



The Effect of Heat on the Settlement Properties of Cement-stabilized Clay Soil

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ABSTRACT

Clay soil may be subjected to heat in various applications, such as nuclear waste burial sites and high voltage transmission lines. The impact of heat on clay soil's physical and mechanical properties has been explored in previous studies. However, previous studies have mainly focused on the mechanical properties of clay soil without stabilizers, and the effect of heat on the properties of the stabilized clay soil is scarcely studied. The present paper has analyzed and studied the combined effects of heat and cement on the settlement properties of kaolinite clay soil. To conduct the study, kaolinite clay mixed with various degrees of cement was exposed to a range of 25 to 600 degrees Celcius. The results showed that the coefficient of consolidation gradually decreased by increasing heat up to the dehydroxylation point. An increase in heat up to 200 degrees Celcius resulted in increasing the coefficient of consolidation in the specimens containing cement. In specimens containing 10 percent of the cement at temperatures higher than 200 degrees Celcius, the coefficient of consolidation in room temperature decreased by 73 percent compared to kaolinite. Moreover, the void ratio increased in kaolinite specimens without cement when subjected to heat up to 400 degrees Celcius. By increasing the heat, the void ratio decreased in specimens containing 10 percent cement.

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1. INTRODUCTION

The ever-increasing expansion of construction and building, and lack of access to suitable sites have led humans to utilize sites with inappropriate engineering properties. Generally, the soil in most construction sites is not entirely capable of bearing the weight of the structure [1, 2]. The mechanical properties of soil are determined by various factors, including soil texture, moisture, volumetric density, grain distribution, shape and mineralogy, interlocking of grains, grain adhesion and chemical weathering, grain cohesion mechanisms, and presence of vegetation. Fine-grain soil is not exclusively applicable to wet environments. Due to the incompressibility of fine-grain soil, it is not suitable to be loaded in wet environments [3]. Soil stabilization is the process of changing soil properties to increase its bearing capacity and resistance to physical and chemical tension in various environments [4-6].

Various stabilization methods can be used to change soil properties such as strength, stiffness,

compressibility, swelling sensitivity to water, and volume change behavior. Thermal and electrokinetic methods may also be combined with additives to change soil grain and density [7-11].

To summarize, the process of soil stabilization results in a change of bonds between its particles. The bond change results in a new structure that is more adhesive than before. In some methods, the previous grain structure is broken, but other methods increase soil resistance through the injection of additives [12].

Soil may be subjected to heat for various reasons, which changes soil's physical and mechanical properties (especially in clayey soils). Moreover, these changes may be reversible or irreversible [13-15].

Improvement of soil properties through heat has been used in the past, and the effect of heat on soil's engineering properties such as the compressive strength has been observed empirically. These improvements have been used in construction of roads and construction materials [15].

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The effect of heat on clay soil's engineering properties is essential in various applications such as soil stabilization, application of heat to the clay soil surrounding nuclear waste burial sites and high voltage transmission lines, remediation of polluted soil, and construction materials.

Many scholars have studied soil remediation contaminated by crude oil, heavy metals, and radioactive material [16, 17]. Recent studies have primarily focused on the burial of high-level radioactive waste and the result of heat on the properties and function of the surrounding soil [18, 19]. The application of heat can significantly improve the geotechnical engineering properties and is useful in the remediation of polluted soil [20].

With an increase in number of nuclear power plants, many developed countries bury their nuclear waste deep into the earth. The development of uranium revival technology, the establishment of new nuclear plants, and an increase in radioactive waste call for more burial sites. Radioactive waste produces heat for a long time after its burial. The low void ratio of clay soil has made it the best choice for the burial of high-level nuclear waste, which is done hundreds of meters underground. The soil surrounding nuclear waste is subjected to heat for extended periods. The heat of nuclear waste is absorbed by the clay soil, which significantly affects its physical and chemical properties.

Dehydration – Clay soil dehydration is the first event that occurs after exposure to increased temperatures. In this process, the water between silicate layers of clay soil is evaporated [21]. Dehydration results in the elimination of pore water and absorbed water. Pore water is eliminated after the increase of temperature up to 100C, whereas absorbed and interlayer water is eliminated as the temperature goes up to 300C [11]. Dehydration also changes plasticity, the porosity of fine-grained and coarse grain soil, and reduced cation-exchange capacity (CEC). Moreover, dehydration decreases the distance between soil layers, hence reducing its mass [22]. Dehydration is a relatively reversible reaction, and the soil may retain its ability to absorb water with a decrease in temperature.

Dehydroxilation – Dehydroxilation is the process through which the hydroxyl ion is released from crystallized clay minerals by forming a water molecule [21]. This process increases temperature, and a reaction between two hydroxyl groups in the octahedral layer happens (Equation (1)) [23].



Dehydroxylation is an endothermic reaction that occurs between 400°C and 1000°C and results in the elimination of water from clay soil's crystallized structure and the destruction of soil minerals. Destruction of clay mineral structure subsequently creates amorphous shapes

[24]. Figure 1 shows the effect of hydroxyl elimination on Silica (Si) and Alumina (Al) frameworks.

Dehydroxylation in most clay soils occurs in a particular thermal range. For instance, the thermal range for dehydroxylation in kaolinite is 300 to 600 °C which destroys crystallized structures and the creation of metakaolin. Metakaolin is the amorphous leftover created after the hydroxyl group's release. Dehydroxylation of illite starts in the thermal range of 350 to 600 degrees Celcius, and its crystallized structure is destroyed in temperatures ranging from 700 to 850 degrees Celcius. Smectite clays – such as Montmorillonite – are dehydroxylated in temperatures of 500 to 2000 degrees Celcius. Similar to illite, smectite clays initially form a stable phase where parts of the crystallized structure remain intact. This structure is then entirely destroyed at 800 degrees Celcius [15, 25].

Heat causes dehydroxylation and destroys kaolinite. However, Mica and Chlorite remain intact, which means higher temperatures are needed for their dehydroxylation. Finally, heat has only reduced the distance between layers in the smectite [24].

The present paper conducts a series of macrostructure examinations on clay containing various degrees of cement under heat to study the effect of heat on the consolidation features of cement-stabilized clay soil.

2. MATERIAL AND METHODOLOGY

2. 1. Kaolinite The kaolinite used in the present paper obtained from a mine in Zarand (Kerman), located in southeast of Iran. The technical properties of soil determined using ASTM standards, and the soil was classified as CL using the united soil classification system [26, 27]. The physical properties of the soil used in this study are presented in Table 1.

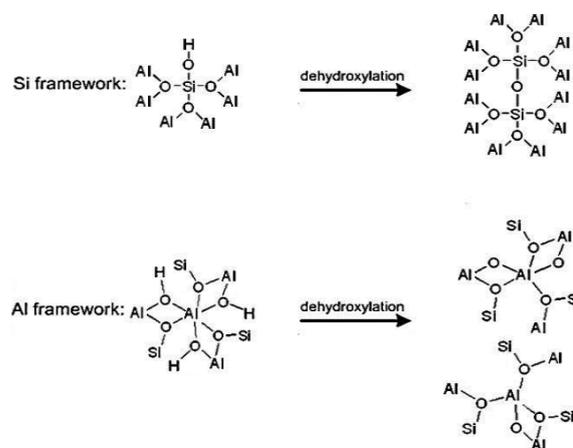


Figure 1. The effect of dehydroxylation on Silica and Alumina frameworks [24]

TABLE 1. Physical properties of kaolinite used in the present paper

Properties	Amount
Liquid limit (%)	30.3
Plastic Limit (%)	19
Plasticity index (%)	11.3
Sand	36.6
Slit	44.4
Clay	19
Unified Classification	CL
Color	Brown

2. 2. Cement Type 2 Portland cement was used to prepare specimens and was obtained from the Kerman Cement Plant. The properties of cement used in this study are presented in Table 2.

2. 3. Specimen Preparation and Experiments

More than 99% of the soil used in the present study was sifted through a size 10 sieve. Due to the adhesive nature of clay particles and their tendency to form clods, the soils were initially sifted through a size 10 sieve (to increase soil homogeneity). Afterward, 20% of moisture (plastic limit levels) was added to the soil, and it was kept for 24 hours in seal-top storage bags. Kaolinite specimens were mixed with 0, 5, 10, and 20 percent of cement (dry mixing of cement with kaolinite clay in the plastic limit) according to the standard methods, and the mix was consolidated using Teflon mallets. The surface area between each layer was scraped and scuffed to create sufficient integration. The specimens were then placed in a seal-top storage bag for protection against moisture and

TABLE 2. Physical and chemical properties of the used cement (obtained from Kerman Cement Plant)

Physical properties	Initial setting time (min)	170
	Final setting time (min)	220
	7-day compressive strength (MPa)	35.30
	Specific surface area (cm ² /g)	3900
Chemical compounds	Calcium Oxide (CaO)	62.88%
	Silicon Dioxide (SiO ₂)	21.30%
	Aluminum Oxide (Al ₂ O ₃)	5.17%
	Sulphur Trioxide (SO ₃)	2.16%
	Ferric Oxide (Fe ₂ O ₃)	4.37%
	Magnesium Oxide (MgO)	1.57%
	Sodium Oxide (Na ₂ O)	0.15%
	Potassium Oxide (K ₂ O)	0.33%

were cured for 7 days. In the next step, the specimens were put in the oven for 24 hours at a temperature of 110 degrees Celcius. This was done to prevent the specimens from cracking in the higher temperatures of the furnace. Then, the specimens were put into the ELE furnace. Given the aim of studying the effects of heat on clay soil properties, the specimens were examined under temperatures of 25, 110, 200, 400, and 600 degrees Celcius. Except for the specimens exposed to 25 (no thermal history) and 110 degrees Celcius, the rest were put in the furnace at temperatures of 200, 400, and 600 degrees Celcius. Figure 2 shows two kaolinite specimens containing 5% of cement after 7 days of curing in zipper plastic bags and experiencing 110 degrees Celcius.

The temperature in the furnace was automatically increased at a rate of 12 degrees Celcius per minute, and the specimens were left in the furnace for 2 hours after reaching the determined temperature. After the furnace was shut down, the specimens were cooled down in the closed furnace. A consolidation test was used to measure the settlement features of the specimens. This test was conducted based on ASTM D-2435 standard [28]. Moreover, the specimens' weight was measured in each level and under each thermal condition, and the changes were calculated.

3. RESULTS ANALYSIS

3. 1. Weight Change In Kaolinite Specimens

Sudden weight change is a suitable parameter for determining dehydroxylation temperatures [15]. Dehydroxylation happens due to the release of hydroxyl ions from the crystalized structures of clay minerals by forming water molecules. The soil's weight abruptly decreases when reaching the dehydroxylation temperature. Therefore, weight changes in the specimens were monitored at various temperatures, and the results are presented in this paper. Figure 3 shows the weight changes in kaolinite specimens containing cement under various temperatures. According to Figure 3, it can be concluded that an increase in temperature has resulted in a decrease in kaolinite specimens' weight. The decrease in specimens' weight has happened with a slow, steady pace up to 200 degrees Celcius. However, the kaolinite

**Figure 2.** Kaolinite specimens containing 5% of cement

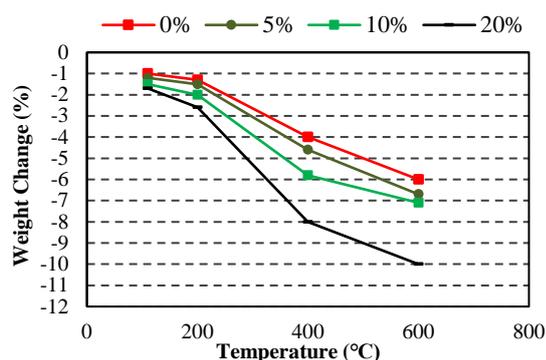


Figure 3. Weight change in kaolinite specimens containing cement under various temperatures

specimens' weight has decreased by 4 to 5 percent when reaching 400 degrees Celcius. This sudden change shows the start of kaolinite dehydroxylation and the destruction of clay mineral structure. The specimen's weight continues to decrease as the temperature increases up to 600 degrees Celcius. Similarly, the weight of specimens containing cement has steadily and slowly decreased as the temperature rises to 200 degrees Celcius. However, the specimens' weight changes abruptly in higher temperatures. Figure 3 shows that the weight change in specimens containing cement is more dramatic compared with the untreated specimen. At 600 degrees Celcius, the specimen containing 20 percent cement has had a 10 percent weight loss compared to the specimen containing no cement at 25 degrees Celcius.

As it can be seen, an increase in the temperature results in decreasing the weight of Kaolinite specimens. This decrease can be due to the removal of hydroxyl ions from the crystal structure of clay minerals, degradation of the structure of clay minerals, and the beginning of the dehydroxylation process [15, 29]. The size of clay particles increases by enforcing the heat on the specimens, which increases the volume of cavities. Therefore, The void ratio is very likely to increase by increasing the temperature [30, 31].

3. 2. Consolidation Coefficient

According to Figure 4, the consolidation coefficient of specimens containing no cement has decreased with an increase in temperature. The decrease of consolidation coefficient in 200 degrees Celcius may result in from dehydration and a decrease of interlayer distance between clay platelets. An increase in temperature from 200 to 400 degrees Celcius has no significant impact on the consolidation coefficient. However, an increase in temperature up to 600 degrees Celcius has resulted in a sudden decrease in consolidation coefficient. This may be due to the formation of bigger particles, a decrease in activity in clay's surface particles, and a lack of particles' tendency to absorb molecules of water. The decrease in consolidation coefficient coincides with weight changes,

which shows that a sudden decrease in consolidation coefficient occurs after reaching dehydroxylation temperatures.

According to Figure 4, the consolidation coefficient decreased in the specimen containing 5 percent cement as the temperature increases up to 600 degrees Celcius. A decrease in consolidation coefficient at temperatures up to 200 degrees Celcius has probably occurred due to dehydration and a decrease in interlayer distance between clay particles. The decrease in consolidation coefficient from 400 to 600 degrees Celcius in the specimen containing cement has a lower ratio compared to the one containing no cement. This may be due to the effect of high temperature on cement particles. The consolidation coefficient of the specimen in 400 degrees Celcius has decreased by 31 percent, compared to the specimen in 25 degrees Celcius. The consolidation coefficient of the specimen in 600 degrees Celcius has decreased by 14 percent compared to the specimen in 400 degrees Celcius.

According to Figure 4, the consolidation coefficient of specimens containing 10 percent cement has decreased up to 400 degrees Celcius, similar to those containing 5 percent cement. Therefore, the decrease of consolidation coefficient in 400 degrees Celcius can be attributed to dehydration and a decrease in interlayer distance between clay platelets. An increase in consolidation coefficient between 400 and 600 degrees Celcius may be attributed to the breakage of the hydration bond between cement and kaolinite. It can be concluded that 200 degrees Celcius is the optimal temperature for thermal stabilization of kaolinite soil containing 10 percent of cement. The consolidation coefficient of the specimen in 400 degrees Celcius has decreased by 40 percent compared to the one in 25 degrees Celcius. However, the consolidation coefficient of the specimen in 600 degrees Celcius has increased by 57 percent compared to the one in 400 degrees Celcius. These significant changes show the sensitivity of the kaolinite-cement bond to the heat.

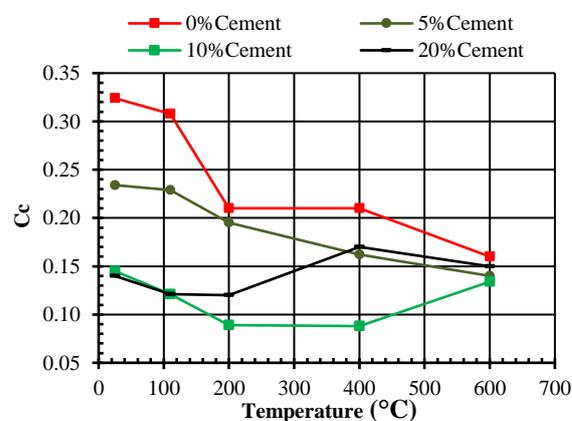


Figure 4. Changes of consolidation coefficient under heat in kaolinite specimens

According to Figure 4, the consolidation coefficient of specimens containing 20 percent cement has decreased at temperatures rising to 200 degrees, and then increased in temperatures between 200 and 400 degrees Celcius. However, the consolidation coefficient decreases as the temperature rise to 600 degrees Celcius. An increase in consolidation coefficient at temperatures from 200 to 400 degrees Celcius can be attributed to the breakage of the bond between kaolinite and cement. The repeated increase in consolidation coefficient can result in from dehydroxylation overshadowing the breakage of the bond between cement and kaolinite. The consolidation coefficient of the specimen at 200 degrees Celcius has decreased by 14 percent compared to the one in 25 degrees Celcius. Then, the coefficient increases by 41 percent and reaches 0.17 as the temperature rises from 200 to 400 degrees. Finally, the consolidation coefficient decreases by 11 percent as the temperature rises from 400 to 600 Celcius.

3. 3. Coefficient of Permeability (k) Figure 5 shows the changes in the permeability of kaolinite specimens with no cement against the void ratio. The results show an increase in permeability as the temperature rises. Permeability increases as the temperature rises to 400 degrees Celcius. It can be deduced that temperatures as high as 400 degrees Celcius result in the elimination of interlayer water, an increase in macroscopic voids within the structure, and the formation of clods in the soil. However, permeability suddenly decreases as the temperature rises from 400 to 600 degrees Celcius. The significant change in permeability can be attributed to dehydroxylation and the destruction of clay mineral structure.

Figure 6 shows the changes in the permeability of kaolinite specimens stabilized with 5 percent of cement against changes in void ratio and heat. The results show that permeability decreases as the heat rise to 600 degrees Celcius. The decrease in permeability can be due to the

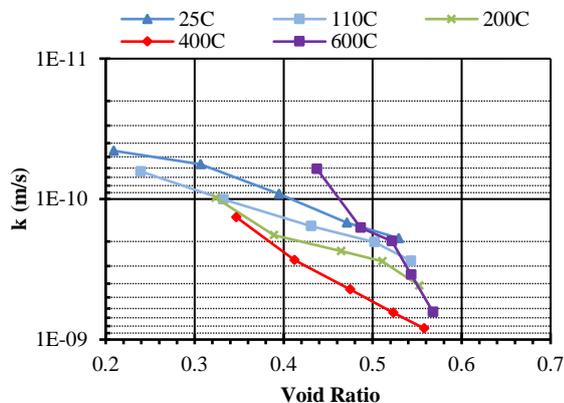


Figure 5. Changes in kaolinite specimens' permeability under heat – containing no cement

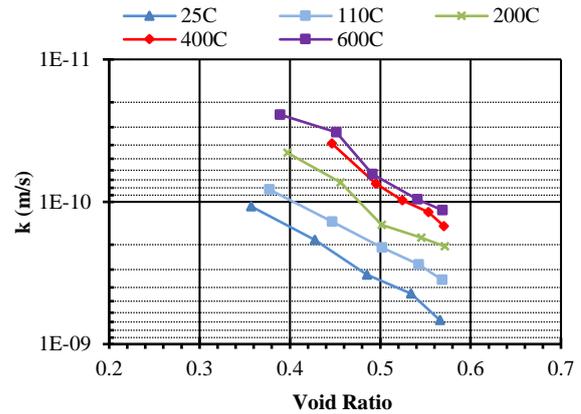


Figure 6. Changes in permeability of kaolinite specimens against heat and void ratio stabilized with 5 percent of cement

effect of heat on the hydration reaction of cement and kaolinite. The permeability of the specimen at 600 degrees Celcius has decreased by 83 percent compared to the permeability of the specimen at 25 degrees Celcius.

Figure 7 shows the changes in the permeability of kaolinite specimens stabilized with 10 percent of cement. The results show that as the heat rises to 600 degrees Celcius, the permeability of these specimens dramatically decreased. This significant change in permeability can be attributed to the effect of heat on the reaction of cement and kaolinite. The most significant changes in permeability occur at temperatures between 25 to 200, and 400 to 600 degrees Celcius. According to Figure 7, an increase in heat from 200 to 400 degrees does not significantly impact the permeability of the specimen. The permeability coefficient of the specimen at 200 degrees Celcius was decreased by 50 percent compared to that of the specimen at 25 degrees Celcius. At 600 degrees Celcius, the permeability coefficient of the specimen was decreased by 60 percent compared to the specimen at 400 degrees Celcius.

Figure 8 demonstrates the permeability of kaolinite specimens with 20 percent of cement under heat. The results show that at temperature of 400 degrees Celcius, the permeability of specimens containing 20 percent of cement significantly decreased. However, the permeability coefficient suddenly increases as the temperature rises from 400 to 600 degrees Celcius. This change is a result of the clay particles being replaced by cement. Therefore, it can be concluded that the optimal amount of cement for improving clay soil's permeability against heat is 10 percent.

The sudden changes in the specimens' weight reveal the dehydroxylation temperature of kaolinite to be about 400 degrees. Joshi et al. [15] found that the temperature range of 300 to 600 degrees Celcius is kaolinite's dehydroxylation point, which occurs as hydroxyl ions exit clay mineral structure. Mitchell and Soga [24]

demonstrated that the application of 550 degrees Celcius on kaolinite, mica, chlorite, and smectite clay minerals result in dehydroxylation and destruction of kaolinite's structure. The findings of the present study correspond with the literature mentioned earlier.

The present study shows that the permeability of unmixed kaolinite specimens increases against heat. Ouhadi et al. [19] found that permeability of soil decreases at 200 degrees Celcius as interlayer water is eliminated and the number of macroscopic voids is increased (see Figure 9). However, the present study showed that the permeability of kaolinite specimens decreases against heat by adding various amounts of cement. Therefore, the behavior of mixed kaolinite specimens follows an opposite trend compared to that of the unmixed specimens.

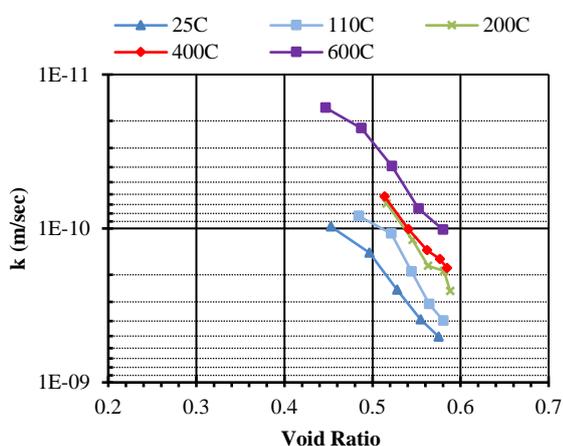


Figure 7. Changes in permeability of kaolinite specimens against heat and void ratio stabilized with 10 percent of cement

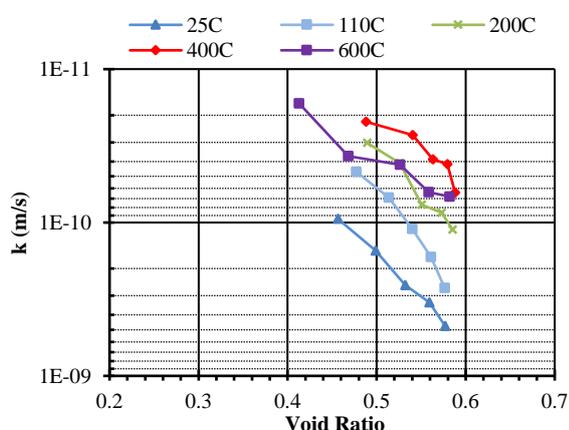


Figure 8. Changes in permeability of kaolinite specimens against heat and void ratio stabilized with 20 percent of cement

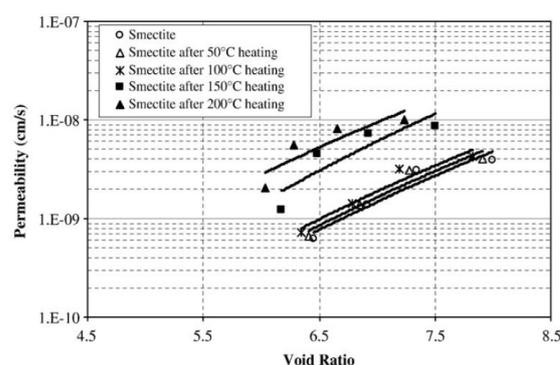


Figure 9. Changes in clay's permeability against heat

4. CONCLUSION

The clayey soil may be exposed to very high temperatures in some sites like nuclear waste burial sites which can change settlement properties of the soil and threaten the environment. The present study investigated the effect of heat on the settlement properties of cement-stabilized kaolinite clay. Kaolinite clay specimens with different percentages of cement were prepared and cured at different temperatures (25, 110, 200, 400, and 600 degrees Celcius). Then, the performance of the specimens was evaluated using specimens' weight change, consolidation coefficient, and permeability coefficient. Based on the experiments, the following conclusions can be drawn.

1. The consolidation coefficient gradually decreased as the temperature rose to the dehydroxylation point. The consolidation coefficient decreased dramatically as the clay mineral structure was destroyed in dehydroxylation. At 600 degrees Celcius, the consolidation coefficient of the specimen decreased by 52 percent compared to the specimen at room temperature.
2. The consolidation coefficient decreased in specimens containing cement as the temperature rose to 200 degrees Celcius. However, applying temperatures more than 200 degrees Celcius on the same specimens yielded opposite results. This showed cement's sensitivity to high temperatures. Therefore, 200 degrees Celcius was the optimal temperature for thermal stabilization of specimens containing 10 percent cement. The consolidation coefficient of the kaolinite specimen containing 10 percent cement at 200 degrees Celcius decreased by 73 percent compared to that of the specimen at room temperature.
3. The permeability coefficient of kaolinite specimens containing no cement increased as the temperature rose to 400 degrees Celcius. The permeability coefficient of specimens containing 10 percent of cement decreased as the temperature rose. Thus, addition of 10 percent of cement can reduce the harmful environmental challenges of nuclear waste burial.

5. REFERENCES

1. Sheikhsosseini Lori, I., Toufigh, M.M. and Toufigh, V., "Improvement of poorly graded sandy soil by using copper mine tailing dam sediments-based geopolymer and silica fume", *Construction and Building Materials*, Vol. 281, (2021), 122591. doi.org/10.1016/j.conbuildmat.2021.122591
2. Manimaran, A., Seenu, S. and Ravichandran, P.T., "Stimulation behaviour study on clay treated with ground granulated blast slag and groundnutshell ash", *International Journal of Engineering, Transactions B: Applications*, Vol. 32, No. 5, (2019), 673-678. doi: 10.5829/ije.2019.32.05b.08
3. Wang, D.-y., Ma, W., Niu, Y.-h., Chang, X.-x. and Wen, Z., "Effects of cyclic freezing and thawing on mechanical properties of qinghai-tibet clay", *Cold Regions Science and Technology*, Vol. 48, No. 1, (2007), 34-43. doi:10.1016/j.coldregions.2006.09.008
4. Winterkorn, H.F. and Pamukcu, S., Soil stabilization and grouting, in Foundation engineering handbook. 1991, Springer. 317-378. doi: 10.1007/978-1-4615-3928-5_9
5. Mir, B.A. and Reddy, S.H., "Mechanical behaviour of nano-material (al₂o₃) stabilized soft soil", *International Journal of Engineering, Transactions C: Aspects*, Vol. 34, No. 3, (2021), 636-643. doi: 10.5829/IJE.2021.34.03C.07
6. Bahrani, M. and Marandi, S.M., "Large-scale experimental study on collapsible soil improvement using encased stone columns", *International Journal of Engineering, Transactions C: Aspects*, Vol. 34, No. 5, (2021), 1145-1155. doi: 10.5829/ije.2021.34.03c.07
7. Nguyen, D.T. and Phan, V.T.A., "Engineering properties of soil stabilized with cement and fly ash for sustainable road construction", *International Journal of Engineering, Transactions C: Aspects*, Vol. 34, No. 12, (2021), 2665-2671. doi:10.5829/IJE.2021.34.12C.12
8. Rahmannejad, M. and Toufigh, V., "Influence of curing time and water content on unconfined compressive strength of sand stabilized using epoxy resin", *International Journal of Engineering, Transactions B: Applications*, Vol. 31, No. 8, (2018), 1187-1195. doi: 10.5829/ije.2018.31.08b.05
9. Javdani, H., "The effect of geopolymerization on the unconfined compressive strength of stabilized fine-grained soils", *International Journal of Engineering, Transactions B: Applications*, Vol. 30, No. 11, (2017), 1673-1680. doi: 10.5829/ije.2017.30.11b.10
10. Arjomand, M.A., Abedi, M., Gharib, M. and Damghani, M., "An experimental study on geogrid with geotextile effects aimed to improve clayey soil", *International Journal of Engineering, Transactions B: Applications*, Vol. 32, No. 5, (2019), 685-692. doi: 10.5829/ije.2019.32.05b.10
11. Gharib, M., Arjomand, M.A., Abdi, M.R. and Arefnia, A., "Influence of chitin nanofiber and rice husk ash on properties and bearing resistance of soft clay soils", *International Journal of Engineering, Transactions C: Aspects*, Vol. 32, No. 3, (2019), 373-380. doi: 10.5829/ije.2019.32.03c.04
12. Evstatiev, D., "Loess improvement methods", *Engineering Geology*, Vol. 25, No. 2-4, (1988), 341-366. doi.org/10.1016/0013-7952(88)90036-1
13. Wang, M., Benway, J.M. and Arayssi, A.M., The effect of heating on engineering properties of clays, in Physico-chemical aspects of soil and related materials. 1990, ASTM International.
14. Jefferson, I., "Temperature effects on clay soils", Loughborough University, (1994).
15. Joshi, R., Achari, G., Horsfield, D. and Nagaraj, T., "Effect of heat treatment on strength of clays", *Journal of Geotechnical Engineering*, Vol. 120, No. 6, (1994), 1080-1088.
16. Alcocer, C. and Chowdhury, H., "Experimental study of an environmental remediation of gulf coast crude-oil-contaminated soil using low-temperature thermal treatment", in SPE Western Regional Meeting, OnePetro., (1993).
17. Varlakov, A., Sobolev, I., Barinov, A., Dmitriev, S., Karlin, S. and Flit, V., "Method of treatment of radioactive silts and soils", *MRS Online Proceedings Library*, Vol. 465, (1996).
18. Gu, B., Wang, L., Minc, L. and Ewing, R., "Temperature effects on the radiation stability and ion exchange capacity of smectites", *Journal of Nuclear Materials*, Vol. 297, No. 3, (2001), 345-354.
19. Ouhadi, V., Yong, R., Goodarzi, A. and Safari-Zanjani, M., "Effect of temperature on the re-structuring of the microstructure and geo-environmental behaviour of smectite", *Applied Clay Science*, Vol. 47, No. 1-2, (2010), 2-9.
20. Morris, P.H. and Wong, L., "Modification of dredged sediments to produce useful product by heating to high temperatures", *Sustainable Tourism CRC*, (2005).
21. Brindley, G., "Thermal transformations of clays and layer silicates", in Proceedings of the international clay conference, Applied Publishers Wilmette, IL., (1975), 119-129.
22. Heller-Kallai, L., Thermally modified clay minerals, in Developments in clay science. Elsevier. (2013), 411-433. doi.org/10.1016/B978-0-08-098258-8.00014-6
23. Emmerich, K., Madsen, F.T. and Kahr, G., "Dehydroxylation behavior of heat-treated and steam-treated homoionic cis-vacant montmorillonites", *Clays and Clay Minerals*, Vol. 47, No. 5, (1999), 591-604. doi:10.1346/CCMN.1999.0470506
24. Mitchell, J.K. and Soga, K., "Fundamentals of soil behavior, John Wiley & Sons New York, Vol. 3, (2005).
25. McConville, C.J. and Lee, W.E., "Microstructural development on firing illite and smectite clays compared with that in kaolinite", *Journal of the American Ceramic Society*, Vol. 88, No. 8, (2005), 2267-2276. doi.org/10.1111/j.1551-2916.2005.00390.x
26. International, A., ASTM D422 standard test method for particle-size analysis of soils. (2007).
27. International, A., ASTM D4318-00 standard test methods for liquid limit, plastic limit, and plasticity index of soils. (2017).
28. International, A., ASTM D2435 standard test methods for one-dimensional consolidation properties of soils using incremental loading. (2011).
29. Habert, G., Choupy, N., Escadeillas, G., Guillaume, D. and Montel, J.M., "Clay content of argillites: Influence on cement based mortars", *Applied Clay Science*, Vol. 43, No. 3, (2009), 322-330. doi:10.1016/j.clay.2008.09.009
30. Yilmaz, G., "The effects of temperature on the characteristics of kaolinite and bentonite", *Scientific Research and Essays*, Vol. 6, No. 9, (2011), 1928-1939. doi: 10.5897/SRE10.727
31. Wang, M., Jao, M. and Ghazal, M., "Heating effect on swelling behaviour of expansive soils", *Geomechanics and Geoengineering: An International Journal*, Vol. 3, No. 2, (2008), 121-127. doi: 10.21275/28121602

Persian Abstract

چکیده

خاک های رسی به دلایل مختلف، از جمله اعمال حرارت در مراکز دفن زباله های هسته ای، در مناطق دفن کابل های برق فشار قوی، ممکن است در معرض حرارت قرار بگیرند. بررسی تحقیقات گذشته نشان دهنده تاثیر حرارت بر خصوصیات فیزیکی و مکانیکی خاک های رسی است. با این وجود مطالعات گذشته عمدتاً بر رفتار مکانیکی خاک رس بدون تثبیت کننده بوده است و مطالعات مربوط به تاثیر حرارت بر رفتار خاک رس تثبیت شده محدود میباشد. در این مقاله تاثیر توامان حرارت و سیمان بر خصوصیات نشست پذیری خاک رس کائولینیت مورد مطالعه و تجزیه و تحلیل قرار گرفته است. بدین منظور خاک رس کائولینیت ترکیب شده با درصد های مختلف سیمان در معرض سطوح حرارتی متفاوت شامل دماهای ۲۵ تا ۶۰۰ درجه سانتیگراد قرار داده شده اند. نتایج نشان داد که با افزایش حرارت تا پیش از دمای دی هیدروکسیلاسیون، ضریب تحکیم بتدریج کاهش یافته است. افزایش حرارت تا ۲۰۰ درجه سانتیگراد، باعث کاهش ضریب تحکیم در نمونه های حاوی سیمان شده است. لیکن در نمونه های حاوی ۱۰ درصد سیمان و افزایش حرارت به بیش از ۲۰۰ درجه سانتیگراد نتیجه عکس داشته و ۷۳ درصد نسبت به نمونه کائولینیت در دمای محیط کاهش داشته است. همچنین ضریب نفوذ پذیری در نمونه های خاک کائولینیت بدون سیمان با افزایش حرارت تا دمای ۴۰۰ درجه سانتیگراد افزایش پیدا کرده است. با اضافه نمودن سیمان تا ۱۰ درصد، با افزایش درجه حرارت ضریب نفوذ پذیری کاهش پیدا کرده است.
