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Shear strength characteristics of a thermally cured sand-bentonite mixture

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Abstract. An experimental program was employed to evaluate the effects of curing time and temperature on the shear behavior of a sand-bentonite mixture. The specimens were treated at temperatures of 40°C, 60°C, and 80°C on Days 1, 3, and 5 under 100 kPa, 500 kPa, and 1000 kPa confinements. The results of the consolidated undrained triaxial shear tests indicated that an increase in the temperature from 40°C to 80°C on Days 1, 3, and 5 of curing intensified the shear strength by 25%, 24%, and 23%, respectively. In addition, an increase in the curing time from 1 to 3 and from 1 to 5 days at 80°C increased the shear strength of samples up to 12% and 24%, respectively. The failure of pre-cured samples was observed in lower strains as a result of greater induced brittleness. Moreover, the secant modulus and size of yield loci as well as slope of the critical state line increased by pre-curing. Application of thermal cycles resulted in increasing the shear strength and experiencing a negative pore water pressure that exhibited a transition towards the quasi-structured behavior. The results of Scanning Electron Microscopy (SEM) studies confirmed an increase in the void ratio during thermal curing.

1. Introduction

The thermo-mechanical behavior of clays has been widely studied by a number of researchers owing to their utilization of thermal technology such as energy piles, energy conservation, hazardous wastes disposal, and recovery systems in soils and rocks in many countries as well as the Aquifer Thermal Energy Storage (ATES) systems in Iran [1]. A number of experiments have been conducted on the behavior of clays in the temperature range of 20°C to 100°C with respect to the significance of clay behavior at elevated temperatures. Based on the results of previous studies, both the temperature and time affect the behavior of clayey soils depending on soil type, mineralogy, and test conditions.

In many cases, clay or clay mixtures are exposed to elevated temperatures in a long period of time such as the buffer layer of high-level radioactive wastes, energy piles, and electricity buried cables, to name a few. This type of behavior has been investigated in a number of studies by applying a constant temperature for a specific time period. Long time temperature induces variations in diffuse double layers of clay and its mechanical properties such as compressibility, pore water pressures, strength, and hydraulic conductivity [2]. In many other studies, a quasi-structured type of behavior or a secondary structure has been

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reported for clays subjected to thermal loading for a period of time [3,4]. In this regard, Pusch and Guven conducted microscopic studies of [5] to evaluate the effects of temperature and confined pressure on the bentonite structure to demonstrate that the application of elevated temperatures for a long time could affect montmorillonite flakes to form a denser structure separated by larger voids. In addition, Scanning Electron Microscopy (SEM) studies performed by Attah and Etim [6] on clayey sand also revealed that the initial porous structure of soil turned to a dense fragmented one after preheating to 150°C for 4 hours. Shirasb et al. [7] evaluated the effect of thermal pre-curing on the consolidation characteristics of a sand-bentonite mixture and illustrated the transition of behavior from reconstituted to a structured one with a distinct yield stress. The yield stress increased upon increasing the curing time and temperature.

The temperature can effectively affect the soil behavior and its shear strength [8,9]. However, a brief review of previous studies reveals that despite several studies conducted on the thermal behavior of clays, the effects of applying long-time temperature have not been considered in studying the shear behavior of clay soils. In the present study, the effect of thermal pre-curing on the shear behavior of a sand-bentonite mixture is precisely studied. To this end, the process was employed to reflect the status of the buffer layer of nuclear waste repositories or energy piles exposed to temperature gradients for a specific time which can also be subjected to shear stresses. The curing process was performed at different temperatures for different time periods to evaluate their effects on the soil behavior. A comprehensive experimental program was planned using consolidated undrained triaxial tests. The results were then compared with the mechanical response of the samples at ambient temperature and changes in the soil response were evaluated. Moreover, through SEM, the changes in the structure of the soil under study were monitored under different curing conditions.

2. Materials and properties

A type of sodium bentonite with the Liquid Limit (LL) of 179% and Plasticity Index (PI) of 125% which is classified as CH according to USCS as well as fine and crushed well graded silica sand were used in this study. The LL and PI of the buffer layer in FEBEX site were about 102% and 49%, respectively; however, these values were reported as 75% and 55% for Boom Clay in CERBERUS and ATLAS tests [10]. Figure 1 depicts the gradation curves, and Table 1 shows the physical properties of the used soils. Table 2 shows the chemical composition of sand and bentonite.

Various studies have reported different bentonite-to-sand weight ratios [11]. Based on oedometer tests on various sand-clay mixtures, it was concluded that the behavior of mixtures was significantly affected by the amount of clay and size or shape properties of

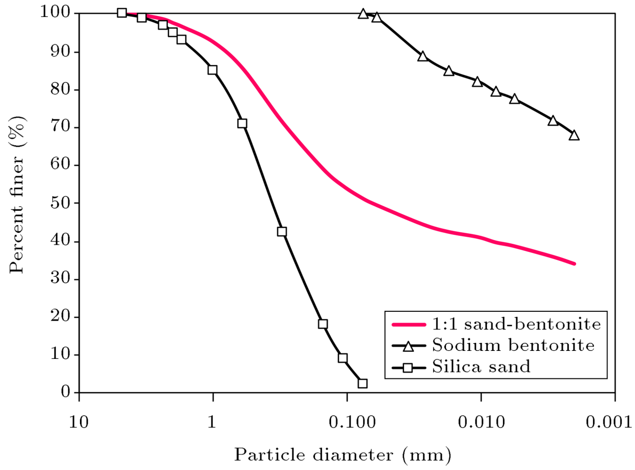

Figure 1. Particle size distribution curves of silica sand, sodium bentonite, and 1:1 sand-bentonite mixture.

Table 1. Physical properties of the used soils.

Property	Sand	Bentonite	1:1 mixture
Name (USCS*)	SW	CH	CH
Clay (%)	0	68	34
Silt (%)	2	31	16.5
Sand (0.06 mm–0.2 mm)	23	1	12
Sand (0.2 mm–1 mm)	55	0	27.5
Sand (> 1 mm)	20	0	10
LL (%)	–	179	83
PI (%)	NP	125	57
w_{opt} (%)	–	–	21.4
$\gamma_{\max}$ (kN/m^3)	–	–	17.76
$\gamma_{d,\max}$ (kN/m^3)	–	–	17.0

*USCS: Unified Soil Classification System.

Table 2. Chemical composition of soils.

Chemical composition	Bentonite	Silica sand
SiO_2	58.12	96.0
Al_2O_3	14.43	1.99
Fe_2O_3	3.01	0.24
Na_2O	3.01	0.07
MgO	2.79	0.43
CaO	2.13	0.64
K_2O	58.12	0.63
CL	1.47	–
SO_3	0.46	–
TiO_2	0.3	–
P_2O_5	0.1	–
L.O.I	13.07	–

sand grains [12]. In a study on gas migration through saturated bentonite-sand mixtures, Liu et al. [13] used a 3:7 weight ratio of sodium bentonite to silica sand to achieve the least permeability. The thermal conductivity of buffer is an important factor for HLW disposals depending on dry density, water content, and sand content [14].

Dixon et al. [15] defined effective porosity (n_{eff}) as another factor to calculate the optimum weight ratio of bentonite to sand in buffer layers based on Eq. (1):

$$n_{eff} = 1 - \rho_d \left(\frac{1}{G_{s,mix}} + \frac{0.15F}{1+F} \right), \qquad (1)$$

where ρ_d is the maximum dry density, $G_{s,mix}$ the specific gravity of mixture, and F the weight ratio of clay to sand fractions. To obtain the most appropriate and impermeable protecting layer with minimum effective porosity, a 1:1 mixture by weight of silica sand and sodium bentonite was used [7]. The same ratio was selected in other programs on HLW disposals in Germany as well as Canada [16]. Drinkable water was used in sample preparation whose chemical composition is presented in Table 3.

The stress-strain behavior of soils depends on their mineralogy, and the response of the samples with higher plasticity characteristics is significantly affected by temperature [17]. While investigating the plasticity changes in the studied soil during curing, some index tests were done on thermally-cured sand-bentonite mixtures to determine variations in LL and PI. The results of index tests are shown in Figure 2. The values of LL and PI were 83% and 57%, respectively, at ambient temperature. However, both LL and PI decreased at the curing temperatures of 20–80°C, mainly due to the formation of larger particles resulting from water precipitation around clay particles and pasting clay [18]; in addition, reduction of specific surface caused by drying and the subsequent decrease in the water absorption capacity of clay particles were other reasons for such a decrease [19] in the range of the mentioned temperatures in the present study (up to 80°C). At high temperatures, transformation from a mineral to another type causes changes in initial fabric [20–22]. The same trend for two different tropical clayey sands was observed by Attah and Etim [6].

Table 3. Chemical analysis of the used water.

Parameter	Content
Cl	374 mg/L
SO_4	320 mg/L
Na	230 mg/L
Ca	75.2 mg/L
Mg	19.4 mg/L
NO_3	38.0 mg/L
K	1.2 mg/L
NO_2	$<$ 0.1 mg/L
PO_4	$<$ 0.1 mg/L
F	$<$ 0.1 mg/L
Br	$<$ 0.1 mg/L
Li	$<$ 0.01 mg/L
pH ($T = 25°$C)	8.3
Conductivity	1655.3 μs/cm

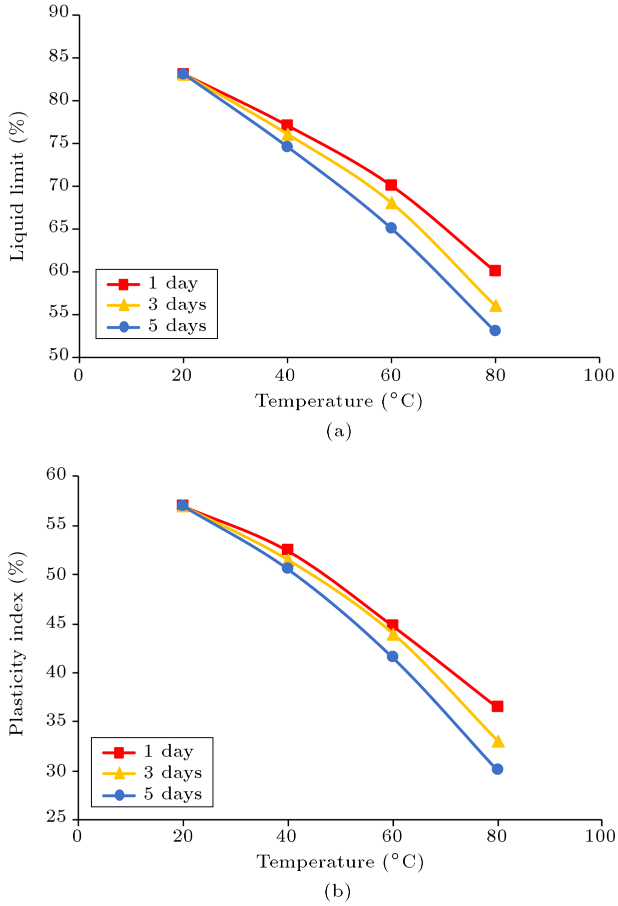

Figure 2. Variations of liquid limit and plasticity index with curing time and temperature.

The swelling pressure of the studied soil was determined based on the method C of ASTM D-4546 [23]. It was regarded as the pressure at which the swelling of specimen was prevented. The swelling pressure was calculated as approximately 20 kPa after four stages of increasing pressure. The obtained value is in agreement with the empirical equations of Erzin and Erol [24]. The low plasticity of the applied bentonite (PI = 57%) caused swelling pressure to be much lower than the values reported by Komine and Nobuhide [25], i.e., about 100 kPa for a mixed soil containing 30% bentonite with a PI of 447%. It is expected to obtain lower swelling pressure after thermal curing due to a reduction in the plasticity characteristics.

3. Triaxial testing program

Silica sand and bentonite were mixed and compacted in eight equal layers in a cylindrical mold of 100 mm in diameter and 200 mm in height. A compaction ratio of 90% was reached by adding de-aired water to achieve a dry unit weight of 15.3 kN/m^3. An optimum water content of 21.4% and maximum dry density of 17 kN/m^2 were also obtained for the sand-bentonite mixture based on the modified Proctor test using a 4.5 kg weight hammer and a mold of 100 mm in diameter under 25 blows in each of five layers. The dry density of sand-bentonite mixture in the buffer layer of nuclear waste disposals was measured as 14.7 to 16.3 kN/m^3 in a number of experiments in which the weight sand-bentonite mixture at 1:1 was used at the compaction ratio of 85% to 95% [15,26]. In CERBERUS and ATLAS tests as well as the Boom Clay at Hades laboratory in Mol, a dry density of 15.8–17.5 kN/m^3 was reported [10]. The bentonite used in FEBEX site had an average unit weight of 15.7–16.1 kN/m^3, as presented by ENRESA [27].

Consolidated undrained triaxial tests were carried out using a modified thermal triaxial cell with an electronic data logger system capable of measuring axial stress, axial strain, volume change, and excess pore water pressure, as illustrated in Figure 3. The triaxial cell was calibrated to handle the pressures up to 2000 kPa and temperatures up to 90°C. Heating was induced by a spiral heater placed around the specimen controlled by a thermocouple placed vertically in the cell at a distance of 10 mm from the sample with a precision rate of 0.1°C. Due to the small dimensions of specimens, the temperature at a center of the sample was equal to the cell temperature after 100 minutes which was measured in the calibration process.

After preparing the specimen, a back pressure of 700 kPa was applied until achieving Skempton's B value of 0.95 during six days of saturation. The final B coefficient depends on several factors including clay content, plasticity characteristics, back pressure, and saturation time. With the consideration of the lower Liquid Limit ($LL = 83\%$) and Plasticity Index ($PI = 57\%$) of the mixture used in the present study, the applied back pressure and saturating time were consistent with the results from a study conducted by Mukherjee and Mishra [28] who obtained a B-value of 0.93 using back pressures of 480 to 565 kPa in 12–17 days for two sand-bentonite mixtures with 10% and 20% clay contents ($LL = 286\%$), respectively.

The curing temperatures were chosen so that they can fit with different thermal applications such as buffer layer in HLW disposal, energy piles, or underground buried power cables. The design temperature for the buffer layer of HLW disposals should not exceed 90°C due to the reduction of plasticity characteristics. In many cases, high temperature of HLW can be reduced before placing it in repositories [29]. The energy piles in Europe are designed for the temperature range of −1°C to 35°C. However, in some other cases, increasing temperature up to 40°C or 50°C is possible [30]. Maximum temperatures of 80°C and 60°C were reported around the buried cables and 0.25 m far from them, respectively [31].

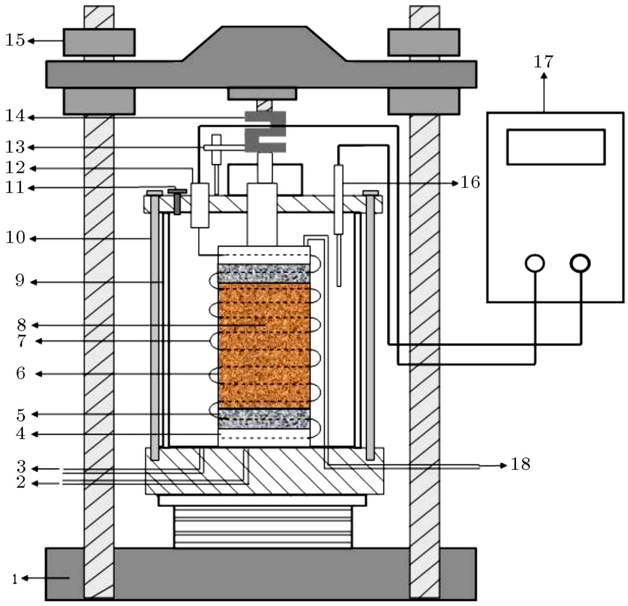

Figure 3. Schematic diagram of the pressure chamber in the temperature-controlled triaxial test system. (1) Loading frame, (2) Pore pressure line and testing tube, (3) Confining pressure line and testing tube, (4) Ceramic plate, (5) Porous stone, (6) Rubber membrane, (7) Heater, (8) Soil sample, (9) Stainless steel cylinder, (10) Fixed rods of pressure chamber, (11) Venture valve, (12) Heating source, (13) Axial displacement sensor, (14) Axial load piston and sensor, (15) Fixing bolt of loading frame, (16) Temperature sensor, (17) Temperature controller, and (18) Back pressure imposition and testing tube.

The time required to finish the primary consolidation of the applied mixed soil was previously determined through isotropic consolidation tests by Shirasb et al. [7] whose findings revealed that the primary consolidation time increased upon increasing both temperature and confining pressure. The obtained values were less than 24 h at all temperatures under 100 kPa. When the confining pressure increased up to 500 kPa, it was achieved in less than 24 h at 20, 40, and 60°C. At 1000 kPa, it was less than 24 h only at 20°C and 40°C; however, it was less than 40 h at all temperatures and confinements [7]. For this reason, the pre-curing times of 1, 3, and 5 days were chosen in the present study.

Two sets of tests were carried out to study the shear behavior of sand-bentonite mixtures. In the first set, in order to evaluate the time-dependent thermal behavior of the mixed soil, the samples were pre-cured for one, three, and five days at constant temperatures of 40°C, 60°C, or 80°C under the confining stresses of 100 kPa, 500 kPa, or 1000 kPa while keeping the drainage valve open. Similar to the findings of Lingnau et al. [26], the consolidation process was considered complete when the rate of volumetric strain was less than 0.1%/day. The temperature was correctly controlled to remain constant during this time period and up to the end of the test. Moreover, three reference tests were done under the mentioned conditions and at ambient temperature of 20°C. After consolidation, the undrained shear loading started at a rate of 0.2 mm/min. The loading continued up to the axial strain of about 20%. During shear loading, deviatoric stress, axial strain, and excess pore water pressure were continuously measured using calibrated sensors and data acquisition system. To evaluate the effects of repeatability, 30% of the total triaxial tests were randomly repeated.

In the second group of tests, thermal stress paths were applied to the samples and their behavior was monitored. Two samples were heated from the ambient temperature (20°C) to 80°C under the confining pressure of 100 kPa for one and five days. Then, the temperature decreased again to the ambient value (20°C-80°C-20°C) and sheared after thermal equilibrium in an undrained condition. The results were compared with those from the tests done on samples at the same curing time without any thermal cycling. Table 4 provides a summary of the testing program in this study.

4. Results of triaxial tests

4.1. Stress-strain and pore pressure behavior

Figures 4–6 show the deviatoric stress-axial strain and excess pore water pressure-axial strain curves of thermally cured samples obtained from consolidated undrained triaxial tests under initial confinements of 100, 500, and 1000 kPa, respectively. The range of variations is also shown by toolbars for repeated tests. Table 5 provides a summary of the experimental results obtained from triaxial tests. The samples were consolidated at elevated temperatures of 40, 60, and 80°C under the confining pressures of 100, 500, and 1000 kPa for 1, 3, and 5 days, which were referred to as "cured samples" in this study. Then, undrained shear

Table 4. The variables in testing program and number of experiments.

Type of tests	Testing condition	Consolidation temperature (°C)	Consolidation time (day)	Total number of tests
Thermal triaxial compression test	Consolidation at confining pressures of 100, 500, and 1000 kPa at defined temperature and time. Undrained shearing at a strain rate of 0.2 mm/min with record of deviatoric stress, axial strain, and pore pressure.	40, 60, and 80	1, 3, and 5	24
Reference thermal triaxial compression test	Primary consolidation at confining pressures of 100, 500, and 1000 kPa at ambient temperature. Undrained shearing at a strain rate of 0.2 mm/min on thermally consolidated samples.	20	End of primary consolidation	3
Cyclic thermal triaxial compression test	Heating from the ambient temperature to 80°C under a confinement of 100 kPa and then, thermal curing at 80°C on Days 1 or 5. Again, cooling to 20°C and shearing after thermal equilibrium.	20-80-20	1, 5	2
Reference cyclic thermal triaxial compression test	Consolidation at confining pressure of 100 kPa at ambient temperature of 20°C on Days 1 and 5 and shearing.	20	1, 5	2

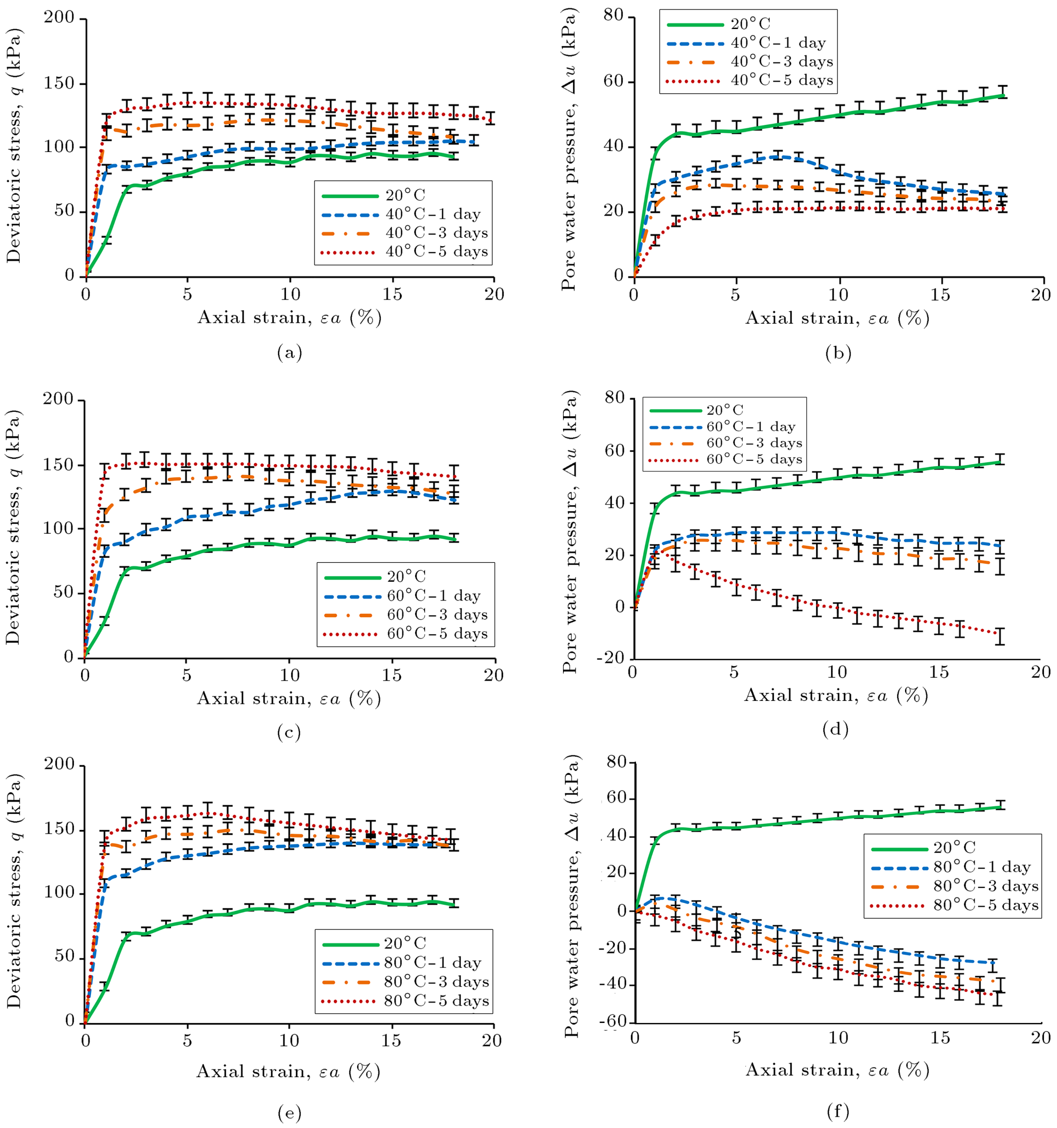

Figure 4. Triaxial shear behavior of sand-bentonite mixture at different temperatures and curing times for $p'_0 = 100$ kPa: (a) Deviatoric stress-axial strain at 40°C, (b) pore pressure-axial strain at 40°C, (c) deviatoric stress-axial strain at 60°, (d) pore pressure-axial strain at 60°C, (e) deviatoric stress-axial strain at 80°C, and (f) pore pressure-axial strain at 80°C.

loading started on the cured samples. Figures 4–6 show the results of triaxial tests at the ambient temperature of 20°C used for evaluating the curing effects on the shear behavior of soil.

Based on these figures, the samples at the ambient temperature showed smaller shear strength than those consolidated at higher temperatures; however, their shear strength increased upon increasing the confining stress. The trend of behavior for these samples was consistent with the thermal behavior of the normally consolidated clays reported in other studies [32,33].

For the cured samples, the deviatoric stress-axial strain behavior was dependent on the curing time, showing more strength for the samples cured for a longer period. An increase in the shear strength under the influence of temperature can be elaborated through different theories such as oxidization of aluminum and iron during heating and dehydration of iron oxides that created bonds between clay particles [18]. According to Figure 4, a distinct failure point can be observed in the samples with 3 and 5 days of curing; however, samples on Day 1 of curing exhibit a hardening behavior during shear loading. The shear strength of the cured samples increased upon increasing the confining pressures of 500 kPa and 1000 kPa, respectively, as shown in Figures 5 and 6. Based on Figure 7(a), the shear strength of the cured samples increased with an increase in both curing time and temperature. Moreover, these samples also failed at the smaller level of strain and experienced softening behavior, as illustrated in Figure 7(b). The behavior trend for the thermally cured samples was much similar to those

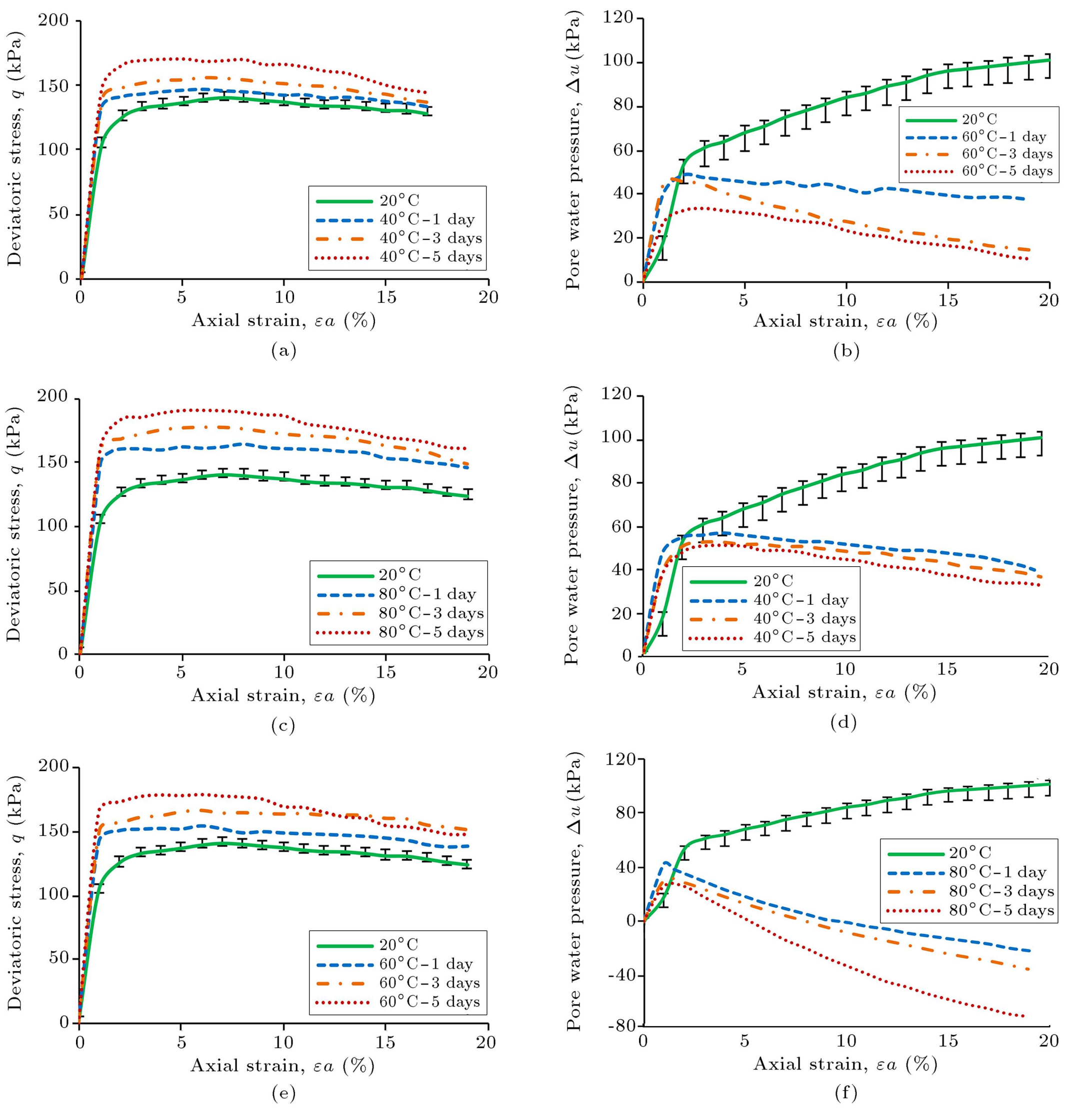

Figure 5. Triaxial shear behavior of sand-bentonite mixture at different temperatures and curing times for $p'_0 = 500$ kPa: (a) Deviatoric stress-axial strain at 40°C, (b) pore pressure-axial strain at 40°C, (c) deviatoric stress-axial strain at 60°C, (d) pore pressure-axial strain at 60°C, (e) deviatoric stress-axial strain at 80°C, and (f) pore pressure-axial strain at 80°C.

for the structured or overconsolidated clays [34] and artificially structured soils [35]. It should be noted that a similar transition of behavior is observed during the consolidation tests on the studied cured sand-bentonite mixture [7].

The effect of the elevated temperature on the elastic modulus is presented in Figure 8. In this figure, the undrained secant modulus is calculated at a shear strength (E_{50}) of 50%. The toolbars were used to show the range of variations in the repeated tests. The results indicated that the elasticity modulus was higher in the specimens with more curing time and curing temperature than that in the reconstituted ones tested at the ambient temperature. The rate of increase was higher under lower confinements where thermal curing increased the elastic modulus more than three times of its value for the reconstituted samples.

Figures 4–6 indicate the variations of excess pore water pressure with axial strain. The samples consolidated at ambient temperature showed positive pore water pressure; however, the samples cured at elevated temperatures in different curing times and confinements exhibited a different trend of behavior. The induced pore pressure in these samples decreased upon increasing the curing time and curing temperature. For the samples cured at higher temperatures in longer time periods, the pore pressure reached negative values. The samples cured at 80°C experienced negative pore pressure at all curing times and confinements; however, at a temperature of 60°C, negative pore pressures were only observed on Day 5 of curing under a confining stress of 100 kPa. The samples consolidated at 40°C did not show negative pore pressures at any consolidation time and confinement. This type of behavior is

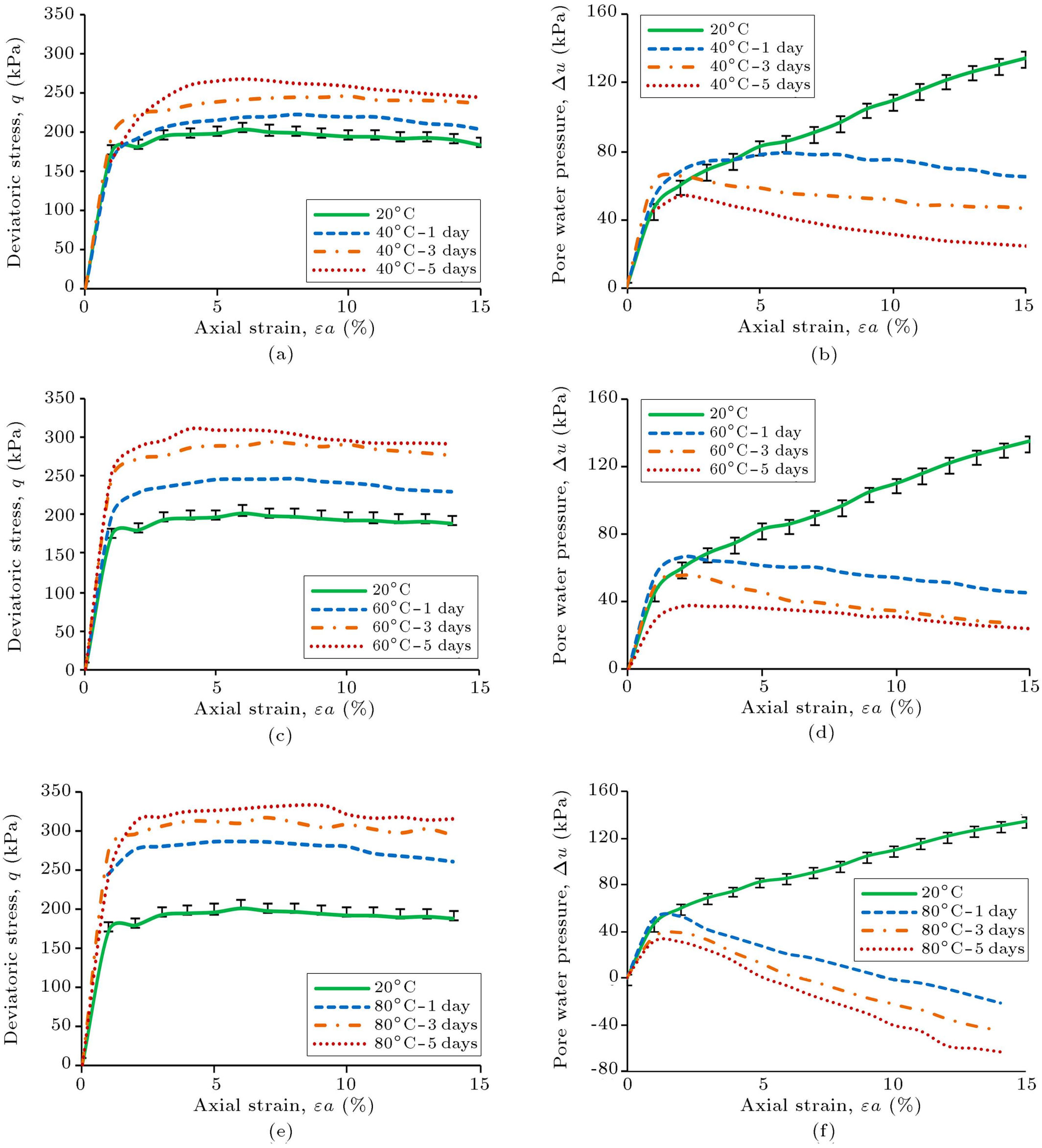

Figure 6. Triaxial shear behavior of sand-bentonite mixture at different temperatures and curing times for $p'_0 = 1000$ kPa: (a) deviatoric stress-axial strain at 40°C, (b) pore pressure-axial strain at 40°C, (c) deviatoric stress-axial strain at 60°C, (d) pore pressure-axial strain at 60°C, (e) deviatoric stress-axial strain at 80°C, and (f) pore pressure-axial strain at 80°C.

similar to that of the structured soils, indicating that thermal curing up to the longer periods of time (more than the required time for primary consolidation) results in a behavior transition from the reconstituted to the structured state. In fact, the reduction of excess pore water pressure with temperature for the reference specimens (samples tested at the ambient temperature) is in good agreement with the results obtained from the study on soft Bangkok clay conducted by Abuel-Naga et al. [33]. In addition, the general trend of changes in excess pore water pressure for the samples cured at elevated temperatures is similar to the results from the studies of Rios and Baudet [36] on the cemented silty clay and Amini et al. [37] on the cemented gravely sand categorized as structured soils. Some other soils can also be considered as structured due to cation exchange, flocculation and agglomeration, cementitious hydration, and pozzolanic reaction [38].

As previously illustrated, increasing temperature can make bonding among particles due to the dehydration of iron oxides, which can be referred to as the reason for the observed negative pore pressures. Since it is a time-dependent procedure [39], the induced negative pore pressure is more apparent as curing time increases.

4.2. Stress path and yield surface evolution

Total Stress Path (TSP) and Effective Stress Path (ESP) for the samples under confining pressures of 100, 500, and 1000 kPa are presented in Figure 9. The stress

Table 5. Summary of thermal triaxial compression test results.

Test no.	Consolidation temperature (°C)	Consolidation time (day)	Confining stress (kPa)	Deviatoric stress (kPa)		Mean effective stress (kPa)		Axial strain (%)		Pore pressure (kPa)	
				At peak	At critical state	At peak	At critical state	At peak	At critical state	At peak	At critical state
1	20	–	100	93	90	80	73	11	20	51	57
2	40	1	100	98	105	96	110	7	19	37	25
3	60	1	100	111	123	108	117	6	18	29	24
4	80	1	100	129	139	143	174	4	18	0	–28
5	40	3	100	119	108	112	113	7	18	28	23
6	60	3	100	139	125	120	125	5	19	26	17
7	80	3	100	143	135	151	184	3	19	–3	–39
8	40	5	100	135	121	124	120	5	20	21	21
9	60	5	100	151	136	135	156	3	20	15	–11
10	80	5	100	160	143	163	193	3	18	–10	–45
11	20	–	500	140	124	469	440	8	20	78	101
12	40	1	500	146	129	495	503	7	20	54	40
13	60	1	500	154	139	506	508	6	19	45	38
14	40	3	500	156	128	500	506	6	20	52	37
15	60	3	500	165	151	516	535	5	19	39	15
16	80	3	500	172	147	533	586	3	20	24	–37
17	40	5	500	170	135	506	512	5	20	51	33
19	60	5	500	179	148	527	538	4	19	33	11
19	80	5	500	183	159	535	627	2	20	26	–74
20	20	–	1000	202	183	981	926	8	15	86	135
21	40	1	1000	223	204	996	1003	8	15	78	65
22	40	3	1000	242	235	1027	1032	7	16	54	46
23	60	3	1000	294	276	1042	1064	6	14	56	28
24	80	3	1000	314	296	1066	1144	4	14	39	–45
25	40	5	1000	267	240	1035	1058	5	17	54	22
26	60	5	1000	312	268	1067	1068	4	17	37	21
27	80	5	1000	333	315	1080	1169	3	13	31	–64

paths were plotted at 40, 60, and 80°C on Days 1, 3, and 5 of curing and they were compared with those of the samples tested at ambient temperature. It was concluded that an increase in the curing temperature at a constant confinement shifted ESP towards the right side of TSP due to the induced negative excess pore water pressure. This trend was more evident at a confining pressure of 100 kPa (Figure 9(a)–(c)). Moreover, an increase in the confining stress at a constant temperature shifted ESP towards the left hand of TSP due to the reduction of negative pore pressures. This type of behavior can be observed more clearly for the samples cured at a temperature of 80°C (Figures 9(c), (f), and (i)).

Figure 10 shows the comparison of the slope of the critical state line (M_T) at different curing times and temperatures in the present study and that in others. According to the results, M_T which is also related to the critical state friction angle slightly varies based on both curing time and curing temperature.

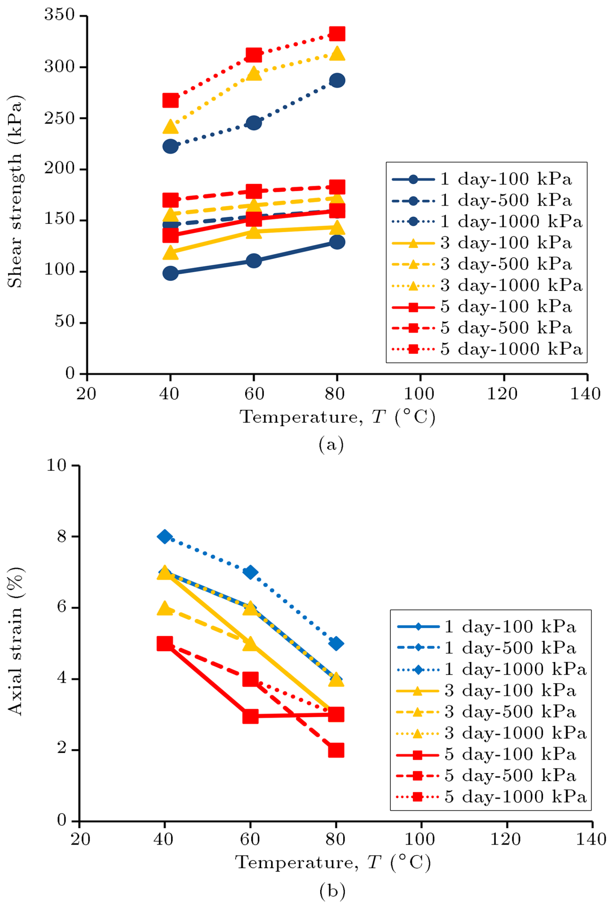

Figure 7. The change in shear characteristics with temperature for different curing times:(a) Shear strength and (b) axial strain at failure.

The normalized slope to values at ambient temperature (M_0) slowly increased by increasing temperature and curing time that confirmed the expansion of the size of yield loci at elevated temperatures. Of note, laboratory studies of many other researchers showed that the critical state friction angle increased, slightly increased, remained constant, or decreased upon increasing temperature [40–43]. Eq. (2) shows the trend of variations when M_T increases as the temperature increases [40–43]. Here, ζ is a calibration parameter calculated as 0.007 for the sand-bentonite mixture considered in the present study.

$$M_T = M_0 + \zeta \left(\frac{T}{T_0} \right). \tag{2}$$

The mutual effect of temperature and curing time on the evolution of the yield surface is shown in Figure 11. The Cam clay yield surfaces are depicted on the normalized $q/p'_0 - p'/p'_0$ plane ($p'_0 = 100$ kPa) using M_T at different curing times. According to this figure, at all temperatures, an increase in the curing time slightly increased the size of the yield surface.

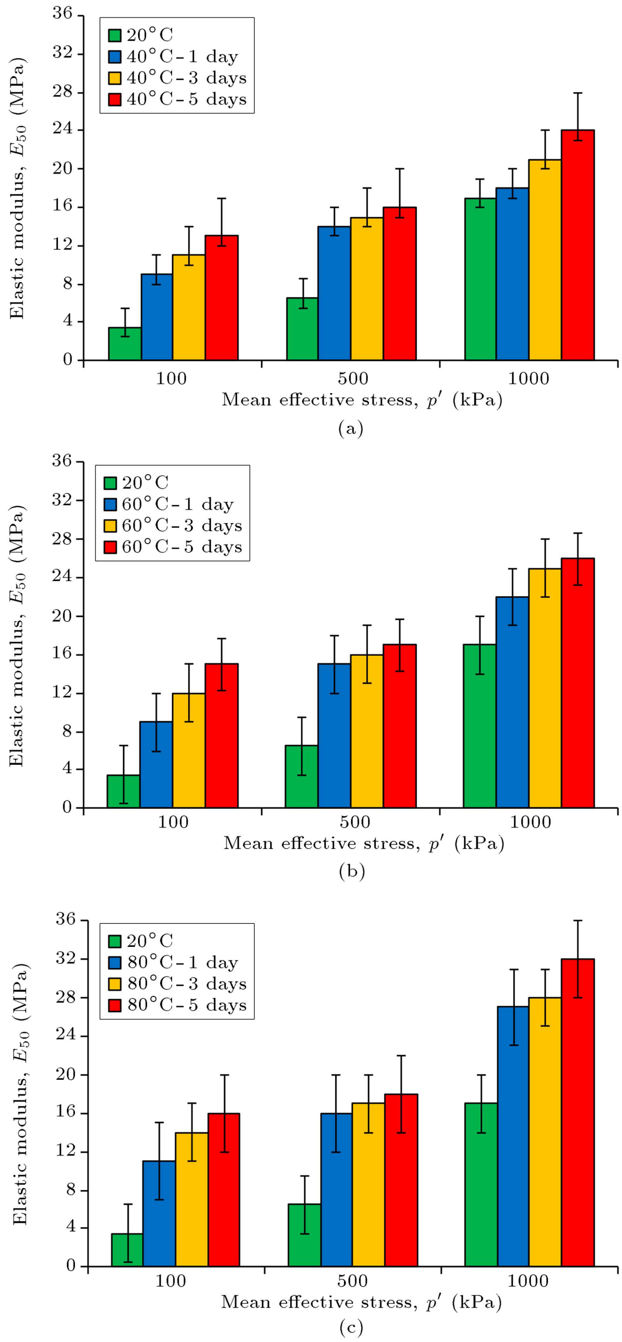

Figure 8. Effect of temperature and curing time on the secant modulus at 50% of peak strength: (a) $T = 40$°C, (b) $T = 60$°C, and (c) $T = 80$°C.

5. Discussion

In order to elaborate the effect of curing process on the behavior of the sand-bentonite mixture, a few specimens were subjected to the cycles of thermal paths. To prove this hypothesis, two samples were exposed to thermal paths of 20°C-80°C-20°C at the confining pressure of 100 kPa. First, the temperature increased from 20°C to 80°C and remained constant to cure on Days 1 or 5. Then, the temperature decreased

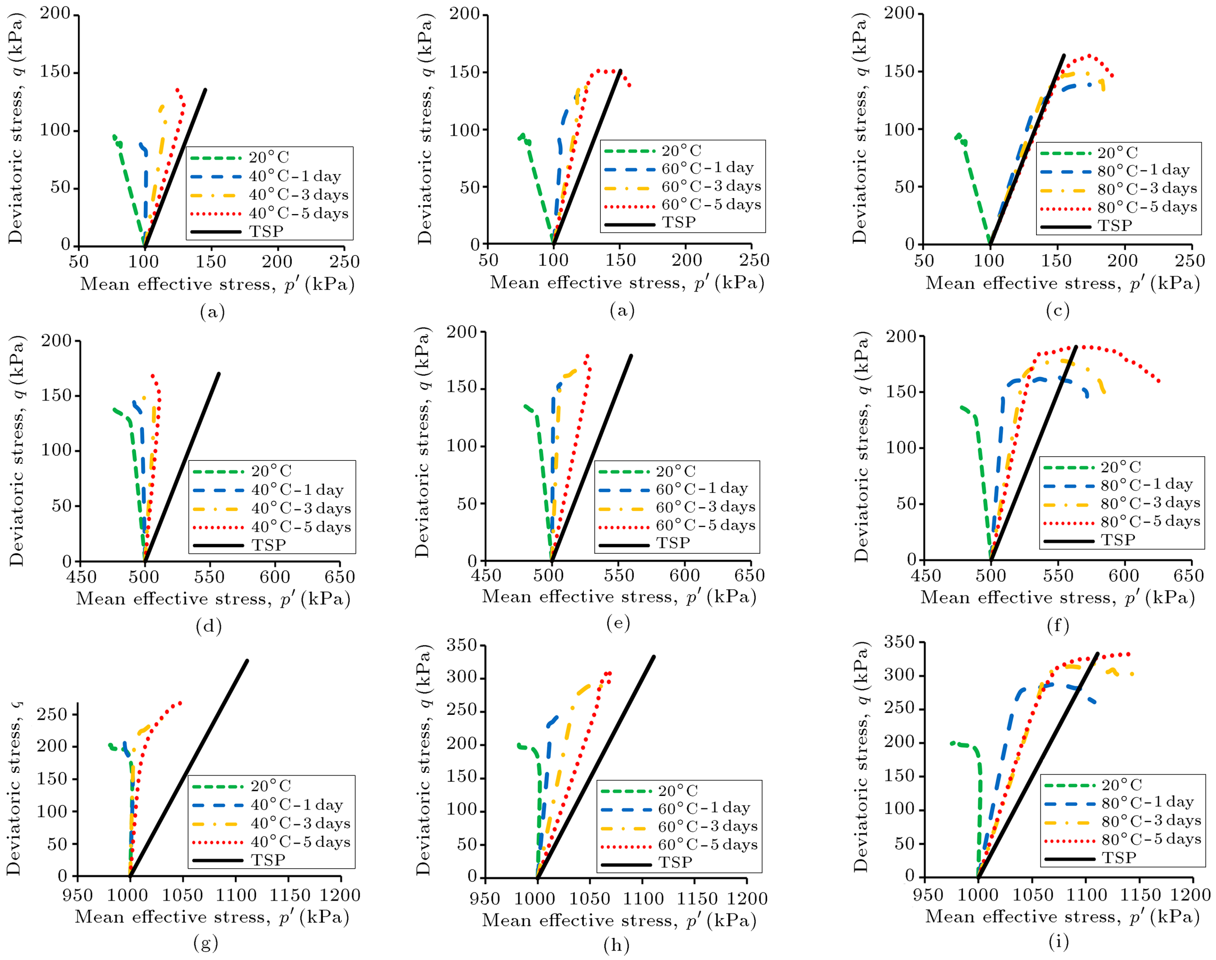

Figure 9. Total and effective stress paths of sand-bentonite mixtures at different temperatures and curing times: (a) $p'_0 = 100$ kPa, $T = 40$°C, (b) $p'_0 = 100$ kPa, $T = 60$°C, (c) $p'_0 = 100$ kPa, $T = 80$°C, (d) $p'_0 = 500$ kPa, $T = 40$°C, (e) $p'_0 = 500$ kPa, $T = 60$°C, (f) $p'_0 = 500$ kPa, $T = 80$°C, (g) $p'_0 = 1000$ kPa, $T = 40$°C, (h) $p'_0 = 1000$ kPa, $T = 60$°C, and (i) $p'_0 = 1000$ kPa, $T = 80$°C.

to 20°C and the samples were sheared after thermal equilibrium. The obtained results were compared with those from the tests on samples at ambient temperature

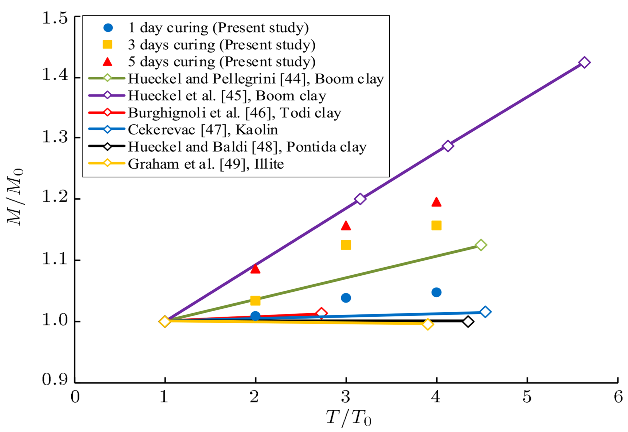

Figure 10. Effect of temperature on the slope of critical state line for different clays.

(20°C) without any thermal cycles in Figure 12.

Variation in the shear strength of these samples with temperature is shown in Figure 12(a) for an initial confinement of 100 kPa and an increase in strength of samples during the curing cycle can be clearly observed. The sample with Day 5 of curing reached greater shear strength than the sample on Day 1 of curing. In case the samples are cooled again to ambient temperature, the shear strength of the sample on Day 5 of curing is about 62% greater than the initial strength; however, the shear strength for the sample with Day 1 of curing increased by about 43%.

Figure 12(b) plots the variations of Skempton's pore pressure coefficient, A (associated to the peak shear strength), with temperature at a confining pressure of 100 kPa. In this figure, changes in the pore pressure during the curing procedure can be investigated. When the value of A was about 0.6 for the sample sheared at the ambient temperature of 20°C, it decreased to about zero for the sample cured on Day 1

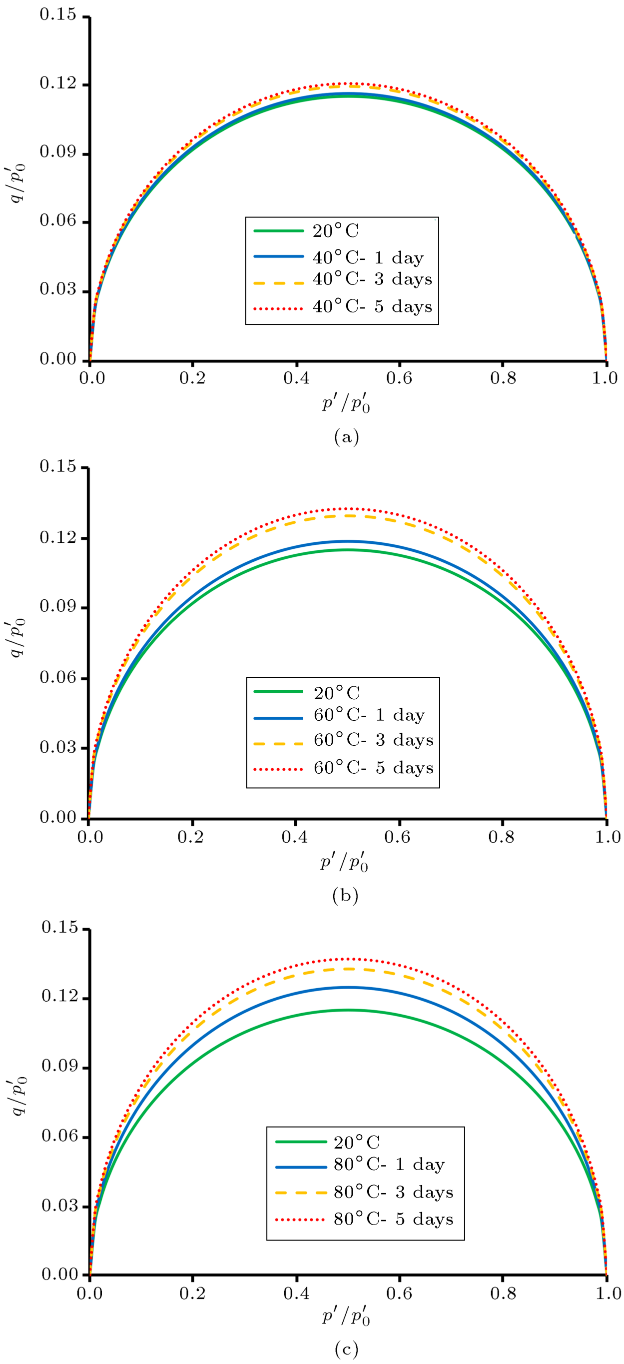

Figure 11. Effect of curing time and temperature on the yield surface of sand-bentonite mixture at $p'_0 = 100$ kPa: (a) 1 day curing, (b) 3 days curing, and (c) 5 days curing.

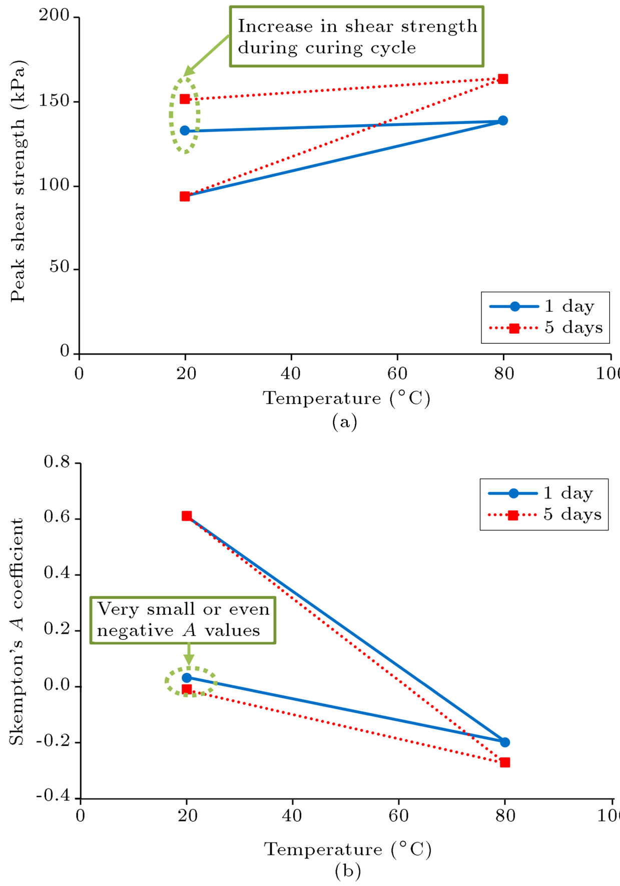

Figure 12. Variation of shear characteristics for the temperature cycle of 20°C-80°C-20°C at a confining pressure of 100 kPa: (a) Shear strength and (b) Skempton's A coefficient.

at 80°C and then, the sample was cooled to 20°C, or even to a negative value for the sample that has been cured for 5 days at 80°C and was cooled back to the ambient temperature.

Based on the cyclic temperature experiments, the effect of thermal curing on the shear response of sand-bentonite mixture was clearly demonstrated. It can also explain the formation of a quasi-structured behavior for the samples during thermal curing. It should be noted that in the present study, the changes in behavior were investigated for only short curing times; however, it can be visualized that when the soil is subjected to temperature for a long period, how would be the changes of the behavior after cooling the system to the ambient temperature. This can be helpful in characterization of the soils and sites that have been previously used for thermal structures.

In order to investigate thermal curing effects on the structure of sand-bentonite mixture, SEM studies have been performed. A number of images have been taken from the studied soil cured at different times and temperatures. It should be noted again that the used range of temperatures in the present study (20°C to 80°C) does not influence the composition of the tested sand-bentonite mixture. This behavior has been explained previously by Wang et al. [41–50] who carried out a detailed investigation on the dehydration process in clays. They showed that dehydration of water layers would lead to greater bonding between particles. However, mineral destruction of clay and formation of new silicate crystals occur at temperatures higher than 500°C.

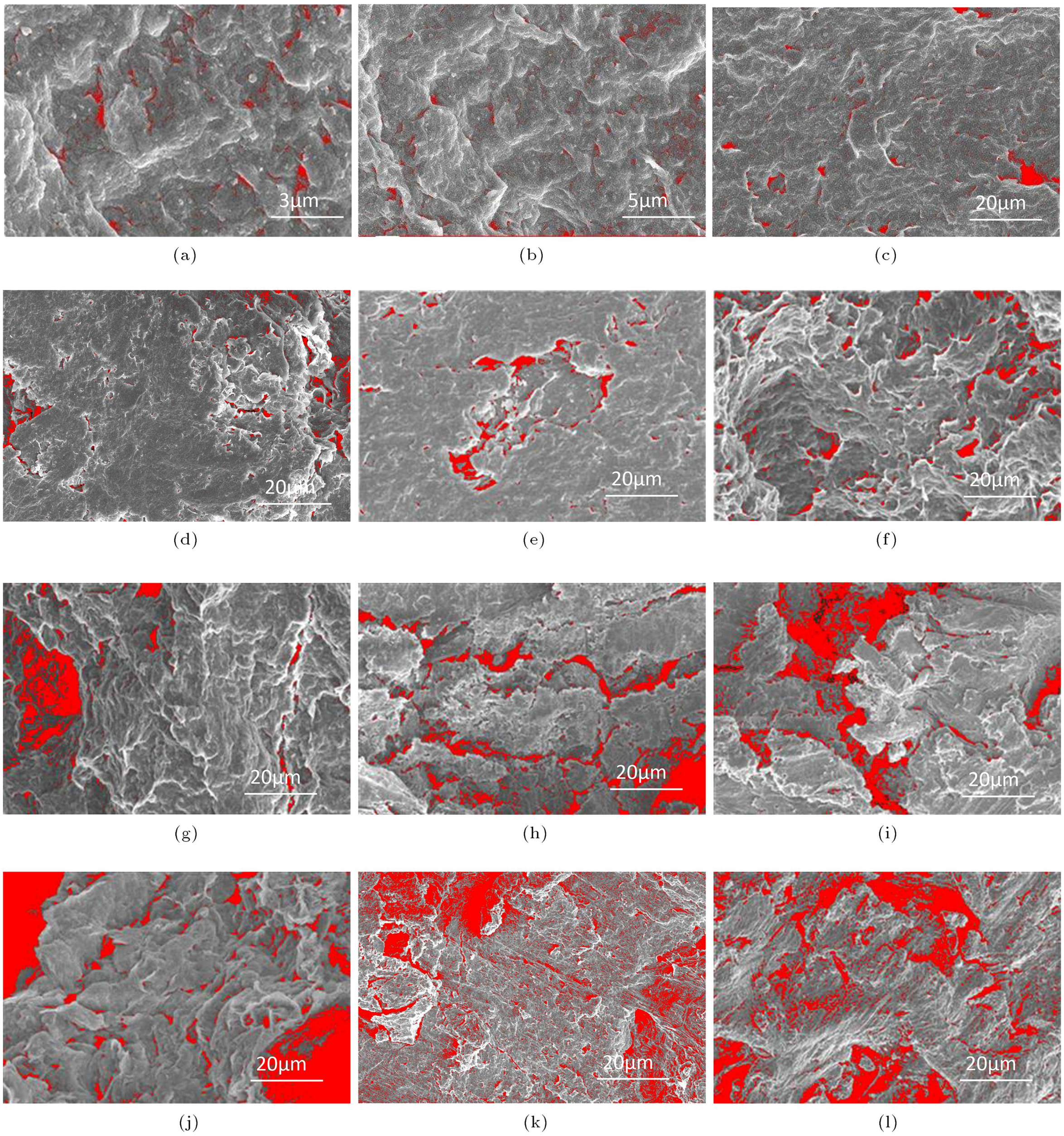

Figure 13. Scanning Electron Microscopy (SEM) images of the studies soil at different curing times and temperatures: (a) 20°C, no curing, (b) 20°C, no curing, (c) 20°C, no curing, (d) 40°C, 1 day, (e) 40°C, 3 days, (f) 40°C, 5 days, (g) 60°C, 1 day, (h) 60°C, 3 days, (i) 60°C, 5 days, (j) 80°C, 1 day, (k) 80°C, 3 days, and (l) 80°C, 5 days.

Table 6. The changes in the void ratio of sand-bentonite mixture during pre-curing.

Curing temperature (°C)	**20**		**40**			**60**			**80**	
Curing time (day)	0	1	3	5	1	3	5	1	3	5
Void ratio (%)	1.6	1.8	2.4	3.6	5.6	9.0	14.5	16.9	17.7	18.3

The effects of thermal curing on the sand-bentonite mixture considering the time factor are depicted in Figure 13. The void ratio of the cured samples at elevated temperatures is obtained using *Image J* software and is highlighted in red in Figure 13. The void ratio of samples in different pre-curing conditions has been determined by dividing the highlighted area to the total area in each figure and is depicted in Table 6. Based on the results, the void ratio of samples increases with curing time and curing temperature from 1.6% for the sample at the ambient temperature to 18.3% for the pre-cured sample at 80°C on Day 5.

The increase in void ratio during the pre-curing process confirms the increase in water content of the saturated sample and reduction of its unit weight. This leads to the increase in permeability of mixture which is in line with results of Shirasb et al. [7] who reported an increase in permeability of pre-cured samples using the values obtained indirectly from consolidation tests on the same soil. These findings are in agreement with those by Attah and Etim [6] who also reported changes in the structure of tropical soils due to the thermal preheating process.

6. Conclusions

A comprehensive experimental program was planned in this study to evaluate the effects of thermal curing on the shear behavior of a sand-bentonite mixture. The following remarks can be made:

- Based on the deviatoric stress-axial strain diagrams for different temperatures, it was found that the shear strength of sand-bentonite mixture increased upon increasing the curing time and temperature; however, the strain associated with the peak shear strength decreased by curing the sample more. The excess pore water pressure was also reduced by increasing the curing parameters (time and temperature) from the positive to negative values. The trend of variations in the excess pore water pressure at higher temperatures was similar to those of the structured clays;
- The effective stress path of the tested specimens at each temperature was shifted towards the left side of the total stress path upon increase in the confining pressure. However, as the time or temperature of thermal curing increased at a constant confinement, the effective stress path was shifted to the right side of total stress path;
- The slope of the critical state line increased slightly with curing time and temperature. In addition, the undrained secant elastic modulus increased with curing of the soil;
- According to the cyclic thermal paths, after curing at higher temperatures and returning to the ambient value, the induced pore pressure and deviatoric stress are not the same as the initial condition. The samples had a greater shear strength while pore pressure dropped to smaller values, similar to the trend of behavior which is usually observed for structured soils. In the present study, it was inferred as a quasi-structured behavior of the soil induced by thermal curing;
- Based on the results of Scanning Electron Microscopy (SEM), the void ratio of samples increased with increase in curing time and curing temperature;
- Based on the results of the present study, although the shear strength of sand-bentonite mixture improves due to the pre-curing process, the increase in its brittleness and the reduction of its plasticity and unit weight should be crucially controlled. Moreover, increase in the void ratio of mixture during the pre-curing process is an indicator of the increase in its permeability. Due to the important role of buffer layer as an impermeable barrier in HLW disposal sites, the values should be controlled carefully based on standards and provisions.

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Testing was done at the Soil Mechanics Laboratory in the School of Engineering of Kharazmi University, Iran. The authors would like to thank the effort of all the technicians who made assistance during testing. The constructive comments of Antonio Gens and Enrique Romero from UPC, Spain are also gratefully appreciated.

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