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Effect of Temperature on the Compressibility Behavior of Glass Fiber-bentonite Mixture

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Abstract

In line with the global need for energy, various renewable and clean energy sources have become increasingly popular. Heat piles, buried high-voltage cables, and high-level nuclear waste (HLW) storage areas are examples of energy structures. Since these energy structures emit high temperatures and increase the temperature of the surrounding soil, investigating and improving the thermo-hydro-mechanical behavior of soils under high temperatures has become essential. Bentonite is a clay with high montmorillonite content, which is preferred as a buffer material due to its high swelling capacity, low hydraulic conductivity and chemical resistance.

In the present study, a series of laboratory experiments were conducted to investigate the volumetric deformation behavior of bentonite at 80 °C. Tests were performed on the samples kept at 80 °C to observe the effect of high temperature on the volumetric deformation of bentonite in short and long (6 months and 1 year) terms. Glass fiber (GF) was added to bentonite due to its favorable engineering properties at high temperatures. The results have shown that high temperature increased the compressibility of bentonite mixtures while decreasing swelling deformation. The compressibility of the mixtures after curing decreased. Compared to room temperature (RT), the compression strain increased by 22.8% at 80 °C. With 6-months curing at 80 °C, it further increased by up to 33.2%. However, after 1-year curing, a slight decrease of 4.9% was observed. GF significantly increased the swelling behavior of bentonite at RT. However, this effect decreased at high temperature.

Keywords

bentonite, glass fiber, high temperature, volumetric deformation, curing effect

1 Introduction

Considering the limited availability of fossil fuels and their harmful effects on the environment, it is inevitable that the trend towards environmentally friendly and sustainable energy sources has increased in the last century. In this respect, other than wind and solar energies, which are thought to be a solution to the energy problem, energy structures that come to mind are also taking their place, such as high-power buried cables, heat piles, and high-level nuclear waste (HLW) repositories. These energy structures interact with the surrounding soil and transmit high temperatures and thermal cycles to the soil for long periods. Hence, there is an increased emphasis on studies examining the thermo-hydro-mechanical behavior of soils that have been observed over the past two decades. Studies have shown that the engineering behavior of soils may significantly alter in the presence of high temperatures. Examining and improving the engineering behavior of soils that will be exposed to thermal changes for many years under high temperatures are of great importance for the integrity of energy structures and, thus, to prevent harm to the environment and human beings.

Storage of nuclear waste in deep geological disposal is an important concept in terms of energy geotechnics. With its low permeability and high swelling potential, bentonite clay is considered in HLW repositories. The long-term heat release by nuclear waste causes changes in the structure

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of the buffer material bentonite clay. Hence, it is critical to determine the short and long-term engineering parameters of bentonite under high temperatures.

The former studies have shown that high temperatures affect the consolidation behavior of clayey soils. The main focus of these studies has ranged widely in terms of types of soils, experimental methods, soil properties investigated, etc. Among the most important factors affecting the compressibility parameter of soils under the influence of temperature are temperature range, stress range, mineralogical structure of the soil, and stress history.

In one of the earliest studies, drained isotropic consolidation experiments of remolded and water-saturated illite samples were performed at three temperature conditions (24.7, 37.8, 51.4 °C) and as a result, it was stated that the effect of temperature on the compression index (C_c) parameter was negligible [1]. Towhata et al. [2] used normally consolidated (NC) and over-consolidated (OC) MC kaolin clay and bentonite with a liquid limit value of 450%. A conventional oedometer test apparatus was used, and the temperature range was 25–90 °C. As a result, it was stated that temperature causes volumetric contraction, and volumetric contraction is independent of stress level and over-consolidation ratio (OCR). The higher contraction of bentonite than MC clay is related to the plasticity of clays. Abuel-Naga et al. [3] studied the thermo-mechanical behavior of natural soft Bangkok clay, with temperatures up to 90 °C. When the volumetric strains of the samples with different OCR values were observed with the heating/cooling cycle (22–90–22 °C), it was observed that NC clays experienced an irreversible contraction and increased nonlinearly with increasing temperature, while highly OC clays showed a reversible expansion. Abuel-Naga et al. [4] compared the plasticity index and volumetric strain data of other studies to show the variation of the plasticity of clays to volumetric strain, and as a result, it was stated that increasing the plasticity index in clays increases the volumetric strain nonlinearly. Also, it was stated that the volumetric strain increased slightly with increasing temperature and the change in C_c and swelling index (C_s) was insignificant.

The compacted unsaturated bentonite pellets used in HLW storage repositories will take a long time to reach water saturation. Furthermore, the geostatic stress at the top of bentonite pellets at depths of 500–1000 meters is expected to be in the range of about 9–16 MPa [5]. Therefore, it is very important to investigate the thermo-hydro-mechanical properties of compacted unsaturated bentonites. In this respect, some researchers have developed suction and temperature-controlled oedometers or isotropic cells [6–8]. Ye et al. [8] conducted experiments with unsaturated compacted GMZ bentonite, which has a dry density of ρ_d = 1.70 Mg/m^3 in a suction and temperature-controlled oedometer. A very wide range of experiments were performed, such as the suction range from 0–110 MPa, temperature range from 20–80 °C, and vertical pressure range from 0.1–80 MPa. As a result, it was observed that high temperature causes expansion in bentonite at high suction values and contraction at low suction values. Furthermore, the elastic and plastic compressibility decreased with increasing suction. It was emphasized that the effect of temperature was insignificant in elastic compressibility, and it caused a small decrease in plastic compressibility as in the same with saturated soils. Hoseinimighani and Szendefy [9] conducted an extensive review of the studies about volumetric change in fine soils under thermal conditions. It was reported that NC clays showed irreversible contractions during drained heating tests. For OC clays (OCR > 8), an initial expansion followed by a small amount of contraction was observed with increasing temperature, while for lightly OC soils, an initial small expansion followed by contraction was observed, as in NC clays. It was also stated that pre-consolidation pressure decreases with increasing temperature, also high plasticity decreases pre-consolidation pressure more in temperature change.

Fibers are extremely thin, thread-like forms defined by high length to width ratios. These materials play a key role in many industries, applications and composites due to their outstanding strength, flexibility and versatility. These materials are classified into two main categories: natural fibers derived from plants (e.g., bamboo, cotton, cane, flax) or animals (e.g., wool, silk) and man-made synthetic fibers made from different materials (e.g., basalt, carbon, polypropylene, glass). Each type of fiber has unique features that make it suitable for different applications. Natural fibers generally offer breathability and biodegradability, while synthetic fibers are superior in strength, stiffness and durability. Today, the production of glass fiber (GF) starts with the necessary raw materials (sand for silica, clay for alumina, colemanite for boron oxide and limestone or calcite for calcium oxide) being mixed and fed into a furnace at 1600 °C. At this temperature, the raw materials melting in the furnace become glass and form the glass melt. At this stage, the glass melt is directed into channels for flow. The glass melt, which

flows freely through the barrel holes, is mechanically wound on a mandrel rotating at high speed to produce GFs of constant diameter. Many researchers have used GF to reinforce the engineering properties of soils [10–14] because of GF's high tensile strength, high elastic modulus, environmentally friendly features, etc. Studies have shown that GF addition increased the unconfined compressive strength [10], shear strength [12], hydraulic conductivity [13], while decreasing the C_c [15], volumetric strain [16] and desiccation shrinkage [17] of soils.

Various fiber materials are used to improve the mechanical properties of the clayey soils. In this study, the short-term and long-term compressibility behavior of bentonite with GF additive under high temperature was investigated.

2 Materials and methods

In this study, bentonite clay and GF were used as materials. It is a commercial bentonite and was obtained from Unye Madencilik. The photos of the bentonite and GF used in the study are given in Fig. 1. The bentonite used in this study is a calcium-based bentonite that was activated with sodium bicarbonate to enhance its swelling and impermeability properties. It can be classified as sodium-activated calcium bentonite.

All laboratory tests were carried out at the Soil Mechanics Laboratory of Dokuz Eylul University, Izmir, Türkiye. As can be seen from Fig. 1, bentonite is grey in color and powder form. The specific gravity (G_s) of bentonite is 2.60, the natural water content is between 6–8% and the bentonite sample passes through a No.200 sieve. The experiments were conducted in the laboratory for the characterization of bentonite. These include hydrometer, consistency limits, pH measurement, X-ray diffraction (XRD), methylene blue index (MBI) and cation exchange capacity (CEC) tests. The physico-chemical properties of bentonite are summarized in Table 1.

The grain size distribution of the bentonite was obtained by hydrometer analysis according to ASTM

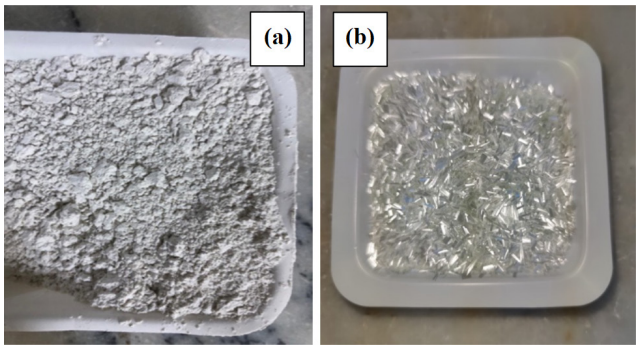

Fig. 1 Samples used in this study: (a) bentonite, (b) GF

Table 1 The physico-chemical properties of bentonite

Parameter	Value
G_s	2.6
Passing sieve	No.200
Natural water content (%)	7
pH	9.13
Liquid limit (%)	270
Plastic limit (%)	63
Clay fraction < 2 mm (%)	82
CEC (meq/100 g)	68
Specific surface area (m^2/g)	611

D422-63(2007)e2 [18]. The grain size distribution curve of bentonite is given in Fig. 2. According to the results, the clay content of bentonite was found to be 82%. In this study, the term 'clay content' refers to the percentage of particles smaller than 2 μm, which was determined through hydrometer analysis in accordance with ASTM D422-63(2007)e2 [18].

The pH measurement of bentonite and GF samples was performed according to ASTM D4972-19 [19].

XRD analyses of bentonite were performed using Thermo Scientific ARL X'TRA device. XRD analyses were performed with focusing geometry between 0° and 89°, scanning speed at 0.1° 2θ/s, and radiation at 60 kV on Thermo Scientific ARL X'TRA XRD equipment. In addition, XRD analyses of bentonite were conducted both at room temperature (RT) and on samples exposed to 80 °C to determine the effect of high temperature on its mineralogy. For the analysis carried out at RT, bentonite was prepared in its original form (as powder), while for the analysis of the material exposed to 80 °C, the sample was placed in the ring in powder form, kept in the thermal pool at 80 °C with the help of a clamped mold for 48 h, then dried in the oven and broken with the help of a pestle. Then the sample was sieved through a No.200 sieve.

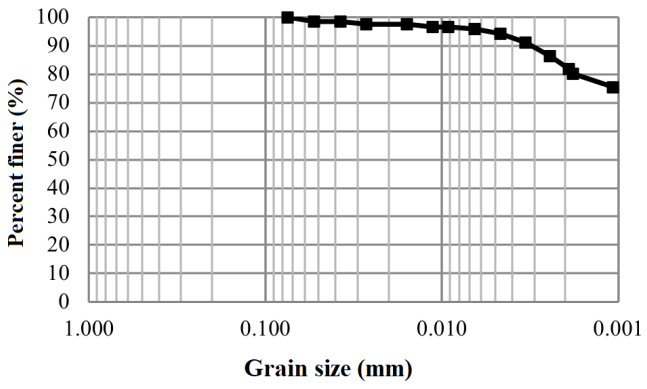

Fig. 2 Grain size distribution curve of the bentonite

When the XRD analyses were examined, montmorillonite, quartz, calcite and albite minerals were found in bentonite at RT (Fig. 3 (a)). When the temperature was increased to 80 °C, changes occurred in the structure of bentonite. While the montmorillonite ratio in bentonite decreased, calcite mineral was not observed at high temperatures (Fig. 3 (b)).

Liquid and plastic limit tests were conducted according to ASTM D4318-17e1 [20]. Casagrande and Fall Cone tests were conducted to determine the liquid limit of bentonite and bentonite-GF mixtures. The results are presented in Table 2.

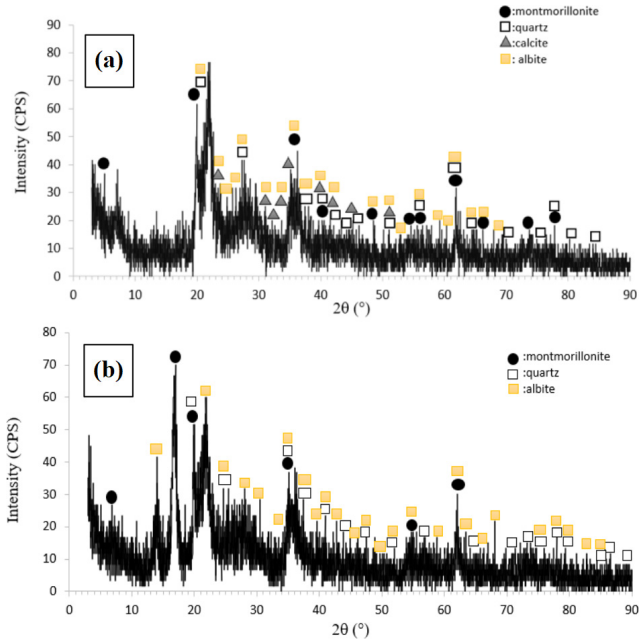

Fig. 3 XRD analysis results of bentonite at: (a) RT; (b) 80 °C

Table 2 Liquid and plastic limit test results

Sample	LL* (Casagrande method)	LL* (Fall cone method)	PL**
Bentonite	270.0	265.0	63.0
0.5% GF	267.7	263.9	59.1
1% GF	263.6	262.3	56.2

* Liquid limit
** Plastic limit

Table 3 Technical properties of GF [21]

Property	GF
G_s	2.6
Tensile strength (MPa)	3400
Modulus of elasticity (GPa)	77
Application temperature limits (°C)	710
Melting temperature (°C)	1120
pH	7.18
Diameter (μ)	13
Length (mm)	3

The properties of the used GF are given in Table 3 [21]. The GF used in this study is a commercially available E-glass type, which is primarily composed of SiO_2, CaO, Al_2O_3, and B_2O_3.

Consolidation tests were performed according to ASTM D2435/D2435M-11(2020) [22]. Test samples were prepared with a water content of 1.5 times the liquid limit value obtained from the Casagrande experiment. Tap water was used to prepare the mixtures. Mixing of the samples was performed with the help of a mixer. The prepared mixtures were kept 24 h in a closed plastic bag for uniform moisture distribution and then placed in a specially manufactured sample preparation apparatus (Fig. 4). The purpose of the sample preparation apparatus was to load the seating pressure on the sample and to prepare identical samples.

A perforated drainage plate, porous stone, and filter paper were placed in the steel drainage container, respectively (Fig. 4). A stainless-steel consolidation ring was used in the consolidation tests, and there were filter papers on the top and bottom of the sample. The diameters of the steel drainage container, consolidation ring and acrylic glass cell were 7.0 cm. Samples were placed above the ring height plus up to a height of 2 cm. Tap water was administered from above in a controlled manner to ensure that the water

Fig. 4 Sample preparation apparatus: (a) perforated drainage plate; (b) porous stone; (c) filter paper; (d) consolidation ring and acrylic cell

content of the samples did not change throughout the process. The samples were left to be consolidated under seating pressure for 14 days. The seating pressure was 12.25 kPa. The samples removed from the apparatus after 14 days were used by trimming the part outside the consolidation ring.

Consolidation experiments were carried out at RT and 80 °C. Modifications were made to the oedometer cell to perform the experiments at 80 °C. The heat ring and thermostat probe were placed inside the oedometer cell to maintain a constant 80 °C temperature inside the cell. The temperature was increased by 5 °C/h with the help of a thermostat to prevent excess pore water pressure formation. In order to prevent water loss inside the consolidation cell due to evaporation, a thick membrane was placed on top of the cell and a continuous tap water supplement was supplied from the top through pipes.

To understand the long-term behavior of bentonite, experiments were also carried out on samples which were left to cure in a hot water pool for 6 months and 1 year. For curing, two identical hot water pools were manufactured. There were four heat rods, and these heat rods were connected to Arduino system thermostats and served to measure and change the temperature. To prevent the formation of excess pore water pressure within the samples, the samples were closed with a clamped mold, were kept in a pool, where it will increase by 1 °C/h before being pleased into the other pool at a constant temperature of 80 °C. The samples prepared in the apparatus in the consolidation ring were placed in the manufactured stainless steel clamped mold with porous stones on top and bottom (Fig. 5 (a)). The samples were taken out of the pool after the curing periods and were also subjected to consolidation tests. Thanks to the clamped mold, the swelling of bentonite under water was prevented (Fig. 5 (b)). A representative photograph of the sample taken after the curing period is shown in Fig. 6.

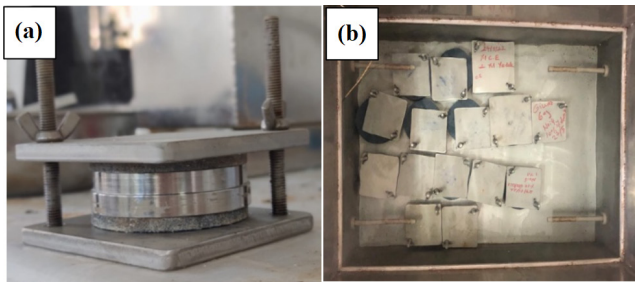

Fig. 5 Sample curing equipment: (a) stainless-steel clamped mold; (b) internal view of the thermal pool

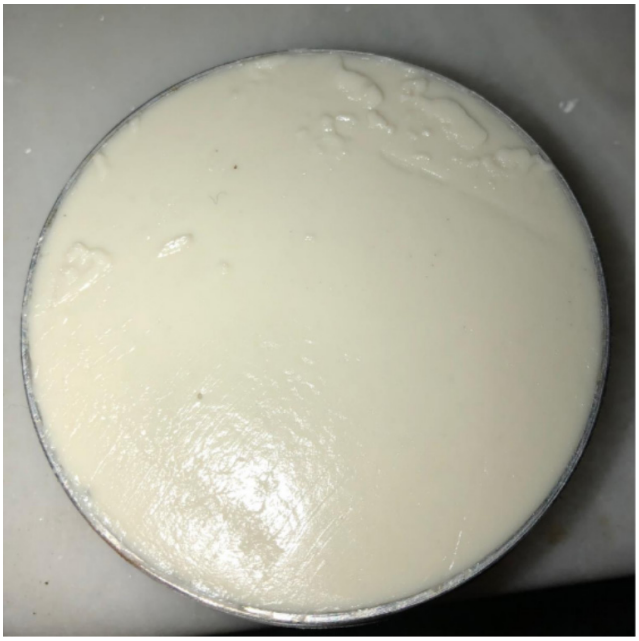

Fig. 6 Photograph of the sample after curing

As shown in Fig. 6, the sample retained its shape and remained within the mold boundaries without significant shrinkage or deformation.

GF was added corresponding to 0.5% and 1% by dry weight of bentonite. The liquid limit value of the bentonite-GF mixture was found to be 265%.

3 Results and discussion

To investigate the consolidation behavior of the specimens, vertical stress (σ_v) and vertical strain (ε_v) plots and normalized e-log σ plots were obtained at the end of the experiment. Total compression and swelling strain values were determined from the σ_v and ε_v graphs. Compression strain values represent the deformation in the range of 24.5–784 kPa, while swelling strain values represent the deformation in the range of 784–49 kPa from the rebound curve. Since the initial void ratio values of all experiments varied in a wide range between 6.0 and 8.4, normalized e-log σ graphs were presented by starting the initial void ratios of all samples from 1.0 in order to explain the void ratio change visually. C_c and C_s values were obtained from the original void ratio values. For C_c values, void ratio values in the range 196–784 kPa were considered, while for C_s, void ratios in the range 784–49 kPa were considered.

To investigate the effect of two different contents of GF additives on the consolidation behavior of bentonite under different thermal conditions, consolidation tests were performed. These thermal conditions were RT, 80 °C

temperature, short-term (6 months) and long-term (1 year) curing periods. The results were discussed and interpreted by comparing the C_c, C_s, compression and swelling strain, coefficient of consolidation (c_v) and coefficient of volume compressibility (m_v) values.

3.1 Compression and rebound behavior under RT

Consolidation tests of bentonite and GF-added bentonite samples were conducted at RT. Normalized e-log σ' plots of experiments at RT are given in Fig. 7. As can be seen from Fig. 7, the compression strain of bentonite was 53.3%. The compression strain values of 0.5% and 1% GF added bentonites were 52.5% and 58.0%, respectively. With 0.5% GF additive, the compression strain change was −1.4%, while with 1% GF additive, this change was 8.9%. The swelling strain of bentonite was found to be 7.2% at RT. GF additives with 0.5% and 1% contents improved the swelling strain of bentonite at RT (Table 4). GF additives increased the C_c and C_s values of bentonite at RT.

The C_c and C_s values and the compression and swelling strain values with the additives are shown in Table 4. The C_c of bentonite at RT was found to be 2.46. With 0.5% GF additive, the C_c changed by −10.4% to 2.21. With 1% GF additive, it changed by 46.2% to 3.6. The C_s of bentonite and mixtures with 0.5% and 1% GF additives were 0.52, 0.88 and 1.38, respectively. The GF additive contents increased the C_s value of bentonite (Table 4).

3.2 Settlement and rebound behavior under high temperature (80 °C)

The results of consolidation tests carried out at 80 °C in the modified oedometer test apparatus for high temperature and the normalized e-log σ' plots of the experiments at 80 °C temperature are shown in Fig. 8. Compression and swelling strain values are also given in Table 5.

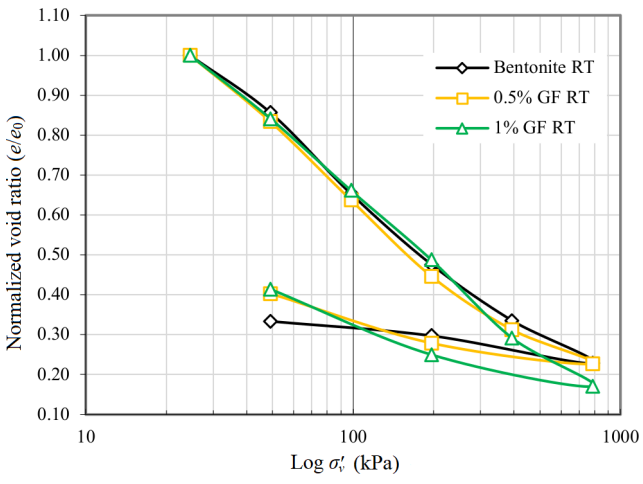

Fig. 7 Normalized e-log σ' curves of GF added bentonite mixtures at RT

Table 4 The compression and swelling strain, C_c and C_s at RT

Sample	Compression strain (%)	Swelling strain (%)	C_c	C_s
Bentonite	53.3	7.2	2.46	0.52
Bentonite – 0.5% GF	52.5	12.0	2.21	0.88
Bentonite – 1% GF	58.0	17.0	3.60	1.38

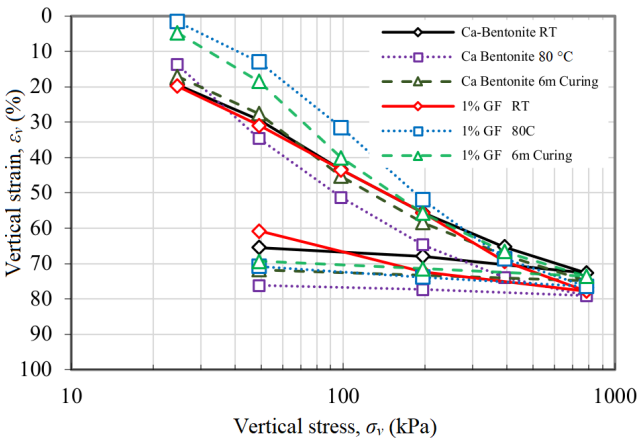

Fig. 8 Stress-strain graphs of the samples

Table 5 The compression and swelling strain, C_c and C_s at high temperature (80 °C)

Sample	Compression strain (%)	Swelling strain (%)	C_c	C_s
Bentonite	65.5	4.0	3.31	0.37
Bentonite – 0.5% GF	68.8	4.8	3.37	0.38
Bentonite – 1% GF	74.9	5.7	3.67	0.43

According to the results, the compression strain of bentonite at 80 °C was 65.5%. The compression strain of bentonite with 0.5% and 1% GF additives were 68.8% and 74.9%, respectively. GF additive increased the compression strain of bentonite under high temperature (80 °C).

In terms of swelling strain, GF additive increased the swelling strain of bentonite for both contents at 80 °C. While the swelling strain of bentonite under high temperature was found to be 4.0%, the swelling strain values increased with 0.5% and 1% GF additives and were found to be 4.8% and 5.7%. When the experiments performed at RT are compared with the experiments performed in the presence of 80 °C, the compression strain of all three mixtures increased while the swelling strain decreased. It was observed that the GF additive increased the compression strain and swelling strain of bentonite both at RT and at 80 °C, while its effect on the swelling strain decreased at 80 °C.

The C_c and C_s of bentonite were 3.31 and 0.37, respectively. GF additive increased the C_c and C_s of bentonite at 80 °C. With 0.5% GF addition, C_c increased to 3.37, while with 1% GF addition, C_c increased to 3.67. The C_s values also increased with GF additive and increased from 0.37

to 0.38 and 0.43 with 0.5% and 1% GF additives, respectively (Table 5).

3.3 Effects of curing, high temperature and GF content on the volume deformation

The experiments were conducted at RT and at 80 °C to understand the effect of high temperature on consolidation behavior. In order to examine the long-term effects of high temperatures, some samples were kept in water pools at 80 °C for 6 months and 1 year, and then consolidation experiments were performed. The effect of GF additives on the consolidation behavior of bentonite at these thermal conditions was also investigated. The compression strain, swelling strain, C_c and C_s obtained from the results of the experiments were compared. Fig. 9 shows the bar graph distribution of the compression strain values obtained from the experiments. Table 6 shows the compression and swelling strain values.

The results indicated that while 1% GF content resulted in increased compression strain under all thermal conditions, the addition of 0.5% GF caused a slight decrease at RT but led to higher compression strain at 80 °C and after long-term curing. This behavior may result from the interaction between the GF and the bentonite matrix, which varies with temperature and moisture conditions. At RT, a small amount of GF may limit deformation without disturbing the matrix. However, at elevated temperatures, bentonite becomes denser and less plastic due to water loss and thermal effects. In this case, limited GF content may not provide sufficient reinforcement and could even facilitate internal movement and increasing strain. These findings are consistent with previous studies. For example, Xu et al. [23] and Libos and Cui [24] reported that fiber performance under thermal conditions is closely related to the distribution and bonding quality between fibers and the matrix. Under certain temperatures, limited fiber content may no longer act as reinforcement but instead behave as a weak inclusion in the system.

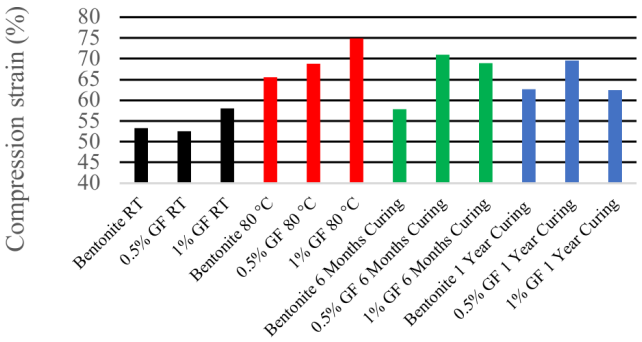

Fig. 9 The compression strain values of the samples

Table 6 Compression and swelling strain and index values of all mixtures under different thermal and curing conditions

Sample	Condition	Compression strain (%)	Swelling strain (%)	C_c	C_s
Bentonite	RT	53.3	7.2	2.46	0.52
	80 °C	65.5	4.0	3.31	0.37
	80 °C–6m	57.8	–	–	–
	80 °C–1y	62.6	–	–	–
Bentonite +0.5% GF	RT	52.5	12.0	2.21	0.88
	80 °C	68.8	4.8	3.37	0.38
	80 °C–6m	71.0	–	–	–
	80 °C–1y	69.6	–	–	–
Bentonite +1% GF	RT	58.0	17.0	3.6	1.38
	80 °C	74.9	5.7	3.67	0.43
	80 °C–6m	68.9	–	–	–
	80 °C–1y	62.4	–	–	–

As can be seen from Fig. 8, there is no specific trend in the compression strain values. However, it can be concluded from the results that the compression strain of all mixtures increased in the presence of 80 °C temperature. In terms of the curing effect, while the compression strain values of bentonite decreased slightly, no change was observed in 0.5% GF mixtures and the curing effect had a positive effect as a decrease in 1% GF mixtures. In addition, both contents of GF additives caused an increase in the compression strain of bentonite at all thermal conditions.

The change in C_c according to the mixtures is shown in Fig. 10. As in the compression strain, C_c also showed an increasing trend in the presence of 80 °C. The insignificant change in the C_c was observed with the effect of high temperature for the 1% GF mixture. There is a decrease in C_c, as seen in compression strain in all mixtures during both curing periods. It can be concluded that the GF additive caused a slight increase in the C_c value of bentonite at all thermal conditions.

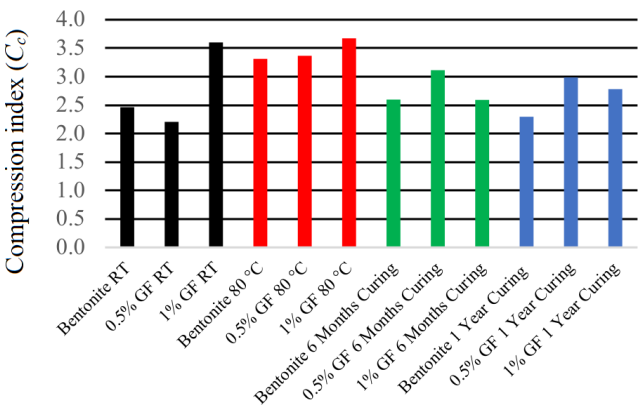

Fig. 10 The distribution of the C_c values

It is expected that when soils are exposed to high temperatures, the quantity of energy they possess will increase; therefore, the energy of soil particles will increase. Molecules with elevated energy will become more mobile and thus weaken the existing bonds even more. As a result, the amount of compression in the soil will increase [25, 26]. Bag and Rabbani [27] reported that the C_c value increased from 0.76 to 0.96 as the temperature increased from 25 °C to 90 °C in their study with Bikaner bentonite. Considering the effect of GF on the compressibility of bentonite, it can be said that it increases the compressibility as a general trend. However, studies on clayey soils in the literature have given contradictory results. Mukherjee and Mishra [17], Jadda et al. [15] in their studies on sand-bentonite mixtures and clayey soils stated that the C_c decreased slightly with the addition of GF, while Güneri [28] and Çirkin [29] in their studies with sand-bentonite and zeolite-bentonite mixtures showed that the addition of GF led to a slight increase in the C_c. The compressibility values found in this study gave high values in terms of compression strain and C_c values due to the fact that the sample used was only bentonite and the initial water content was high. Due to the high-water content of the sample in this, GF may not have been able to improve the compressibility by providing adhesion between the clay grains.

In addition, as a general trend, the compressibility behavior of mixtures decreased with the curing effect. This may be due to the change in bonds between layers of bentonite under high-temperature curing effect. The montmorillonite mineral due to illitization transforms mineral which has less swelling with prolonged heat.

A large positive effect of GF additive on the swelling behavior was observed at RT (Fig. 11). In the presence of 80 °C, this effect decreased but still had a positive influence. The effect on swelling behavior decreased even more under the curing effect. This change is also seen in the C_s values. Comparing the mixtures at 80 °C and the mixtures under the curing effect, a slight decrease in the swelling behavior of bentonite and GF-added mixtures was observed during the curing effect.

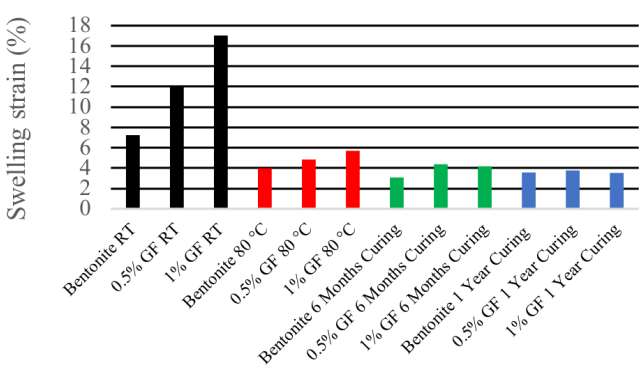

Fig. 11 The distribution of the swelling strain values

Former studies have indicated that temperature significantly affects the swelling behavior of bentonite. Xiang et al. [30] stated that the swelling deformation decreased under high temperature with the effect of σ'. The Gouy-Chapman equation represents the volume change of clays. The equation is also known as the diffuse double layer (DDL) model and previous studies have reported that the thickness of DDLs increases with increasing temperature. Thus, increasing temperature induces swelling of clays [31, 32].

The values of the c_v and m_v were obtained from the consolidation tests. The values of c_v were taken from 196 kPa load level. The results have shown that c_v values increased with temperature. In addition, this increase continued with the curing effect and the c_v values of the samples at 1 year curing time were higher than the c_v values of the samples at 6 months curing time. In addition, GF additive increased the c_v value of bentonite. This increase became more noticeable in the presence of 80 °C. The bar graph for c_v are given in Fig. 12. As in c_v values, it was observed that higher temperature increased the m_v value. Although the curing effect was not clearly seen in the change in m_v, m_v values varied between 2.71×10^{-5} and 3.62×10^{-5} m^2/kg in all experiments performed at 80 °C temperature.

4 Conclusions

Consolidation tests of bentonite and GF added bentonite samples were conducted at room and high temperatures. In addition, the samples were cured under high temperatures for six months and one year. In consolidation experiments conducted at RT, GF additive caused an increase

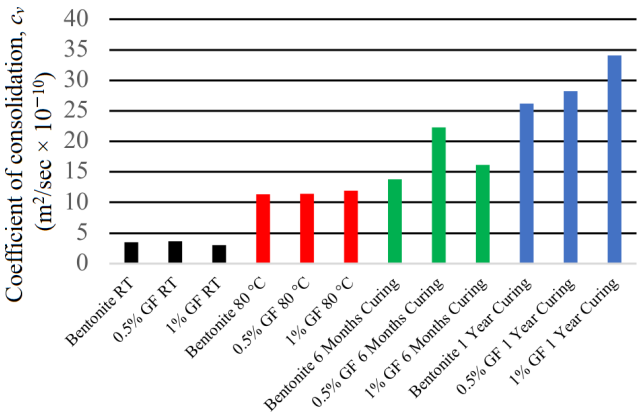

Fig. 12 The c_v values of the mixtures according to log fitting method

in rebound behavior. This increment increased as the GF content increased and while the C_s value of the bentonite without additive was 0.52, it increased to 0.88 and 1.38 with 0.5% and 1% GF additive, respectively. The rebound behavior of the mixtures decreased significantly in the presence of 80 °C temperature. At 80 °C temperature, GF addition increased the compressibility. However, the change remained negligible. C_c values are 3.31, 3.37 and 3.67 for bentonite, 0.5% and 1% GF mixtures, respectively. In the specimens kept under 80 °C temperature for a curing period of 6 months, a decrease in compressibility was observed in the specimens due to the curing effect. There was also a decrease in swelling strain. The change in compressibility and swelling behavior with the increase in curing time from 6 months to 1 year is negligible.

The addition of GF into bentonite may offer potential benefits; however, based on the current findings, its use cannot yet be recommended without further evaluation. Particularly, the increase in compressibility observed with 1% glass fiber under all conditions suggests that its application should be carefully reconsidered. A more comprehensive assessment including swelling potential, hydraulic conductivity, and microstructural behavior is required before determining the feasibility and optimal content of GF in thermally affected barrier materials.

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