International Journal of Advances Engineering and Civil Research

Print ISSN 2974-4385

VOLUME 2, ISSUE 1, 2022, 48 - 65.

Online ISSN 2974-4393

The Impact of Temperature on Heat Transfer Mechanism and Geotechnical Properties of Collapse Soil

Nehal Ali

Department of Engineering Physics and Mathematics, Faculty of Engineering, Tanta University.

Mohamed Metwally

[2]Structural Department, Faculty of Engineering, Tanta University.

Mostafa El Sawwaf

[2]Structural Department, Faculty of Engineering, Tanta University.

Ashraf Nazir

[2]Structural Department, Faculty of Engineering, Tanta University.

Abstract

Soil collapse potential is a crucial factor in geotechnical engineering, and heating collapsed soil under different temperature and water content conditions can significantly affect its geotechnical properties, including collapse potential, maximum dry density, optimum water content, liquid limit, and plasticity limits. A research study was performed on soil samples with different water content (0%, 10%, 15%, and 20%) tested at temperatures of 50°C, 100°C, 150°C, and 200°C. The relationship between soil temperature distribution and the distance from the heating source was examined. The findings showed that heating the soil can improve its geotechnical properties. The collapse potential of the soil decreased as the temperature increased, indicating a decrease in moisture content due to evaporation. Furthermore, as the temperature increased, the soil's maximum dry density and optimum water content also increased, indicating an improvement in the soil's compaction properties. The liquid limit of the soil increased up to a temperature of 100-150°C and then decreased, while the plasticity limits decreased with increasing temperature. These findings have significant implications for geotechnical engineering applications, such as building foundations, embankments, and pavements.

Keywords: Temperature, Geotechnical Properties, Collapse Soil

1. Introduction

A recently released study extensively researched unsaturated and saturated soil stratification in subsurface soils. It was discovered that ignoring changes in soil water content resulted in an underestimation of heat transfer capability [1]. The findings also revealed that soil water content improves heat transmission in all geological materials, including sand and gravel [2]. It was also discovered that, except for certain experiments that reached temperatures of 150°C [3], the majority of investigations on collapsing soil were conducted at low temperatures between 0°C and 60°C [4-5-6]. The effect of temperature on unsaturated conductivity becomes increasingly obvious as water content increases. [7].

The upper Pleistocene loess may include the most collapsed soils in North America, Central Europe, China, Africa, Russia, India, Argentina, and other areas [8-9]. It was observed on the tenth of Ramadan in Egypt's northern and western deserts, mainly in the Burj al-Arab region and near Cairo. Collapsible soil causes serious geotechnical and engineering issues all around the world [10-11]. The dominant components of natural collapsible soil are silt and fine sand particles, along with clay. The linkages between soil particles can be created by capillary forces (suction) [12-13-14] or by using fine materials (clay or silt) [15-16-17]. Rapid failure happens when the yield strength of those bonding materials is surpassed by vertical stresses brought on by loading or wetness [18-19].

One especially promising form of renewable energy is geothermal energy [20]. Ground heat exchangers employ this subsurface energy to generate heat, air conditioning, and electricity. Soil thermal characteristics significantly impact how well a heat exchanger performs in such situations [21]. Current research methodologies cover numerous issues related to enhancing and maximizing the performance of heat exchangers' performance [22]. Understanding heat transfer methods in different soil types, from which energy is first extracted, as well as issues with soil thermal instability that impact geothermal system effectiveness, should also be a top priority.

In this study, we construct a lab-scale 3D-tank system to experimentally study the impact of rising temperatures on the heat transfer mechanism and the geotechnical properties of collapsed soil. It is challenging to evaluate the relationship between the heat transfer behavior of unsaturated soils and their geotechnical properties at elevated temperatures because air and water exist in the pore space. The effects of various temperatures on collapsed soil still need to be discussed and cannot be proven by data from previous studies. Various tests are performed, including the single oedometer test (SOT), the modified proctor test, and the Atterberg limit**.** These methods can provide a thorough understanding of the non-isothermal behavior of soil when combined with other geotechnical properties. This study aims to look into the effect of heating on heat transport and the geotechnical characteristics of collapsed soil at temperatures as high as 200 °C.

2.1 Research equipment

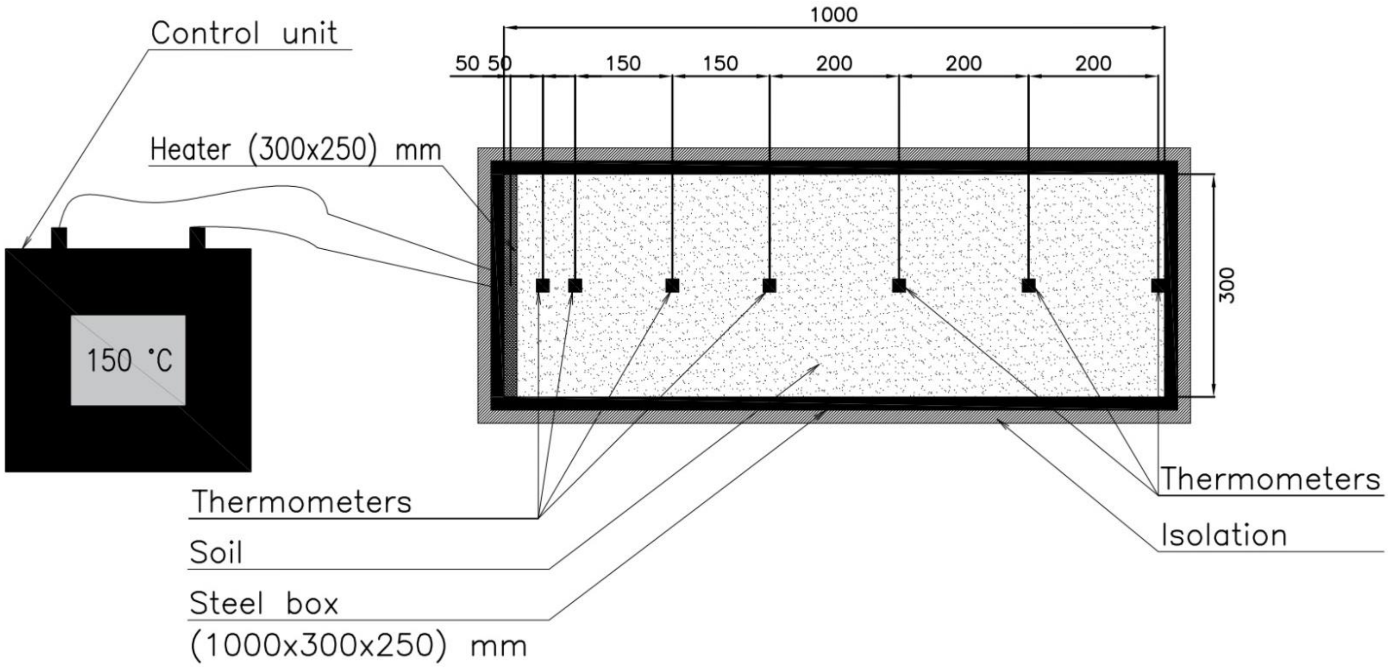
The Research equipment described in this study is used for heat transfer experiments involving soil samples. The setup is designed to maintain one-dimensional heat flow through the soil sample by preventing heat leakage from the source, lateral boundaries, or soil sample. This is achieved by enclosing the entire tank with various thermal insulation materials, as shown in Figure 1. Three primary elements make up the setup: the experimental tank, which has the following measurements: (1000×300×250 mm); the heater, which has the following surface area: (300×250 mm^2); and, lastly, the thermometers, which were positioned at spaces of (5-10-25-40-60-80-100 cm) from the heater to cover the entire length of the tank. The heater's surface area and the tank's dimensions are carefully selected to ensure the heat is uniformly distributed throughout the sample. The thermometers were placed at different distances from the heater to monitor the temperature changes and calculate the rate of heat flow through the soil sample. The experiments can measure the heat flow rate at varying distances up to 1 meter by fixing the heater at one end of the tank. The independent control unit automates the system and maintains the temperature constant throughout the experiments. The data logger records the temperature changes over time, and the control unit's accuracy range of ±10°C ensures reliable results.

The experimental setup described in the study is a reliable and effective way to measure the rate of heat flow through soil samples. It is commonly used in geotherm energy, soil physics, and agricultural engineering research. The setup can be modified to suit different research needs by changing the tank's dimensions, heater's surface area, or the thermometers' placement.

Figure 1. The schematic diagram of the experimental setup consists of one-dimension isolated soil heating lab-scale tank with measuring and automatic controlling systems of temperatures.

2.2 Materials

The soil from the Burj al-Arab district in Alexandria, Egypt, was collected and analyzed for its physical properties. The sand particles in the soil were separated using a mesh size of 40–50 and then dried by air. After preparing the soil sample, several physical properties were determined, including the collapse potential, maximum dry density, optimum water



content, liquid limit, and plasticity limits. These properties can provide insights into the behavior of the soil under different conditions, such as its ability to support structures, its susceptibility to erosion, and its potential for settlement.

2.3 Research conditions

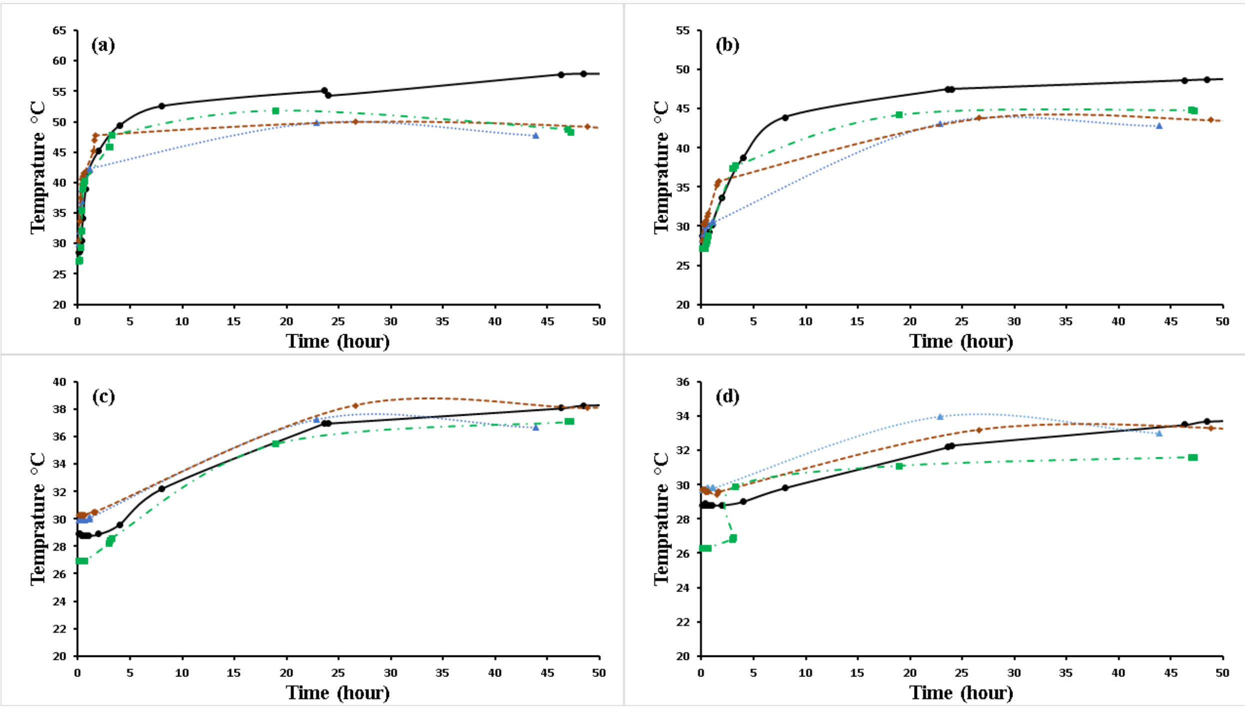
For each of the four-water content (Wc) conditions: 0%, 10%, 15%, and 20%, the temperatures chosen for the tests were 50° C, 100° C, 150° C, and 200°C. The temperature was casually recovered in each scenario by diffusing itself across the surroundings, which took at least a few days. The studies lasted nearly 48 hours to attain steady-state conditions, corresponding to the time between switching on and off the heating element. The soil's original temperature and Wc cases were accurately obtained before each test. The soil samples were collected 5.00 to 10.00 cm away from the heating side of the tank. Because the nature of the samples changed from fine powders to solid particles at higher temperatures (more than 100 °C), the samples had to be broken up with a hammer.

3. Results and discussion

3.1 Temperature measurement

Sensors were placed at different intervals along a tank filled with collapsing soil to measure the temperature changes when the heater was switched on over time. The sensors were placed at 5, 10, 25, 40, 60, 80, and 100 cm from the heat source. Figures 2, 3, 4, and 5 illustrate the change in temperature at different water content levels from 5 cm to 100 cm from the heat source. The range from 5 cm to 100 cm was chosen because it accurately represents the behavior of linear heat transfer. The figures show that the distance from the heat source significantly affects the temporal behavior of the heating distribution in the collapsing soil. This suggests that the thermal properties of the soil, such as thermal conductivity [23], play an important role in determining how heat is distributed through the soil [24-25]. Initial temperatures were similar for all water content cases studied, starting at room temperature and reaching equilibrium after 40 hours. This suggests that the thermal properties of the soil dominate the behavior of the system over long timescales, while the water content may have a more significant effect on shorter timescales [26-27].

For the case of a temperature of 50 °C, as shown in Figure 2, the highest temperature observed in each water content case was observed at a different distance from the heat source. In the case of 0% water content, the highest temperature was observed at a distance of 5 and 10 cm. Since soil with a low water content has less thermal conductivity, heat is less easily transferred through the soil. In the case of 10% water content, the highest temperature was observed at a greater distance from the heat source (40, 60, 80, and 100 cm). This may be because soil with a higher water content has a higher thermal conductivity, allowing heat to be more easily transferred through the soil [28]. In the case of a 15% water content, the highest temperature was observed at a distance of 25 cm. The four cases were nearly identical for 30 minutes, starting at room temperature and then increasing. This suggests that the differences in temperature observed at later times may be due to differences in the thermal properties of the soil at different water contents.



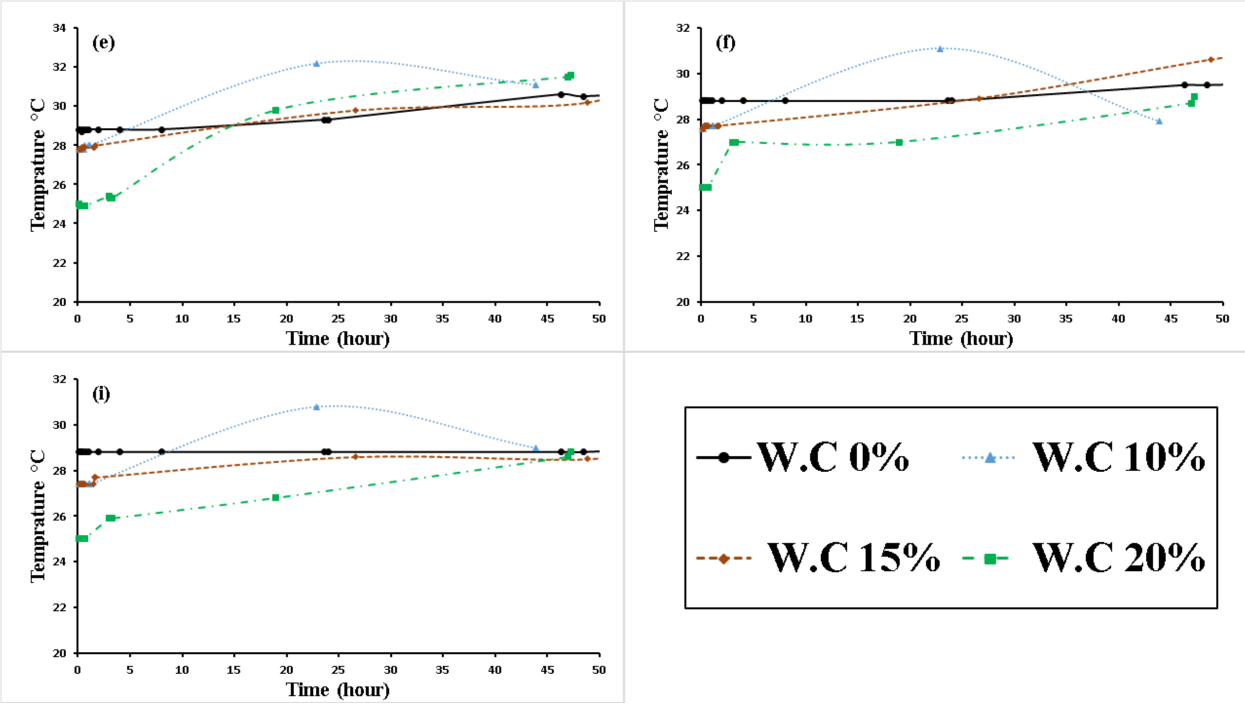


Figure 2. The heat release rate for the four cases of W.C was 0%, 10%, 15%, and 20% at a distance of (a) 5– (b) 10– (c) 25– (d) 40 – (e) 60 – (f) 80 – (i) 100 cm and a temperature of 50 °C.

At a temperature of 100°C, as shown in Figure 3, the highest temperature was observed at distances of 25, 40, 60, 80, and 100 cm from the heat source for the case of 0% water content. This suggests that the heat was distributed more evenly over a larger area in soil with lower water content, potentially due to its lower thermal conductivity. In the case of 10% water content, the highest temperature was observed at a distance of 10 cm from the heat source, indicating more rapid and localized heating near the heat source. Regarding 15% water content, the highest temperature was observed at a distance of 5 cm from the heat source, suggesting that the heat was concentrated in a very small area near the heat source.

International Journal of Advances Engineering and Civil Research

Print ISSN 2974-4385

VOLUME 2, ISSUE 1, 2022, 48 - 65.

Online ISSN 2974-4393

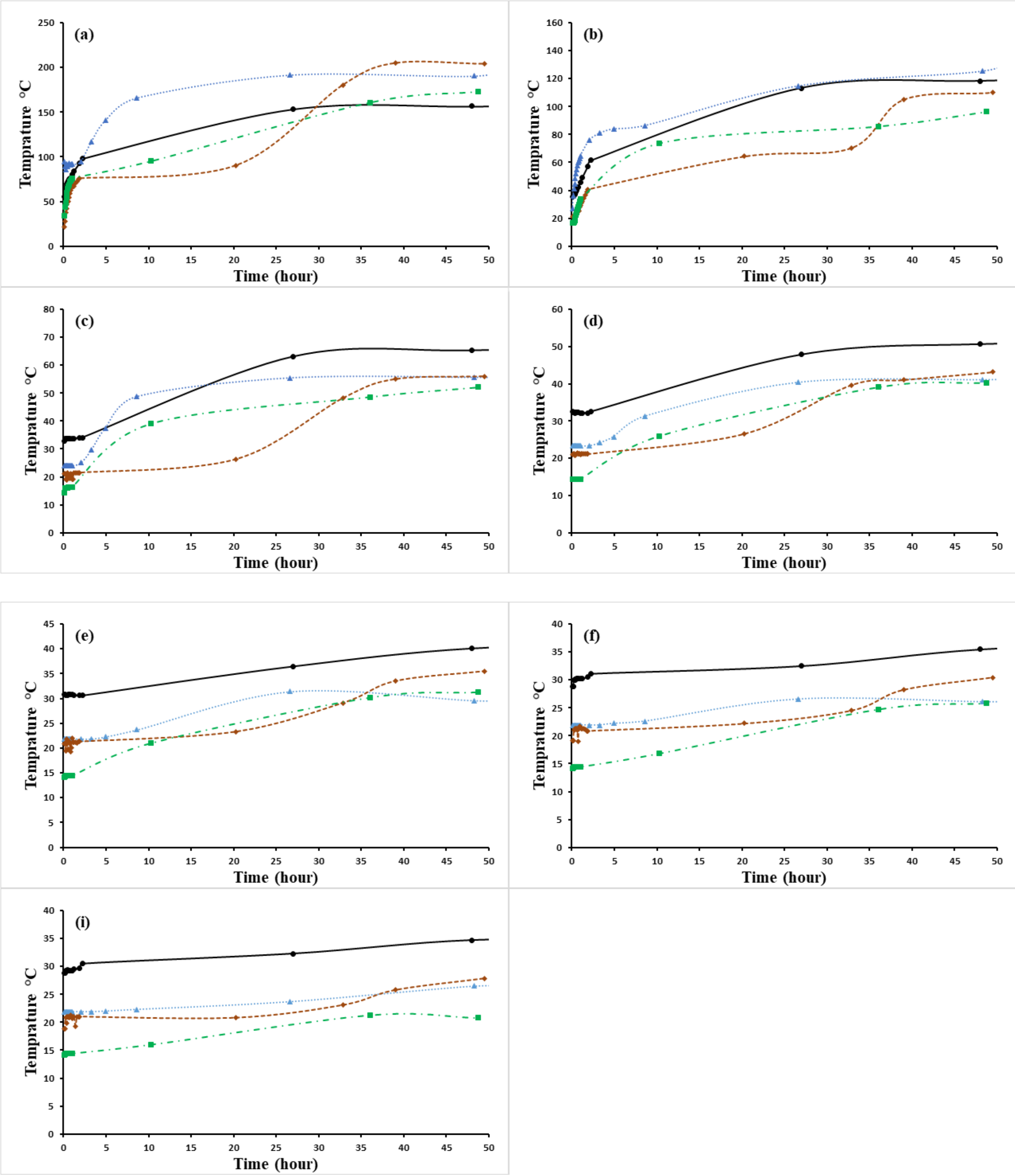
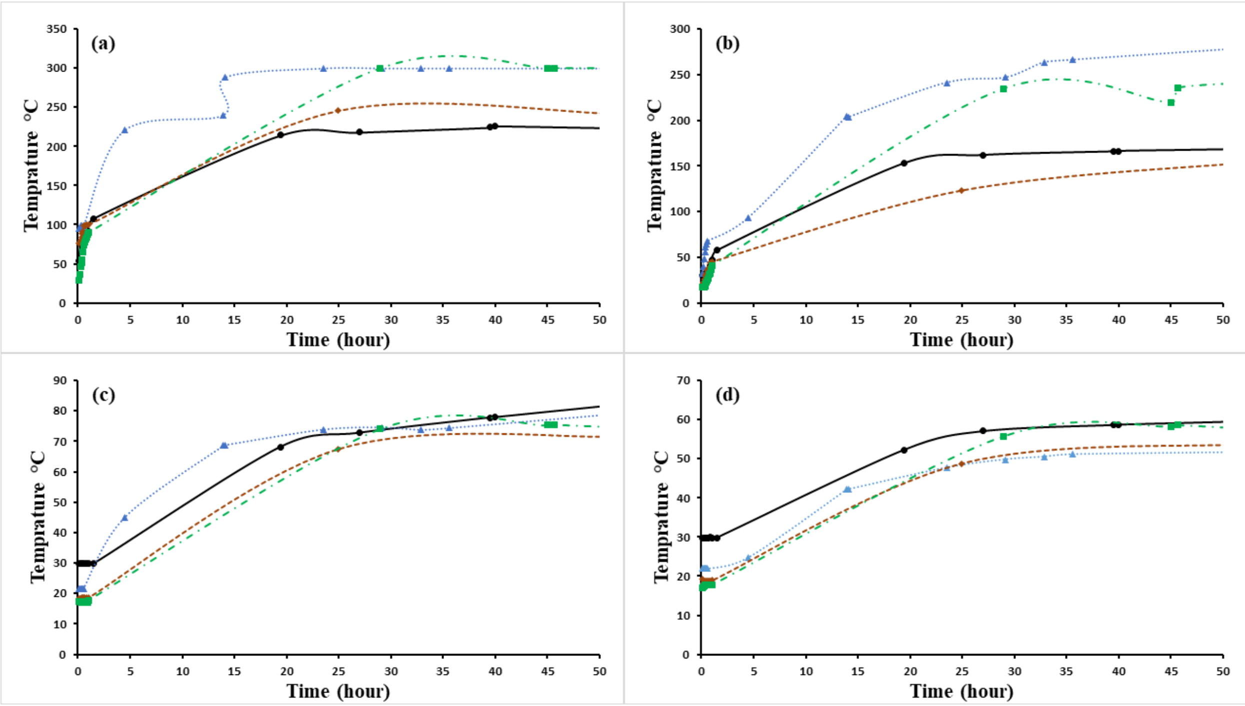


Figure 3. The heat release rate for the four cases of W.C was 0%, 10%, 15%, and 20% at a distance of (a) 5– (b) 10– (c) 25– (d) 40 – (e) 60 – (f) 80 – (i) 100 cm and a temperature of 100 °C.

At a temperature of 150°C, as shown in Figure 4, the highest temperature was observed at different distances from the heat source depending on the water content of the soil. In the case of 0% water content, the highest temperature was observed at distances 60, 80, and 100 cm from the heat source. This indicates that the heat was distributed over a larger soil area with lower water content. In the case of 10% water content, the highest temperature was observed at a distance of 10 cm from the heat source, suggesting more rapid and localized heating near the heat source. In the case of 20% water content, the highest temperature was observed at distances of 5, 10, and 25 cm from the heat source, indicating that the heat was concentrated in a very small area near the heat source.



International Journal of Advances Engineering and Civil Research

Print ISSN 2974-4385

VOLUME 2, ISSUE 1, 2022, 48 - 65.

Online ISSN 2974-4393

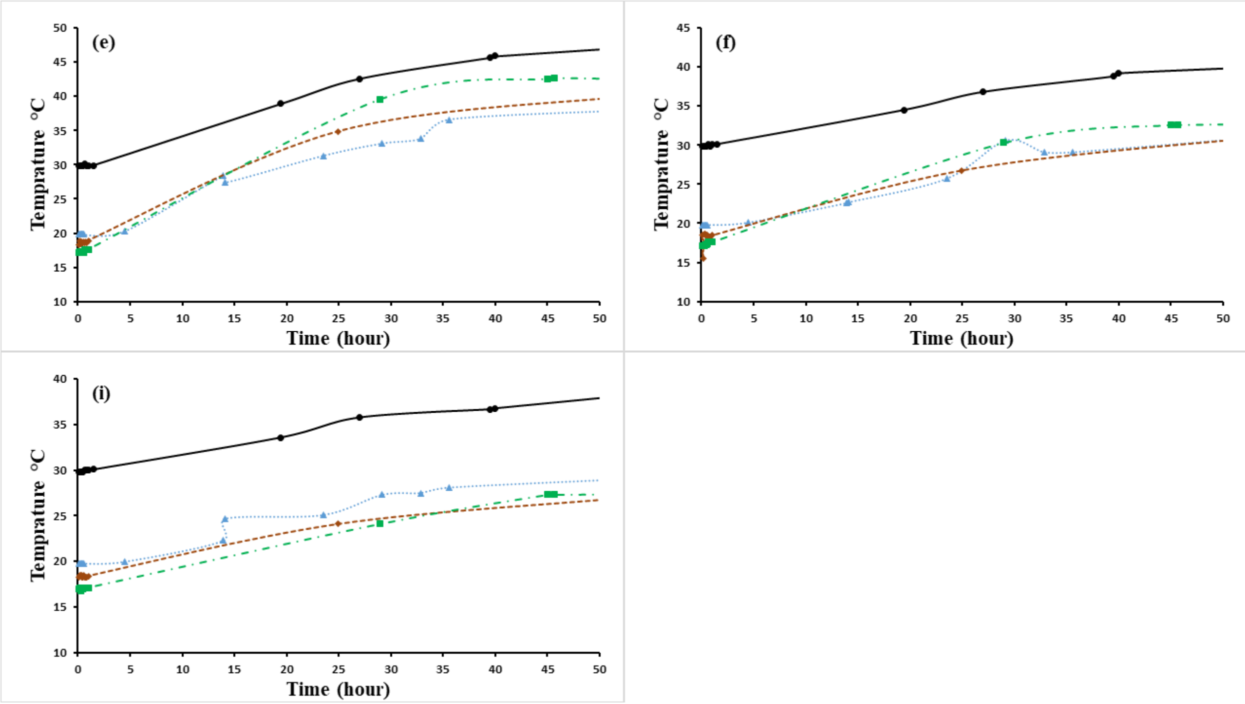


Figure 4. The heat release rate for the four cases of W.C was 0%, 10%, 15%, and 20% at a distance of (a) 5– (b) 10– (c) 25– (d) 40 – (e) 60 – (f) 80 – (i) 100 cm and a temperature of 150 °C.

When the temperature was increased to 200°C, as shown in Figure 5, the highest temperature observed varied depending on the water content of the soil and the distance from the heat source. In the case of 0% water content, the highest temperature was observed at distances of 25, 40, 60, 80, and 100 cm from the heat source. This suggests the heat was distributed more evenly over a larger soil area with lower water content. In the case of 20% water content, the highest temperature was observed at distances of 5 and 10 cm from the heat source, indicating that the heat was concentrated in a very small area near the heat source.

We explained that the initial rise in temperature is caused by the large temperature gradient between the heat source and the soil, which rapidly increases soil temperature. However, as the soil temperature increases, the temperature difference between the heat source and the soil decreases, causing the temperature to increase more gradually over time.

International Journal of Advances Engineering and Civil Research
Print ISSN 2974-4385
VOLUME 2, ISSUE 1, 2022, 48 - 65.
Online ISSN 2974-4393

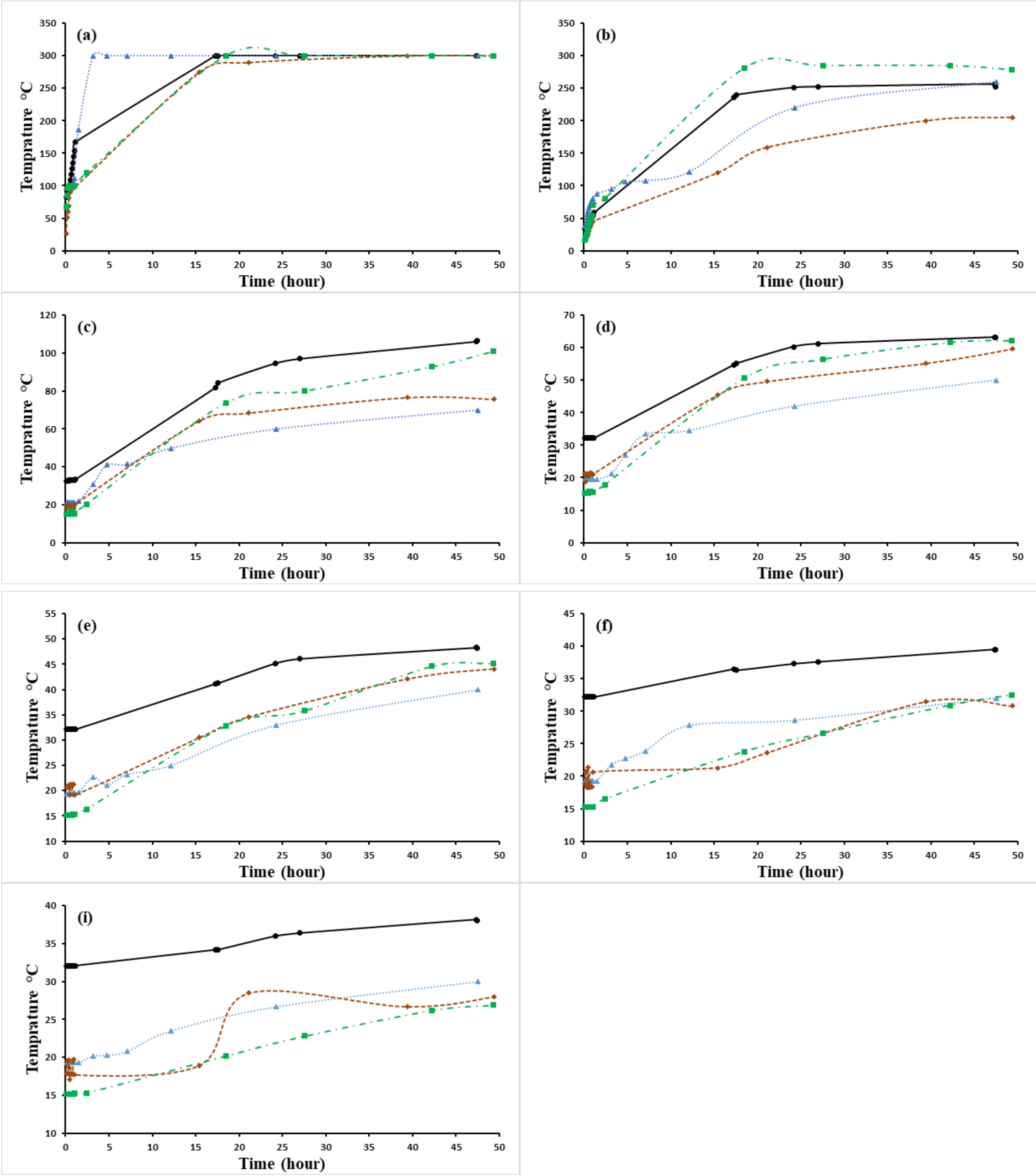


Figure 5. The heat release rate for the four cases of W.C was 0%, 10%, 15%, and 20% at a distance of (a) 5– (b) 10– (c) 25– (d) 40 – (e) 60 – (f) 80 – (i) 100 cm and a temperature of 200 °C.

3.2 Oedometer Results

At temperatures ranging from 50 to 200 °C, oedometer tests were run on the W.C. 10% case [29]. The four samples were combined with 7% water and compressed to a percentage of 70% of their maximum dry density. In

Table 1, the results are displayed. These findings make it clear that raising the collapsing soil temperature to 200 °C decreases the collapse potential from 15% to 9.8%. There has been a roughly 34.7% reduction in the collapse potential.

Table 1. Collapse Potential values for the case of W.C 10% at a temperature of [50 °C, 100 °C, 150 °C, and 200 °C].

WC 10%	
Temperature	Collapse potential (%)
50° C	15
100° C	14.65
150° C	9.9
200° C	9.8

3.3 Compaction Results

In constructing subgrades for roads, highways, and large structures, significant engineering parameters include the compaction characteristics of the collapsing soil, the optimal water content, and the maximum dry unit weight. A material with a stable structure will have a higher maximum dry unit weight, indicating a stronger material.

Table 2. Modified Proctor Tests Results for the case of W.C 10% at a temperature of [50 °C, 100 °C, 150 °C, and 200 °C

W.C 0%		
Temperature	Ɣdmax (KN/M3)	O.W.C (%)
50	18.63	10.9
100	19.92	10.95
150	18.89	11.8
200	18.8	10.327
W.C 10%		
50	19.81	11.2
100	20.23	13.32
150	20.3	13.172
200	19.93	14.2
W.C 15%		
50	20.23	11.64

100	20.61	14.92
150	20.16	15.23
200	19.77	15.407
W.C 20%		
50	20.16	11.98
100	20.59	16.14
150	20.34	16.014

Using modified proctor tests following ASTM D1557 [30]. on the four-water content (Wc) conditions: 0%, 10%, 15%, and 20%, at temperatures of [50 °C, 100 °C, 150 °C, and 200 °C], it was possible to determine the compaction characterization that is shown in table 2. As shown in Table 2, the maximum dry unit weight for W.C. 0% is 19.92 KN/m3 at an optimum water content of 10.95% at a temperature of 100 °C. The maximum dry unit weight for W.C. 10% is 20.3 KN/m3 at an optimum water content of 13.17% at a temperature of 150 °C. As shown in Table 6, the maximum dry unit weight for W.C. 15% is 20.61 KN/m3 at an optimum water content of 14.92% at a temperature of 100 °C, the maximum dry unit weight for W.C. 20% is 20.59 KN/m3 at an optimum water content of 16.14% at a temperature of 100 °C. Also, this table demonstrates that the dry unit weight rises with increasing W.C.% up to a temperature of about 100 °C before decreasing after this point. The maximum dry density peaks at 100 °C and decreases until it reaches 200 °C; we recommend that while heating the soil, the voids in the soil decrease by heating to 100 °C and then increasing slightly up to 200 °C, due to water evaporation from the soil and is replaced by air voids so that when the voids decrease, the density increases by compaction [31-32].

3.4 Atterberg Limit

Clay and silt soils pass through four distinct stable states - solid, semi-solid, plastic, and liquid - as their moisture content increases. Each state exhibits unique variations in behavior, reliability, and capacity. Atterberg limit tests are performed to accurately identify the boundaries between these states by measuring the water content at the points where physical changes occur [33]. Test results and generated indexes can be used to predict the behavior of soil infills, embankments, pavements, and the design of structural foundations. Following ASTM D18 [34], Atterberg limit tests were conducted on soil samples with water contents of 0%, 10%, 15%, and 20% at temperatures of 50°C, 100°C, 150°C, and 200°C. The Atterberg limits were determined, as shown in Figure 6. The figure also indicates that the liquid limit increases as the water content percentage increases to a temperature of 100-150°C and then decreases after this temperature.

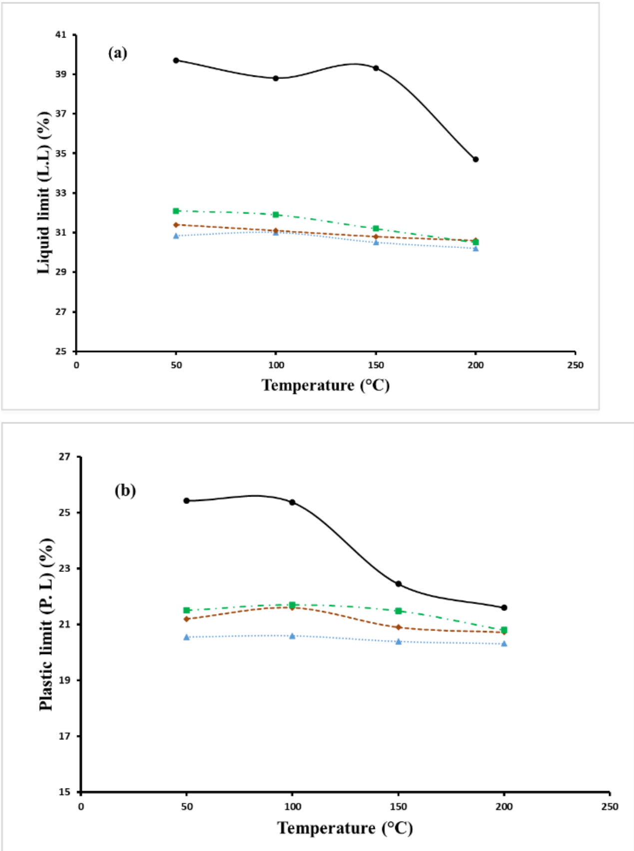


Figure 6. Liquid and plasticity limits of the chosen samples of collapsed soil with temperatures ranging from 50 to 200°C with various saturation conditions.

Conclusion:

The influence of heating on heat transmission and the geotechnical characteristics of collapsed soil under conditions of variable water content and increased temperatures were investigated using a lab-scale 3D-tank system. Based on the results of the research, it can be concluded that:

- The amount and condition of water content in the soil greatly impact heat transmission; soil with high water content may reach a steady heat transfer state more rapidly.

- This study provides insight into how temperature changes in collapsing soil in response to a heat source and how different factors, such as distance from the heat source and water content, can influence this behavior.

- The collapse potential of the soil is greatly enhanced when heated to 200 °C, which is lowered by roughly 34.7%.

- The percentage of water content and the degree of heating affect the maximum dry density of the soil and soil properties such as collapse potential and Atterberg limits, and based on compaction results, a water content of 10% at 100 and 150 °C provides the best geotechnical properties.

References:

[1] LI, Chaofeng, et al. Numerical simulation of ground source heat pump systems considering unsaturated soil properties and groundwater flow. Applied Thermal Engineering, 2018, 139: 307-316.
[2] CHIASSON, Andrew D.; REES, Simon J.; SPITLER, Jeffrey D. A preliminary assessment of the effects of groundwater flow on closed-loop ground source heat pump systems. Oklahoma State Univ., Stillwater, OK (US), 2000.
[3] ATTAH, Imoh Christopher; ETIM, Roland Kufre. Experimental investigation on the effects of elevated temperature on geotechnical behaviour of tropical residual soils. SN Applied Sciences, 2020, 2.3: 1-16.
[4] KHOLGHIFARD, Mehrdad, et al. Temperature effect on compression and collapsibility of residual granitic soil. 2014.
[5] PARK, Mincheol. A study on heat-transfer characteristics by a ground-heating method. Sustainability, 2018, 10.2: 412.
[6] XU, Jian, et al. Heat transfer and water migration in loess slopes during freeze–thaw cycling in Northern Shaanxi, China. International Journal of Civil Engineering, 2018, 16.11: 1591-1605.
[7] ORAKOGLU, MugeElif; LIU, Jiankun; NIU, Fujun. Experimental and modeling investigation of the thermal conductivity of fiber-reinforced soil subjected to freeze-thaw cycles. Applied Thermal Engineering, 2016, 108: 824-832.
[8] TROFIMOV, V. T. *Loess mantle of the Earth and its properties*. Moscow University Press, 2002.
[9] ROGERS, C. D. F.; DIJKSTRA, T. A.; SMALLEY, I. J. Hydroconsolidation and subsidence of loess: studies from China, Russia, North America and Europe: in memory of Jan Sajgalik. Engineering Geology, 1994, 37.2: 83-113.
[10] GAAVER, Khaled E. Geotechnical properties of Egyptian collapsible soils. Alexandria Engineering Journal, 2012, 51.3: 205-210.
[11] SAKR, Mohamed; MASHHOUR, Mohsen; HANNA, Adel. Egyptian collapsible soils and their improvement. In: GeoCongress 2008: Geosustainability and Geohazard Mitigation. 2008. p. 654-661.
[12] MAHMOOD, Mohammed Shakir; ABRAHIM, Mustafa Jamal. A review of collapsible soils behavior and prediction. In: *IOP Conference*

Series: Materials Science and Engineering. IOP Publishing, 2021. p. 012044.

[13] AL-OBAIDI, Q. A.; KARIM, H. H.; AL-SHAMOOSI, A. A. Collapsibility of gypseous soil under suction control. In: IOP conference series: materials science and engineering. IOP Publishing, 2020. p. 012103.

[14] LI, Ping; VANAPALLI, Sai; LI, Tonglu. Review of collapse triggering mechanism of collapsible soils due to wetting. *Journal of Rock Mechanics and Geotechnical Engineering*, 2016, 8.2: 256-274.

[15] ALI, Naema A. Practical engineering behavior of Egyptian collapsible soils, laboratory and in-situ experimental study. Open Journal of Civil Engineering, 2021, 11.3: 290-300.

[16] OKWEDADI, Anne C.; NG'AMBI, Samson; JEFFERSON, Ian. Laboratory testing regime for quantifying soil collapsibility. International Journal of Geological and Environmental Engineering, 2014, 8.12: 849-854.

[17] MALEKI, Mohammad; BAYAT, Meysam. Experimental evaluation of mechanical behavior of unsaturated silty sand under constant water content condition. Engineering geology, 2012, 141: 45-56.

[18] FATTAH, Mohammed Y.; DAWOOD, Basma A. Time-dependent collapse potential of unsaturated collapsible gypseous soils. World Journal of Engineering, 2020.

[19] MORSY, Osama; BASSIONI, Hesham; TAREQ, M. Soil improvement techniques of collapsible soil. Int. J. Sci. Eng. Res, 2017, 8.8.

[20] DICKSON, Mary H.; FANELLI, Mario. Geothermal energy: utilization and technology. 2013.

[21] DIAO, Nairen; LI, Qinyun; FANG, Zhaohong. Heat transfer in ground heat exchangers with groundwater advection. International Journal of Thermal Sciences, 2004, 43.12: 1203-1211.

[22] DEHKORDI, S. Emad; SCHINCARIOL, Robert A. Effect of thermal-hydrogeological and borehole heat exchanger properties on performance and impact of vertical closed-loop geothermal heat pump systems. Hydrogeology Journal, 2014, 22.1: 189.

[23] LU, Ning; DONG, Yi. Closed-form equation for thermal conductivity of unsaturated soils at room temperature. Journal of

Geotechnical and Geoenvironmental Engineering, 2015, 141.6: 04015016.

[24] ZHU, Feiyu; ZHOU, Yasu; ZHU, Shuiping. Experimental study on heat transfer in soil during heat storage and release processes. Heat and Mass Transfer, 2021, 57.9: 1485-1497.

[25] WANG, Chong, et al. A generalized thermal conductivity model of geomaterials based on micro-structures. Acta Geotechnica, 2019, 14.5: 1423-1436.

[26] QIAO, Xiaoying, et al. Effects of temperature change on the soil water characteristic curve and a prediction model for the mu us bottomland, northern China. Water, 2019, 11.6: 1235.

[27] SONG, Xiaoyu; WANG, Miao-Chun; ZHANG, Katherine. Molecular dynamics modeling of unsaturated clay-water systems at elevated temperature. In: The 7th International Conference on Unsaturated Soils 2018 (UNSAT2018)-Ng, Leung, Chiu & Zhou (Eds) The Hong Kong University of Science and Technology, ISBN 978-988-78037-3-7. 2018.

[28] HONGBING, Chen, et al. Comparative study on heat and moisture transfer in soil heat charging at high temperature for various soils. Energy Procedia, 2015, 75: 3148-3153.

[29] Egyptian Code of Particles (ECP) 202.2001, in part 5. 2007.

[30] ASTM, Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lbf/ft3(2,700 kN-m/m3)), Designation: D1557 – 12. 2013.

[31] SMALLEY, Ian; NG'AMBI, Samson. Problems with collapsible soils: particle types and inter-particle bonding. Open Geosciences, 2019, 11.1: 829-836.

[32] ASSALLAY, A. M.; ROGERS, C. D. F.; SMALLEY, I. J. Formation and collapse of metastable particle packings and open structures in loess deposits. Engineering Geology, 1997, 48.1-2: 101-115.

[33] SRIDHARAN, A.; PRAKASH, K. Characteristic water contents of a fine-grained soil—water system. Geotechnique, 1998, 48.3: 337-346.

[34] ASTM COMMITTEE D-18 ON SOIL AND ROCK. *Standard test methods for liquid limit, plastic limit, and plasticity index of soils*. ASTM international, 2010.