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Electrochemical Soil Remediation from Environmental Toxicants: Results and Prospects

V. A. Korolev

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Abstract—The main results of a ten-year investigation into the mechanism and factors of electrochemical remediation of contaminated dispersed soils from various environmental toxicants (heavy metals, nitrates, phenol, oil and petroleum products, radionuclides etc.) are presented. The investigations were performed at the Chair of engineering and environmental geology at Lomonosov Moscow State University and were aimed at evaluation of the feasibility and the development of efficient industrial technologies for remediation of contaminated areas. The further prospects of a method for electrochemical soil remediation are demonstrated.

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INTRODUCTION

The development of an industrial society is accompanied by rapidly increasing pollution of the environment, including the geological environment, with various environmental toxicants. Therewith, the natural processes of the self-cleaning of the geological environment cannot any longer cope with the pollution, which results in the degradation of ecosystems and sometimes leads to local environmental crises. In such situations, ecosystem rehabilitation is possible only by means of large-scale application of remediation technology for geological environment reclamation. The author suggests that this branch of environmental geology, dealing with the feasibility evaluation of rational methods for remediation of the geological environment in order to nullify toxic contaminants should be termed geopurgology (from Greek Gaea (Mother Earth) and Latin purgo, pure—to purify) [Korolev, 1998].

One of the most popular methods of soil decontamination is an electrochemical method based on passing a direct current flow through a contaminated soil. The resulting processes (electrolysis, electroosmosis, electrophoresis, electromigration, etc.) remove toxic components from the soil.

This method has been known for a considerable time; however, its application to soil remediation started only in the second half of the 20th century, and became especially wide-spread during its last quarter. In the 1960s, Academician V.M. Prokhorov studied the possibilities for using this method for soil remediation from radionuclides. Since the early 1980s, electric fields have been increasingly applied to the removal of various toxicants from soil. Thus, in Great Britain J. Agard (1981) studied electroreclamation and its applications to the removal of toxic metals from contaminated soils. In the 1990s, Probstein, Hicks, and Shapiro [Probstein, Hicks, 1993; Shapiro, Probstein, 1993] were granted US patents for removal of contaminants from soils by electroosmosis. Since the late 1980s, the "Geokinetcs" corporation in the Netherlands and later "Holland Milieutechniek" applied electrochemical remediation for treatment of areas contaminated with arsenic and other toxicants, based on the research by Lageman and Pool [Lageman, Pool, 2001]. In the 1990s, they successfully implemented several projects in the USA, Europe, Australia, and Asia. Intensive research on rock remediation is being performed in Denmark based on the investigations of such scientists as H. Hansen [Hansen et al., 1999], I. Christensen, L. Ottosen, etc. Dialysis plants have been worked out and dialysis schemes applied for remediating contaminated soils.

Currently, there are numerous companies engaged in soil decontamination and remediation of contaminated areas in some countries of Western Europe and America. A sharp increase in the number of successfully implemented projects of electrochemical remediation of contaminated areas was observed in the mid-1990s. Thus, the annual scope of work carried out by the Dutch company "Turnover Hak Environmental" was 1–2 projects of this kind prior to 1995, with the project costs ranging from 75 to 600 thousand euros. 1
From 1996 to 2002, the number of environmental projects successfully implemented by this company rose to a range of 10–30 a year, and their cost was over 7 million euros in 2002 alone. The trend toward increasing 1
costs of environmental reclamation incurred by western-European countries has continued in recent years.

In Russia, however, the level of financing environmental works aimed at remediation and reclamation of contaminated areas is much lower than in the first world. Only a few business ventures in our country provide remediation of contaminated areas, including remediation by electrochemical methods; there are no federal programs for environmental rehabilitation and reclamation of polluted territories (although their area is large in Russia). There are still many theoretical and technological problems of electrochemical soil remediation requiring thorough consideration.

Since the mid-1990s, at the Chair of engineering and environmental geology at Lomonosov Moscow State University, large-scale laboratory research on electrochemical remediation of clay soils from heavy metals (Cu, Pb, Cd, Zn, etc.), nitrates, and organic toxicants 2 (phenol oil, lube oil, etc.) has been carried out by the author and his collaborators [Korolev, 1998, 2001 (a, b), 2002, 2003; Korolev, Babakina, 2001; Korolev, Samulina, 2004; Korolev, Sitar, 2004 (a, b); Korolev, Romanyukha, 2006; Kucherov, Korolev, 2003, 2005; Korolev, Nekrasova, 1995, 1998; Korolev, 2001; Korolev, Babakina, Lazareva, 2001; Korolev, Babkina, 2001; Korolev, Babakina, Mitojan, 2001; Korolev, Kucherov, 2003]. In particular, in 1996 the fact that oil moves in oil–water-saturated soil under the action of an electric field was first (to the best of our knowledge) experimentally established, which pointed to the potential of this method in the remediation of oil-contaminated soils. The main results of those and other investigations performed by the Chair personnel over the last decade (1998–2007), as well as the prospects of further research are considered in this paper.

SUBJECT AND METHOD OF RESEARCH

In the course of our investigations, we worked out a method for electrochemical soil remediation for various environmental toxicants. A laboratory study of electrochemical migration of contaminants was performed in two types of electroosmotic cells: one for experiments without flow and the other for a continuous-flow type of experiment, simulating the sample "flushing" and the electrochemical leaching of the contaminant.

The method of experimentation under *non-flow conditions* consisted in the following. A prepared soil sample with a disturbed or natural structure, a known amount of introduced contaminant, and a specified water content [humidity] was placed in an electroosmotic device and connected to a direct current power supply. This started the process of electrochemical remediation of the sample, which took from 6–8 hours to several days. In this case, the electroosmotic filtrate with the toxicant was removed. After completing the treatment, the current was switched off, the cell was dismantled, and the sample was cut into equal pieces along the electroosmotic filtration direction; the final contents of the contaminant and humidity were then determined in each of them. Based on these results, graphs were plotted of the contaminant concentration distribution over the sample from the anode to the cathode, which enabled us to assess the soil sample purification efficiency.

Our experiments under *continuous-flow conditions* followed the same procedure, with the only difference being that an open-type cell was connected with a vessel filled with "flushing" anolyte fluid, and on the cathode 3 side, catholyte was collected enriched in the leached toxicant.

In our investigations into electrokinetic soil remediation from various environmental toxicants, different dispersed soils from sands to heavy clays were studied. In addition, artificial sand–gel soils were investigated and used as protective geochemical barriers to the migration of radioactive waste (RAW). About 25 kinds of the most common dispersed soils of variable age, genesis, mineral composition, and degree of dispersion were studied. Among the soils researched, there were six genetic types that are most widespread in the European part of Russia: from peat soil and forest floor to sod-podzol soil and various chernozem soils.

We selected those soils as the key types of the most common dispersed soils exposed to the most intensive technogenic pollution in the territory of Russia.

In all the examined soils, chemical and mineral composition and salinity were studied by means of X-ray diffraction analysis and their structural and textural features were investigated viz., their grain-size and microaggregate composition, and their macro and microstructure (the latter was studied by means of an electronic microscope). In addition, complexes of physical and physicochemical properties, including adsorption parameters, were studied by using conventional and standard methods.

The environmental toxicants used and studied as contaminants were the most common substances, the removal of which from soils is of a great ecological significance. Among those, we studied inorganic pollutants, i.e., heavy metals (Cu, Pb, Cd, etc.), nitrates; organic pollutants: oil (several grades) and petroleum products, phenol, alcohols; and radioactive contaminants (^{90}Sr and ^{137}Cs and their salts, which are assimulators 4 of radionuclides). We examined soil remediation of radionuclides in collaboration with the NPO (scientific development and production center) "Radon" and LOGS (the Laboratory of Geological Environment Protection) at the Moscow University Department of Geology. Among the participants of those investigations were V.V. Kucherov, Yu.Ye. Barkhatova, and Ye.V. Shevtsova. The electrochemical remediation of soils for heavy metals was studied with the participation of undergraduate, bachelors, masters, and postgraduate students of engineering and environmental geology, O.A. Babakina, V.A. Nekrasova, and V.V. Kucherov; phenol decontamination was investigated by O.A. Babakina, D.C. Inozemtseva, and N.V. Samulina; and oil decontamination was explored by M.A. Nekrasova, A.D. Tokarchuk, K.A. Sitar, O.V. Romanyukha, and A.M. Abyzova.

The concentrations of heavy metals in soil samples were determined by atomic absorption, X-ray dispersion and photocolorimetric techniques; the nitrate and phenol concentrations were determined by means of

Changes in adsorption of organic substances in the examined soils

Soil	Organic substances, adsorption of which in the presence of copper	
	increases	decreases
Kaolinitic clay	Diphenylamine, m-toluidine, phenol, pyrogallol, resorcine, quinoline, furfurol, benzaldehyde, benzonitrile; nitromethane, nitrobenzene	?-naphthol, benzoic acid, benzamide, 2-aminopyridine, 1.3-dinitrobenzene, diphenyl oxide, indole
Hydromica clay	Dimethylaniline, diphenylamine, aniline, a-naphthol, quinoline, pyridine, benzamide, phenol, ?-nitrobenzaldehyde, nitrobenzene, acrylonitrile, diphenyl oxide	Furfurol, 2-aminopyridine
Moraine loam	?-naphthylamine, aniline, pyrogallol, quinoline, benzonitrile, benzamide, nitromethane, indole, phenol	p-cresol, resorcine, nitrobenzene, acrylonitrile, 2-aminopyridine, diphenyl oxide
Fluvioglacial sand	Picoline, quinoline, phenol, furfurol, nitrobenzene	Indole, pyridine, benzaldehyde, nitromethane

photocolorimetric and spectrophotometric methods, oil and lubricants, by the thermal weight method, and the content of radionuclides, by the atomic absorption and gamma-spectrometric methods.

SOIL REMEDIATION FOR HEAVY METALS

Electrochemical soil remediation for the case of heavy metals was studied in various clay soils with disturbed structures. Several internal factors of clay soils (mineral composition, dispersivity, moisture content/density, etc.) affecting the efficiency of their electrokinetic remediation from some heavy metals (Cu, Cd, Zn, Pb, etc.) were also examined. Simultaneously, the sorption characteristics of these heavy metals in the examined soils were studied.

It was discovered that the above-listed heavy metals can be removed from soils by the electrochemical method, since they regularly move in the field of direct current from the anode to the cathode, are removed from the sample along with the electroosmotic filtrate, and are partially reduced on the electrode. The degree of clay soil remediation from heavy metals ranged from 30% to 70% and more, depending on the soil's composition and state [Korolev, 2001 a, b; 2003; Kucherov, Korolev, 2003; Korolev, Nekrasova, 1998].

We found that the form of the heavy metals and the specific features of their sorption by clay soils influenced electrokinetic soil remediation for heavy metals. It was established that electrochemical remediation can be performed, not only by removing free moving forms of heavy metals from the soils but also via mobilization and removal of their exchangeable and sorbed forms. We investigated the sorption peculiarities of various organic toxic contaminants in the presence of heavy metals (copper) affecting their absorption by soils [Korolev, Babakina, 2001; Korolev, Babakina, Mitojan, 2001].

These studies were based on determination of the ionization potential in soils, i.e., the energy required for removing an electron from an electrically neutral atom of the studied substance, as well as the resonance soil potential, that is, the ionization potential under which the maximum absorption of the examined substance was observed. In a soil that simultaneously contains heavy metals and various organic substances, organic compounds are adsorbed, both on mineral particles of the soil, and on additional adsorption centers generated by the heavy metals present. Resonance potentials were studied in the presence of copper in monomineral kaolinite and hydromica clay, and also in polymineral moraine loam and fine-grained fluvioglacial quartz sand under the absorption of a wide range of various organic substances (table).

Generally, soils saturated with a copper solution contain organic contaminants in which the adsorption rate increases and exceeds the abundance of substances with a decreasing adsorption rate (table). Consequently, copper sorbed on the soil surface creates additional adsorption centers for organic contaminants, which increases their adsorption rate.

Among the external factors affecting the remediation of soil for heavy metals, we studied the impact of the remediation mode (static or with continuous flow), time, and activators. Thus, we found that an increase in the time of electrokinetic treatment enhanced the efficiency of clay soil remediation from heavy metals, although there is an optimum time range at which the largest amount of heavy metals is removed. This range depends on the type and composition of a clay soil.

It was also found that in the continuous-flow mode the rate of electrokinetic remediation of clay soil from heavy metals increases significantly. This implies that the continuous-flow remediation method can be proposed for industrial applications. Activators of electrokinetic remediation of clay soils from copper ions were identified. In some cases, their presence in the soil can significantly enhance the efficiency of electrochemical soil remediation due to the modification of the electric double layer (EDL) and of soil adsorption centers.

Moreover, they can help to regulate the pH of the soil pore solution in order to attain the required state. We can recommend sodium nitrate, oligochitosan (polysaccharide), and glycerin as activators in the continuous-flow version. Thus, whereas the remediation of kaolinite clay for copper was only 30% without activators, it reached almost 70% in the presence of glycerin and it was 50% in the presence of sodium nitrate.

SOIL REMEDIATION FROM NITRATES

The potential of electrochemical soil remediation from nitrate compounds was studied in kaolinite clay, in which the sodium nitrate content exceeded the maximum permissible concentration (MPC) by several times.

It was found that upon applying direct current to clay soil containing nitrates, NO_3^- ions began to move from the cathode to the anode. The removal of Na NO_3 from the soil occurred due to electroosmotic transport and electromigration.

The efficiency of the remediation of soil for nitrates grows as the initial moisture water content increases. Thus, lengthwise redistribution of a nitrate contaminant in the sample is more efficient when the initial moisture content W_{init} of a clay soil is equal to 70% than when $W_{init} = 30\%$. At a higher moisture content in the sample, the soil remediation from a nitrate contaminant is more complete and when W_{init} is 30%, the residual concentration of the contaminant after the experiment was only a little lower than the initial level. The migration ability of nitrates when the soil moisture is 50% is characterized by average values. The time for electrochemical remediation of a kaolinite clay sample at different initial moisture contents was the same.

The effect of using an alkali as an activator of soil remediation in the case of nitrates was studied for the effects of its addition changing the pH of the soil pore solution and for its physicochemical exchange capacity and modifying EDL. It was found that ions migrate towards the cathode in the presence of alkali nitrates, since a portion of them evidently move with sodium ions. The maximum remediation efficiency was attained in the anode zone, and an intermediate rate was observed in the cathode area, whereas the greatest remediation efficiency was characteristic of the cathode zone and the lowest for the anode zone when the experiment was carried out without alkali addition. The total efficiency of the sample remediation was almost 80% when alkali was added, which was almost 25% higher than in experiments without alkali addition.

In the continuous-flow mode (water washing), the continuous inflow of water enabled us to enhance the efficiency of the sample remediation by 17–20% in comparison with non-flow conditions.

SOIL REMEDIATION FOR OIL AND PETROLEUM PRODUCTS

Over the last decade we carried out a wide scope of comprehensive investigations into the factors affecting the applicability and efficiency of electrochemical remediation for various dispersed soils using oil and petroleum products. Clay soils of different dispersivity and chemical and mineral compositions were examined. In addition, since organic soils are most frequently subject to oil pollution (oil spills, transportation accidents, etc.), special attention was paid to the specifics of their electrochemical remediation for oil. Thus, samples of organic soils from various horizons with natural structure were studied, which provided the maximum similarity of laboratory conditions to the natural ones. The complex analysis of factors affecting the efficiency of electrokinetic remediation of dispersed soils for oil showed that all the investigated dispersed oil–water-saturated soils (from heavy clays to sandy silt, including organic soils) can be cleaned using the electrochemical method in the case of oil contamination [Korolev, 2001); 2002, 2003; Korolev, Sitar, 2004; Korolev, Romanyukha, 2006; Korolev, 2001]. The decontamination efficiency ranges from 25 to 75% and higher depending on various internal and external factors. Oil in the direct current field moves in the form of droplets together with electroosmotic filtrate from the anode to the cathode and is carried away by the flow due to viscous friction. A part of the oil in dissolved form moves in the same direction as its dissolution takes place under an increased pH value in the cathode zone.

The influence of the chemical and mineral composition of clay soils, including organic soils, on the rate of their electrokinetic remediation is shown in the EDL parameters: the higher the physicochemical activity is of individual clay minerals, the greater is their EDL development under these conditions, and the more efficient is the remediation of clay soil for oil.

As the dispersivity of a clay soil rises, the remediation efficiency increases. In sandy–argillaceous soils, the optimum proportion for electrochemical remediation is a content of 65–75% of the particles with a particle size >0.01 mm. An increase in the soil porosity (or a reduction in its density) enhances the efficiency of its electrokinetic remediation for oil.

A decrease in the values of parameters of the physicochemical activity of clay soils viz., the plasticity index (I_p), indices of hydrophilicity (K_h), and colloidal activity (K_a), also leads to a decline in the intensity of the electrochemical migration of oil and, as a consequence, to a reduction in the rate of soil remediation from hydrocarbons.

Experiments showed an optimum proportion of solid and liquid phases in clay soils for electrochemical oil removal. A moisture content close to the content of free soil swelling and a water : oil proportion equal to or exceeding 2 : 1 are optimal for the process of electrochemical oil migration in dispersed oil–water-saturated soils and for their remediation for oil. When the water content decreases and the oil proportion in the sample increases, the amount of removed oil decreases, which leads to a drastic decrease in electrochemical oil migration.

The influence of oil degradation on its electrochemical removal from soils was studied. It was found that the older the oil-contaminated soil is, the less efficient this method will be; in this case, the degraded oil must be rendered into a more mobile state (possibly by adding chemical agents, surfactants, or solvents, etc.). This remediation method is not feasible for soils polluted by oil more than 6 months earlier.

The influence of oil composition on the efficiency of dispersed soil remediation for oil was also studied. It was established that the efficiency of electrochemical soil remediation for oil contamination drops with an increase in the initial density of the oil and the content of pyrobitumens and resins. In the case of paraffins, no such pattern was observed. Electrokinetic soil remediation for light oils is more efficient then for heavy crude.

For the case of oil contamination, the most successful remediation can be performed in a continuous–flow mode, i.e., via electrochemical leaching of hydrocarbons. Lixiviant selection showed that the best results were obtained by using an aqueous solution of sodium hydroxide with a concentration of approximately 0.1–
3 0.2 H. Alkali acting as an anolyte provides better oil dissolution, not only in the cathode zone, but in the entire interelectrode space, which facilitates more complete soil remediation [Korolev, Romanyukha, 2006].

SOIL REMEDIATION FOR PHENOL

Phenol is a highly toxic and highly water-soluble organic toxicant, which can be a serious environmental hazard as a soil pollutant. Therefore, in the case of phenol contamination electrochemical soil remediation is of the greatest importance. We examined the influences of lithological and mineral composition, phenol concentration, and the water content in soils on their electrochemical remediation. The results obtained were published in the following papers: [Korolev, Babakina, 2001; Korolev, 2001, a, b; Korolev, Samulina, 2004; Korolev, Babakina, Lazareva, 2001]. Phenol is actively adsorbed on the clay minerals of soil. The adsorption isotherm of phenol by polymineral hydromica–kaolinite–smectite loam has a characteristic shape with three sections reflecting various sorption mechanisms. A concentration of interacting solution of 40 mg/l, which was selected for further study of the peculiarities of electrochemical remediation, provided the most complete phenol absorption by hydromica–kaolinite–smectite loam. Monomineral montmorillonite clay proved to have the maximum sorption capacity with respect to phenol (358.3 mg/kg of the soil solid phase under an equilibrium concentration of contaminant solution equal to 40 mg/l).

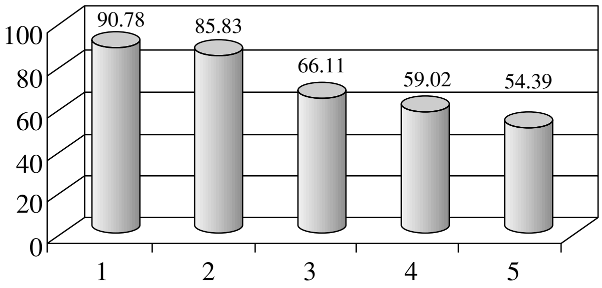

Fig. 1. Electrochemical remediation rate (%) of various soils from phenol in an anode zone: 1, montmorillonite clay (htⱣ$_2$); 2, kaolinite clay (eⱣ$_2$); 3, smectite–hydromica–kaolinite clay (mK$_1$ap); 4, hydromica–kaolinite loam (al-pQ$_{2-3}$); 5, hydromica loam (mP$_2$kw).

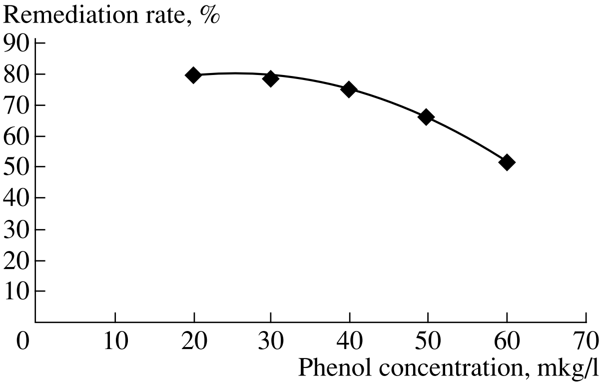

Fig. 2. Efficiency of electrokinetic remediation (%) of surface loam (prQ$_3$) versus initial phenol concentration in the soil.

Depending on the pH of a soil pore solution, phenol occurs in the soil in various forms (phenol, phenol oxiradical, phenolate), each of which has a certain migration capacity in a direct current field. Depending on the conditions, the rate of remediation for various soils for phenol ranges from 87% to 96–97%, which proves the high efficiency of this method.

The efficiency of electrochemical soil remediation for phenol is enhanced with the increasing content of clay minerals in the soil and is also determined by specific features of the crystal lattice of the soil component minerals. The highest remediation efficiency was obtained in soils containing clay minerals with an expanding crystal lattice (Fig. 1).

As dispersion increases, the efficiency of sandy–argillaceous soil remediation for phenol goes up. The maximum efficiency of electrochemical soil remediation for phenol was observed in samples with a free swelling water content (i.e., under conditions of completely formed EDL). With an increase in the initial phenol concentration in the soil pore solution, the efficiency of soil remediation for this contaminant goes down (Fig. 2).

Therefore, the investigations showed that the electrochemical method can be used as a high-performance method for the phenol decontamination of various soils.

SOIL REMEDIATION FOR RADIONUCLIDES

Of equal significance is the problem of radionuclide decontamination in soils.

Investigations here involved several problems connected with the insufficient information available and with the limitations of working with radioactive materials. In order to simulate the radionuclides ^{137}Cs and ^{90}Sr in our experiments, the salts of their stable isotopes, ^{133}Cs and ^{90}Sr, which have similar ionic radii and physical and physicochemical characteristics in the solutions of the respective salts of caesium CsCl and strontium $Sr(NO_3)_2$, were used. In other experiments carried out in cooperation with the "Radon" NPO the radioactive contaminants ^{137}Cs and ^{90}Sr were studied. The general results of studying the factors influencing the efficiency of electrokinetic remediation of clay and sand and gel soils for various radionuclides can be described as follows.

It was found that electrochemical decontamination is possible in the case of radionuclides, both in clay soils and in artificial sand and gel screens used as protective barriers to migration of liquid radioactive waste [Kucherov, Korolev, 2003, 2005; Korolev, Kucherov, 2003]. The electrochemical treatment of such soils leads to the general redistribution of the strontium content (^{88}Sr) along the length of the sand and gel samples from 1.4 mg/g in the anode sector to 5.6 mg/g in the cathode area of the sample; the caesium percentage ^{133}Cs varies within a range of 2–4.8 mg/g in the same direction in a constant direct current field (with an initial concentration of elements in the sand–gel samples of 3.5 mg/g). The main mechanisms for the migration of radioactive waste in the electrokinetic remediation of dispersed soil for radionuclides are electroosmosis and electromigration.

The specific features of strontium and caesium sorption in clay soils were studied. The electrokinetic migration of ^{88}Sr, both free and adsorbed, in a clay soil was established, with its concentration increasing from the anode to the cathode. At the same time, ^{88}Sr migrates and its concentration changes from 1.9 to 5.0 mg/g from the anode to the cathode. The area adjacent to the anode is characterized by a high rate of remediation for ^{88}Sr totaling 51%, which proves the high efficiency of this method. The total amount of adsorbed ^{88}Sr after electric treatment is reduced in clay soil and changes from 35% (of the initial amount) in the anode region to 81% in the cathode area, which confirms the general high efficiency of electrokinetic remediation for the used artificial clay screens applied as a geochemical barrier to the migration of liquid radioactive waste.

For the first time, electrokinetic migration of ^{88}Sr and ^{133}Cs in the pore solution of an artificial sand and gel screen (used as a protective barrier) was established, with an increase in the concentration of these radionuclides from the anode to the cathode. Migration of ^{133}Cs and ^{88}Sr was observed, with a change in the strontium concentration from 1.2 to 4.4 mg/g and that of caesium from 1.8 to 4.4 mg/g in the direction from the anode to the cathode. The highest efficiency of soil remediation for radionuclides was observed in a region adjacent to the anode (48% and 37% for ^{88}Sr and ^{133}Cs, respectively), which is an indication that the migration processes intensity.

The total amount of sorbed ^{88}Sr changed from 45% (of the initial amount) in the anode area to 80–83% in the cathode zone; the figures are similar for ^{133}Cs, and they vary from 57% to 92%. This, in combination with the high remediation rate, clearly demonstrates the efficiency of the electrokinetic remediation process for the used protective artificial screens regarded as a geochemical barrier to liquid RAW migration.

The efficiency of electrokinetic remediation of clay and artificial sand and gel soils from ^{88}Sr is comparable. However, the maximum rate of remediation of the latter can be attained by regulating the experimental parameters (time, voltage, etc.), as well as by applying supplementary methods for preliminary preparation of the contaminated soils.

Laboratory and semi-industrial bench-top experiments in collaboration with the "Radon" NPO demonstrated a sufficiently high efficiency of the electrochemical removal of radioactive ^{137}Cs from clay soil using NH_4NO_3 as a buffer solution (leaching-out agent) in the continuous-flow mode. The removal rate of this radionuclide was 21% over 48 days; the rate of RAW removal could be increased to 50% and higher with longer electric treatment.

PROSPECTS OF FURTHER INVESTIGATIONS

The investigations of electrochemical soil remediation from various environmental toxicants performed over the last decade have enabled us to outline the main prospects of our further work in this field. The most important of those are as follows:

(1) *Further investigations of the insufficiently studied factors affecting the electrochemical remediation of soils and determining its efficiency.* Within this task, it will be necessary to continue the investigation into internal and external factors affecting the efficiency of electrochemical remediation and to simultaneously expand the range of studied environmental toxicants. Among the latter ones, electrochemical methods can be used to remove different chlororganic compounds (COC), polychlorinated biphenyls (PCB), pesticides, polyaromatic hydrocarbons (PAH), and synthetic detergents, among other substances from soils; however, many of those are insufficiently studied;

(2) *identification and selection of the most efficient leaching agents for various environmental toxicants.* The solution of this problem could significantly enhance the rate and efficiency of electrochemical soil remediation by electrochemical leaching. This also involves a search for new activating substances for the remediation process;

(3) *working out schemes for the rational combination of various soil decontamination methods, including physical, chemical, and physicochemical methods.* Since there is currently no universal method for soil remediation from environmental toxicants, complex decontamination techniques should be applied. However, combination of remediation methods depends on the toxicant type, the characteristics of the contaminated soil and soil body, and on many other factors. Therefore, the development of rational schemes for combining various remediation methods is a very significant innovation problem;

(4) *Pilot tests of soil decontamination intended for substantiating comprehensive industrial innovation technologies for contaminated areas remediation from environmental toxicants.* The transfer from laboratory research to pilot and production tests is a necessary and crucial stage of this investigation. The problems of its implementation include many issues yet to be addressed, including a lack of adequate financial support for this kind of work, absence of a production base, etc.

CONCLUSIONS

(1) The electrochemical method is a highly efficient technique for soil remediation for various inorganic (including radionuclides) and organic toxic contaminants..

(2) The advantages of this method include the following: (a) soil remediation is possible directly in the soil body and at a considerable depth; (b) the high rate and efficiency of remediation; (c) the wide range of environmental toxicants that can be removed from the soil by this method; (d) the relatively low cost of the method (in comparison with biological remediation and other techniques); (e) the relatively rapid remediation performance; (f) the possibility of the rational combination of these methods with other methods.

(3) The development prospects of this method are determined by the necessity of more comprehensive study of the individual factors affecting remediation processes and by selection of efficient leaching agents and of working out rational combinations with other remediation techniques and a transfer to pilot tests.

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