Electroosmosis in the Remediation of Tropical Soils Contaminated with Cadmium: Effect of the Incubation Time

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Abstract. This paper addresses the effect of cadmium incubation time on the electroosmotic decontamination of three residual soils from the *Zona da Mata Norte*, Minas Gerais State, Brazil. The laboratory testing program included the following: (i) materials, encompassing a lateritic clayey silty sand (soil 1), a non-lateritic clayey silty sand (soil 2), and a non-lateritic sandy silty clay (soil 3) impregnated with an aqueous solution of cadmium nitrate in the concentration of 100 mg.L⁻¹; (ii) soils and mixtures specimens compaction at the Standard AASHTO compaction effort; (iii) mixtures contaminant incubation times of 1, 10 and 20 days before performing the electroosmotic decontamination tests; (iv) sequential extraction analysis in order to identify the different contaminant chemical forms in the mixtures specimens. The results support that incubation time and soils chemistry and mineralogy were significant and influential factors in the decontamination process, as well as the 20 days incubation period was the optimum among the tested times. **Keywords:** soils contaminated with Cadmium, electroosmotic remediation, incubation time, sequential extraction.

1. Introduction

Soils may be contaminated by heavy metals from several sources, including disposal of mining residues, inadequate treatment of industrial hazardous wastes, improper disposal of used batteries, accidental leaks and military activities (Adriano, 1986).

Even though several soil decontamination techniques have been developed in the past decades, many of them proved to be unsatisfactory and, in some cases, too expensive for *in situ* remediation. However, the use of electroosmosis and, consequently, of electrokinetic phenomena has been a technical and economical solution for the remediation of clayey soils contaminated by heavy metals, once these materials generally present low hydraulic conductivity, high specific surface, and also because many reactions that happen during the soil remediation process are dynamic, pH dependent, reversible and currently not yet well understood, as emphasized by Alshawabkeh *et al.* (1999).

According to Chang & Liao (2006), electrokinetic phenomena have been a better way to the remediation of contaminated areas by different pollutes, such as: heavy metals, organic compounds and tailings from radionuclides and mining. According to these authors, the main practical aspects of interest to the application of decontamination of soils by electrokinetic phenomena are: (i) it is a technique that can be used in-situ or in laboratory; (ii) it has high efficiency in the decontamination of different contaminants; (iii) there is electro-osmotic flux in any kind of soil, including heterogeneous soils; (iv) it has applicability in contaminated soils with low hydraulic conductivity; (v) it has high economic efficiency; and (vi) it can be used interacted or integrated with other chemical or biological remediation technique. These authors mention that electrokinetic remediation technique presents some advantages, and the main one is the generation of an acid front in the anode, which can be beneficial because it releases the metals in the soil, but it can be also responsible for the destruction of minerals presents in the soil.

The electrokinetic phenomena in soils involve relative movements of electricity, charged surfaces, and liquid phases, basically, represented by four conduction mechanisms known as electroosmosis, streaming potential, electrophoresis and migration or sedimentation potential, as reported by Mitchell (1993). However, it should be emphasized that the most important mechanisms for the removal of soil contaminants through electrokinetic processes are the electroosmosis and the electrophoresis.

The electroosmosis remediation technique uses a direct and low density electric current of order of mA by cm² of the transversal section area between the electrodes or a difference of electric potential of few volts per centimeter through distant electrodes in soil with open-flow arrangement (Shapiro & Probstein, 1993; Acar & Alshawabkeh, 1993, 1996).

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Submitted on December 23, 2009; Final Acceptance on April 3, 2012; Discussion open until September 30, 2012.

According to Darmawan & Wada (1999), the heavy metals in soils take up different chemical forms, especially: (i) ionic and dissolved; (ii) electrostatically adsorbed; and (iii) complexation to the mineral surface. In other study, Gu & Yeung (2010) analyzed the effect of citric acid industrial wastewater as an enhanced agent to electrokinetic extraction of cadmium from natural clay using sequential extraction in the chemical analysis to quantify the proportions of cadmium of different states in the soil. In this study were analyzed five different chemical forms of cadmium in the soil, which was also used by Reddy et al. (2001): (i) exchangeable; (ii) carbonated bound; (iii) Fe-Mn oxides bound; (iv) organic bound; and (v) residual form. Therefore, it seems that viability of the electrokinetic remediation strongly depends on the soil mineralogical composition, especially on the clay fraction that reflects its active and colloidal part, and on the quantity of organic matter. Previous studies by Puppala et al. (1997), Grundl & Reese (1997), as well as by Reddy et al. (2001) suggest that the electrokinetic methods are not always effective for the decontamination of soils with high specific capacity of adsorption, and also for those containing calcium carbonate. However, Schmidt et al. (2007) obtained good results in the decontamination of an organic tropical clayey soil with high cationic exchange capacity contaminated with crude oil and saline water, when introduced nitrogen compounds, mainly ammonium nitrate, in the initial solution of distilled water in the anolyte compartment. Accordingly, sequential extraction techniques have been applied before and after application of electrokinetic phenomena for soils remediation, in order to gather information about the different forms that contaminants assume when integrated to fine grained soils, as referred by Reddy et al. (2001) and Darmawan & Wada (2002).

Regarding the referred sequential extraction techniques, the one depicted by Reddy *et al.* (2001), and originally developed by Tessier *et al.* (1979), is not, generally speaking, applicable to tropical soils. Darmawan & Wada (2002) understand that this technique does not separate the strongly absorbed metals from the residual fraction. On the other hand, in published works about soil remediation, independently of the process used, and generally speaking, there is no conclusive information about the contaminant incubation time that should be used, although it is common to refer to 7 days. Obviously, comparative studies about the influence of this parameter in the process of remediation are significantly important for the adequate use of the decontamination electrokinetic techniques.

This paper addresses the effect of the incubation time on the electroosmotic remediation of residual soils from the *Zona da Mata Norte*, Minas Gerais State, Brazil, contaminated with Cadmium in order to reach a better understanding of the development of reactions between contaminant and soils minerals.

2. Materials Characterization

2.1. The soil type

All soil samples were collected in the campus of the Universidade Federal de Viçosa (UFV), located in the Zona da Mata Norte, Minas Gerais state, Brazil, as follows: (i) sample 1, from a mature gneiss residual clayey silty sand, and pedologically classified as Red-Yellow Latosol (B horizon). The sample was collected from a cut slope, at the point of geographic position coordinates 20° 45'11.1" of South latitude and 42° 51' 31.2" of West longitude; (ii) sample 2, from a young gneiss residual clayey silty sand (saprolite). The sample was collected from a cut slope situated on the road that connects the cities of Viçosa and Paula Cândido, on the place of geographic position coordinates 20° 46' 48.2" of South latitude and 42° 52' 52" of West longitude; (iii) sample 3, from a mature gneiss residual sandy silty clay, and pedologically classified as Red-Yellow Argisol. The sample was collected from a cut slope located at the UFV Alcohol Plant, on the left side of route MG-60, on the place of geographic position coordinates 20° 45' 23.5" of South latitude and 42° 50" 22.4" of West longitude.

Tables 1 and 2 show, respectively, geotechnical parameters and classifications of the soils samples following the Transportation Research Board (TRB) and Unified Soil Classification (USC) Systems (DNIT, 2006), as well as according to the Miniature Compacted Tropical (MTC) Methodology (Nogami & Vilibor, 1995).

The sand fraction of soils 1, 2 and 3 showed quartz as the dominant mineral, even though peaks of kaolinite, mica and hydroxy-interlayer-vermiculite (HIV) were identified in soils 2 and 3; the kaolinite peaks in the sand fraction of these soils were classified as pseudomorphic mica. The clay fraction of the three soils showed kaolinite as the dominant mineral, as well as gibbsite, goethite, hematite and hydroxy-interlayer-vermiculite (HIV) peaks. Table 3 shows the dominant minerals identified in the sand and clay fractions of the tested soils by X-ray diffractometry.

Table 4 presents the chemical characterization of soils 1, 2 and 3 following the standard procedures proposed by EMBRAPA (1997). Soils 1, 2 and 3 presented pH higher than 5, low organic matter content and little amount of exchangeable bases. Regarding the PZC, defined as the soils pH at the point of zero charge, soils 1 and 3 presented PZC higher than its pH, while soil 2 showed PZC lower than their respective pH.

2.2. The contaminant

The heavy metal cadmium was selected to be used throughout the study based on the fact that it is commonly found in contaminated areas as a waste from electronic products, among others, and also because it exhibits intermediate specific adsorption by fine-grained soil clay minerals.

The amount of contaminant added to the soil samples was based on the CETESB-SP (2001) minimum guiding

Geotechnical parameters	Units	Soil 1	Soil 2	Soil 3
Sand (2 mm $< \phi \le 0.06$ mm)	%	38	58	8
Silt (0.06 mm < $\phi \le 0.002$ mm)	%	37	30	40
Clay ($\phi \le 0.002 \text{ mm}$)	%	25	13	52
Liquid limit (w_L)	%	79	31	81
Plastic limit (w_p)	%	41	19	58
Plastic index (I_p)	%	38	12	22
$A_{_c}$	$[I_{P} / (\% \phi \le 2 \mu m)]$	1.52	0.92	0.42
γ_{s}	kN/m ³	27.33	26.29	27.59
W_{ot}	%	30.50	20.23	33.68
$\gamma_{d \max}$	kN/m ³	13.90	15.57	12.87

Table 1 - Geotechnical parameters of soils.

 Table 2 - Geotechnical classifications of soils according to the

 TRB and USC Systems, and the MCT Methodology.

Soil	Geotec	chnical classific	ations
	TRB	USC	MCT
1	A-7-5 (18)	MH	LG
2	A-6 (2)	SC-SM	NS
3	A-7-5 (17)	MH	NG

values that require intervention in agricultural or residential contaminated areas, which are in the range of 10 to 12 mg/kg of dry soil mass.

A cadmium mono-species solution with concentration of 100 mg/L of salt was added to the soil samples in different volumes, according to their original moisture contents and considering the water amounts required to make them reach the cadmium concentration of 10 to 12 mg/kg of dry soil mass. The cadmium salt used was cadmium nitrate tetra hydrated [Cd(NO₃)2.4H₂O] 99% from Riedel-de Haën with molecular weight of 308.48 g.

3. Methodology

3.1. Electroosmotic cell

The electroosmotic cell used in this study, Figs. 1 and 2, was originally projected and built by Damasceno (2003). Currently, this cell has been modified in order to include graphite in substitution to copper electrodes which usually suffer oxi-reduction reactions. A description of the cell parts can be found in Damasceno (2003).

3.2. Decontamination tests

3.2.1. Samples preparation

The following sequence was adopted during soil samples preparation:

• Soil samples were air dried and passed in the #2 mm;

Table 3 - Mineralogy of soils 1, 2 and 3.

Soils fractions	Soil 1	Soil 2	Soil 3
		Quartz	Quartz
Sand	Quartz	Kaolinite	Kaolinite
		Mica	Mica
		HIV	
	Kaolinite	Kaolinite	Kaolinite
	Gibbsite	Goethite	Goethite
Clay	Goethite	Hematite	Gibbsite
	Hematite	HIV	HIV
	HIV		

- Compaction tests carried out at the AASHTO Standard compaction effort according to ABNT (1986), in order to determine the soils optimum water content (w_{ot}) and maximum dry density ($\gamma_{d \text{ max}}$);
- Addition of water and 100 mg.L⁻¹ cadmium nitrate solution to the air dried soil samples, in order to reach the optimum moisture content previously determined in the compaction tests, and the cadmium concentration of 10 to 12 mg/kg of dry soil;
- Incubation of the contaminated soil samples during 1, 10 and 20 days in a temperature controlled chamber (20 °C ± 1 °C).

3.2.2. Test procedure

The following sequence was adopted when performing the electroosmotic decontamination tests:

 After soils sample incubation times, it was taken a small fraction of each of the contaminated soil to the UFV's Laboratory of Mineralogy of the Department of Soils in order to perform sequential extraction test and pH determination;

Table 4 - C	hemical characteri	zation of soi	ls 1, 2 and 3 - F	EMBRAPA (1	997).							
Soil	$pH in H_2O$	PZC	P (mg.dm ⁻³)	K (mg.dm ⁻³)	Na (mg.dm ⁻³)	Ca^{2+} (cmol _c .dm ⁻³)	Mg ²⁺ (cmol _e .dm ⁻³)	Al ³⁺) (cmol ₆ .dm ⁻³	H + AI (cmol _e .dm ⁻³)	SB (cmol _c .dm ⁻³)	(t) $(\text{cmol}_{\text{c}}^{-3})$	(T) (cmol _c .dm ⁻³)
1	5.00	5.04	0.6	1	0.0	0.00	0.07	0.00	1.0	0.07	0.07	1.07
2	5.75	3.73	0.9	2	0.0	0.00	0.05	0.45	1.9	0.06	0.51	1.96
3	5.81	6.00	2.2	8	0.0	0.00	1.11	0.00	0.6	1.13	1.13	1.73
Soil		В	ISS	OMC	P-re	e me	Zn	Fe	Mn	Cu	B	s
	(%)	(0_{0}^{\prime})	(%)	(dag.k	g ⁻¹) (mg	.L ⁻¹) (mg	(r (r (r	mg.dm ⁻³)	(mg.dm ⁻³)	(mg.dm ⁻³)	(mg.dm ⁻³)	(mg.dm ⁻³)
1	6.5	0.0	0.00	0.38	4.	2 8.	.41	36.5	2.7	0.44	ı	·
2	3.1	88.2	0.00	0.00	13	.0 7.	.18	14.4	7.2	0.09	ı	
3	65.3	0.0	0.00	0.38	4	0 5.	.39	44.2	16.2	1.13	I	



Figure 1 - Tridimensional view of the electroosmotic cell.



Figure 2 - Layout, views and dimensions of parts of the electroosmotic cell (dimensions in mm).

- From each remaining contaminated soil sample were molded 5 cm internal diameter and 10 cm long specimens using Plexiglas cylinders at the AASHTO Standard optimum compaction parameters (w_{ot} and $\gamma_{d max}$) to be tested in the electroosmotic cell;
- After placing each specimen in the electroosmotic cell, its anode and cathode were filled with distilled water up to the desired level. The cell was then left to rest for 24 h in order to prevent operational and leaking problems;
- A decontamination test was carried out under controlled temperature (20 °C ± 1 °C) for a period of time of approximately 216 h (9 days), using an electric potential difference of 30 V allowing the electric current to vary throughout the test. Considering that the electrodes of the

electroosmotic cell were 180 mm apart, it was generated an electric gradient of 1.67 V/cm;

- During decontamination test, the solutions presented in the anode and cathode reservoirs were collected each 3 days to analyze cadmium concentration and cadmium amount that was removed with the process;
- At the end of the decontamination test, the specimen was taken from the cell in order to determine its moisture content. It was subdivided in five equally apart layers in order to determine their cadmium concentrations, taking samples from the anode e cathode cells solutions.

Determination of cadmium concentrations in all the specimen layers and in the anode and cathode cell solutions were carried out using the Flame Atomic Absorption Spectrophotometry technique (FAAS).

3.3. Sequential extraction technique – Chemical analyses

After the decontamination tests, each specimen was divided into five parts approximately equal which were identified and submitted to chemical analyses of sequential extraction (Egreja Filho, 2000), in order to determine the different chemical forms of the contaminant.

In the sequential extraction technique, the soil samples were submitted to continuous extractions with different extractors in each step, and using higher extraction power as the process advanced. In this test, the extractor acted by changing the interaction between the heavy metal and the solid phase, promoting solubilization to be dosed by a convenient analytic method. The sequential extraction was carried out in four steps, as illustrated in Table 5 and in Fig. 3.

4. Results

4.1. Electroosmotic parameters

Table 6 presents the geotechnical parameters of the tested soils before and after performing the electroosmotic decontamination tests.

During the electro-osmotic decontamination tests performed in specimens of the tested soils, the geotechnical parameters called electroosmotic conductivity coefficient $(k_{e \ stable})$ were determined. Besides, it was observed that the behavior of the test parameters, generally speaking, was similar, noting that the electric current decreased with time



Figure 3 - Fluxogram of the sequential extraction technique developed by Egreja Filho (2000).

Steps	Extractor	Determination
A	Distilled water	Soluble metals in the soil solution
В	$0.1 \text{ mol } L^{-1} \text{ de } CaCl_2$	Exchangeable metals (weakly absorbed)
С	Solution composed by 0.167 mol L^{-1} of Na_2HPO_4 , 0.03 mol L^{-1} of NaF and 0.0083 mol L^{-1} of EDTA	Specifically absorbed metals (strongly adsorbed)
D	Nitric-perchloric digestion	Metals in the residual fraction

Table 5 - Steps of the sequential extraction technique referring to the used extractor and to the determined chemical form.

 Table 6 - Geotechnical parameters of specimens submitted to the electro-osmotic decontamination tests, which were obtained before and after tests.

Soil	Contaminant incu- bation time (day)	Electroosmotic test duration (h)	${igwedge w_o \over (\%)}$	$\stackrel{W_f}{(\%)}$	$\frac{Sr_{_o}}{(\%)}$	Sr_{f} (%)	$k_{e \ stable} \ [cm^2/s^*V]$
	1	215.20	29.95	34.33	86.89	98.63	0.740 x 10 ⁻⁶
1	10	219.75	29.95	32.86	87.19	97.16	1.204 x 10 ⁻⁶
	20	217.12	29.95	36.31	86.97	100.00	1.092 x 10 ⁻⁶
	1	217.17	21.21	24.35	78.75	93.68	5.009 x 10 ⁻⁶
2	10	218.93	21.21	25.17	80.89	96.04	3.815 x 10 ⁻⁶
	20	220.48	21.21	24.35	78.67	94.32	4.443 x 10 ⁻⁶
	1	217.32	37.19	42.22	86.99	97.74	2.127 x 10 ⁻⁶
3	10	217.54	37.19	43.34	86.84	98.61	4.071 x 10 ⁻⁶
	20	216.78	36.51	41.39	86.43	95.39	2.992 x 10 ⁻⁶

and the electroosmotic flow increased in the beginning of each test, tending to stabilize with time.

Researches performed in some Brazilian soils showed that the electroosmotic conductivity coefficient is in the order of 10^{-7} cm²*s⁻¹*V⁻¹ (Araruna *et al.*, 2002; Damasceno, 2003).

4.2. Decontamination by electrokinetic phenomena

During decontamination tests the solutions at the anode and cathode compartments were collected each three days in order to perform chemical analysis. Besides, it was measured the pH of soils before tests and in each section of the specimens after tests. Figures 4 to 6 show these data.

It should be emphasized that soils 1 and 3 showed reverse electroosmotic flow, *i.e.*, in a cathode-anode direction. The main explanation for this fact is based on the behavior of its electrochemical parameter called Point of Zero Charge (PZC), observing that this value was higher than their pH, which caused the inversion of the electro-osmotic flow in accordance with the observations of Yang & Lin (1998). According to these authors, when soil pH is higher than its PZC, the soil presents more negative charges in its clayey mineral surfaces than positive charges, which favors cationic exchangeable and, as a result, the electro-osmotic flow is normal (anode-cathode direction). On the other hand, when the soil pH is lower than the soil PZC, it presents more positive than negative charges in the clayey

mineral surfaces, which favors anionic absorption and, as a result, occurrence of electroosmotic reversal flow (cathode-anode direction).

The results illustrated in Figs. 4 to 6 showed that in soils 1 and 3, which present clayey texture and pH below PZC, the cadmium concentration decreased with time in both compartments. Regarding soil 2, which presents sandy texture and pH higher than its PZC, the cadmium concentration decreased with time in the anode compartment, but increased in the cathode compartment. Besides, these figures showed that soils pH increased from anode to cathode, which confirms data presented in the technical literature (Yang *et al.* 1998); also, in general, it was observed that soil pH increased after application of the electrokinetic process.

4.3. Sequential extraction data analysis

Figures 7 to 9 show the results of the sequential extraction analyses performed on contaminated specimens from soils 1, 2 and 3 before (named *initial*) and after performing the electroosmotic decontamination tests, considering the incubation times of 1, 10 and 20 days, and the respective distances of the five specimen layers from the cathode to the anode, which were labeled 1, 2, 3, 4 and 5.

Regarding the behavior of the tested soils and considering all cadmium extracted forms, Figs. 7 to 9 shows that the behavior of the cadmium ion before electroosmotic de-



Figure 4 - Cadmium concentration in the anode and cathode compartments during decontamination tests, and pH values determined in the specimens before and after decontamination tests: soil 1.



Note: Laboratory testing problems prevented to measure the pH at 20 days of incubation time.

Figure 5 - Cadmium concentration in the anode and cathode compartments during decontamination tests, and pH values determined in the in the specimens before and after decontamination tests: soil 2.

contamination (initial stage) varied with the incubation time.

As illustrated in Fig. 7, when the incubation time was increased, more contaminant was taken from soil 1, especially in the soluble, specifically absorbed, and residual fractions. However, considering the exchangeable form, which is the fraction electrostatically attracted by the soil

colloidal phase, the opposite happened; in other words, the quantity extracted decreased with the increase of the incubation time. Arguably, an explanation for this behavior is that with the increase of incubation time, the strongly absorbable fraction became attracted to the soil colloids with less strength; therefore, the metals were more dissolved with the application of electric potential, settling in



Figure 6 - Cadmium concentration in the anode and cathode compartments during decontamination tests, and pH values determined in the in the specimens before and after decontamination tests: soil 3.

electrostatic form. Thus, the electrostatic fraction quantitatively increased and reached such amount that could not be taken away in the adopted periods of time. Also, increasing the incubation time, reactions which occurred in soil 1 and application of the electric potential difference made the ions less strongly absorbed and more electrostatically attracted to soil colloids.

As shown in Fig. 8, the efficiency of the decontamination process increased with the incubation time, in all sequential extraction fractions, which may be associated with the fact that soil 2 has low quantity of iron and aluminum oxides, which are the most important minerals in the cation absorption process. However, when the incubation period changed from 10 to 20 days, the differences were not significant. Thus, the results indicated that chemical and mineralogical factors of soil 2, as well as incubation time had significant influence in the electroosmotic decontamination process.

Concerning soil 3, based on the results presented in Fig. 9, it was observed that the increase of the incubation time led to an increase on the amount of extracted cadmium, in all sequential extraction fractions, inferring that there was decrease of the electrostatically attracted fraction and increase of the strongly absorbed fraction with the incubation time, before and after the remediation process.



Figure 7 - Results from the sequential extraction performed in the contaminated specimen from soil 1 before and after the electroosmotic decontamination test, considering the incubation times of 1, 10 and 20 days, and the distances of the specimen layers to the cathode.



Figure 8 - Results from the sequential extraction performed in the contaminated specimen from soil 2 before and after the electroosmotic decontamination test, considering the incubation times of 1, 10 and 20 days, and the distances of the specimen layers to the cathode.



Figure 9 - Results from the sequential extraction performed in the contaminated specimen from soil 3 before and after the electroosmotic decontamination test, considering the incubation times of 1, 10 and 20 days, and the distances of the specimen layers to the cathode.

The contaminant behavior observed in soils 1 and 3 after the electrokinetic process was similar to that reported by Gu & Yeung (2010). Certainly, the measurement of the quantity of cadmium before and after each step of the sequential extraction could provide a basis to explain the behaviors previously reported.

Table 7 shows the final quantities of cadmium taken in each extraction in comparison with its initial quantity, in percentage. It should be emphasized that at the beginning of the decontamination process, each slice of the specimen had the same cadmium concentration that can be represented by a constant line in a figure that shows cadmium concentration in the Y axe versus distance from cathode in the X axe. At the end of the process, it was possible to obtain a curve of cadmium concentration using the cadmium concentrations determined from each slice of the specimen in each step of the sequential extraction procedure. Therefore, from comparison of the areas under these curves, the amount of cadmium extracted from the specimen in each step of the sequential extraction could be inferred by the ratio of the difference between the area determined after the electrokinetic remediation and the area determined before electrokinetic remediation by the area determined before electrokinetic remediation.

From Table 7 data, the values of the negative percentages found in soils 1 and 3 were unexpected. One possible explanation for this behavior can be related to the fact that more contaminant remained in that fraction at the end of the test, although it does not necessarily mean that decontamination was effective, once the other fractions presented high positive percentages, overcoming the observed negative fraction. On the other hand, it could be noticed that soil 1 (clayey) presented a great amount of retained cadmium in the specifically absorbed fraction, while soil 2 (sandy soil with lower iron and aluminum oxide contents) presented the best global decontamination results.

Soil	Contaminant incubation	% of cadmium removed					
	time (day)	Soluble	Exchangeable	Specifically absorbed	Residual		
	1	93.89	52.13	-3.57	57.08		
1	10	92.59	19.92	9.70	63.40		
	20	96.98	12.91	29.94	69.11		
	1	98.76	32.77	40.68	100.00		
2	10	96.57	41.37	52.39	100.00		
	20	96.59	51.32	52.28	100.00		
	1	31.96	-15.12	10.98	58.68		
3	10	38.16	42.75	-4.46	61.48		
	20	100.00	40.37	16.18	77.30		

 Table 7 - Percentage of cadmium removed from the analyzed soils by the electroosmotic process in each step of the sequential extraction.

To sum up and based on the results shown on Figs. 7 to 9 and on Table 7, among the tested incubation times, it was observed that 20 days ended up being the most satisfactory period for soils 1 and 3, and 10 days ended up being satisfactory for soil 2; however, further research is required to confirm this behavior. On the other hand, soil surface chemistry and mineralogy influenced the results obtained in the decontamination tests. All soils analyzed presented Kaolinite, Goethite, Gibbsite, HIV and/or Hematite minerals in their clayey fractions; however, soils 1 and 3 presented higher percentages of clay fraction than soil 2 and, consequently, higher adsorption capacity.

5. Conclusions

Regarding the tested soils, applied ddp and incubation times, the analysis of the results obtained supports the following conclusions:

- The PZC of soils influenced the cadmium migration under application of the electric potential difference; specifically, soils 1 and 3 presented reversal electroosmotic water flow, *i.e.*, in the cathode-anode direction;
- In soils 1 and 2, application of the electric potential difference generated cadmium migration in the electroosmotic flow direction. However, in soil 3 the contaminant migrated in the anode-cathode direction, bringing up to attention the importance of the parameter of soil PZC in the electroosmotic decontamination process;
- In general, the values of pH of all tested soils determined after decontamination tests were higher than those determined before, increasing from the anode to the cathode direction;
- It was observed that changing the incubation time, the results obtained from the sequential extraction performed before and after application of the electrokinetic remediation process showed that chemical and mineral-

ogical characteristics of the tested soils influenced their cadmium adsorption;

• 20 days and 10 days were, respectively the optimum tested incubation times for soils 1 and 3, and for soil 2.

Acknowledgments

The authors would like to express their thanks to CAPES for granting a scholarship to the first author, to the Departments of Civil Engineering and of Soils from UFV for all the support required for the development of this research, as well as to FAPEMIG for his support through the grant TEC-PPM-00081-10.

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List of Symbols

- w_L : liquid limit
- w_p : plastic limit
- I_p : plasticity index
- A_c : Skempton's activity index $(I_p/(\% \phi \le 2 \mu m))$
- γ : Specific gravity of soil solids
- w_{ot} : optimum water content
- $\gamma_{d \max}$: maximum dry density
- w_o : initial moisture content
- w_t : final moisture content
- Sr_o : initial degree of saturation
- Sr_{t} : final degree of saturation
- $k_{e \text{ stable}}$: electroosmotic conductivity coefficient after water flow stabilization
- SB: Sum Exchangeable Bases
- CEC (t): Cationic Exchange Capacity
- CEC (T): Cationic Exchange Capacity in pH 7.0
- V: Base Saturation Index
- m: Aluminum Saturation Index
- SSI: Sodium Saturation Index
- OMC: Organic Carbon x 1.724 Walkley-Black
- P-rem: Remanescent Phosphorus