous phase of pores of the material continuously, which imply the alteration of the solid/liquid equilibrium in the pores that could lead to a modification of the microstructure with dissolution and/or precipitation, adsorption/desoption, of the phases present in the matrix or to the formation and precipitation of new ones. Additionally if enhancing agents, with their specific chemical characteristics, are used, this additional parameter has to be taken into account in the global balance.

When applying an electrokinetic treatment for remediation of contaminated construction materials, the final efficiency is a combination of all these processes, not having found in literature any attempt to discriminate between the relative weights of each in the global process, which is the aim of this article. For undertaking this objective, mortar and brick contaminated with Cs, Sr, Co, Cd and Cu have been submitted to electrokinetic treatments with different enhancing electrolytes (distilled water, Na_2-EDTA, oxalic acid and citric acid), and the efficiency of the process has been analysed in function of the parameters involved in the process.

2 Experimental procedure

2.1 Materials

Two different materials have been used: Mortar and Brick. The mortar was cast with cement type IV-B-32.5 SR/BR that includes fly ashes in their composition, with the mix proportions given in Table 1, making cylindrical specimens of 75 mm diameter and 150 mm height. The brick was a solid type brick commonly used in facades, were cores of 75 mm diameter were taken. The chemical composition of the cement used in the mortar and that of the brick used are given in Table 2.

The pH of the materials were characterised by shaking 1 g of powdered sample in 2 mL of distilled water.

For making the remediation experiments, the cylindrical specimens were cut into slices of 10 mm depth.

2.2 Procedures

2.2.1 Contamination of the specimens

The specimens, of 75 mm diameter and about 10 mm depth, were contaminated with a nominally 0.05 M solution of Sr, Cs, Co, Cu and Cd that was prepared in distilled water with the corresponding chloride of each metal. The final concentration of each metal was dependent on the interferences with the other species and was analysed by ICP. In order to achieve reproducible contamination of the specimens, a vacuum saturation method was chosen, and the ASTM C1202-97 [16] procedure was followed, with some modifications. The objective of this procedure was to replace the air that fills the pores of the materials with the solution of metals. The details of the procedure were as follows: Before proceeding to the saturation, the specimens were maintained for 3 days at 40 °C; then they were placed in a vacuum desiccator with all the sides of the specimens exposed by placing them in a grid. After sealing the desiccator and start the vacuum pump, the pressure decreased to less than 1 mm Hg within a few minutes. The vacuum was maintained for 3 h. With the vacuum pump still running, enough solution of the metals was drained into the desiccator to cover the specimens. Then, the vacuum pump was allowed to run for one additional hour. After this time, the vacuum line stopcock was closed, and air was allowed to enter into the desiccator. The specimens were let under this solution for 18 ± 2 h.

Once saturated the samples, metals concentrations were obtained by furnace-assisted fluorhidric acid digestion and ICP spectrometry.

Table 1 Mix proportions of the mortar used

Cement IV-B-32.5 SR/BR (%)	Sand (%)	Water (%)	Admixture (%)
31.51	56.01	11.87	0.61

Table 2 Chemical composition of the cement used in the mortar and that of the brick and granite (%)

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
Cement	30.46	10.58	4.49	46.49		2.59		
Brick	73.54	14.20	5.38	1.64	1.40	0.013	0.63	2.65

2.2.2 *Determination of the diffusion coefficients*

Provided that the target treatment is an electrokinetic decontamination, it was decided to the take the diffusion coefficient, determined by using migration tests [17], as the key parameter of the transport, as it takes into account the ability of movement through the sample under an electrical field including also the porosity of the material and the interaction with the substrate in the conditions of the tests.

Clean discs of mortar and brick were introduced between the two chambers of the migration cell. The compartment were the anode was placed (anolyte) was filled with a solution of 0.05 M in Cs, Sr, Co, Cd and Cu and the catholyte was filled with distilled water. The voltage applied was of 12 V, and the potential drop across the concrete disc was monitored by means of placing two reference electrodes of saturated calomel in contact with its surfaces. Periodically along the experiment, concentration in both compartments of the studied species was monitored by taking aliquots of the solutions.

Calculation of diffusion coefficients for each species in each material was made by using the modified Nerst-Einstein equation as follows [18]:

$$D_{\mathrm{ef}} = \frac{JRTl}{zFC_1\gamma\Delta\Phi} \tag{1}$$

where D_{ef} is the effective diffusion coefficient (cm^2 s^{-1}), J flux of the studied species (mol cm^{-2} s^{-1}), $\Delta\Phi$ effective voltage applied (V), C_1 concentration of the studied species in the source compartment (mol m^{-3}), γ activity coefficient of the solution, and l is the thickness of the specimen (cm).

2.2.3 *Remediation experiments*

Remediation experiments were carried out by using the Electroosmotic Cell Device (ECD) described in [19], in order to obtain at the same time the zeta potential of the hardened material. The set-up of the ECD is very similar to the migration cell used by the authors to determine the diffusion coefficient of different ions through concrete by migration tests [17] with the main modification that the ECD includes two capillary tubes in order to precisely measure the flow of the transported liquid.

The contaminated disc of the material to be tested was used for separating the two chambers, of around 400 cm^3 each, of the ECD, where the solutions (catholyte and anolyte) and the electrodes (cathode and anode) were located. Two meshes of activated titanium were used as electrodes and a difference of potential was applied between them. The volume of liquid in both chambers was periodically monitored, as well as the potential drop at the surface of the disc by placing two reference electrodes in contact with the surfaces. At regular intervals, samples of catholyte and anolyte were extracted and pH, conductivity and amount of the contaminants were analysed. Distilled water was used in the anodic compartments while the specific solutions were placed in the cathodic compartments. A summary of the characteristics of the different solutions are given in Table 3.

Due to the different materials and solutions tested, the voltages applied have been adjusted (ranging from 12 and 75 V DC), in order to reach total current densities passed in a comparable range for the different experiments, around 5×10^6 C m^{-2}.

The zeta potential was determined by measuring the flux of liquid transported from one compartment to the other according to Eq. 2 [15]:

$$\xi = \frac{V\eta}{\varepsilon_0 DEA} \tag{2}$$

where ξ is the zeta-potential (V), V electroosmotic flux (m^3 s^{-1}), η viscosity (N s m^{-2}), D dielectric constant, ε_0 permittivity of free space (F m^{-1}), E electrical field applied (V m^{-1}) and A is the transversal area for the flux of liquid (m^2).

3 Results

3.1 Characterisation tests

The relative pH of the aqueous phase of the samples obtained by dissolving 1 g of powdered sample in 2 mL of distilled water until equilibrium was of 12.4 and 7.8 for mortar and brick respectively.

Table 3 Characteristics of the different solutions used in the cathodic compartment

	Concentration (M)	pH	Conductivity (mS cm^{-1})
Distilled water		7	0.05
Na_2-EDTA	≈0.2	4.4	13
Oxalic acid	≈0.1	1.5	19
Citric acid	≈0.2	4	4.7

The diffusion coefficients of the different contaminants in the materials, determined according to Eq. 1, are presented in Fig. 1.

3.2 Remediation experiments

The evolution of the pH in the anolyte and catholyte compartments is presented in the Fig. 2a–b.

In Fig. 2, it can be noticed that, as expected, in all the cases, the pH of the anolyte decreases as the experiment proceeds due to the hydrolysis of the water that generates H^+ until reaching values, depending on the charge density passed, in the range of 2–4. In the case of the catholyte, the hydrolysis of water leads to the production of hydroxyl ions. When the catholyte is distilled water, the pH increases very quickly, reaching values up to more than 12. With the rest of the solutions, the OH^- ions are neutralised by the acid character of the initial solutions remaining, at the charge densities reached in this research, more or less stable at a pH close to that of the initial solution. From more to less acidic: oxalic acid, citric acid and EDTA.

Concerning the zeta potential values, from the measured fluxes at each point of the experiment, and considering the punctual effective potential between the two sides of the specimen, the differential zeta potential values have been calculated using Eq. 2. As expected, provided the conditions of the experiments are continually changing, the zeta potential values change correspondingly and are time-dependent, in agreement with [11]. A comprehensive study on the zeta potential determination through electrophoresis and electroosmosis experiments, including these materials and solutions, is given in [20]. In [20], the differential curves of the zeta potential are given and it can be seen that for these experiments the shape of the curves is quite different depending on the material and on the dissolution used: Mortar exhibits smaller values than brick, being the higher absolute value, for mortar, that corresponding to distilled water being a positive value; so, with flux towards the anode [20]. The enhancing solutions behave differently, obtaining negative values of the zeta potential for all of them, with the maximum absolute value for Na_2–EDTA. In the case of brick, the maximum zeta potential is obtained for citric acid, only in one region of the charge density diagram. The maximum absolute values of zeta potential are given in Fig. 3 for mortar and brick for the different electrolytes, where again it can be seen that for the same electrolyte, the absolute values are higher for brick than for mortar, being the maximum one that of the citric acid for brick.

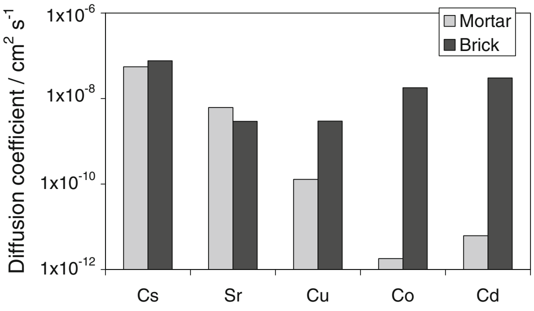

Fig. 1 Diffusion coefficients of the different contaminants in the materials determined according to Eq. 1

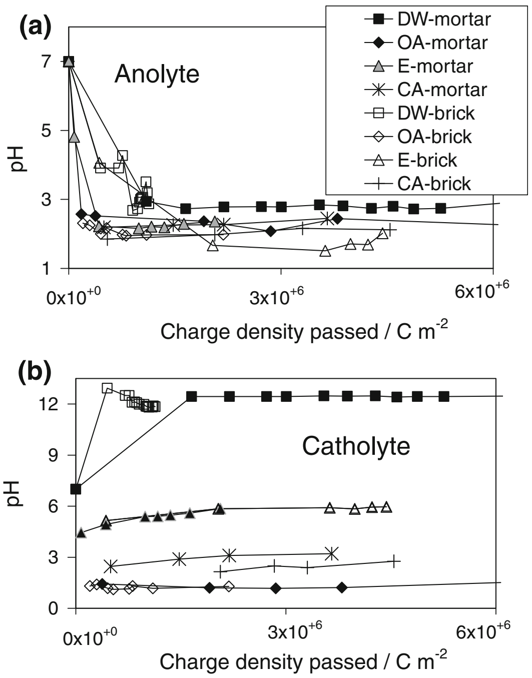

Fig. 2 Evolution of the pH in the **a** anolyte and **b** catholyte during the decontamination experiments for the different solutions (*DW* distilled water, *OA* oxalic acid, *E* EDTA, *CA* citric acid)

The shape of the accumulated curves of percentage extracted in function of the charge density in some cases goes through a maximum due to the changes in the pH and composition of the solutions that leads to precipitation process in the compartments. As an example, in Fig. 4 the accumulated curves of percentage extracted in function of the charge density for Sr^{++} in mortar have been depicted.

Therefore, in order to consider a quantitative value of extraction, the maximum detected during the period has been considered. Figure 5 shows the maximum percentages of extraction obtained through analysis of the contaminants in the samples of the anodic and cathodic compartments.

From Fig. 5, it can be deduced that, in general, the percentages of decontamination obtained for mortar are lower than that for brick. It is also noticeable that using water for both materials only Cs and in a lesser extent Sr are extracted, while using other solutions the extraction is much enhanced, especially with citric acid for both materials and also with EDTA for brick. For this material, the

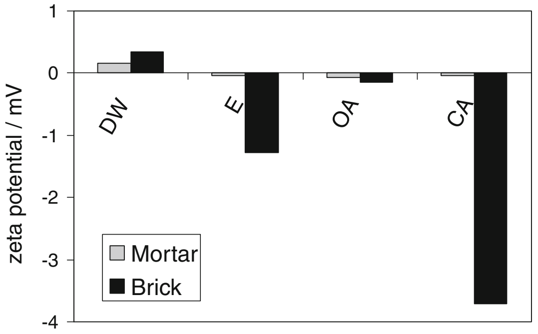

Fig. 3 Maximum absolute value of zeta potential for mortar and brick for the different electrolytes (*DW* distilled water, *E* EDTA, *OA* oxalic acid, *CA* citric acid)

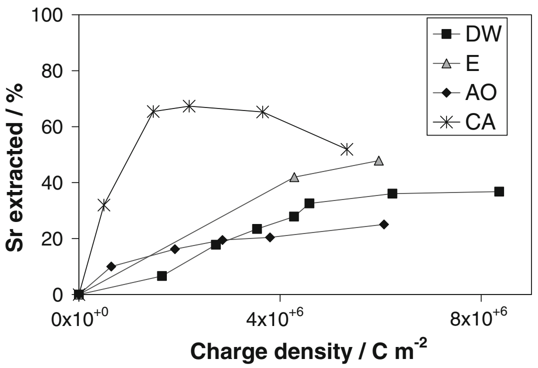

Fig. 4 Accumulated curves of percentage extracted in function of the charge density for Sr in mortar (*DW* distilled water, *E* EDTA, *OA* oxalic acid, *CA* citric acid)

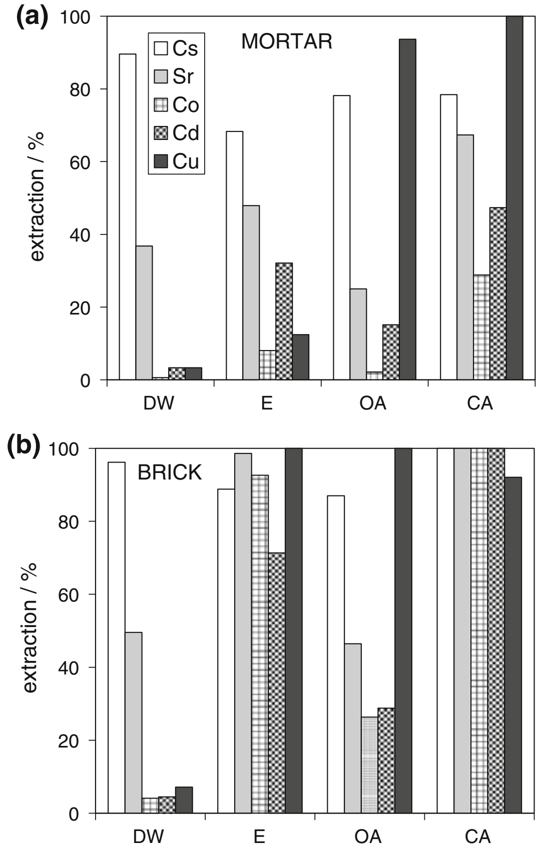

Fig. 5 Maximum percentages of decontamination after the experiments (*DW* distilled water, *E* EDTA, *OA* oxalic acid, *CA* citric acid)

remediation is almost complete using these two extracting agents.

4 Discussion

To analyse the efficiency of the remediation experiments in function of the parameters involved, as a first step, the following key variables have been identified: V1 = zeta potential of the electrical double layer of the pore walls, ζ (mV); V2 = diffusion coefficient of the contaminant through the material, D (cm^2 s^{-1}); V3 = pH of the cathodic solution, pH$_c$; V4 = conductivity of the cathodic solution, C_c (mS cm^{-1}); V5 = electrical charge of the contaminant, z; V6 = pH of the leachant of the material, pH$_{mat}$; V7 = charge density passed (C m^{-2}), V8 = constants of precipitation as hydroxide (p*K*s) for the different solutions and metals; V9 = constants of chelation equilibriums (log β) for the different solutions and metals [21], as presented in Table 4.

With the data obtained in this research, a matrix including 40 cases (2 types of material × 4 electrolytes × 5 contaminant species) is available, in which all these nine variables are known:

This matrix has been studied by means of several linear and non linear fitting analysis (multiple regressions, exponential growths, polynomial regressions, several non linear equations, etc.) with the general purpose of learning more about the relative weights of each factor involved in the global process of an electrokinetic treatment for remediation.

Table 4 Constants of chelation equilibriums (log β) and of precipitation as hydroxide (p*K*s) for the different solutions and metals involved in the processes [21]

		Cs (I)	Sr (II)	Co (II)	Cu (II)	Cd (II)
EDTA Me/Y^{4-}	log β_1		8.6	15.9	17.8	16.1
Me/Hcit^{3-}	log β_1		2.7		14.2	4.3
Me/$C_2O_4^{2-}$	log β_1/β_2		2.5		6.2/10.2	4.0
Me/CH_3COO^-	log β_1				2.2	
Me(OH)$_x$↓	p*K*s		3.4	15.4	18.8	14.4

From the results obtained in the different fittings, several interesting deductions can be extracted:

- On the one hand, concerning charge density passed (variable V7), including it in the correlations does not improve the goodness of the fit; thus, according to this analysis, this variable does not influence the results. However, it is well known that current density passed is an important factor that should be related to the decontamination results. The explanation comes from the fact that these decontamination values are the maximum ones obtained at large charge densities passed; in other words, the dependence with the charge density passed must exist in a previous step of the experiments where extraction has not finished. Therefore, for the analysis of these results of maximum decontamination, the electrical charge is not an influencing variable.
- On the other hand, the electrical charge of the contaminant, V5, does not influence significantly any of the fittings tried. This is attributed to the fact that the different species can form complexes with the different enhancing electrolytes, leading to other differently charged species. Therefore, the electrical charge has discarded as a key variable in further analysis.

Therefore, taking out V5 and V7, seven variables have been left for further analysis. From the different fittings tried, the best correlation found, including the seven variables (two constants of chelation), is able to explain a variance of the 78.5% of the data, and is a non linear exponential grow regression, being an equation of the form (Eq. 3):

$$\text{Decontamination }(\%) = 100 \times \Big[c + \exp\big(b0 + b1 \times \zeta + b2 \times \text{pH}_{\text{c}} + b3 \times C_{\text{c}} + b4 \times \text{pH}_{\text{mat}} + b5 \times D + b6 \times K\text{s} + b7 \times \beta\text{-chel-1} + b8 \times \beta\text{-chel-2}\big)\Big] \tag{3}$$

where $b0$, $b1$, …, $b8$ are fitting parameters, whose final values are given in Table 5.

If the values of decontamination given by Eq. 3 are slightly negative or higher than 100 then they are considered as 0 and 100 respectively. In Fig. 6, the comparison between the experimental values of decontamination and that obtained through Eq. 3 is presented, where it can be seen that the fitting is good enough, with a correlation coefficient of 0.910.

It has to be pointed out that Eq. 3, that has still to be validated for other cases, by itself is considered not to be the most important result, being the weight of each parameter in the efficiency of the global process much more relevant. Starting from this best correlation (Eq. 3), some of the terms corresponding to different variables have been take out examining the accuracy of the fitting. A summary of the results with different combinations of variables is given in Table 6.

In Table 6, from the cases 2 to 8, only an independent variable has been removed in each case, analysing the percentage in reduction in the correlation coefficient, r, when taking the variable out in relation to that obtained, considering all of them. The results are given graphically in Fig. 7, where it can be seen that the variable that contributes more to the global fitting are the constants of chelation equilibriums, being reduced the r in a 19%, if these terms are taking out of the correlation. Even though it is necessary to point out that this is a qualitative approach, an order of contribution can be established that, from bigger to smaller contribution, would be: β-chelation > Ks > zeta potential > conductivity of the catholyte > pH catholyte > diffusion coefficient > pH material.

From cases 9 to 18 in Table 6, always with the exponential grow type equation, consideration of different cases have been undertaken, with the main deductions that only considering the transport variables (D and zeta potential) or the interaction-adsorption ones (pKs and β-chelation) the global data cannot be fitted. Considering these four variables, even though the fitting is worse that considering also the pH's and conductivity, could be enough, having a 71% of the variance of the data explained.

Starting from Eq. 3, a sensitivity analysis of the decontamination efficiency in function of the different variables can be made, by varying one of the variables, and maintaining the rest constant to calculate the decontamination percentage. The results are presented in Fig. 8a–d.

From Fig. 8, it can be seen that the zeta potential value strongly influences the decontamination percentage: increasing the negative absolute value of the zeta potential increases the decontamination percentage. It has to be pointed out, on one hand, that the actual values of ζ are corresponding to electroosmotic measurements on monolithic materials, as zeta potentials determined by electrophoresis in diluted suspensions of the same powdered material give different values [20]. Maintaining constant the rest of parameters, changing the value of zeta potential from -3 to $+3$ mV implies a change from almost a 60% of decontamination to a 10% of remediated material.

Concerning diffusion coefficients of the contaminants through the materials, according to the equation used, it exists a threshold value in the sense that higher than a value, a bit higher than 1×10^{-7} cm^2 s^{-1} (higher than all the coefficients found in this research) the decontamination is complete, as electromigration becomes the main decontamination force, while being lower than about 5×10^{-10} cm^2 s^{-1} the decontamination reaches a minimum, and additional lowering in the diffusion coefficient do not imply any other reduction in the remediation percentage.

Table 5 Final equation of maxima decontamination in function of the variables of the process, with the constants for the parameters in the following units: ζ (mV); D (cm^2 s^{-1}); C_c (mS cm^{-1})

Decontamination (%) = $100 \times [c + \exp(b0 + b1 \times \zeta + b2 \times \mathrm{pH_{cat}} + b3 \times C_c + b4 \times \mathrm{pH_{mat}} + b5 \times D + b6 \times K\mathrm{s} + b7 \times \beta\text{-chel-1} + b8 \times \beta\text{-chel-2})]$

c	*b*0	*b*1	*b*2	*b*3	*b*4	*b*5	*b*6	*b*7	*b*8
−596.5	6.394	-1.252×10^{-4}	-2.029×10^{-4}	-6.433×10^{-5}	-5.528×10^{-5}	6.337×10^{3}	-4.591×10^{-5}	5.760×10^{-5}	1.022×10^{-4}

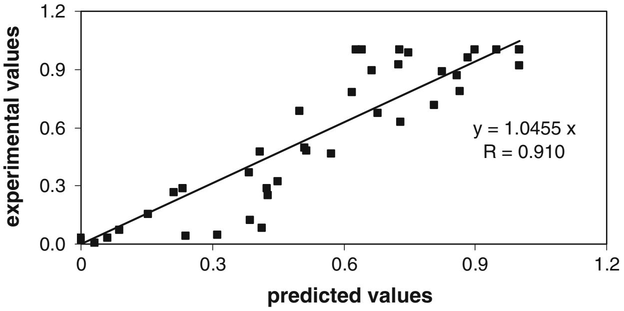

Fig. 6 Comparison between the experimental values of decontamination and that obtained through Eq. 3, including every variable with the exception of the charge density passed and the pH of the material

Table 6 Summary of the results of the non linear exponential grow regression, with different combination of independent variables; dependent variable: maximum decontamination percentage

Case	ζ	D	$\mathrm{pH_c}$	C_c	$\mathrm{pH_{mat}}$	pK_s	β-chel	r	Variance explained (%)
1	X	X	X	X	X	X	X	0.8860	78.49
2	X	X	X	X	X	X		0.7137	50.94
3	X	X	X	X	X		X	0.8070	65.13
4	X	X	X	X		X	X	0.8716	75.98
5	X	X	X		X	X	X	0.8465	71.66
6	X	X		X	X	X	X	0.8560	73.28
7	X		X	X	X	X	X	0.8631	74.50
8		X	X	X	X	X	X	0.8421	70.90
9	X	X	X	X	X			0.7065	49.92
10			X	X	X	X	X	0.8420	70.90
11						X	X	0.5950	35.40
12	X	X						0.6920	47.98
13							X	0.2305	5.31
14						X		0.4478	20.06
15	X							0.5851	34.24
16		X						0.0000	0.00
17	X					X		0.6880	47.34
18	X	X				X	X	0.8414	70.80

Concerning the rest of variables, on the one hand, as expected, maintaining constant the rest of parameters, the decontamination efficiency diminishes when increasing the pH and the conductivity of the solution in the catholyte. In the case of pH, apart from the fact of the effect of the anion associated to the acid that goes through the specimen [20], the more acidic the solution, the more easiness to make the heavy metals soluble. The same effect operates for the pH of the material. Concerning the conductivity, as higher it is, the transference number of the species of interest diminishes, and thus their transport due to electromigration.

On the other hand, as long as the constants of precipitation as hydroxide (p*K*s) for the different solutions and metals is concerned, as higher it is, more tendency for the metal to precipitate as hydroxide which implies less easiness to be removed. The opposite case operates for the constants of chelation equilibriums (log β), being easy to remove the metal as more affinity to be soluble by complex formation with the enhancing agents.

5 Conclusions

In this research, electrokinetic remediation experiments of mortar and brick, contaminated with Cs, Sr, Co, Cd and Cu have been carried out with different enhancing electrolytes (distilled water, $\mathrm{Na_2}$-EDTA, oxalic acid and citric acid), and the efficiency of the process has been analysed in function of the parameters involved in the process. From it, the following conclusions that can be drawn up:

- The remediation treatment of contamined construction materials can be improved by the addition of specific electrolytes enhancing the electrokinetic phenomena. Using water for both materials only Cs, and in a lesser extent Sr, are extracted, while using other solutions, the extraction is much enhanced, especially with citric acid for both materials and also with EDTA for brick. For this material, the remediation is almost complete using these two extracting agents.
- When applying an electrokinetic treatment for remediation of contaminated construction materials, the final efficiency is a combination of the different processes involved, after having identified, apart from the charge density passed, the following key affecting parameters: zeta potential of the electrical double layer of the pore walls, diffusion coefficient of the contaminant through

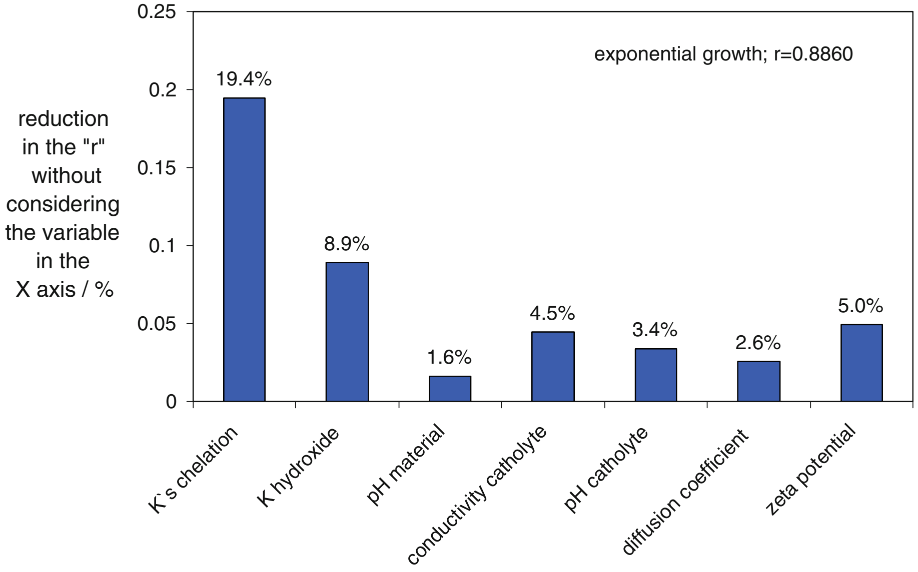

Fig. 7 Percentage in reduction in the correlation coefficient, *r*, when taking one variable out in relation to that obtained considering all of them

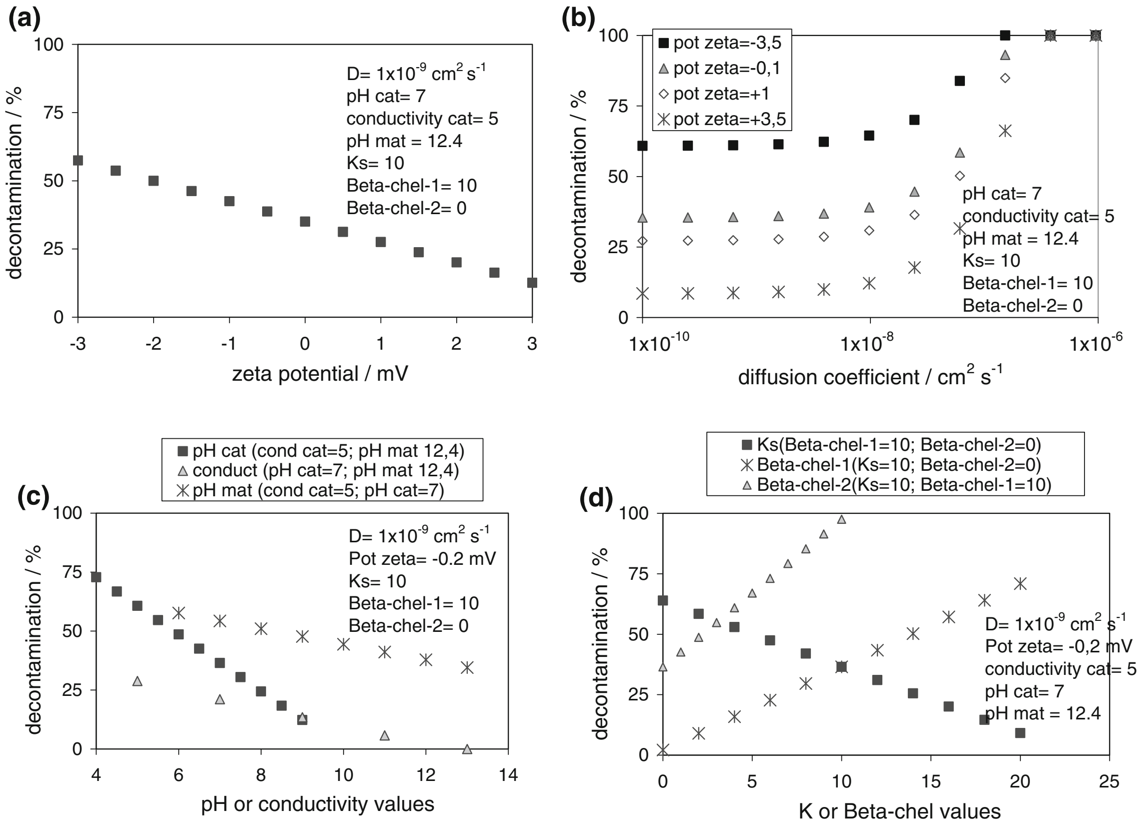

Fig. 8 a–d Sensitivity analysis of the decontamination efficiency to the different variables, according to Eq. 3 (Table 5)

the material, pH and conductivity of the cathodic solution, pH of the material, constants of precipitation as hydroxide (p*K*s) and constants of chelation equilibriums (log β) for the different solutions and metals.

- The best correlation found, that has to be validated for other cases, which correlates the maximum decontamination percentage in function of these variables being able to explain a variance of the 78.5% of the data, is a non linear exponential grow regression.
- According to this correlation, the parameters that contribute more to the global fitting are the constants of chelation equilibriums. An order of contribution has been established that, from bigger to smaller contribution, is: β-chelation > *K*s > zeta potential > conductivity of the

catholyte > pH catholyte > diffusion coefficient > pH material.

- Only considering either the transport variables considered here (*D* and zeta potential) or the interaction-adsorption ones (p*K*s and *β*-chelation) the global data cannot be fitted. Considering these four variables, even though the fitting is worse that including also the pH's and conductivity, could be enough, having a 71% of the variance of the data explained.

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