Shear Strength Characteristics of a Thermally Cured Sand-Bentonite Mixture

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Abstract
An experimental program was conducted to investigate the effects of curing time and curing temperature on shear behavior of a sand-bentonite mixture. The specimens were cured at temperatures of 40°C, 60°C and 80°C for 1, 3 and 5 days under 100kPa, 500kPa and 1000kPa confinements. The results of consolidated undrained triaxial shear tests showed that an increase in temperature from 40°C to 80°C at 1, 3 and 5 days of curing increased the shear strength by 25%, 24% and 23%, respectively. Also, the increase in curing time from 1 to 3 and from 1 to 5 days at 80°C increased the shear strength of samples 12% and 24%, respectively. The failure of pre-cured samples occurred in lower strains as a result of more induced brittleness. Moreover, the secant modulus as well as the size of yield loci and critical state line’s slope increased by pre-curing. The application of thermal cycles resulted in increasing shear strength and experiencing a negative pore water pressure which shows a transition towards the quasi-structured behavior. The results of scanning electron microscopy (SEM) studies confirmed the increase in void ratio during thermal curing.

**KEYWORDS:** Thermal curing; sand-bentonite mixture; consolidated undrained triaxial tests; quasi-structured behavior; temperature.

1. **Introduction**
The thermo-mechanical behavior of clays has been studied vastly by a number of researchers due to the utilization of thermal technology such as energy piles, energy conservation, hazardous wastes disposal and recovery systems in soils and rocks in many countries besides the aquifer thermal energy storage (ATES) systems in Iran [1]. Due to the importance of clay behavior at elevated temperatures, there are a number of experimental studies on the behavior of clays at the range of 20°C to 100°C. Based on the results of previous studies, both the temperature and time influence the behavior of clayey soils and the effects are dependent to the soil type, mineralogy and test conditions.

In many cases, clay or clay mixtures are exposed to elevated temperatures for a long period of time, like buffer layer of high-level radioactive wastes, energy piles and electricity buried cables. This type of behavior has been investigated in a number of studies by applying a constant temperature for a specified time period. Long time temperature induces variations in diffuse double layers of clay, and in turn, 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 reported for clays subjected to thermal loading for a period of time [3,4]. The microscopic studies of Pusch et al. [5] to investigate the effects of temperature and confining pressure on bentonite structure showed that application of elevated temperatures for a long time affects montmorillonite flakes to form a denser structure separated by larger voids. The SEM studies performed by Attah and Etim [6] on clayey sand also revealed that the initial porous structure of soil turns to a dense fragmented one after preheating to 150°C for 4 hours. Shirasb et al. [7] investigated the effect of thermal pre-curing on consolidation characteristics of a sand-bentonite mixture and showed the transition of behavior from reconstituted to a structured one with a distinct yield stress. The yield stress increased with increase in curing time and curing temperature.
The temperature can effectively influence the soil behavior and its shear strength [8,9]. However, the review of previous studies shows that although there are several studies on thermal behavior of clays, the effects of applying long-time temperature has not been considered on shear behavior of clay soils. In present work, the effect of thermal pre-curing is precisely investigated on shear behavior of a sand-bentonite mixture. The process has been mainly used here to reflect the status of the buffer layer of nuclear waste repositories or energy piles which are exposed to temperature gradients for a specified time and can be subjected to shear stresses. The curing process performed at different temperatures of for various time periods to consider their effects on the behavior of soil. A comprehensive experimental program was planned using consolidated undrained triaxial tests. The results have also been compared with the mechanical response of the samples in ambient temperature and changes in the response of soil was evaluated. Moreover, using SEM, the changes in the structure of studied soil was monitored at different curing conditions.

2. Materials and Properties

A sodium bentonite with the liquid limit of 179% and plasticity index of 125%, which is classified as CH according to USCS has been used besides a fine and crushed well graded silica sand. The liquid limit and plasticity index of buffer layer in FEBEX site was about 102% and 49%, respectively while these values were reported as 75% and 55% for Boom Clay in CERBERUS and ATLAS tests [10]. Figure 1 shows gradation curves and Table 1 depicts physical properties of the used soils. The chemical composition of sand and bentonite are also given in Tables 2.

In different studies, various bentonite to sand weight ratios have been recommended [11]. As it has been concluded from oedometer tests on various sand-clay mixtures, the behavior of mixtures is significantly affected by the amount of clay and size or shape properties of sand grains [12]. In a study of gas migration through saturated bentonite-sand mixtures, Liu et al.
used a 3:7 weight ratio for sodium bentonite to silica sand to achieve the least permeability. The thermal conductivity of buffer is an important factor for HLW disposals which depends on dry density, water content and sand content [14]. Dixon et al. [15] defined effective porosity ($n_{eff}$) as another factor to calculate optimum weight ratio of bentonite to sand in buffer layers according to Equation 1.

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

Where, $\rho_d$ is the maximum dry density, $G_{s,mix}$ is the specific gravity of mixture and $F$ is 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 has been selected in other programs on HLW disposals in Germany as well as Canada [16]. Drinkable water was used in sample preparation and its chemical composition is presented in Table 3.

The stress-strain behavior of soils is dependent to their mineralogy and response of samples with higher plasticity characteristics is significantly affected by temperature [17]. In order to investigate plasticity changes of studied soil during curing, some index tests performed on thermally cured sand-bentonite mixtures to determine variations in liquid limit (LL) and plasticity index (PI). The results of index tests are shown in Fig. 2. The values of LL and PI were 83% and 57% respectively in ambient temperature. However, both LL and PI decreased in the curing temperatures of 20°C to 80°C. The reasons are water precipitation around clay particles and pasting clay fractions together to form larger particles [18], besides the reduction of specific surface due to drying and the resulted decrease in the water absorption capacity of clay particles [19]. The latter seems to be the most effective reason at the range of considered temperatures in present study (up to 80°C). For high temperatures, transformation from a
mineral to another type comprises changes in initial fabric [20-22]. The same trend has been observed by Attah and Etim [6] for two different tropical clayey sands.

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

3. Triaxial Testing Program

The silica sand and bentonite were mixed and then were compacted in eight equal layers in a cylindrical mold, 100mm in diameter and 200mm 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$^2$ have been obtained for sand-bentonite mixture based on modified Proctor test using a 4.5kg weight hammer and a mold, 100mm in diameter under 25 blows in each of 5 layers. The dry density of sand-bentonite mixture in buffer layer of nuclear waste disposals has been noted between 14.7 to 16.3 kN/m$^3$ in a number of experiments where a 1:1 by weight sand-bentonite mixture has been used at compaction ratios of 85% to 95% [15,26]. In CERBERUS and ATLAS tests besides the Boom Clay at Hades laboratory in Mol, a dry density of 15.8 to 17.5 kN/m$^3$ has been reported [10]. The bentonite used in FEBEX site had an average unit weight of 15.7 to 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 shown in Fig. 3. The triaxial cell was calibrated to handle pressures up to 2000kPa 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 10mm from the sample with a precision of 0.1°C. Due to the small dimensions of specimens, the temperature in the center of sample was equal to the cell temperature after 100 minutes which was measured during calibration process.

After preparing the specimen, a back pressure of 700kPa was applied until a Skempton’s $B$ value of 0.95 was achieved through 6 days of saturation. The final $B$ coefficient depends on several factors like clay content, plasticity characteristics, back pressure and saturation time. Considering lower liquid limit (LL=83%) and plasticity index (PI=57%) of the mixture used in present study, the applied back pressure and saturating time are consistent with the results of Mukherjee and Mishra [28] who obtained a $B$-value of 0.93 using back pressures of 480 to 565kPa in 12 to 17 days for two sand-bentonite mixtures with 10% and 20% clay content (LL=286%), respectively.

The curing temperatures were selected to include different thermal applications like buffer layer in HLW disposal, energy piles or underground buried power cables. The design temperature for buffer layer of HLW disposals should not exceed 90°C due to the reduction of plasticity characteristics. In many cases, the high temperature of HLW is reduced before placing in repositories [29]. The energy piles in Europe are designed for temperature range of -1°C to 35°C. However, in some cases, an increased temperature up to 40°C or 50°C is possible [30]. A maximum temperature of 80°C has been reported around the buried cables and 60°C for 0.25m far from it [31].
The required time to finish primary consolidation of the applied mixed soil has been previously determined through isotropic consolidation tests by Shirasb et al. [7]. The results showed that primary consolidation time increases with increase in temperature and confining pressure. The values were less than 24h for all temperatures in 100kPa. When the confining pressure increased to 500kPa, it was achieved in less than 24h at 20, 40 and 60°C. At 1000kPa, it was less than 24h only at 20°C and 40°C, however, it was less than 40h at all temperatures and confinements [7]. For this reason, the pre-curing times of 1, 3 and 5 days were chosen in present study.

Two sets of tests were carried out to study the shear behavior of sand-bentonite mixtures. At the first set, in order to investigate the time dependent thermal behavior of mixed soil, the samples were pre-cured for 1, 3 and 5 days at a constant temperature of 40°C, 60°C or 80°C under the confining stresses of 100kPa, 500kPa or 1000kPa keeping the drainage valve open. Similar to Lingnau et al. [26], the consolidation process was considered to be complete when the rate of volumetric strain was less than 0.1%/day. The temperature was correctly controlled to remain constant in this time period and up to the end of the test. Moreover, three reference tests have been performed at the mentioned confinements and ambient temperature of 20°C. After consolidation, the undrained shear loading started at a rate of 0.2mm/min. The loading continued up to the axial strain of about 20%. During shear loading, deviatoric stress, axial strain and excess pore water pressure have been continuously measured using calibrated sensors and data acquisition system. To consider the effects of repeatability, 30% of total triaxial tests were randomly repeated.

At the second group of tests, thermal stress paths were applied to the samples and their behavior has been monitored. Two samples were heated from the ambient temperature (20°C) to 80°C under the confining pressure of 100kPa for 1 and 5 days. Then, 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 tests on samples at the same curing time without any thermal cycling. Table 4 depicts a summary of testing program at this study.

4. Results of Triaxial Tests

4.1. Stress-strain and pore pressure behavior

Figures 4 to 6 show deviatoric stress-axial strain and excess pore water pressure-axial strain curves of thermally cured samples obtained from consolidated undrained triaxial tests at initial confinements of 100, 500 and 1000kPa, respectively. The range of variations has been shown by toolbars for repeated tests. Table 5 shows a summary of the experimental results obtained from triaxial tests. The samples were consolidated at elevated temperatures of 40, 60 or 80°C under confining pressures of 100, 500 or 1000kPa for 1, 3 or 5 days, which were named as “cured samples” in present study. After that, undrained shear loading started on the cured samples. In order to investigate the curing effects on shear behavior of soil, the results of triaxial tests at ambient temperature of 20°C have been also depicted in Figs. 4 to 6.

Based on the figures, samples at the ambient temperature showed smaller shear strength than the samples consolidated at higher temperatures; however, their shear strength increased with increase in confining stress. The trend of behavior for these samples was consistent with 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 to curing time showing more strength for the samples cured for a longer period. The increase in shear strength with temperature can be explained by different theories such as oxidizing of aluminum and iron during heating and dehydration of iron oxides which create bonds between clay particles [18]. According to Fig. 4, a distinct failure point can be observed for the samples with 3 and 5 days of curing, while samples with 1 day of curing show a hardening behavior during shear loading. The shear strength of cured samples increased with increase in confining pressure as
shown in Figs. 5 and 6 for 500kPa and 1000kPa confinements, respectively. Based on Fig. 7a, the shear strength of cured samples increased with increase in curing time and curing temperature. Moreover, these samples also failed in smaller level of strain and experienced softening behavior according to Fig. 7b. The trend of behavior for thermally cured samples was much similar to that of the structured or overconsolidated clays [34] or artificially structured soils [35]. It should be noted that a similar transition of behavior has been observed during the consolidation tests on the studied cured sand-bentonite mixture [7].

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

Figures 4 to 6 also show the variations of excess pore water pressure with axial strain. The samples consolidated at ambient temperature showed positive pore water pressure; however, samples cured at elevated temperatures in different curing times and confinements showed a different trend of behavior. The induced pore pressure in these samples decreased with increase in curing time and curing temperature. For the samples cured at higher temperatures for longer time periods, the pore pressure even reached to negative values. The samples cured at 80°C experienced negative pore pressure at all curing times and confinements; however, for a temperature of 60°C, negative pore pressures were only observed for 5 days of curing at a confining stress of 100kPa. The samples consolidated at 40°C did not show negative pore pressures at any consolidation time and confinement. This type of behavior is similar to the structured soils and certifies that thermal curing up to the longer periods of time (more than the
required time for primary consolidation) results to a transition of the behavior from the reconstituted to the structured state. Indeed, the reduction of excess pore water pressure with temperature for the reference specimens (samples tested at the ambient temperature) agrees well with the results of Abuel-Naga et al. [33] on soft Bangkok clay. Also, the general trend of changes in excess pore water pressure for the samples cured at elevated temperatures is similar to the results of Rios and Baudet [36] for cemented silty clay and Amini et al. [37] on cemented gravely sand which are among the category of structured soils. Some other soils can be also considered as structured due to cation exchange, flocculation and agglomeration, cementitious hydration, and pozzolanic reaction [38].

As it is implemented before, increase of temperature can lead to bonding between particles due to the dehydration of iron oxides, which can be considered as the reason for the observed negative pore pressures. This is a time dependent procedure [39]; so, 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 at confining pressures of 100, 500 and 1000kPa have been presented in Fig. 9. The stress paths have been plotted at 40, 60 and 80°C for 1, 3 and 5 days of curing and were compared with the stress path of the samples tested at the ambient temperature. It was concluded that increase in 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 100kPa (Figs. 9a, 9b and 9c). Moreover, increase in 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 (Figs. 9c, 9f and 9i).
A comparison of the critical state line’s slope ($M_T$) at different curing times and temperatures in present study with other works has been displayed in Fig. 10. The results show that $M_T$ which is also related to the critical state friction angle slightly varies with both curing time and curing temperature. The normalized slope to values in ambient temperature ($M_0$) slowly increase with increase in temperature and curing time that confirms the expansion of the size of yield loci in elevated temperatures. It should be noted that laboratory studies of many other researchers showed that the critical state friction angle increases, slightly increase, stays constant, or decreases with increase in temperature [40]. Equation 2 shows the trend of variations when $M_T$ increases with increase in temperature [40]. Here, ζ is a calibration parameter which has been determined as 0.007 for the sand-bentonite mixture considered in present study.

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

(2)

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

5. Discussion

In order to demonstrate the effect of curing process on the behavior of sand-bentonite mixture, a few specimens were subjected to cycles of thermal paths. To prove this hypothesis, two samples have been exposed to thermal paths of 20°C-80°C-20°C at a confining pressure of 100kPa. At first, temperature increased from 20°C to 80°C and remained constant to cure for 1 or 5 days. Then temperature decreased to 20°C and the samples were sheared after thermal equilibrium. The results of these tests have been compared with tests on samples at ambient temperature (20°C) without any thermal cycles in Fig 12.
The variation in shear strength of these samples with temperature is shown in Fig. 12a for an initial confinement of 100kPa; where, increase in strength of samples during the curing cycle can be clearly observed. The sample with 5 days of curing reached to greater shear strength than the sample with 1 day of curing. When the samples are cooled again to the ambient temperature, the shear strength of the sample with 5 days of curing was about 62% greater than the initial strength while the increase in shear strength for the sample with 1 day of curing was about 43%.

The variations of Skempton’s pore pressure coefficient, $A$ (associated to the peak shear strength) with temperature is also plotted in Fig. 12b at a confining pressure of 100kPa. Based on the figure, changes in pore pressure during the curing procedure can be investigated. When the $A$ value was about 0.6 for the sample sheared in ambient temperature (20°C), it decreased to about zero for the sample that has been cured for 1 day in 80°C and then was cooled to 20°C, or even to a negative value for the sample that has been cured for 5 days in 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 present study, the change in behavior has been investigated for only low 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 present study (20°C to 80°C) does not influence the composition of tested sand-bentonite mixture. This behavior has been explained previously by Wang et al. [41] where a detailed investigation carried out on the dehydration process in clays. They showed that dehydration of water layers leads to the more bonding between particles; However, the mineral destruction of clay and formation of new silicate crystals occur in temperatures more than 500°C.

The effects of thermal curing on sand-bentonite mixture considering the time factor have been depicted in Fig. 13. The void ratio of cured samples in elevated temperature has been obtained using Image J software and has been highlighted at red color in Fig. 13. The void ratio of samples in different pre-curing conditions has been determined by dividing the highlighted area to the total area at 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 sample at the ambient temperature to 18.3% for pre-cured sample at 80°C for 5 days.

The increase in void ratio during pre-curing process confirms an increase in water content of saturated sample and decrease of its unit weight. This also leads to the increase in permeability of mixture which is in line with the results of Shirasb et al. [7], where they 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 the results of Attah and Etim [6], where they also reported changes in the structure of tropical soils due to thermal preheating process.

6. Conclusions

A comprehensive experimental program has been planned in this study to evaluate the effects of thermal curing on the shear behavior of a sand-bentonite mixture and the following results obtained:

- Considering the deviatoric stress-axial strain diagrams for different temperatures, it was found that the shear strength of sand-bentonite mixture increased with increase in curing time
and temperature, however, the strain associated to the peak shear strength decreased with more curing of the sample. The excess pore water pressure also decreased with increase in curing parameters (time and temperature) from positive towards the negative values. The trend of variations in excess pore water pressure for higher temperatures was similar to the structured clays.

- The effective stress path of the tested specimens in each temperature was shifted towards the left side of total stress path with increase in 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 critical state line increased slightly with curing temperature and curing time. Also, the undrained secant elastic modulus increased with more curing of the soil.

- Cyclic thermal paths revealed that after curing in higher temperatures and returning to the ambient value, the induced pore pressure and deviatoric stress are not the same as initial condition. The samples had more shear strength while pore pressure dropped to smaller values, similar to the trend of behavior which is usually observed for structured soils. In present study, it was inferred as a quasi-structured behavior of the soil induced by thermal curing.

- Based on the results of SEM, the void ratio of samples increased with increase in curing time and curing temperature.

- Based on the results of 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, the increase in void ratio of mixture during 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.
Acknowledgement

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Table Captions

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(c) Deviatoric stress-axial strain at 60°C; (d) Pore pressure-axial strain at 60°C
(e) Deviatoric stress-axial strain at 80°C; (f) Pore pressure-axial strain at 80°C
Figure 6. Triaxial shear behavior of sand-bentonite mixture at different temperatures and curing times for $p'_0=1000\text{kPa}$

(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
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Figure 8. Effect of temperature and curing time on the secant modulus at 50% of peak strength

(a) $T=40^\circ C$; (b) $T=60^\circ C$; (c) $T=80^\circ C$

Figure 9. Total and effective stress paths of sand-bentonite mixtures at different temperatures and curing times

(a) $p'_0=100\text{kPa}, T=40^\circ C$  (b) $p'_0=100\text{kPa}, T=60^\circ C$  (c) $p'_0=100\text{kPa}, T=80^\circ C$
(d) $p'_0=500\text{kPa}, T=40^\circ C$  (e) $p'_0=500\text{kPa}, T=60^\circ C$  (f) $p'_0=500\text{kPa}, T=80^\circ C$
(g) $p'_0=1000\text{kPa}, T=40^\circ C$  (h) $p'_0=1000\text{kPa}, T=60^\circ C$  (i) $p'_0=1000\text{kPa}, T=80^\circ C$

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

Figure 11. Effect of curing time and temperature on the yield surface of sand-bentonite mixture at $p'_0=100 \text{ kPa}$

(a) 1 day curing  (b) 3 days curing  (c) 5 days curing

Figure 12. Variation of shear characteristics for temperature cycle of 20°C-80°C-20°C in a confining pressure of 100kPa

a) Shear strength  b) Skempton’s $A$ coefficient

Figure 13. SEM images of the studies soil in 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  (l) 80°C, 5 days
Biographies

Amir Hamidi

Amir Hamidi is a Professor in Geotechnical Engineering at Kharazmi University, Iran. He received his BS, MSc and PhD degrees in Civil Engineering from Sharif University of Technology in 1997, 1999 and 2005, respectively. He has been a visiting scholar at Barcelona Tech (UPC), Spain in 2018. His research interests include experimental soil mechanics and constitutive modeling, ground improvement (dynamic compaction, cemented soils) and environmental geotechnics (coupled thermal problems and contaminated soils). He has published five books, 80 more scientific articles and about 100 presentations in conferences related to his research fields.

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Mohammad Mehdi Ahmadi

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Table 1. Physical properties of used soils

<table>
<thead>
<tr>
<th>Property</th>
<th>Sand (0.06mm-0.2mm)</th>
<th>Bentonite (0.06mm-0.2mm)</th>
<th>1:1 mixture (0.06mm-0.2mm)</th>
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<tbody>
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<td>Name (USCS(^\dagger))</td>
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<td>CH</td>
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<td>Silt (%)</td>
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<td>31</td>
<td>16.5</td>
</tr>
<tr>
<td>Sand (0.06mm-0.2mm)</td>
<td>23</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>Sand (0.2mm-1mm)</td>
<td>55</td>
<td>0</td>
<td>27.5</td>
</tr>
<tr>
<td>Sand (&gt;1mm)</td>
<td>20</td>
<td>0</td>
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<tr>
<td>LL (%)</td>
<td>-</td>
<td>179</td>
<td>83</td>
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<tr>
<td>PI (%)</td>
<td>NP</td>
<td>125</td>
<td>57</td>
</tr>
<tr>
<td>w(_{opt}) (%)</td>
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<td>-</td>
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</tr>
<tr>
<td>(\gamma_{max}) (kN/m(^3))</td>
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<td>-</td>
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<tr>
<td>(\gamma_{d,max}) (kN/m(^3))</td>
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<td>-</td>
<td>17.0</td>
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\(^\dagger\)Unified Soil Classification System
Table 2. Chemical composition of soils

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>Bentonite</th>
<th>Silica Sand</th>
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<tr>
<td>SiO₂</td>
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<td>Al₂O₃</td>
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<td>Fe₂O₃</td>
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<td>Na₂O</td>
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<td>CaO</td>
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<td>SO₃</td>
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</tr>
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<td>TiO₂</td>
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</tr>
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<td>L.O.I</td>
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Table 3. Chemical analysis of the used water

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<tr>
<td>Type of tests</td>
<td>Testing condition</td>
</tr>
<tr>
<td>---------------------------------------------------</td>
<td>------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Thermal triaxial compression test</td>
<td>Consolidation in confining pressures of 100, 500, and 1000 kPa at defined temperature and time. Undrained shearing at strain rate of 0.2 mm/min with record of deviatoric stress, axial strain and pore pressure.</td>
</tr>
<tr>
<td>Reference thermal triaxial compression test</td>
<td>Primary consolidation in confining pressures of 100, 500, and 1000 kPa at ambient temperature. Undrained shearing at strain rate of 0.2 mm/min on thermally consolidated samples.</td>
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<tr>
<td>Cyclic thermal triaxial compression test</td>
<td>Heating from the ambient temperature to 80°C for a confinement of 100 kPa and then thermal curing at 80°C for 1 or 5 days. Again, cooling to 20°C and shear after thermal equilibrium.</td>
</tr>
<tr>
<td>Reference cyclic thermal triaxial compression test</td>
<td>Consolidation in confining pressure of 100 kPa at ambient temperature of 20°C for 1 and 5 days and then shearing.</td>
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### Table 5. Summary of thermal triaxial compression test results

<table>
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<tr>
<th>Test No.</th>
<th>Consolidation temperature (°C)</th>
<th>Consolidation time (day)</th>
<th>Confining stress (kPa)</th>
<th>Deviatoric stress (kPa)</th>
<th>Mean effective stress (kPa)</th>
<th>Axial strain (%)</th>
<th>Pore pressure (kPa)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>At peak</td>
<td>At critical state</td>
<td>At peak</td>
<td>At critical state</td>
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<tr>
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<td>1000</td>
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Table 6. The changes in void ratio of sand-bentonite mixture during pre-curing

<table>
<thead>
<tr>
<th>Curing temperature (°C)</th>
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<th>60</th>
<th>80</th>
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<tbody>
<tr>
<td>Curing time (day)</td>
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<td>3</td>
<td>5</td>
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<tr>
<td>Void ratio (%)</td>
<td>1.6</td>
<td>1.8</td>
<td>2.4</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Figure 1. Particle size distribution curves of silica sand, Sodium bentonite and 1:1 sand-bentonite mixture
Figure 2. Variations of liquid limit and plasticity index with curing time and temperature
Figure 3. Schematic diagram of the pressure chamber in 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, 18) Back pressure imposing and testing tube.
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°C; (d) Pore pressure-axial strain at 60°C
(e) Deviatoric stress-axial strain at 80°C; (f) Pore pressure-axial strain at 80°C
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;  (f) Pore pressure-axial strain at 80°C
Figure 6. Triaxial shear behavior of sand-bentonite mixture at different temperatures and curing times for $p_0=1000\text{kPa}$

(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; (f) Pore pressure-axial strain at 80°C
Figure 7. The change in shear characteristics with temperature for different curing times

(a) Shear strength (b) Axial strain at failure
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;  (c) T=80°C
Figure 9. Total and effective stress paths of sand-bentonite mixtures at different temperatures and curing times

(a) $p_0'=100$ kPa, $T=40^\circ C$  
(b) $p_0'=100$ kPa, $T=60^\circ C$  
(c) $p_0'=100$ kPa, $T=80^\circ C$  
(d) $p_0'=500$ kPa, $T=40^\circ C$  
(e) $p_0'=500$ kPa, $T=60^\circ C$  
(f) $p_0'=500$ kPa, $T=80^\circ C$  
(g) $p_0'=1000$ kPa, $T=40^\circ C$  
(h) $p_0'=1000$ kPa, $T=60^\circ C$  
(i) $p_0'=1000$ kPa, $T=80^\circ C$
Figure 10. Effect of temperature on the slope of critical state line for different clays
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  (c) 5 days curing
Figure 12. Variation of shear characteristics for temperature cycle of 20°C-80°C-20°C in a confining pressure of 100kPa

a) Shear strength    b) Skempton’s A coefficient
Figure 13. SEM images of the studies soil in 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  (l) 80°C, 5 days