



# Structural curiosities of lanthanide (Ln)-modified bentonites analyzed by radioanalytical methods

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## Abstract

The effects of pH and lanthanide (La, Y) concentration were investigated on the release of iron from Ca-bentonite crystal structure. XRF results revealed that during the Ca–H cation exchange procedure iron loss was not observed. In the case of lanthanide modifications, the pH has low influence, meanwhile the concentration of lanthanide has high influence on iron loss. Thus, high amount of trivalent lanthanides cause the structural iron release.

**Keywords** Lanthanide-bentonites · Cation exchange · Structural changes · X-ray-fluorescence spectrometry (XRF)

## Introduction

Bentonite is favored because it is low-cost. It has many good properties [1–3] e.g. high exchange capacity thanks to the high amount (> 50 mass%) of montmorillonite content. The montmorillonite is a layer silicate clay mineral. This mineral has permanent negative charge because of isomorphic substitution which means that the cations (e.g.  $\text{Al}^{3+}$  ion) in the layer may be exchanged by smaller charged cations e.g.  $\text{Mg}^{2+}$  or  $\text{Fe}^{2+}$  ions [4]. The ion exchange capacity depends on the number of these substitutions. The higher the clay mineral's ion exchange capacity, the more it affects its physical properties by changing its water-absorbing capacity, and thus, its technological behavior [5]. The negative layer charge of the crystal lattice can be neutralized by cations attracted to the interlayer space. This interlayer space can call as 'nano laboratory' where cation exchange takes place which may modify the properties of the bentonites. Interlayer cations may be exchanged to lanthanide cations in the so-called nano laboratory. Lanthanide cations are used as model ions during the study of interactions between soil and transuranium ions. These radionuclides are produced during the fission of  $^{235}\text{U}$  in nuclear power plants [6].

Bentonite is considered as candidate engineer barrier material—among others—for the safe disposal of high-level

radioactive waste [7]. The structural analyses of bentonite have been investigated under different conditions to figure out the stability of the structure. The main points of these studies have been to characterize the clays before and after the modifying experiments and to determine the possible differences in nature or structural stability [8–11]. The important aspect of the interactions between lanthanides (Lns) and clays in the environment is the storage or disposal of nuclear waste. The studies on Ln-clay interactions may eminently be useful in evaluating the adequacy of proposed materials for the engineer barrier of nuclear waste.

Research papers talk about the dissolution of bentonite where the main point of the research is to modify the properties of the bentonite for different reasons [12–31]. The treatment of the bentonite happens usually with inorganic acids ( $\text{HCl}$ ,  $\text{H}_2\text{SO}_4$ ,  $\text{HNO}_3$ ) to replace mainly divalent ions ( $\text{Ca}^{2+}$ ) to monovalent ion ( $\text{H}^+$ ) and to leach out  $\text{Fe}^{2+}$ / $\text{Fe}^{3+}$ ,  $\text{Mg}^{2+}$  and  $\text{Al}^{3+}$  ions, thus modifying the smectite layers and increase the specific surface area, and the porosity. The authors usually use inorganic acids in wide range of concentration ( $0.25\text{--}6\text{ mol dm}^{-3}$ ) and the treatment time is usually between 1 and 36 h at different temperature (from  $25\text{ }^\circ\text{C}$ , up to  $100\text{ }^\circ\text{C}$ ). The results revealed that the dissolution of octahedral sheet is faster than tetrahedral sheets [23, 24]. Kooli and Yan [21, 22] observed about 5% of  $\text{Mg}^{2+}$ ,  $\text{Fe}^{3+}$  and  $\text{Al}^{3+}$  reduction. Upon acid treatments, protons enter the mineral layer and harms the structural OH-groups. Krupskaya et al. [28] treated bentonites with  $\text{HCl}$  and  $\text{HNO}_3$  solutions. The study concluded an interlayer modification which occurs even at early stages of the treatment. Further

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treatment leads to further modification of the montmorillonite structure accompanied by intense leaching of cations from the octahedral positions into interlayer space. These transformations changes layer charge and CEC.

The aim of this work was to prepare La, and Y exchanged bentonites and to characterize the possible changes in the structure of bentonite. In our previous study [32] La ions showed extreme values of sorption while iron quantity of La bentonite was less than that of initial Ca-bentonite. The conclusion was that lanthanum ions can somehow supersede iron from the octahedral positions of crystal lattice. We assume that the departure of positively charged iron ions from the lattice increases the negative layer charge and the cation exchange capacity. This can motivate the enhance sorption of lanthanum.

All the lanthanides releases iron, less than La, and Y. This observation is surprising in the scientific word, no similar scientific result have found about the releases of the structural iron during Ln modification of bentonite. Therefore, in this work the change of the composition in the Ca bentonite was studied depending on the pH during the Ca–H, Ca–Y and Ca–La cation exchange procedure. The change in the chemical composition (mainly the concentration of  $Y^{3+}$ ,  $La^{3+}$ ,  $Ca^{2+}$ ,  $Fe^{3+}$  ions) in the bentonite was analyzed by X-ray fluorescence spectrometry.

## Experimental

The starting material Ca-montmorillonite was collected from Istenmezeje, Hungary. Elemental analysis of the original Ca-bentonite resulted in the following composition: 73.29%  $SiO_2$ , 18.71%  $Al_2O_3$ , 2.98% Fe-oxide, 1.54% CaO and 3.48% MgO. The mineral composition was determined by means of X-ray powder diffraction (XRD) analysis using a Philips PW1710 diffractometer (Philips, (today PANalytical B.V.) De Schakel 18 5651 GH Eindhoven, Netherland), which is operating at 30 mA and 40 kV using Cu  $K\alpha$  radiation source and a graphite monochromator. The scanning rate was  $2^\circ/2\theta/\text{min}$ . The mineral composition was calculated on the basis of the relative intensities of the reflections characteristic of the minerals, applying the literature or experimental corundum factors on minerals [33–36]. The mineral composition was as it follows: 72% montmorillonite, 6 m/m% cristobalite, opal CT, 3 m/m% plagioclase, 4 m/m% mica, 2 m/m% K-feldspar, 2 m/m% quartz, 2 m/m% kaolinite, and 2 m/m% calcite. The basal space  $d(001)$  of montmorillonite was 1.465 nm showing the dioctahedral character of the smectites. The CEC, as determined by the ammonium acetate method [37], was  $2.7 \times 10^{-4} \text{ mol g}^{-1}$  for trivalent cations.

Complexometric titration [32, 38] was used to determine the concentration of  $Ln(ClO_4)_3$  solutions and energy dispersive X-ray fluorescence spectroscopy (XRF) was used

to follow the chemical changes (mainly the concentration of  $Y^{3+}$ ,  $La^{3+}$ ,  $Ca^{2+}$ ,  $Fe^{3+}$  ions) in bentonite [39, 40]. Instrumental parameters were: Si(Li) detector with  $20 \text{ mm}^2$  surface and 3.5 mm evaporated layer (Atomki, Debrecen, Hungary), Canberra DSA 1000 digital spectrum analyzer (Canberra Industries, Meriden, CT 06450, USA), Canberra Genie 2000 3.0 spectroscopy software (Canberra Industries, Meriden, CT 06450, USA).

The  $K\alpha$ -lines of the lanthanide elements was excited with  $185 \text{ MBq } ^{241}\text{Am}$  radioactive source. In addition to the lanthanides, samples were also analyzed for iron, and calcium using a tungsten X-ray tube (type: S6000, Oxford Instruments, Scotts Valley, CA 95066, USA), operating at 60 kV and 1 mA.

The structural modifying effect of lanthanum, and yttrium ions were investigated depending on the pH during cation exchange of Ca-bentonite procedure without and with  $Ln^{3+}$  ions. Therefore, the behavior of Ca bentonite was investigated in acidic medium without  $Ln^{3+}$  ions, i.e., Ca–H cation exchange procedure was carried out by suspending 200 mg of Ca-bentonite in  $20 \text{ cm}^3$   $HClO_4$  solution at pH 2.8–5.2, and at  $25^\circ\text{C}$ . The suspension was shaken for 2 h, filtered ( $0.45 \mu\text{m}$ , nylon, Labex Ltd. Filter-Bio), washed by tridistilled water and then air-dried. Equilibrium is set in half an hour based on our previous experiments [41].

The combined effect of pH and lanthanide concentration on the bentonite structure was studied by the addition of different concentrated lanthanide perchlorate solutions ( $1 \times 10^{-4}$ – $2 \times 10^{-1} \text{ mol dm}^{-3}$ ), at pH 3.5–5.5. However, in the case of  $\text{pH} < 3$ , the structure of bentonite can be destroyed. Thus, the ion exchange experiments were carried out in the pH range of 3.5–5.5. In a series of experiments, either the pH or the lanthanide concentration were changed. Different pH was adjusted by  $1 \times 10^{-4} \text{ mol dm}^{-3}$  Hexamethylenetetramine, and by  $1 \times 10^{-4} \text{ mol dm}^{-3}$   $HClO_4$ .

The Ln-bentonites were produced by suspending 200 mg of Ca-bentonite and  $20 \text{ cm}^3$  Ln perchlorate solution [32]. The ion exchange procedure was carried out only one time, stirring time was 2 h, and different pH and initial concentration of  $Ln(ClO_4)_3$  were used.

## Results and discussion

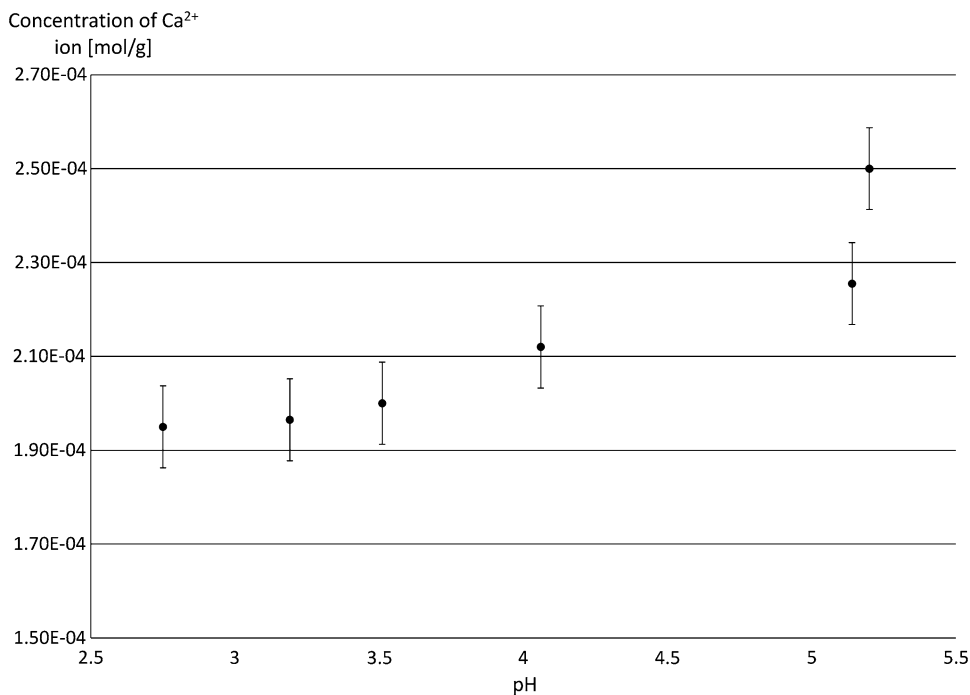
### Ca–H ion exchange

Based on our previous experience [32] during Ca–Ln cation exchange procedure structural iron loss was detected. Thereupon, the influence of the pH of the iron reduction was investigated in this study. In order to investigate the structural modifying effect of lanthanide ions, the effect of pH on cation exchange procedure had to be known. Therefore, the Ca–H cation exchange procedure was first examined in

acidic medium without  $\text{Ln}^{3+}$  ions and then during Ca–Ln cation exchange procedure was examined with  $\text{La}^{3+}$  and  $\text{Y}^{3+}$  ions.

Figure 1 shows the concentration change of  $\text{Ca}^{2+}$  ions in  $\text{mol g}^{-1}$  as a function of pH of initial  $\text{HClO}_4$  solutions. As the concentration of hydrogen ion increases, more and more calcium ions are exchanged, thus, calcium-hydrogen bentonite is formed.

**Fig. 1** The change of concentration of  $\text{Ca}^{2+}$  ion depending on the pH in the bentonite during Ca–H ion exchange procedure



**Fig. 2** The concentration of  $\text{Fe}^{3+}$  ion depending on the pH in the bentonite during Ca–H ion exchange procedure

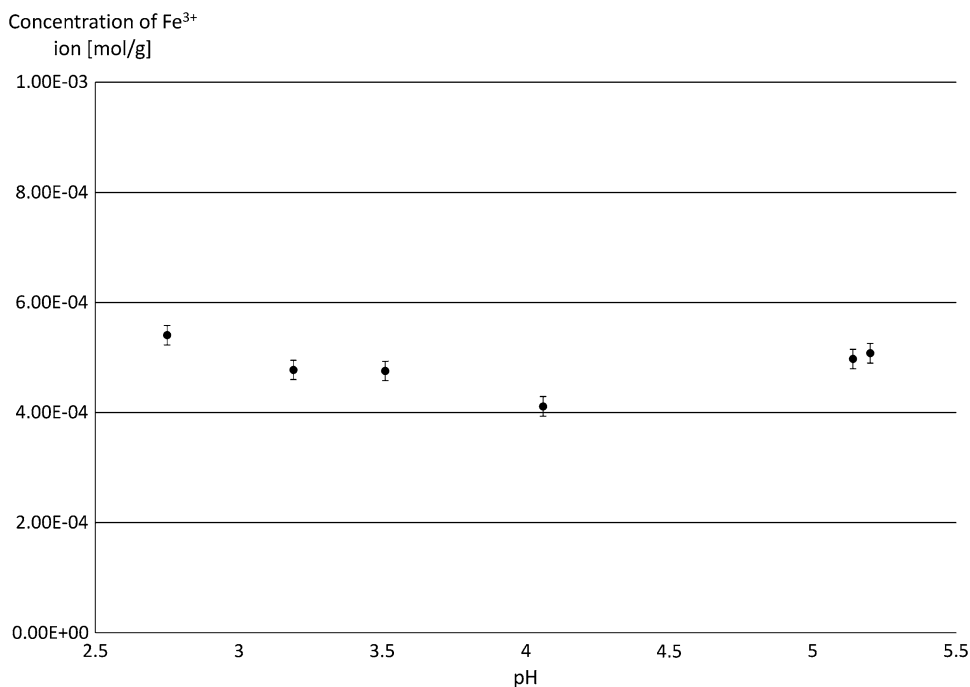


Figure 2 shows the amount of iron ion on Ca bentonite after treatment of  $\text{HClO}_4$  solution of solid phase at different pH. Comparing the results with the Fe content of the starting Ca-bentonite ( $5.2 \times 10^{-4} \text{ mol g}^{-1}$ ), it can be concluded that the Fe content of bentonite does not change within acceptable error limits ( $< 5\%$ ) after the treatment with  $\text{HClO}_4$  solution. That is, since structural iron is not

suppressed by the acidic effect, so lanthanide ions are responsible for the decrease of iron concentration.

### Ca–La ion exchange

Therefore, in a similar experiment, different pH values and different initial concentrations of  $\text{La}^{3+}$  ion were used to follow the structural change during Ca–La cation exchange procedure. The concentrations of these mentioned ions are shown in Figs. 3, 4 and 5 at three different initial concentrations of  $\text{La}(\text{ClO}_4)_3$  after the ion exchange procedure at different pHs.

Figure 3 shows that the calcium ion content of each sample is significantly reduced. The reduction is inversely proportional to the initial lanthanum ion concentration. Cca. 90% of  $\text{Ca}^{2+}$  ions are exchanged to  $\text{La}^{3+}$  ions.

Figure 4 shows that the exchange of  $\text{La}^{3+}$  ions are independent of pH, but the effect of the lanthanum concentration is robust.

The change in structural iron content (Fig. 5) is not influenced by the pH, only by the lanthanum concentration. The released iron content is about 15–25% compared to Ca-bentonite. So, the structural iron is suppressed by the trivalent lanthanum. This requires at least  $5 \times 10^{-3}$  mol  $\text{dm}^{-3}$  lanthanum ion concentration.

### Ca–Y ion exchange

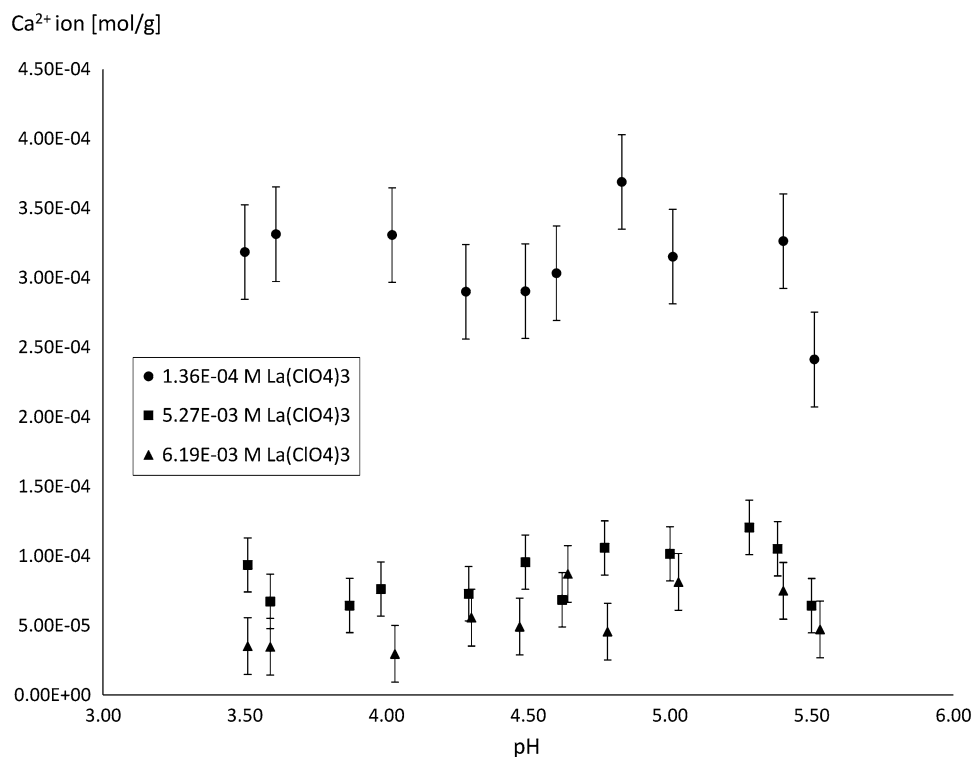
Similar experiment was performed with  $\text{Y}^{3+}$  ion exchange. The experiments were also carried out in the pH range of 3.5–5.5, but the concentration of yttrium ion was further increased. The results can be found in Figs. 6, 7 and 8. Similarly to lanthanum ion, the ion exchange between  $\text{Ca}^{2+}$ – $\text{Y}^{3+}$  ions is not affected by the pH, but with as the concentration of  $\text{Y}^{3+}$  ions increases more and more  $\text{Y}^{3+}$  ions are sorbed on the bentonite (Fig. 7).

At the same time, with increasing concentration, more and more calcium ions are exchanged, using 0.2 mol  $\text{dm}^{-3}$   $\text{Y}(\text{ClO}_4)_3$  solution, almost 100% of the calcium ion is dissolved (Fig. 6).

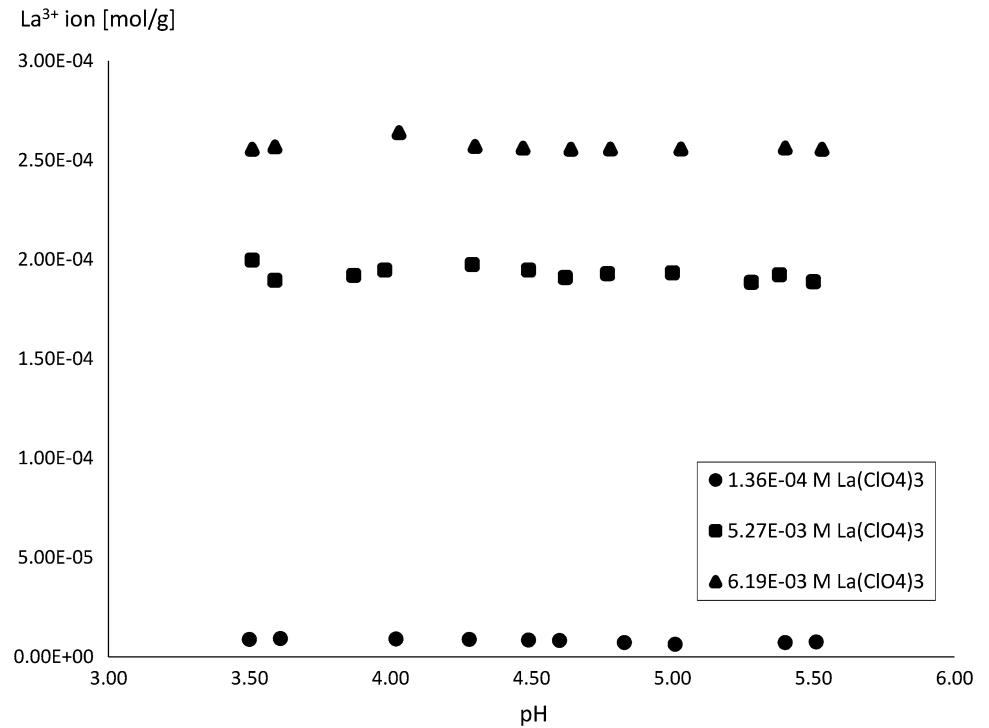
Structural iron content (Fig. 8) shows that the pH has a slightly effect, but the concentration of yttrium ion has a significant effect. The released iron content is about 22–33% compared to Ca-bentonite. The higher release of iron content in case of yttrium ion compare to lanthanum ion is because the higher yttrium ion concentration during the acidic treatment.

Thus, in the case of both ions (lanthanum and yttrium ion), it can be concluded that the cation exchange of Ca–Ln is essentially independent of pH and depends on the concentration of Ln ion.  $\text{Ln}^{3+}$  ions at high concentrations almost exchange interlayer  $\text{Ca}^{2+}$  cations, displacing 30% of the structural iron from the octahedral layer. Some of the leaving iron ions enter the interlayer space [42], and the other part precipitates in the form of  $\text{FeO-OH}$  which is deposited on the wall of the

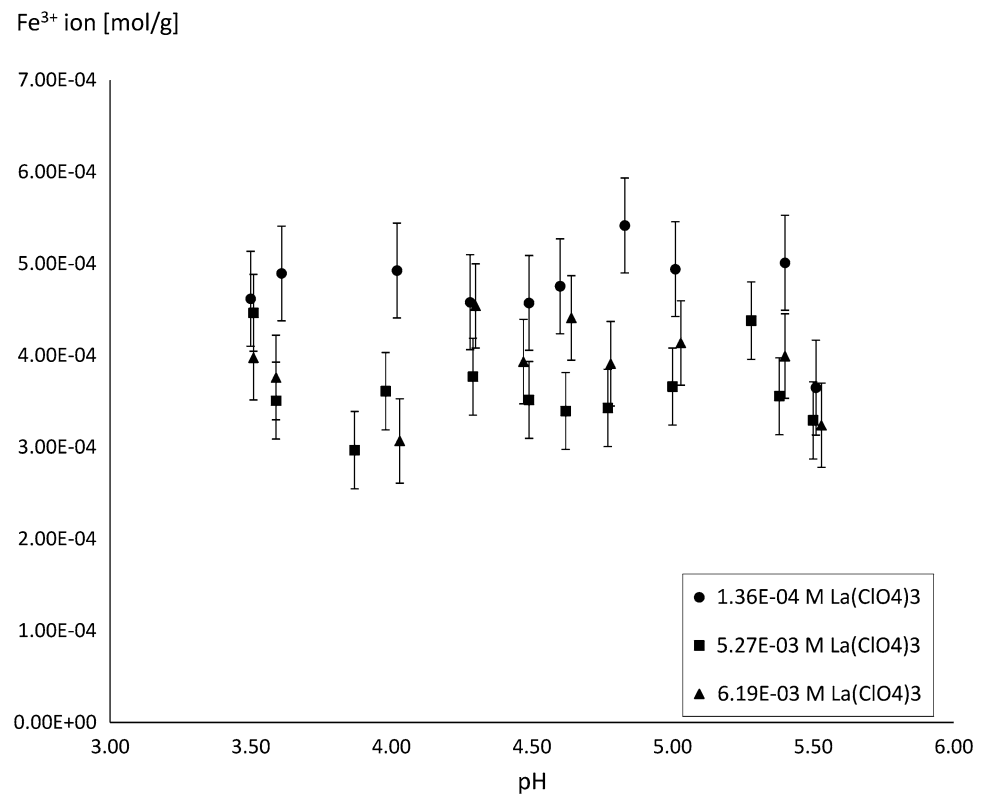
**Fig. 3** The concentration of  $\text{Ca}^{2+}$  ion depending on the pH, and concentration of  $\text{La}(\text{ClO}_4)_3$  in the bentonite during Ca–La ion exchange procedure



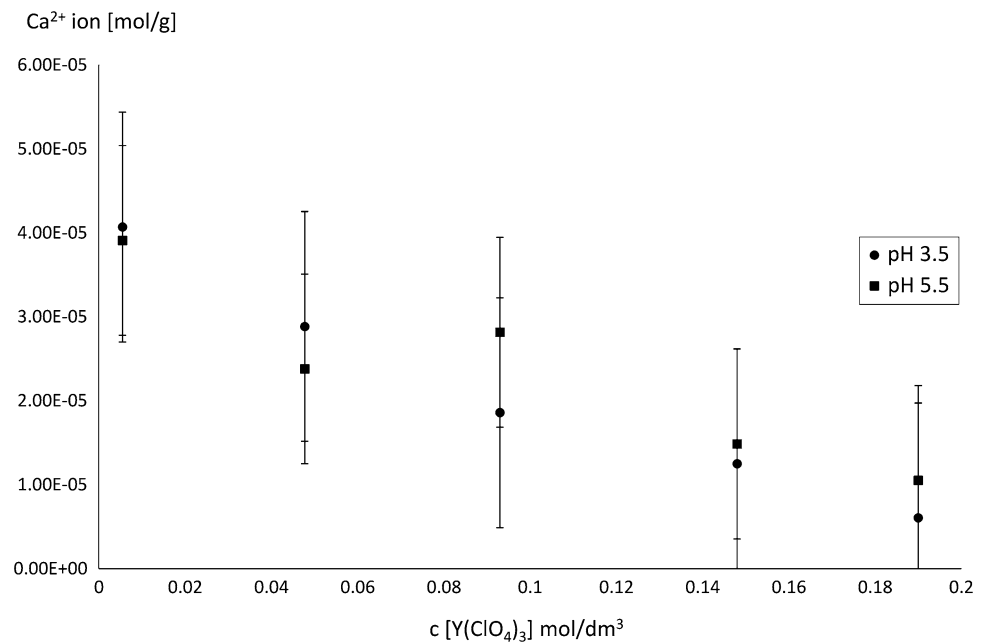
**Fig. 4** The concentration of  $\text{La}^{3+}$  ion depending on the pH, and concentration of  $\text{La}(\text{ClO}_4)_3$  in the bentonite during Ca–La ion exchange



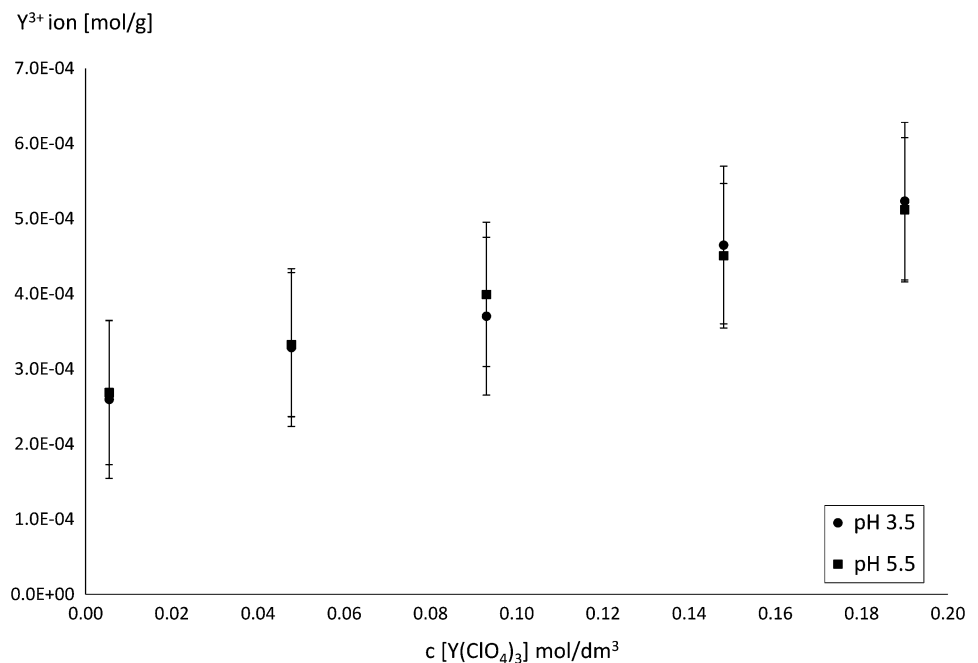
**Fig. 5** The concentration of  $\text{Fe}^{3+}$  ion depending on the pH, and concentration of  $\text{La}(\text{ClO}_4)_3$  in the bentonite during Ca–La ion exchange procedure



**Fig. 6** The concentration of  $\text{Ca}^{2+}$  ion depending on the pH, and concentration of  $\text{Y}(\text{ClO}_4)_3$  in the bentonite during Ca–Y ion exchange procedure



**Fig. 7** The concentration of  $\text{Y}^{3+}$  ion depending on the pH, and concentration of  $\text{Y}(\text{ClO}_4)_3$  in the bentonite during Ca–Y ion exchange procedure



laboratory vessels during the exchange procedure [32]. Therefore,  $\text{Ln}^{3+}$  ion is responsible for the effect, since there was no similar result during Ca–H cation exchange.

## Conclusions

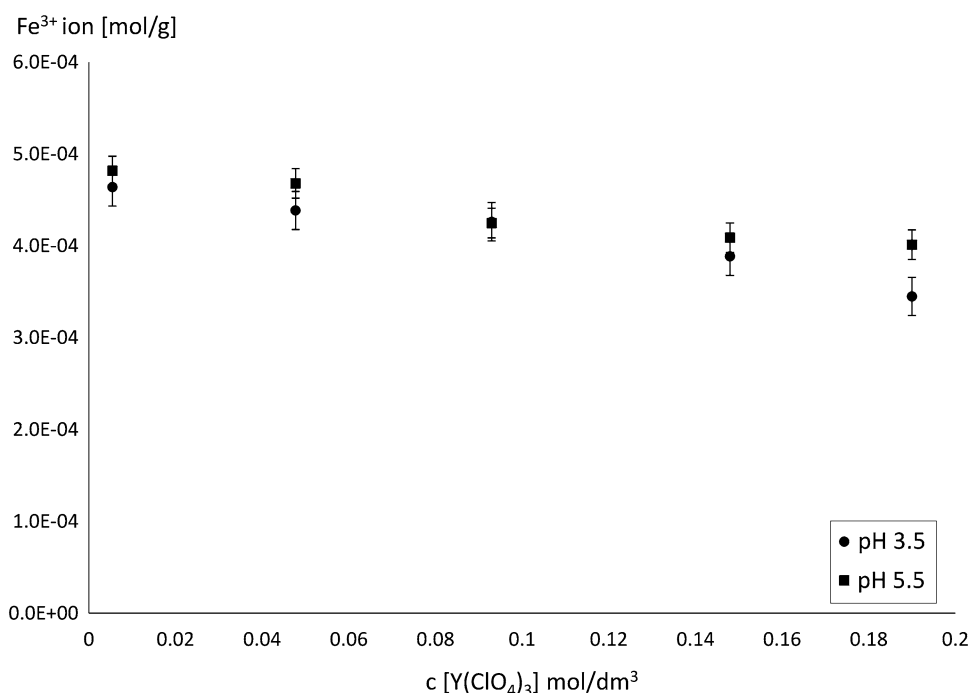
The aim of this study was to investigate the cause of the structural iron decrease during Ca–La, and Y cation exchange procedure. Therefore, the combined effect

of pH and concentration on the bentonite structure was studied during Ca–H, Ca–Y, and Ca–La cation exchange procedure.

This study has proved that during Ca–Ln-cation exchange procedure (in case of Y, and La) iron released from octahedral position of montmorillonite which is not due to the pH but La, and Y concentration.

This study strongly confirms our previous study. However, further studies are needed to be aware of the mechanisms between the Ln and the structural composition of

**Fig. 8** The concentration of  $\text{Fe}^{3+}$  ion depending on the pH, and concentration of  $\text{Y}(\text{ClO}_4)_3$  in the bentonite during Ca–Y ion exchange procedure



the bentonite. Kinetic studies planned to see the structural change by the time at different temperatures.

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