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RESEARCH

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The efficiency of the electro-osmosis method on the consolidation and strength properties of the gray clay of Tabriz

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Abstract

Background Consolidation of clays could be a very time-consuming procedure. However, preloading can increase the speed of consolidation; applying an electric field can accelerate this procedure significantly. The efficiency of the electroosmosis approach has been studied for different types of clays previously. At the same time, there is no information about the performance of the EO method for Tabriz gray clay.

Methods This paper investigates the effects of the EO technology on Tabriz gray clay using a modified oedometer consolidation apparatus. The achieved results of the EO consolidation of the Gray clay of Tabriz are compared with the standard Kaolin clay (KC-which produced industrially). Three different electrodes (Iron, Copper, and Aluminum) are employed to study about effects of the electrode type, and two different voltages (12 V and 24 V) are applied to assess the impact of the input electric field on the settlement of samples.

Results It is shown that the copper electrode leads to maximum volumetric strains while the iron electrode results in minimum volumetric strains. In addition, it is shown that the larger input voltage leads to larger settlements. The results indicate that the EO approach is more efficient for the Gray clay of Tabriz in comparison to the KC, where gray clay shows larger settlements while subjected to an electric field. Unconfined compression tests are also applied to some samples, and the EO method's influence on the samples' strength is discussed.

Conclusions The achieved results demonstrated that the EO method can be efficiently used to improve the consolidation and strength properties of the gray clay of Tabriz.

Highlights

- Effects of the electro-osmosis (EO) method on the consolidation properties of the grey clay of Tabriz were investigated.
- A modified oedometer apparatus was developed to assess efficiency of the EO method for gray clay of Tabriz.
- EO induced settlements of the grey clay of Tabriz were compared with the settlements of Kaolin clay.
- Effects of the different electrodes on the EO induced settlements were evaluated.
- Effects of the EO on the unconfined strength of clays were investigated.

Keywords Electro-osmosis, Consolidation, Gray clay, Kaolin, Unconfined compression, Electrode

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Introduction

Ground improvement technologies such as the application of structural inclusions (Soomro et al. 2022; Poorjafar et al. 2021), grout injection (Golmohamadi et al. 2016), and dewatering approaches (Zeng et al. 2021) have been applied all over the world during the past decades. Regarding the complex mechanical behavior of soils as a natural material, different investigations about such behavior of treated or untreated soils should be conducted by considering various possible conditions (Tohidvand et al. 2022; Maleki et al. 2023). The application of electrokinetic soil improvement methods for clays also has been under development these days. This approach applies an electric field to extract pore water from the anode to the cathode (Casagrande 1949). Different studies have been undertaken to investigate the efficiency of this approach on the consolidation properties, dewatering, injection of additives, increasing strength parameters, and reduction of unfavorable settlements. In these studies, numerous parameters related to the electric supply method, such as the type of the used electrodes, the magnitude of the applied voltage, and the duration of the applied electric field, are studied. Lefebvre and Burnotte (2002) used the electrochemical injection method to improve desired properties of clays. Hamir et al. (2001) used geosynthetics as electrodes and reported that these electrodes could improve drainage, durability, and strength during electro-osmosis consolidation procedures. Zhang et al. (2019), using five different scenarios for applying the time of the electric current, presented an investigation of the effects of the period of the application of the electrical field. Kherad et al. (2020) undertook the electro-osmosis method to study this approach's efficiency in modifying the clays' swelling properties. Zhou et al. (2015) evaluated the effects of electrode type on the electro-osmosis improvement of silts. This research, employing four different types of electrodes, including Iron, Copper, Aluminum, and graffiti, has shown that applying iron electrodes leads to more drainage water compared to the other types of electrodes. Zhang and Hu (2021) studied the effects of suction and preloading in the electro-osmosis consolidation of clays. It was shown that applying suction during electro-osmosis consolidation cannot only improve the drainage volume of pore water but also avoid cracks occurring in the soil adjacent to anode electrodes.

Some other investigations have been done to study the applicability of electro-osmosis soil improvement in collaboration with geotechnical structural elements such as anchors, nails, and piles. For example, Zhang et al. (2019) demonstrated that piles and anchors could be used as electrodes for the electrochemical improvement of soils. Yang et al. (2019) indicated that the change of applied voltage until a specific value could enhance the efficiency of electrochemical improvement of clays, while additional changes in voltage (more than the optimal value) have no significant effect on the electrochemical process. The previously applied studies can be divided into four main categories: small-scale physical modeling tests using a soil box (Ling et al. 2017; Estabragh et al. 2014; Mahalleh et al. 2021), element tests using an electro-osmosis cell (Xue et al. 2017), large scale field tests (Burnotte et al. 2004; Lee 2015; Zhuang 2021) and numerical methods (Bader 2005; Yuan and Hicks 2015). As large-scale field tests are expensive and time-consuming, this approach has been employed less than other ones in research projects, while physical modeling and element tests have been frequently used to study electrokinetic soil improvement methods. Reconstituted clays can be employed in physical modeling and element tests; however, applying the undisturbed soils extracted from boreholes for physical modeling tests is difficult (because of the large volume of the soil that is required).

The city of Tabriz, located in Northwestern Iran, has been constructed on the most fine-grained soils (including silts and clays). As the carbonate calcium precipitation occurred for thousands of years, these soils have natural cementations and can be found in different colors (because of the minerals that precipitated during time). In some regions of Tabriz city, hazardous settlements occurred in buildings because of the consolidation of these fine-grained soils. Figure 1 shows some damages that occurred to this city's buildings because of the unfavorable settlements.

Gray clays of Tabriz (shown in Fig. 2) can be found in almost all areas of the city's ground at variable depths. However, the applicability and efficiency of the electro-osmosis soil improvement technology have been studied well for pure standard clays; there needs to be more information about the efficiency of these improvement

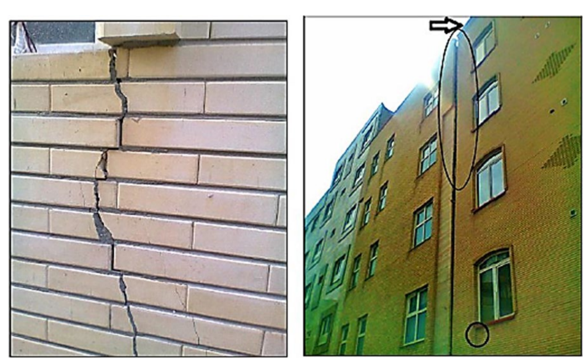

Fig. 1 Occurred damages on the buildings caused by excessive consolidation of soils (Alizadeh Majdi and Dabiri 2018)

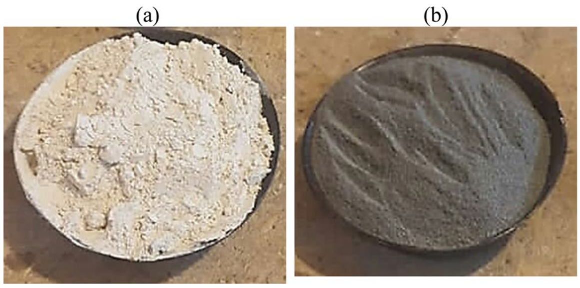

Fig. 2 Selected clays in powder form (without any natural structure) **a** KC, **b** GCT

methods on natural clays like the gray clay of Tabriz (GCT). Effects of the voltage changes, electrode type, and changes in the strength properties of this natural clay have not been studied in the literature previously. Therefore, this research presents a comprehensive study of the effects of the different parameters on the gray clay's electro-osmosis consolidation response. The achieved results for the gray clay of the city of Tabriz are compared with the standard Kaolin clay (as a manufactural-produced clay). The paper is organized as follows: "Details of the experimental study" section describes materials, testing program, studied parameters, and the employed methods. Achieved results are explained in "Results and discussions", and conclusions are summarized in the last section of the paper.

Details of the experimental study

Employed clays

This paper used two types of clays, and the achieved results are compared. The first selected clay is Kaolin clay (KC), produced industrially and has previously been employed for different investigations. Based on the applied Atterberg's limit tests, the KC is categorized as CL soil, where 34% of its contents are larger than 0.000475 m (sand particles), and 48% of its contents are silt particles. Figure 2a shows the used KC for this study. The second clay, the GCT, was extracted from a borehole in the city of Tabriz (shown in Fig. 3), and then its natural structure was removed to create a powder form of gray clay. The produced powder of the GCT is shown in Fig. 2b. Based on the applied Atterberg limits tests, the used GCT is categorized as CH soil. The main mechanical properties of the selected clays are introduced in Table 1, and their grain size distribution is presented in Fig. 4. As shown in this figure, the KC is finer than the GCT. By comparing the properties of clays in Table 1 and Fig. 4 it can be concluded that the GCT contains more active clay minerals compared to KC.

Modified oedometer apparatus

Effects of the electro-osmosis method on the consolidation properties of the GCT were assessed by employing an oedometer test apparatus with modified cells. A schematic view of the used oedometer apparatus and cells are shown in Fig. 5a, b shows a photo of the modified cell to prepare samples for unconfined compression tests. The main modifications that were applied in the conventional apparatus are as follows:

- Conventional oedometer devices cannot apply an electric field in a water-proof path. In the apparatus employed, electrodes were connected to the power supply unit from top to bottom.
- The oedometer apparatus was modified to be suitable for samples with different dimensions.
- The used oedometer apparatus is modified to be able to measurement of drained water content.

As shown in Fig. 5a, the modified oedometer cells have diameters of 0.07 m. The samples used for consolidation tests were prepared with depths equal to 0.02 m. All samples were prepared with a dry density equal to 80% of the maximum dry density of clays. Before applying an electric field to the samples, a pressure equal to 100 kPa was applied to them, and samples were allowed to consolidate under this preloading condition. Effects of the electro-osmosis consolidation procedure on the strength of the used clays were also investigated using some samples with a height of 0.125 m (and diameter of 0.05 m), where unconfined compression tests were applied to them. Consistency between consolidation and unconfined compression tests was ensured using samples with the same volumetric strains for unconfined and electro-osmosis consolidation tests.

Used electric fields and electrodes

In this research, three different electrodes, including Iron, Aluminum, and Copper electrodes, were employed to investigate the effects of the electrode type on the efficiency of the improvement results. In addition to the types of electrodes, two different voltages were used (12 V and 24 V) while the applied ampere was selected constant (10 A). Electric fields were applied for 3 h to samples in consolidation tests, and it is shown that this period was sufficient to reach the end of consolidation for the conducted tests. Details of the test program are introduced in Table 2. As indicated in this Table, this research was undertaken by applying 28 tests, including 24 consolidation tests and four unconfined compression tests.

Fig. 3 Location of the boreholes where the employed gray clay was extracted

Table 1 Main mechanical properties of selected clays

Soil type	*Gs*	*LL*	*PL*	*PI*	Soil type	γ_{dmax} (N/m^3)	ω_{opt} (%)
KC	2.65	32	23	9	*CL*	17,720	10.5
GCT	2.68	58	28	29	*CH*	18,210	21.5

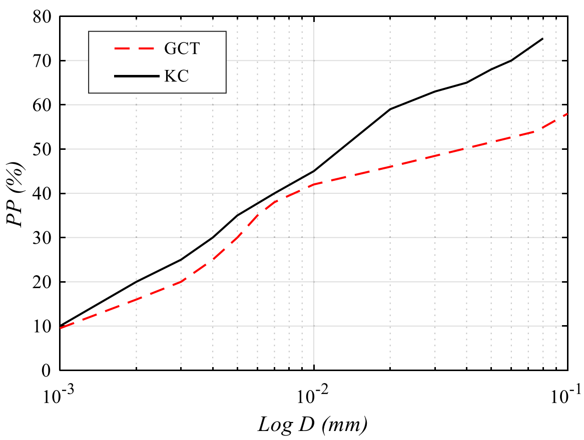

Fig. 4 Grain size distribution of the selected clays

Results and discussions

This section presents the results of the electro-osmosis consolidation for Kaolin Clay (KC) and Gray Clay of Tabriz (GCT). In addition, the effects of the EO treatment on the strength of samples are evaluated. As mentioned in "Details of the experimental study" section, samples were subjected to 100kpa preloading, and an electric field was applied at the end of the consolidation result of preloading. On the preloading phase, gray clay with RD (RD $=\gamma_d/\gamma_{d(max)}$) 80% and 60% exhibited 0.08 mm and 0.11 mm of settlements, respectively, while KC demonstrated 0.02 mm and 0.07 mm. Figure 6 shows settlement-time curves of EO consolidation achieved by tests on KC for RD = 80%, with three different electrodes. This figure shows that larger consolidation settlements

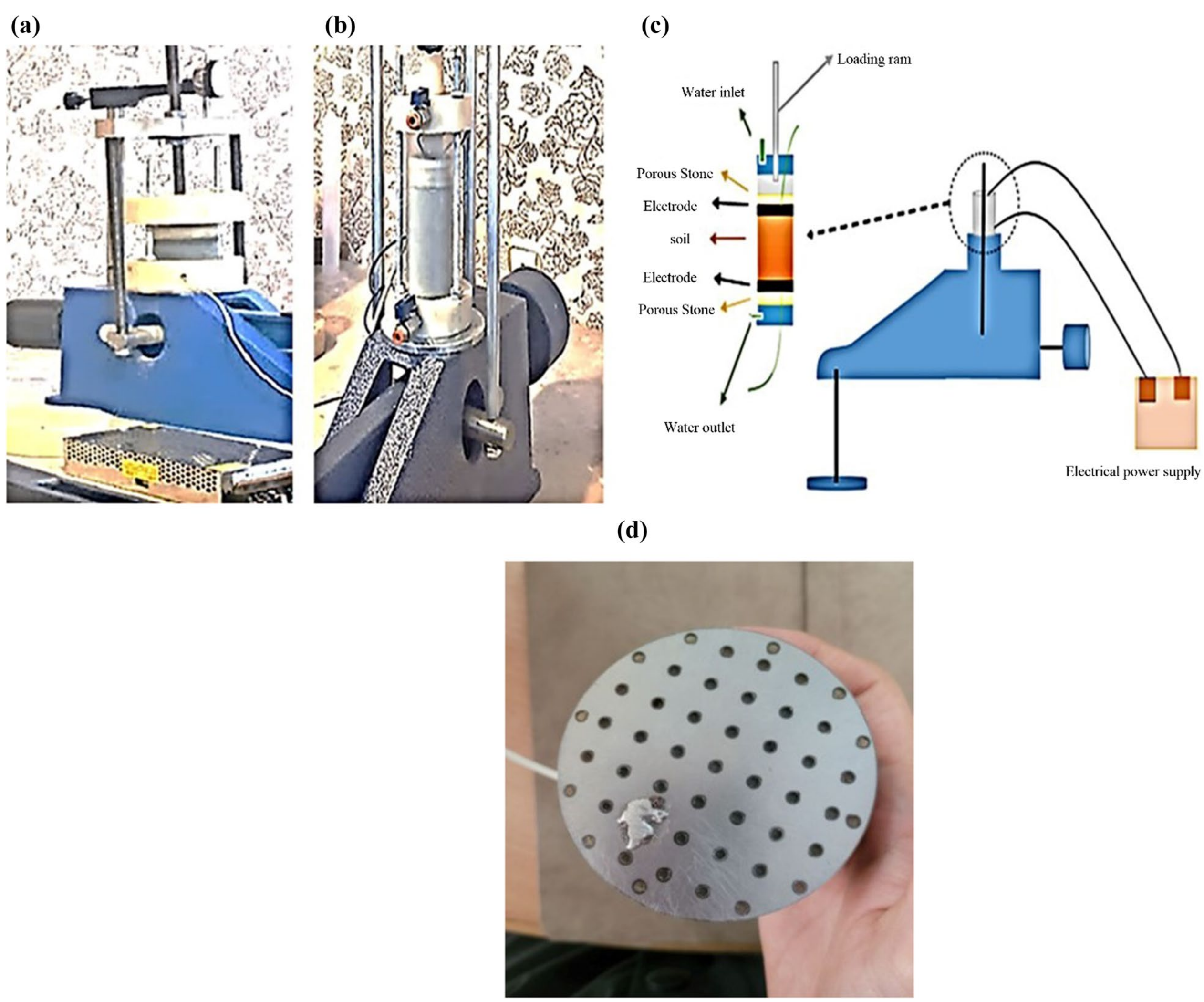

Fig. 5 Used electro-osmosis consolidation cells **a** modified oedometer cell, **b** EO cell to prepare samples for unconfined compression tests, **c** schematic view of the modified oedometer apparatus, **d** a sample of the used electrodes

Table 2 Details of the tests program

Name	Electrode	Voltage (*V*)	Ampere (*A*)	Test type	Soil type	R_D
Consolidation tests						
1	Iron	12	10	Consolidation	Kaolin	0.8
2	Iron	24	10	Consolidation	Kaolin	0.8
3	Aluminum	12	10	Consolidation	Kaolin	0.8
4	Aluminum	24	10	Consolidation	Kaolin	0.8
5	Copper	12	10	Consolidation	Kaolin	0.8
6	Copper	24	10	Consolidation	Kaolin	0.8
7	Iron	12	10	Consolidation	Gray clay	0.8
8	Iron	24	10	Consolidation	Gray clay	0.8
9	Aluminum	12	10	Consolidation	Gray clay	0.8
10	Aluminum	24	10	Consolidation	Gray clay	0.8
11	Copper	12	10	Consolidation	Gray clay	0.8
12	Copper	24	10	Consolidation	Gray clay	0.8
13	Iron	12	10	Consolidation	Kaolin	0.6
14	Iron	24	10	Consolidation	Kaolin	0.6
15	Aluminum	12	10	Consolidation	Kaolin	0.6
16	Aluminum	24	10	Consolidation	Kaolin	0.6
17	Copper	12	10	Consolidation	Kaolin	0.6
18	Copper	24	10	Consolidation	Kaolin	0.6
19	Iron	12	10	Consolidation	Gray clay	0.6
20	Iron	24	10	Consolidation	Gray clay	0.6
21	Aluminum	12	10	Consolidation	Gray clay	0.6
22	Aluminum	24	10	Consolidation	Gray clay	0.6
23	Copper	12	10	Consolidation	Gray clay	0.6
24	Copper	24	10	Consolidation	Gray clay	0.6
Unconfined compression tests						
25	Copper	24	10	Unconfined compression	Kaolin	0.8
26	Copper	24	10	Unconfined compression	Gray clay	0.8
27	Copper	24	10	Unconfined compression	Kaolin	0.6
28	Copper	24	10	Unconfined compression	Gray clay	0.6

were reached using copper electrodes for Kaolin clay. This figure also shows that the smallest values of settlements occurred for tests with iron electrodes.

Figure 7 shows settlement-time curves of EO consolidation achieved by tests on GCT with the same electrodes used for Kaolin clay. Like the EO consolidation of Kaolin clay, copper electrodes led to larger settlements in gray clay, while iron electrodes resulted in the smallest values. By comparing the results of EO consolidation for KC and GCT for RD = 80%, it can be understood that gray clay exhibited more settlements for applied voltage equal to 24 V in all tests. However, there are no significant differences between the EO consolidation settlements that occurred in the tests with voltages equal to 12 V. Therefore, the magnitude of the applied voltage can affect EO consolidation settlements of different clays when the magnitude is large enough.

Results of EO consolidation settlements for samples with RD = 60% are plotted in Figs. 8 and 9. Same as the previously mentioned results, GCT exhibited larger settlements by applying an electric field. However, differences between maximum settlements that occurred during EO consolidation for an electric field with 24 V and 12 V were reduced for these cases compared to samples with RD = 80%. Similar to the previously applied tests (for RD = 80% and an electric field of 24 V), applying copper electrodes led to more settlement, and applying iron electrodes resulted in smaller values in the tests with the electric field. For the tests with lower voltage, Aluminum electrodes resulted in larger settlements.

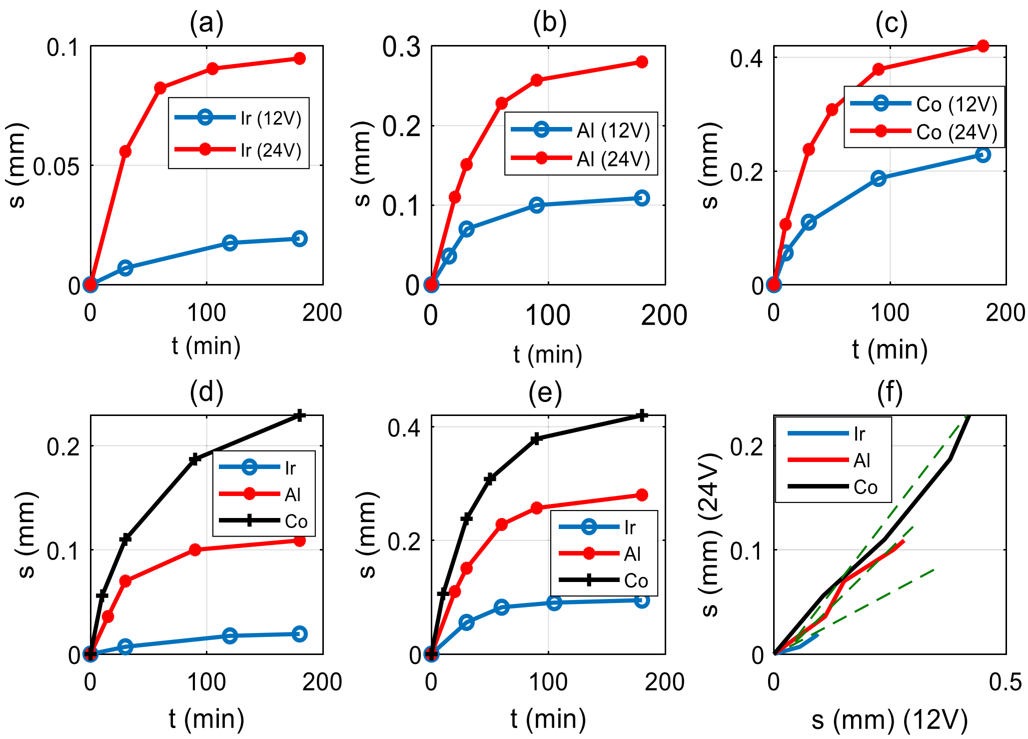

Fig. 6 EO Consolidation settlements occurred in KC with $R_D = 80\%$ using **a** Iron electrodes, **b** Aluminum electrodes, **c** Copper electrodes, **d** Comparison between the results of different electrodes for the electric field with 12 V current, **e** Comparison between the results of different electrodes for the electric field with 24 V current, **f** Relationship between settlements in two different electric currents

There is an almost linear relationship between the occurred settlements for two employed electric fields for all of the applied tests. The achieved results indicate that it is possible to predict EO-induced settlements under specific electric fields using the occurred settlements under another EO field. Comparison between the occurred volumetric strains (ξ_v) of samples are presented in Fig. 10. The volumetric strains were calculated using the principles of the oedometer tests ($\xi_v = \Delta H/H0$), and the achieved results can be related to the after-consolidation strength. Larger volumetric strains will lead to larger increments in the after-consolidation strength of samples. In addition, applying the volumetric strains can remove the effects of minor differences in the initial height of samples from the achieved results. As this figure shows, for the lower value of RD, the effects of electrode type were decreased (especially for an electric field with a voltage equal to 12 V). The maximum volumetric strain was 3.9% for copper electrodes and gray clay samples (voltage equal to 24 V). Therefore, it can be concluded that the copper electrodes for both KC and GCT exhibit efficient results, and applying larger voltages leads to more EO consolidation settlements.

As it is shown in Fig. 11, the GCT exhibited larger EO consolidation-induced settlements, and the differences between the occurred settlements were more considerable for stiffer clay samples (RD = 80%) and larger values of voltages (24 V).

Results of the unconfined compression tests for the treated samples are presented in Fig. 12. The samples for these tests were consolidated using the same procedure of consolidation tests. These tests were conducted using copper electrodes under an electric field with 24 V input voltage (as these electrodes and voltages lead to the maximum settlements). It is shown that the treated gray clay reached more considerable unconfined compression strength. The unconfined compression tests on the gray clay indicate that the samples with copper electrodes and RD = 80% reached a 7% larger strength compared to the samples of KC with the same density. The differences between the unconfined compression strengths of samples with RD = 60% were increased to 12%. Therefore, the applied tests show that the EO procedure can efficiently be applied to improve the consolidation and strength properties of the GCT. In addition, it is shown that the high plastic clay of Tabriz shows more efficiency

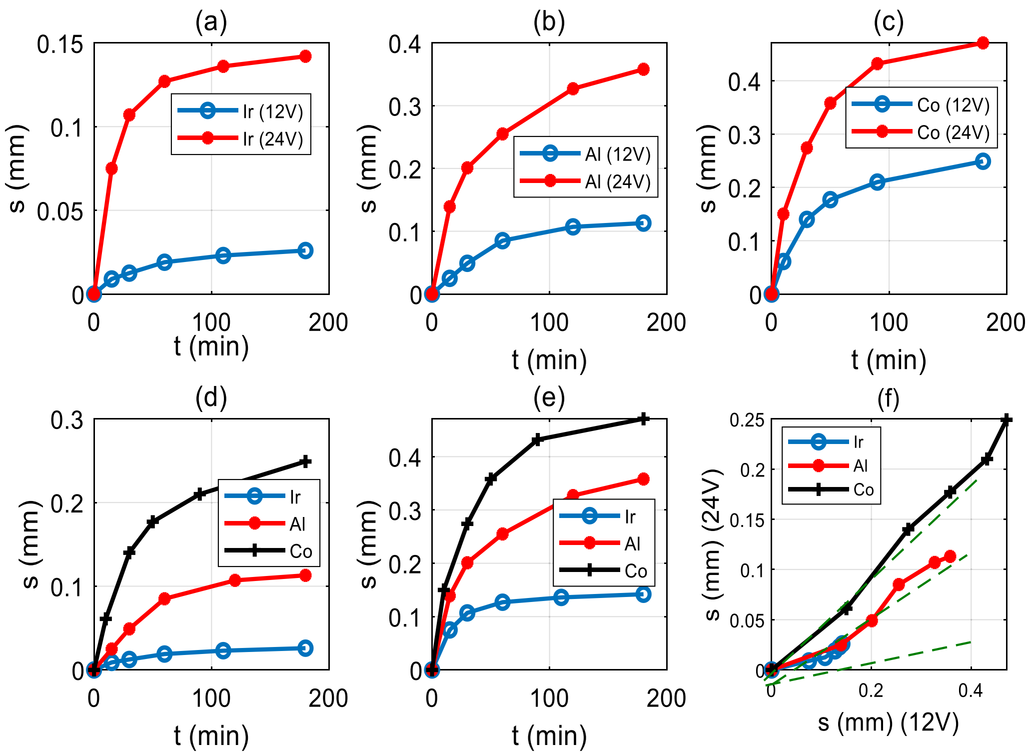

Fig. 7 EO Consolidation settlements occurred in GCT with $R_D = 80\%$ using **a** Iron electrodes, **b** Aluminum electrodes, **c** Copper electrodes, **d** Comparison between the results of different electrodes for the electric field with 12 V current, **e** Comparison between the results of different electrodes for the electric field with 24 V current, **f** Relationship between settlements in two different electric currents

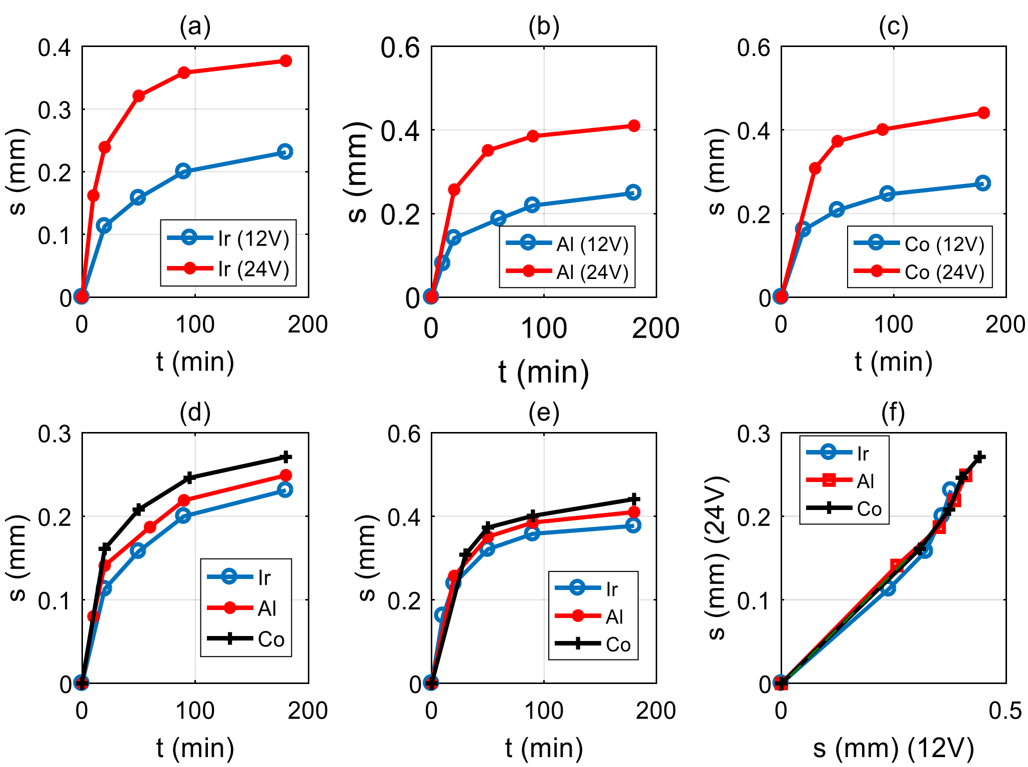

Fig. 8 EO Consolidation settlements occurred in KC with $R_D = 60\%$ using **a** Iron electrodes, **b** Aluminum electrodes, **c** Copper electrodes, **d** Comparison between the results of different electrodes for the electric field with 12 V current, **e** Comparison between the results of different electrodes for the electric field with 24 V current, **f** Relationship between settlements in two different electric currents

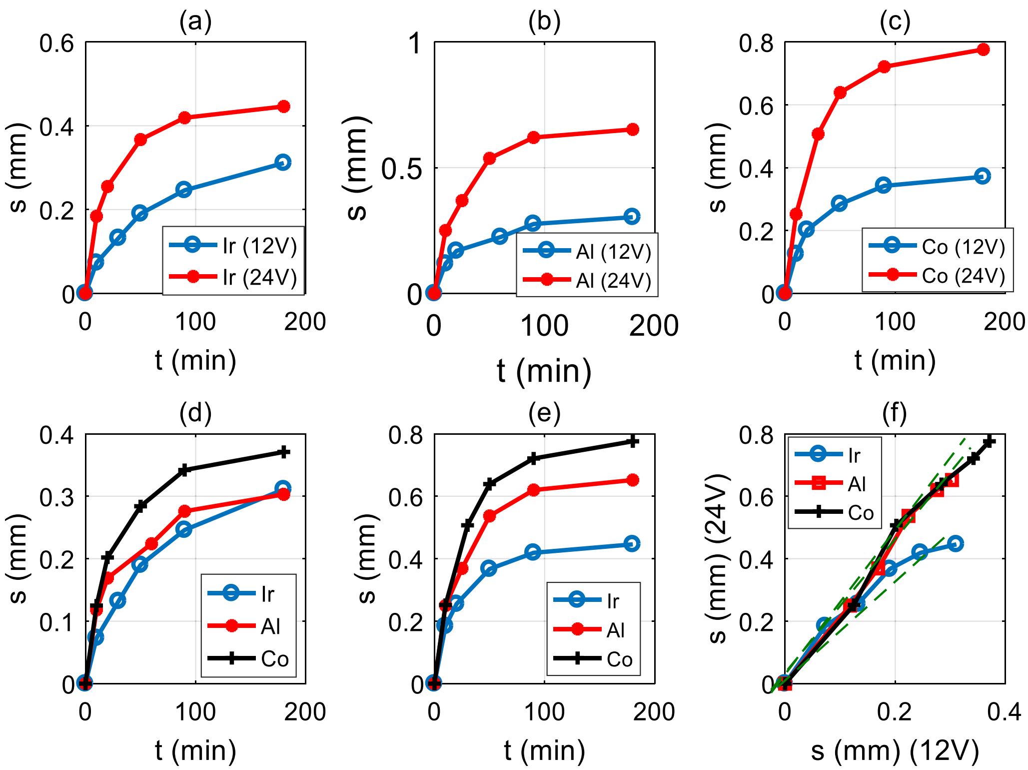

Fig. 9 EO Consolidation settlements occurred in GCT with $R_D = 60\%$ using **a** Iron electrodes, **b** Aluminum electrodes, **c** Copper electrodes, **d** Comparison between the results of different electrodes for the electric field with 12 V current, **e** Comparison between the results of different electrodes for the electric field with 24 V current, **f** Relationship between settlements in two different electric currents

in comparison to the low plastic KC during the EO procedure.

Conclusion

However, previously applied studies revealed that an electric field could accelerate the consolidation procedure of clays significantly; there needed to be more information about the efficiency of this method for Tabriz high-plastic clays. In this paper, using a modified oedometer consolidation cell, the effects of different electrodes and voltages on the settlements of GCT were studied. The achieved results of settlements for GCT were compared with the results of the KC (low plastic clay), which has been used in many studies previously. It was shown that for larger voltages, the application of the copper electrodes leads to maximum values of the settlements for both used clays; however, the gray clay exhibited larger settlements for the same situations. The minimum values of settlements (for an electric field with 24 V) occurred with the Iron electrodes. In addition, it was shown that the larger voltages of the applied electric field resulted in larger settlements. The effects of the electrode type were decreased for the tests under the lower voltage (12 V). Such a different consolidation behavior of samples in the tests with different electrodes can be assumed as a result of the various electrochemical potential that constitutes them, where lower potential can lead to more reducibility and activity of the electrodes. In addition, the ion migrating process (which is different in the different employed electrodes) can be considered as one of the reasons for the different observed efficiency of the electrodes. The unconfined compression tests on the gray clay indicated that the samples with RD = 60% demonstrated 12% larger strength compared to the Kaolin samples with the same EO procedure and preloading conditions. Based on the achieved results, the electro-osmosis procedure can be efficiently used to modify the consolidation and strength properties of the high plastic clays of Tabriz.

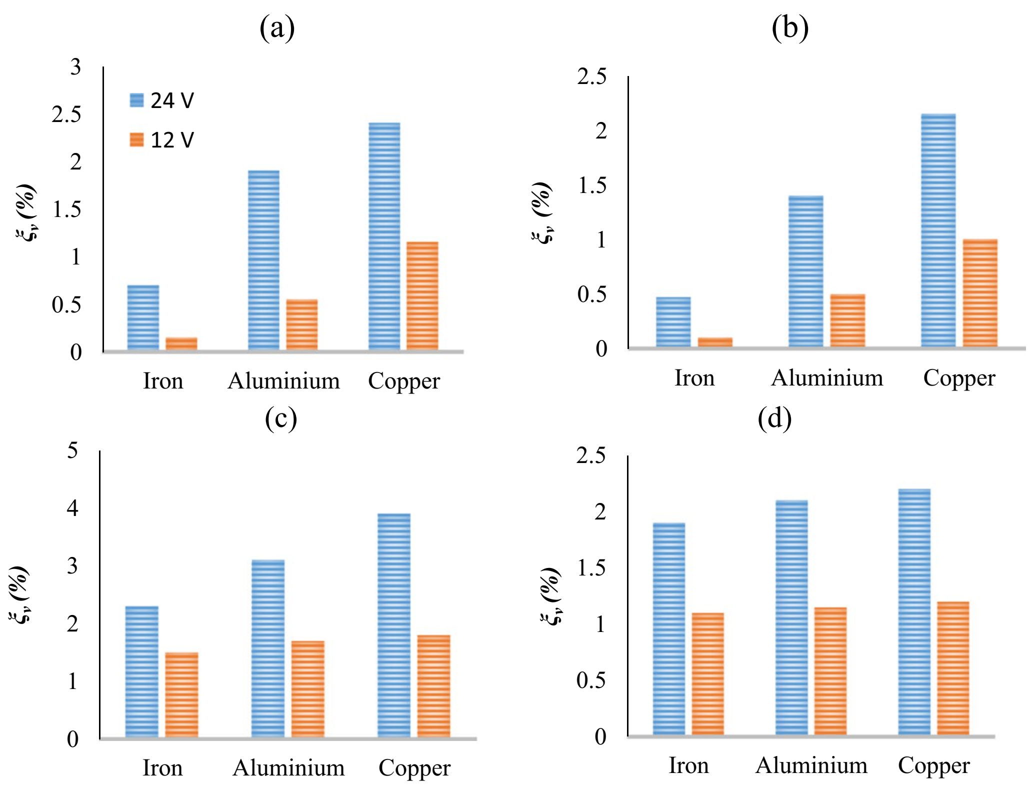

Fig. 10 Maximum EO Consolidation settlements occurred in samples **a** $R_D = 80\%$-GCT, **b** $R_D = 80\%$-KC, **c** $R_D = 60\%$-GCT, **d** $R_D = 60\%$-Kaolin clay

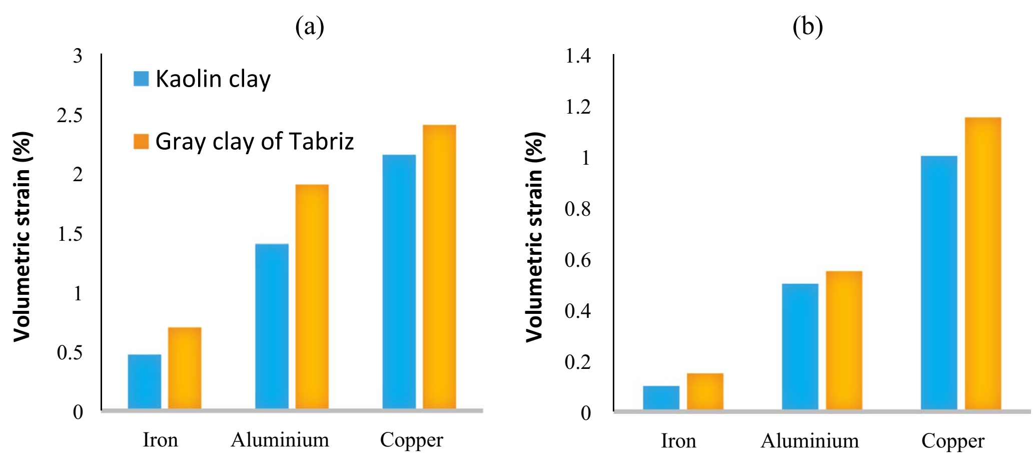

Fig. 11 Comparison between EO consolidation settlements occurred in GCT and KC with $R_D = 80\%$ using **a** 24 V, **b** 12 V

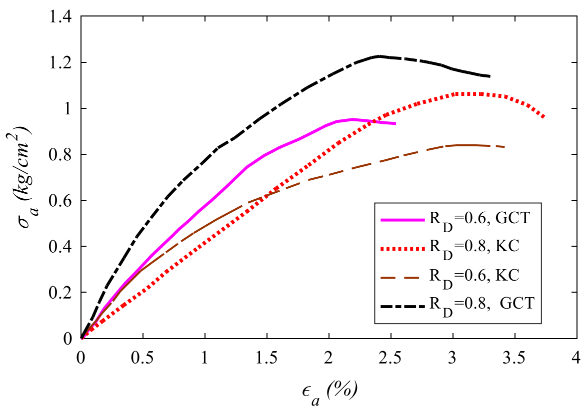

Fig. 12 Results of the unconfined tests on the treated samples using Copper electrodes and 24 V electric field

Abbreviations

γ_d	Dry unit weight
ξ_v	Volumetric strain
GCT	Grey clay of Tabriz
KC	Kaolin clay
EO	Electro-osmosis
CL	Low plastic clay
CH	High plastic clay
RD	Percent compaction

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Author contributions

Idea conceptualization: R.V.P., F.B.S., and A.Z. Literature review and preparation of the complete initial draft: A.Z. and A.A.M., Investigations: A.Z. Repeated review, restructuring, re-writing, and proof-reading A.Z., R.V.P., A.A.M., and F.B.S. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare no competing interests.

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