DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APLIED SCIENCES

THE EFFECT OF PUMICE, PERLITE AND FIBER GLASS ADDITIVES ON THE THERMAL CONDUCTIVITY, COMPRESSIBILITY AND SHEAR STRENGTH BEHAVIOR OF ZEOLITE-BENTONITE AND SAND-KAOLIN MIXTURES UNDER HIGH TEMPERATURES

by
İsa ÇİRKİN

March, 2023
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İsa ÇİRKİN

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"THE EFFECT OF PUMICE, PERLITE AND FIBER GLASS ADDITIVES ON THE THERMAL CONDUCTIVITY, COMPRESSIBILITY AND SHEAR STRENGTH BEHAVIOR OF ZEOLITE BENTONITE AND SAND-KAOLIN MIXTURES UNDER HIGH TEMPERATURES"** completed by **İSA ÇİRKİN** under supervision of **PROF. DR. YELİZ YÜKSELEN AKSOY** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

With the increasing number and variety of energy geo-structures in recent years, it has become very important to investigate the engineering properties of the soils around these structures under high temperatures. Soils surrounding energy structures should be able to maintain their engineering properties for many years when exposed to high temperatures. Studies in the literature report that engineering properties of soils such as compressibility, shear strength and hydraulic conductivity are negatively affected under high temperatures. Perlite, pumice and fiberglass are high temperature resistant materials widely used in thermal insulation. Therefore, they can be used to maintain or improve the engineering properties of bentonite-zeolite and sand-kaolin mixtures under high temperatures.

In this study, shear strength, compressibility and hydraulic conductivity behaviors of sand-kaolin and bentonite-zeolite mixtures in the presence of perlite, pumice and glass fiber additives were investigated. In addition, the effects of perlite, pumice and glass fiber additives on the thermal conductivity of sand-kaolin and bentonite-zeolite mixtures were determined. Direct shear, consolidation and hydraulic conductivity tests were carried out at room and high temperatures (80 degrees Celsius) to investigate the effects of additives. Pumice and fiberglass additives decreased the shear strength of sand-kaolin mixtures both at room temperature and high temperature. Fiberglass additives increased the shear strength of sand-kaolin mixtures at room temperature, but decreased the shear strength at elevated temperature. When the temperature of the bentonite-zeolite mixture was increased to 80 degrees Celsius, the shear strength increased. When the bentonite-zeolite mixtures were analyzed, the hydraulic conductivity value increased with temperature.

Keywords: Perlite, pumice, fiberglass, high temperature, bentonite-zeolite, sand-kaolin, shear strength, consolidation

POMZA, PERLİT VE CAM ELYAF KATKILARININ ZEOLİT-BENTONİT VE KUM-KAOLİN KARIŞIMLARININ TERMAL İLETKENLİK, SIKIŞMA VE KAYMA DAYANIMI DAVRANIŞLARINA YÜKSEK SICAKLIK ALTINDA ETKİLERİ

ÖZ

Son yıllarda sayısı ve çeşitliliği artan enerji yapıları ile birlikte, bu yapıların etrafında yer alan zeminlerin yüksek sıcaklık altındaki mühendislik özelliklerinin incelenmesi oldukça önemli hale gelmiştir. Enerji yapılarını çevreleyen zeminler ise yüksek sıcaklığa maruz kaldıklarında mühendislik özelliklerini uzun yıllar koruyabilmelidir. Literatürdeki çalışmalarda ise zeminlerin yüksek sıcaklık altında sıkışabilirlik, kayma dayanımı ve hidrolik iletkenlik gibi mühendislik özelliklerinin olumsuz etkilendiği rapor edilmektedir. Perlit, pomza ve cam elyaf ısı yalıtımında yaygın olarak kullanılan yüksek sıcaklıklara karşı dayanıklı malzemelerdir. Bu nedenle bentonite-zeolit ve kum-kaolin karışımlarının yüksek sıcaklık altında mühendislik özelliklerinin korunması veya iyileştirilmesinde kullanılabilirler.

Bu çalışmada kum-kaolin ve bentonite-zeolit karışımlarının perlit, pomza ve cam elyaf katkıları varlığında kayma dayanımı, sıkışabilirlik ve hidrolik iletkenlik davranışları incelenmiştir. Ayrıca perlit, pomza ve cam elyaf katkılarının kum-kaolin ve bentonite-zeolit karışımlarına termal iletkenlik açısından katkıları incelenmiştir. Kesme kutusu, konsolidasyon ve hidrolik iletkenlik deneyleri oda sıcaklığı ve yüksek sıcaklık (80 santigrat derece) altında gerçekleştirilerek katkı malzemelerinin etkileri araştırılmıştır. Pomza ve cam elyaf katkıları kum-kaolin karışımlarının kayma dayanımını hem oda sıcaklığı hemde yüksek sıcaklık altında azaltmıştır. Cam elyaf katkısı ise oda sıcaklığında kum-kaolin karışımlarının kayma dayanımını arttırırken, yüksek sıcaklık altında kayma dayanımını azaltıcı etki göstermiştir. Bentonite-zeolit karışımının sıcaklığı 80 santigrat derece ’ye çıkarıldığında kayma dayanımı artmaktadır. Bentonit-zeolit karışımları incelendiğinde ise hidrolik iletkenlik değeri sıcaklıkla beraber yükselmiştir.

Anahtar Kelimeler: Perlit, pomza, cam elyaf, yüksek sıcaklık, bentonite-zeolit, kum-kaolin, kayma dayanımı, konsolidasyon

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CHAPTER 1
INTRODUCTION

1.1 Statement of the Problem

Today, with increasing world population, there is a rapid increase in the amount of energy required and accordingly, the number and diversity of energy structures are increasing. Due to the fact that the currently used fossil fuel resources are running out and there is a need for new energy sources. New energy sources are preferred to be renewable, environmentally friendly and more efficiently sources. Therefore, the number of the new energy sources such as wind, solar, geothermal and nuclear energy and energy piles increased in the last century. Soils around energy structures are exposed to high temperatures and thermal changes. If the soils around energy structures lose their engineering properties under high temperatures, serious problems may occur in terms of human health and the environment. Therefore, the behavior of soils surrounding energy structures under different thermal conditions becomes more important.

According to the studies in the literature, the engineering behavior of soils may change in the presence of different thermal conditions. Especially high temperatures caused change in the compressibility parameters, shear strength behavior and hydraulic conductivity of soils. These changes may affect the performance of energy geo-structures. For that reason, there is a need for more research on the engineering behavior of soils under different thermal conditions.

It is essential in terms of using to buffer materials that keep their engineering properties under high temperature and temperature cycles. For that reason, some additives which are known with their superior thermal properties may be added to common buffer materials in order to improve/keep its engineering properties in different thermal conditions. For this purpose, the effects of pumice, perlite and fiberglass additives on the engineering

behavior of a buffer material canditates which are sand-kaolin and zeolite-bentonite mixtures were investigated under high temperature and temperature cycles.

1.2 Objective and Scope

The scope of the thesis is to determine engineering behavior of sand-kaolin and zeolite-bentonite mixtures using pumice, perlite and fiberglass additives in order to keep/improve engineering properties such as volume deformation, shear strength and hydraulic conductivity under high temperatures. In this frame, the aims of the thesis are listed as follows:

- To investigate the volume deformation, shear strength, and hydraulic conductivity behavior values of sand-kaolin and zeolite-bentonite mixtures under room temperature, high temperature and temperature cycles.
- To determine the effect of pumice, perlite and fiberglass additives on the engineering behavior of mixtures.
- To determine the thermal conductivity values of the candidate buffer materials in the presence of additives.
- To obtain the optimum content and type of the additive for field applications.

1.3 Outline of the Thesis

The content of each chapter in the thesis as follows:

In Chapter 1, the statement of problem, aim and scope of the thesis are given.

Chapter 2 presents a literature review on the former studies on high temperature effect on the soil behavior is given as volumetric deformation, shear strength, hydraulic

conductivity and thermal conductivity. The information about the used additive materials is also given in this chapter.

Chapter 3 presents the material characterization and the methods used in the experiments.

Chapter 4 shows the compaction test results and effect of temperature on the volumetric deformation behavior of sand-kaolin and zeolite-bentonite mixtures in the presence of additives. The results under room temperature and high temperature are presented comparatively.

Chapter 5 presents the effect of temperature on the shear strength behavior of sand-kaolin and zeolite-bentonite mixtures in the presence of additives.

Chapter 6 shows the effect of temperature on the hydraulic conductivity behavior of sand-kaolin and zeolite-bentonite mixtures in the presence of additives. Thermal conductivity measurement results are also given in this chapter.

In Chapter 7, conclusions and recommendations for future studies are given.

CHAPTER 2
LITERATURE REVIEW

The number and type of energy geo-structures is increasing day by day. The number of studies on soil mixtures under different thermal conditions, especially at high temperatures, is also increasing. Sand-bentonite mixtures or only bentonite are generally used as an impermeable barrier especially on nuclear waste isolation applications. It is necessary both to determine the properties of these soil mixtures used in impermeable barrier applications against high temperatures and to investigate other materials that will provide thermal resistance to soil mixtures.

Previous studies have examined the behavior of soils at temperatures up to 50 °C. However, in recent years, the increasing interest in radioactive waste storage in clay barriers has led to the need to determine the thermo-mechanical behavior of soils up to 100 °C (Abuel-Naga et al., 2006). These studies have shown that temperatures below 100 °C, the boiling point of water, have an effect on the hydraulic conductivity, compressibility and shear strength of saturated fine-grained soils. Therefore, it is extremely important to identify the changes in engineering properties under high temperatures and develop durable soil mixtures that keeps their properties under different thermal effects.

In this thesis, it was tried to develop a high temperature resistant soil material that can be used in nuclear waste isolation, in the impermeable barriers and around energy structures. In this context, perlite, pumice and fiberglass additives were added to zeolite-bentonite and kaolin-sand mixtures, which are alternatives to bentonite-sand mixtures used in impermeable barriers, and hydraulic conductivity, compressibility, shear strength behaviors under high temperature (80 °C) were determined. The most important feature that played a role in the selection of these materials is that these materials are heat resistant and used in thermal insulation and are available in large quantities in Turkey.

2.1 Energy Geo-Structures

The need for energy in the world is increasing day by day and in parallel with this, studies on sustainable and environmentally friendly energy sources have been accelerated. These studies have led to an increase in the number and diversity of energy structures. Energy geo-structures include heat storage systems, buried high voltage cables, oil and gas pipelines, heat piles, CO_2 capture facilities, geothermal energy, nuclear waste disposal facilities, landfill facilities, ground improvement techniques using heating and freezing, subway and tunnel fire prevention designs.

2.1.1 Nuclear Waste Storage Site

After 2020, even if all of Turkey's domestic energy resources are put into service, it will not be possible to meet the entire energy demand, so the construction of nuclear power plants (NPPs), the most important alternative to fossil fuels, in Turkey has come to the agenda (TEÜD, 1999). In developed countries, most of the energy need is met by nuclear power plants (NPPs). In these countries, nuclear waste generated by NPPs is disposed of in underground geological repositories. Nuclear waste should be properly isolated to prevent environmental contamination (IAEA, 1990; IAEA, 2003). It is vital for the success of nuclear waste storage isolation that the materials are mechanically stable, chemically resistant and have very low permeability (IAEA, 2001). Because of these qualities, bentonite and sand-bentonite mixtures have been used as buffers and backfill materials in the isolation of underground nuclear waste repositories in Sweden, Switzerland, Canada, Germany and France (Pusch, 2013). The hydraulic permeability of compacted clay barriers should be of the order of 1×10^{-7} cm/sec (Daniel and Benson, 1990). Westsik et al. (1981) and Radhakrishna et al. (1989) stated that the hydraulic conductivity of compacted bentonite-sand mixtures should be 1×10^{-9} cm/sec and below when used to isolate nuclear waste.

The wastes released in nuclear power plants are radioactive and emit heat and nuclear radiation to their environment during their half-life depending on the type of radioactive material in the waste. Many methods have been developed for the disposal of these wastes and the necessary research and experiments are still ongoing in related projects. An international consensus has emerged on deep geological storage for the disposal of high-level waste (HLW). In this way, radioactive wastes are kept in a deep underground repository in such a way that they do not pose any danger. Geological units studied for storage include rock salt, clays, granite, tuff, basalt and various types of metamorphic rock (OECD Nuclear Energy Agency, 1989). Research is ongoing on the disposal of high radioactivity waste (HLW) by placing it in cylindrical waste canisters made of special materials, shown in Figure 2.1, and then burying it in and around compacted bentonite or sand-bentonite materials in and around rock at a depth of about 200~500 m below the surface.

Systems considered for the disposal of highly hazardous radioactive waste have three different parts. These are impermeable host rock, backfill and bentonite (buffer) (Cho et al., 2012). The buffer and backfill are the two main components of the engineered barrier and should have three important functions in terms of safety. The first one is sealing. In a high-level radioactive waste repository (HLW), there needs to be a sealing barrier between the cylindrical box and the bedrock to slow the transport of radionuclides, prevent the formation of a flow path to bedrock, and contribute to stability (Ballarini et al., 2017). The second is the containment function, which limits the rate of release of radionuclides into bedrock in the event of a failure, and the third is the thermal and mechanical function. The material selected as the buffer and backfill design should first ensure sealing. Once both of these properties are satisfied, the thermal and mechanical performance is checked (Cho et al., 2012).

Figure 2.1 Nuclear waste (canister) (M., Wallin et al, 2006)

The required properties for buffer and backfill are low hydraulic conductivity, high swelling potential, low swelling pressure, high water holding capacity, high thermal conductivity, good mechanical properties and long life (Smith et al., 2008; Johnnson et al., 1994). Therefore, the thermal conductivity of the buffer should be enough to ensure conduction of the heat (Posiva, 2006; Rautioaho and Tanttu, 2009) and the hydraulic conductivity should be slow enough to prevent the circulation of water. One of the important properties of the buffer material is its thermal conductivity. In the face of high temperatures, the conductivity value is very important because it is intended to minimize temperature increases on the surface of the waste canister. The role of the buffer is to reduce the thermal stress on the waste canister and bedrock. The buffer must have good mechanical properties to support the waste canister without significant deformation due to loads.

Many countries around the world prefer bentonite as a buffer material around waste containers for high-level radioactive waste disposal (Pusch, 2013). Bentonite provides low hydraulic conductivity and high swelling pressure. The low hydraulic conductivity

prevents water penetration and solute transport and provides a favorable chemical environment. Furthermore, the swelling pressure of bentonite prevents the container from sinking through the supporting bentonite layers and contact with the waste bin (canister) surface of the bedrock.

In many countries (Sweden, Finland, etc.) a temperature limit of 100 °C is taken as the design limit for nuclear waste repositories. The increasing interest in radioactive waste storage in clay barriers in recent years has led to the need to determine the thermomechanical behavior of soils up to 100 °C (Abuel-Naga et al., 2006). In nuclear waste disposal facilities, the temperature rise due to decay heat has significant effects on bedrock and buffer materials. When the temperature approaches 100 °C, the engineering properties of the buffer material may change. These buffer materials need to be sustainable and durable for up to at least 100 years (Sellin and Leupin, 2013). Therefore, it is vital that not only the short-term but also the long-term performance of the buffer materials remain unchanged at the performance values desired in the design. It is necessary to study in detail how these soils behave as a result of exposure to thermal and hydraulic changes.

2.1.2 Heat Piles

In recent years, ground source heat piles have been increasingly used for heating and cooling of buildings to save energy and reduce emissions. In the future, the use of heat piles will increase rapidly due to urbanization, the increasing importance of energy efficiency and regulations, and rising energy prices. The use of heat piles is also supported by environmental policies. In these systems, well heat exchangers are usually used to exchange heat with the underground environment (Figure 2.2).

In many parts of the world, the temperature in the ground stabilizes at 10~24 °C after 6-10 m depth. Due to the constant ground temperature at shallow depths, it is possible to utilize ground layers as a renewable heating and cooling source anywhere in the world and in any season, without the need for generally known geothermal energy sources. Heat

transfer of saturated fine-grained soils is recognized as the dominant mechanism for heat transfer. Previous studies have shown that backfill materials have a certain influence on the thermal performance of heat piles (Gu and Dennis, 1998). In general, the increase in the thermal conductivity of backfill materials is extremely important for shortening the length of heat piles and for energy efficiency.

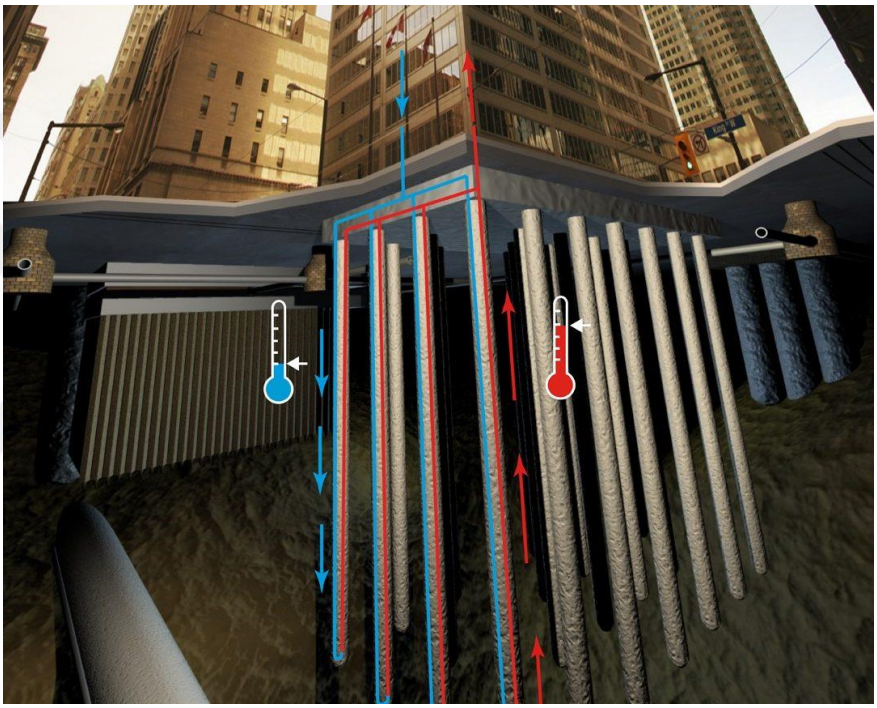

Figure 2.2 Heat piles (EPFL, nd)

2.1.3 High Voltage Buried Power Cables

The thermal conductivity of soils is increasingly becoming critical in the design and application of underground power transmission and distribution systems. Electricity flowing in a conductor generates heat. The heat flow between the cable and its environment (the ground) causes the cable temperature to rise. Cables have temperature ranges for which they are designed. If the design temperature is exceeded, cable life is shortened. Due to the heat flow between the ground and the cable, the thermal properties

of the ground are an important part of the design (Campbell and Bristow, 2009). The greater the thermal conductivity of the ground around high-voltage cables, the faster the ground conducts heat, thus preventing temperature rise due to overheating of the cable. Thermally conductive soils are therefore needed around high-voltage cables. Figure 2.3 shows high-voltage cables installed in the ground.

Figure 2.3 High voltage buried power cables (The Local Electrician, 2021)

2.2 Thermal Effects on the Soil Behavior

Exposure of soils to high temperatures may have a significant impact on the some engineering properties. Previous studies have shown that thermal cycles and high temperatures affect the hydraulic conductivity, volumetric deformation (compressibility-swelling) and shear strength properties of soils (Abuel-Naga et al. 2006; Pusch et al. 1991). Temperature rise in the ground is a significant problem in some cases. The increase in hydraulic conductivity due to temperature rise will lead to irreversible environmental pollution in impermeable barriers used for nuclear waste isolation. Volumetric deformation or loss of strength of soils around other energy structures will damage them. The long-term engineering properties of soils in impermeable clay barriers such as nuclear

power plants, heat piles, heat storage facilities should not be altered by high temperatures and thermal cycles.

2.2.1 Thermal Effect on the Compressibility Behavior of Soils

Previous studies have shown that temperature increase has deformation-enhancing effects on the volume deformation of clay soils. The resistance of changes in clay structure to temperature is explained by the forces between clay particles and the viscous shear resistance of adsorbed water (Abuel-Naga et al. 2007). Abuel-Naga et al. (2006) heated the water in the consolidation cell up to 90 °C in experiments on soft Bangkok clay. In this study, it was determined that soils had a tendency to reduce their volume at high temperatures. The normally consolidated Bangkok clay started to show over consolidated clay behavior due to increased temperature. Also, the compressibility behavior of Bangkok clay affected by heating-cooling cycles. The volumetric changes of the clay were studied by Chen et al. (2016) at temperatures up to 100 °C. Similar to the study of Abuel-Naga (2006), volumetric deformation increase was observed with temperature in this study. The reasons for these effects were reported to be vapor escape causing grain displacement, grain breakage and degradation of organic matter.

The volumetric deformation behavior of soils under high temperature was tested by heating up to 50 °C with water in an odeometer cell (Dalla Santa et al. 2016). According to the results, the soil samples showed a permanent deformation of 9.3% with increasing temperature. Sinha and Kusakabe (2008) investigated the volumetric changes of sand-bentonite mixtures under high temperature. In this study, 10% bentonite - 90% sand mixture was heated up to 75 °C and the volumetric stress behavior was observed. It was observed that the increase in temperature caused an increase in the amount of volumetric deformation. In the experimental results, the unit deformation was 0.37% when the temperature increased from 20 °C to 45 °C, while the unit deformation increased to 0.51% when the temperature increased from 20 °C to 75 °C. Under normally consolidated (NC) conditions, it was determined that the pore water pressure changes with temperature and

therefore the void ratio changes. It was also reported that higher temperatures are more effective in volume changes.

2.2.2 Thermal Effect on the Swelling Behavior of Soils

The sealing performance of bentonite-based materials depends on hydraulic conductivity and swelling properties. As compacted bentonites become saturated, they undergo large volume changes. If this volume change is prevented, the bentonite exerts swelling pressure on the boundaries. The hydraulic conductivity of bentonite decreases with increasing dry density. At high dry density the permeability of bentonite will be very low, but this will increase the swelling pressure. The swelling pressure of the buffer exerts mechanical pressure on the bedrock and the waste canister. Such a situation can lead to failure and deformation. Therefore, the dry density should be optimized (Cho et al. 2012). While the part of the bentonite in contact with the waste canister is exposed to high temperatures, other parts become saturated by taking groundwater from the saturated bedrock. There are limited studies on the swelling behavior of clayey soils in response to temperature. An increase in temperature causes a decrease in hydration forces in bentonite due to the reduction of hydrates on the smectite surface and increases the osmotic pressure in the molecular structure (Pusch et al. 1990). Cho et al. (2002) investigated the swelling pressures of Ca-bentonite and Ca-Mg bentonite. In this study, it was reported that the swelling pressure and hydraulic conductivity increased at high temperature. The behavior of compacted bentonite in response to increasing temperature was studied by Pusch et al. (1990) and Villar and Lloret (2004). According to the results obtained from these studies, increasing temperature causes a decrease in the swelling pressure of Ca-bentonite and Ca-Mg bentonite.

2.2.3 Thermal Effect on the Shear Strength Behavior of Soils

The former studies have shown that high temperature has some effects on the shear strength of soils. These effects can be positive or negative depending on the density, water content, soil type and the mineralogical and chemical composition of the soil (Mitchell, 1969).

Abuel-Naga, Bergado, & Ramana et al. (2006) obtained higher peak shear strength values in experiments conducted under elevated temperature using an electrical heater set-up. The specimens subjected to temperature increase in the previous study were investigated by Wang, Benway and Arayssi (1990). Bentonite and kaolin were heated to 100 °C in an electric oven for 24 hours. The experimental results showed that kaolin showed an increase in the angle of internal friction with increasing temperature. In the case of bentonite, an increase in the angle of internal friction was observed, while a decrease in the cohesion value occurred, and the high cohesion bentonite became a low cohesion soil (Wang et al., 1990).

Hong, Bian, Cui, Gao and Zeng (2013) investigated the shear strength behavior of clay soils under high temperature. They reported that the volume change that occurs with increasing temperature has an effect on the shear strength of clay. It was reported that the shear strength of soils decreased with thermal expansion and increased with thermal contraction.

In another study, the shear strength of specimens heated in NC condition and under drainage conditions was higher than that of unheated specimens. It was noted that the volume change caused by heating did not explain the increase in strength. In the case of, over-consolidted sample the shear strength was not significantly affected by temperature changes. (Kuntiwattanakul et al., (1995).

2.2.4 Thermal Effects on the Hydraulic Conductivity of Soils

The increase in hydraulic conductivity due to increased temperature can lead to major problems in impermeable clay barrier applications and in engineered barrier systems in nuclear waste repositories. Due to the low hydraulic conductivity of bentonite, radionuclides are transported by diffusion in bentonite. By delaying transport, bentonite acts as a very effective barrier. In this case, the hydraulic conductivity of bentonite is of vital importance in nuclear waste isolation systems. The hydraulic permeability of compacted clay barriers should be $1x10^{-7}$ cm/sec (Benson and Daniel 1990; Radhakrishna et al. 1989; Westsik et al. 1981). When bentonite clay is used to isolate nuclear waste, the hydraulic conductivity value should be 1×10^{-9} cm/sec and below.

Former studies in the literature show that the hydraulic conductivity of soils increases with temperature. In the study conducted on soft Bangkok clay up to 90 °C, an electric heater was placed inside the flexible-walled permeameter and triaxial pressure test cell. The temperature of the water in the cell was raised to 90 °C and the experiments were carried out under this temperature. According to the results obtained in the study, it was shown that the hydraulic conductivity value of soft Bangkok clay increased under high temperature (Abuel-Naga et al., 2006). The effect of thermal cycles on hydraulic conductivity was also investigated by Aldaeef and Rayhani (2015). Halton clay and Leda clay were used as clay samples. In this study, the sample was heated to 55 °C for 8 hours by means of a heating blanket and then cooled by turning off the heating blanket. In this way, after 15 and 30 cycles, it was determined that the hydraulic conductivity increased against heat in the experiments performed on three different clays. Cho et al. (2002) and Pusch (2001) reported that the viscosity of the water in the voids decreases due to heating and hydraulic conductivity increases with this effect. For example, the hydraulic conductivity of compacted bentonite at 80 °C was found to be 3-4 times higher than that measured at 20 °C (Cho et al. 2002). Hydraulic conductivity values were determined up to 150 °C for Kyungju Ca-bentonite (dry densities of 1.4 Mg/m^3 to 1.8 Mg/m^3) (Cho et al.

2011). According to the data obtained from this study, the hydraulic conductivity values at a temperature of 80 °C were about three times higher than those at 20 °C. In another study, hydraulic conductivity values of clay with high swelling potential were determined from one-dimensional consolidation test at high temperatures of 40 °C and 60 °C (Shirazi, 2014). It was reported that temperature was the most effective parameter on hydraulic conductivity and hydraulic conductivity values increased significantly with increasing temperature.

Studies in the literature generally obtained hydraulic conductivity values close to the desired criteria with 20% and 30% bentonite content. Kenney et al. (1992) investigated the effect of bentonite/sand ratio and compaction water content on bentonite-sand mixtures. The hydraulic conductivity values of the samples with bentonite ratios of 4%, 8%, 12%, 16% and 22% and compaction water contents of 7%, 12%, 17% and 22% were determined in the range of $2.1x10^{-10}$ - $6.8x10^{-11}$ m/s. Chapuis (1990) determined the hydraulic conductivity values of mixtures containing 2% to 33% bentonite in the range of $2.0x10^{-7}$ - $4.9x10^{-11}$ m/s. Zeolite-bentonite mixtures are suggested as an alternative to sand-bentonite mixtures. The first study on this subject was conducted by Kayabalı (1997) and investigated the suitability of hydraulic conductivity and shear strength properties of zeolite-bentonite mixtures with different bentonite contents (5-40%) for landfill applications. Although relatively wet samples had lower permeability, hydraulic conductivities were clustered between 5×10^{-9} cm/s and 7.5×10^{-8} cm/s and did not change depending on bentonite content. Tuncan et al. (2003) investigated the changes in engineering parameters of zeolite-bentonite mixture with 10% bentonite content (B/Z) after compaction and curing. Hydraulic conductivity tests were performed with flexible-walled permeameters and the hydraulic conductivity of the one-day cured sample was determined as approximately 2.0×10^{-8} cm/s. Ören et al. (2011) obtained the lowest hydraulic conductivity value (5.4×10^{-8} cm/s) for zeolite-bentonite mixtures only if fine zeolite was used in the mixture and at 20% bentonite content [B/(B+Z)].

2.2.4 Importance of Thermal Conductivity in Energy Geo-structures

In parallel with the increase in the variety and number of energy structures, there has been a rapid increase in the number of studies on the thermal conductivity of soils. Heat transfer varies depending on the properties of soils such as water content, dry density and mineralogical composition (Ahn and Jung, 2017, Ömer 2017). The coefficient of thermal conductivity is usually denoted by "λ". The unit thermal conductivity coefficient can be used interchangeably with the unit's W/m-C and W/m-K in the SI unit system.

In energy geo-structures, sometimes thermal conductivity and sometimes thermal insulation are preferred. For example, high thermal conductivity is preferred around heat piles. By adding bentonite ballast material, Engelhardt and Finsterle (2003) obtained a high thermal conductivity between 2.3 and 2.6 W/mK, which they stated led to an increase in heat transmission. Wang et al. (2012) compared the thermal performance of heat piles with saturated medium sand and fine sand as backfill material, where a 6-10% increase in heat transfer was obtained. More recently, due to the good water absorption and swelling property of bentonite grains, sand-bentonite mixtures are often used as a backfill material for vertical borings in many heat pile applications, as recommended by Ashrae (2007). However, in the selection of backfill materials for geothermal boreholes, thermal conductivity is one of the most important factors affecting the design. For these reasons, soils with increased thermal conductivity are needed to improve the performance of energy structures.

2.3 Heat Resistant Materials

2.3.1 Pumice

Pumice is a rock of volcanic origin that has started to enter the industry of our country in the last 20 years. Pumice is a hollow, spongy, porous glassy volcanic rock formed as a result of volcanic events, resistant to physical and chemical factors. During its formation, it contains numerous pores from macro to micro-scale due to the sudden exit of the gases

in the body and sudden cooling. Since there are generally unconnected spaces between the pores, it has low hydraulic conductivity and high heat and sound insulation (Mining Specialization Commission, 2000). Pumice differs from similar volcanic glassy rocks (perlite, obsidian, pumice-tin) with some of its unique properties. It is practically distinguished from them by its color, porosity and lack of crystal water.

Chemically, it can contain up to 75% silica content. The general chemical composition of pumice consists of 60-75% SiO_2, 13-17% Al_2O_3, 1-3% Fe_2O_3, 1-2% CaO, 7-8% Na_2O - 2_2O and trace amounts of TiO_2 and SO_3. The Al_2O_3 composition provides high resistance to fire and heat. Türkiye has a very important potential in terms of pumice reserves. It is estimated that there are approximately 3 billion m^3 of pumice reserves in explored areas (Mining Specialization Commission, 2000). It is known that pumice is used in clay stabilization. Saltan et al. (2011) investigated the stabilizing properties of pumice in road embankments consisting of clay soils. In this study, Atterberg limits, California bearing ratio and dynamically loaded triaxial compression tests revealed that pumice can be used for stabilization of clays used in the lower road embankment layer. Figure 2.4 shows a photographic view of pumice.

Figure 2.4 Photograph of pumice (MTA, nd)

2.3.2 Perlite

Perlite is a type of glassy rock found in significant deposits in Turkey. It does not contain nitrate sulphate, phosphorus, heavy metals, radioactive elements and organic matter. Therefore, it is chemically very pure. The low-density material obtained by heating perlite containing 2-6% water between 800-1150 °C between 4-20 times in volume is called "expanded perlite". The most important feature of perlite is the water content ranging from 2% to 6% and this water provides the stability of perlite (State Planning Organization, 2001). Although the application area of raw perlite is very few and limited, the application area of expanded perlite is many and varied and mainly depends on the physical and chemical properties of perlite. More than half of the perlite produced is used as aggregate in the construction industry, especially in insulation slabs, plasters and concretes. Turkey is one of the countries with the richest perlite reserves in the world. Although our country has rich resources and capacity in terms of perlite, domestic demand remains very limited. Perlite, which is a very good insulation material, has not gained the necessary momentum in domestic consumption (State Planning Organization, 2001).

The studies conducted with perlite are on the stabilization of soils. The stabilization of a high plasticity clayey soil containing smectite group minerals such as montmorillonite with perlite and lime additives was experimentally investigated. For this purpose, mixtures with 0, 10, 20, 20, 30, 40 and 50% perlite and 8% lime (optimum content) were prepared. The experimental results showed that the combination of perlite and lime improved the geotechnical properties of the soil such as workability, plasticity, permeability, compressibility, strength and durability more than perlite alone or lime alone. This experimental study revealed that the SKP30 mixture containing 30% perlite and 8% lime is the optimum solution for the stabilization of this soil. The mathematical equations generated by regression analyses showed that there are strong relationships between geotechnical properties, perlite ratio and time variables (Çalık, 2012). Figure 2.5 shows a photographic view of perlite.

Figure 2.5 Photograph of perlite (MTA, nd)

2.3.3 Fiberglass

Fiberglass is used in many sectors with its thin and durable structure and high temperature resistant structure. Fiberglass is formed by combining glass and polyester melted at high temperature with various chemicals in order to make the plastic or polyester parts produced more robust. In this process, glass fibers obtained by filtering the melted glass through small holes are used. Fiberglass, which is formed by processing glass wires produced in micro sizes, is prepared from a mixture of acid boric, magnesium, siliceous sand, limestone, aluminum and many other components. Known for its low heat conductivity and high mechanical strength, this product can be combined with other chemicals and materials to produce many composite materials (Kompol Fiber, 2023).

Silica-based fiberglass has been widely used for a long time. Fiberglass is readily available commercially in various chemical compositions. Most fiberglass is silica-based (~50-60% SiO_2) and contains other oxides such as calcium, boron, sodium, aluminum, iron, etc. Figure 2.6 shows a photographic view of fiberglass.

Figure 2.6 Photograph of fiberglass (Topolo, nd)

In a study, it was shown that the use of fiberglass improved the behavior of soils under static and dynamic loading conditions, and it was reported that the peak strength of soils with glass fiber under static load increased and limited the post-peak strength decline (Gray, D. H., & Ohashi, H., 1983). Another study showed that glass fiber addition increased the peak compressive strength and ductility of kaolinitic clay. It was observed that the effect on the maximum compressive strength decreased when the length of the glass fiber used increased and the hydraulic conductivity value increased when the glass fiber ratio increased (Maher, M. H., & Ho, Y. C., 1994).

CHAPTER 3
MATERIAL CHARACTERIZATION AND METHODS

3.1 Material Characterization

3.1.1 Materials

In this study, Na -Bentonite, sand, kaolin, zeolite, perlite, pumice and fiberglass were used. Na-bentonite was supplied from Eczacıbaşı Esan Mining Company. The materials used in the tests are shown in Figure 3.1.

Figure 3.1 Materials used in study a) bentonite b) sand c) kaolin d) zeolite e) perlite f) pumice g) fiber glass (Personal archive, 2022)

The grain size distribution curves of sand and zeolite which was used in the tests are given in Figure 3.2. According to this distribution the sand has 3.70% fine content. According to this distribution the zeolite has 48.0% fine content. The sand is classified as sand (SW) according to the United Soil Classification System (USCS) (ASTM: D2487-17).

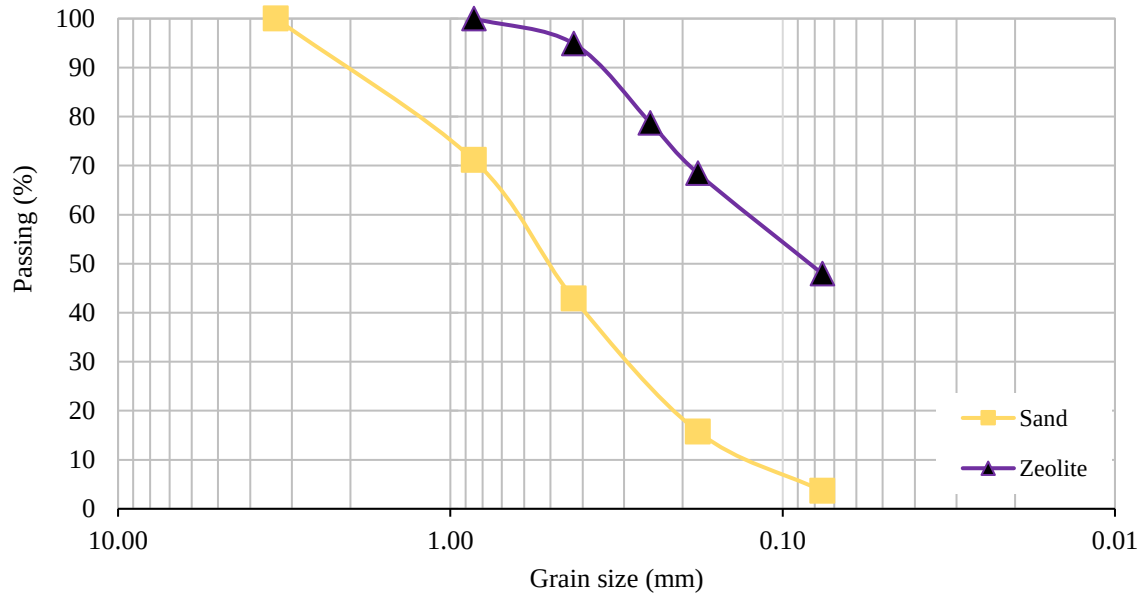

Figure 3.2 Grain size distribution of the samples

The pyhsico-chemical properties of the used materials in the tests are given in Table 3.1. Bentonite has a liquid limit value of 476% and a plastic limit value of 70%. The specific gravity of the bentonite material was found to be 2.70. The liquid limit value of the kaolin material was found to be 34.9%, and specific gravity values was found to be 2.67. The specific gravity values of sand and zeolite materials were found to be 2.63 and 2.30, respectively. The specific gravity values of perlite were found to be 1.50.

Tablo 3.1 Index properties of the materials

	Bentonite	Sand	Zeolite	Kaolin	Perlite	Pumice
Specific gravity	2.70	2.63	2.30	2.67	1.50	2.50
Liquid limit (%)	476.0	-	42.0	34.9	375.1	37.1
Plastic limit (%)	70.10	-	NP*	NP*	NP*	NP*
-No.200 (%)	99.9	3.7	48.0	-	-	-
pH	9.50	-	8.50	-	8.96	8.86

*NP: Non-Plastic

Table 3.2 shows the mechanical properties of the fiberglass. The length of the used fiberglass material was 3.0 mm.

Tablo 3.2 Glass fiber mechanical properties

	Fiberglass
Specific gravity	2.60
Fiber diameter (micron)	13-15
Fiber length (mm)	3.0
Tensile strength (MPa)	3400

3.1.2 X-Ray Diffraction (XRD) Analyses

In this study, XRD analyses of bentonite and sand samples were determined using Rigaku D/Max-2200/C X-ray diffractometer. XRD analyses of zeolite, kaolin, pumice and perlite were performed using Thermo Scientific ARL X'TRA device. According to XRD results, bentonite has quartz (SiO_2), montmorillonite ($Na_{0.3}(Al,Mg)_2Si_4O_4(OH)_{24}H_2O$) and illite. XRD analysis result of bentonite is shown in Figure 3.3.

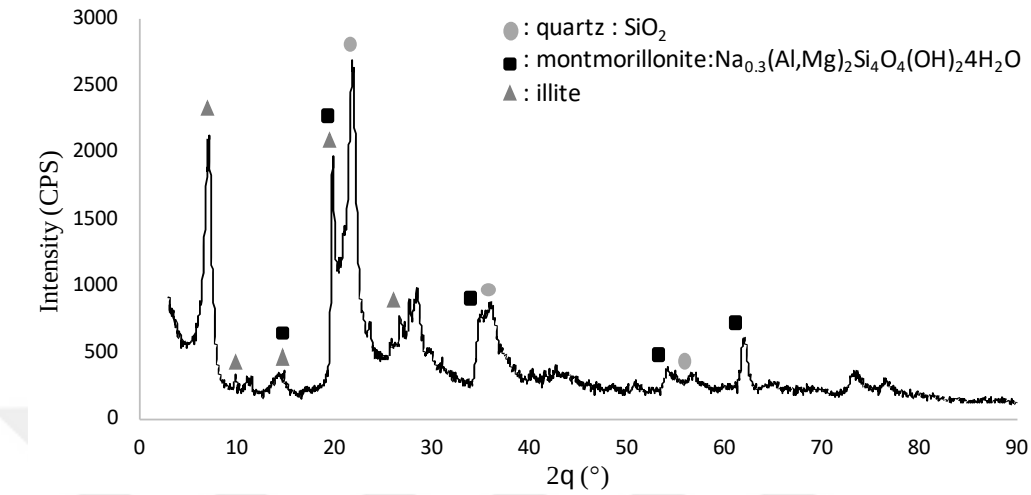

Figure 3.3 XRD analysis results of bentonite sample

As a result of the analysis, clinoptilolite, silica (SiO_2), silicon oxide hydrate, sodium tecta-aluminosilicate hydroxide, and silicon aluminum oxide contents were determined in the zeolite sample (Figure 3.4). In the mineralogic content of kaolin sample, dictate ($Al_2(Si_2O_5(OH)_4)$), mullite and quartz (SiO_2) are present (Figure 3.5).

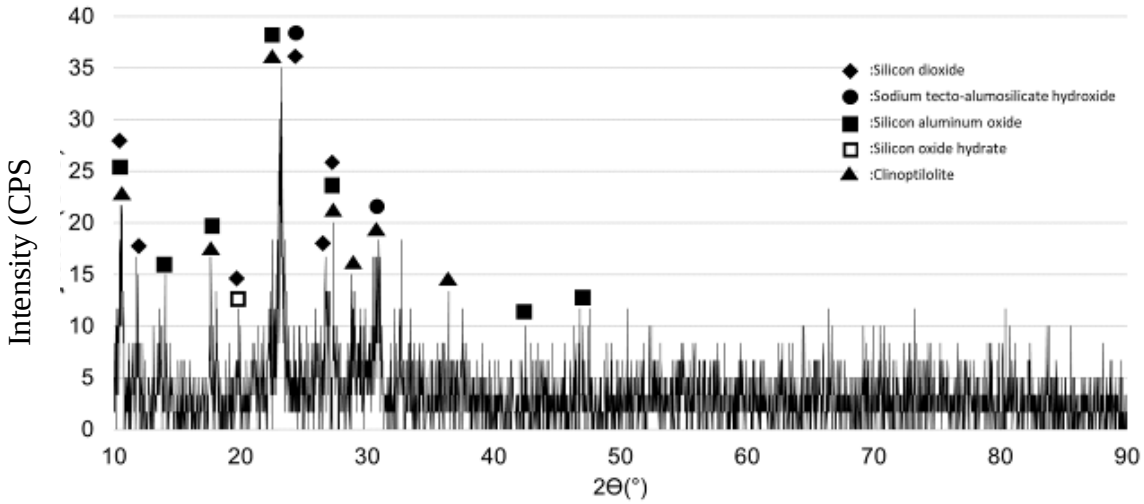

Figure 3.4 XRD analysis results of zeolite sample

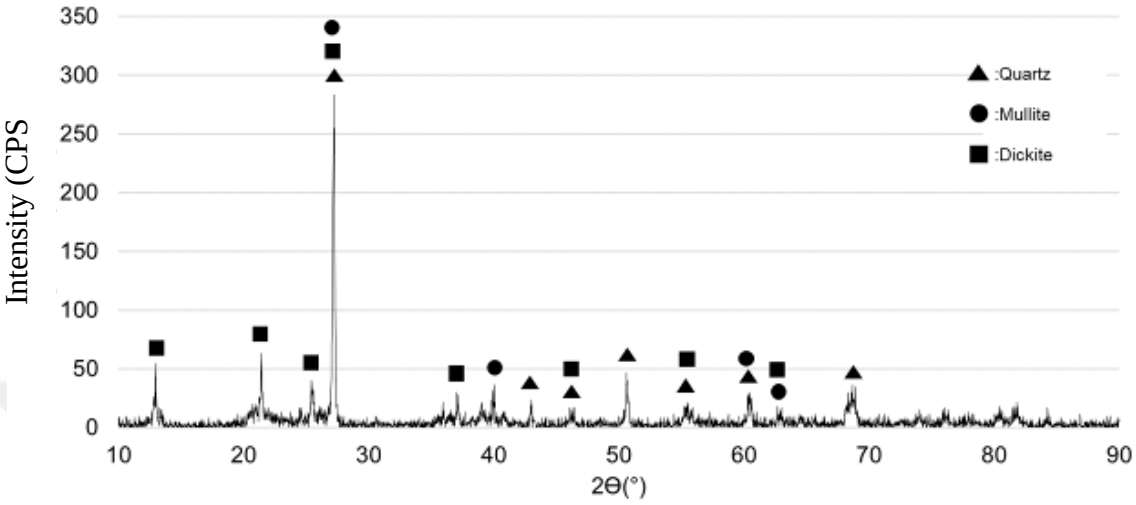

Figure 3.5 XRD analysis results of kaolin sample

In the content of pumice sample, silicate and sodium-aluminum silicate compounds were determined (Figure 3.6). Aluminum oxide, iron oxide, calcium magnesium aluminum oxide silicate was determined in the perlite sample (Figure 2.7).

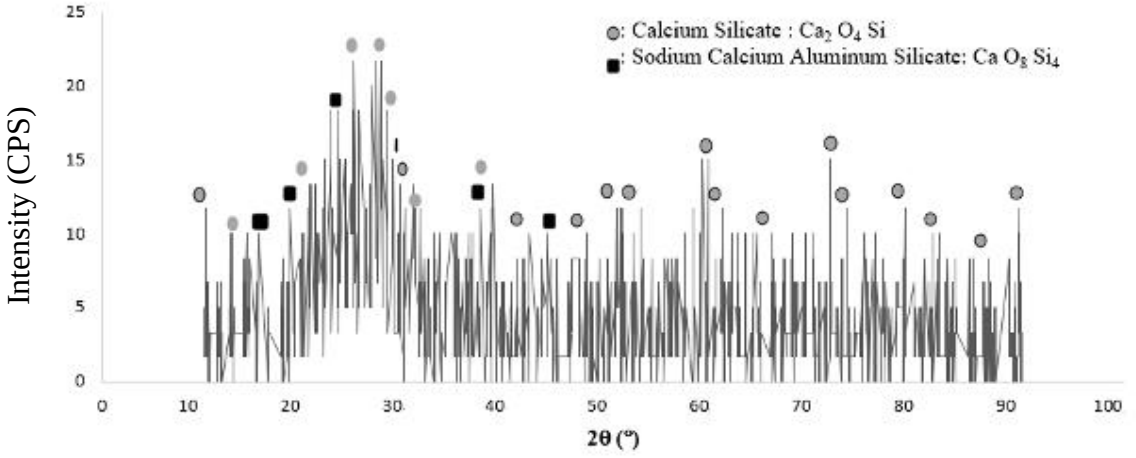

Figure 3.6 XRD analysis results of pumice sample

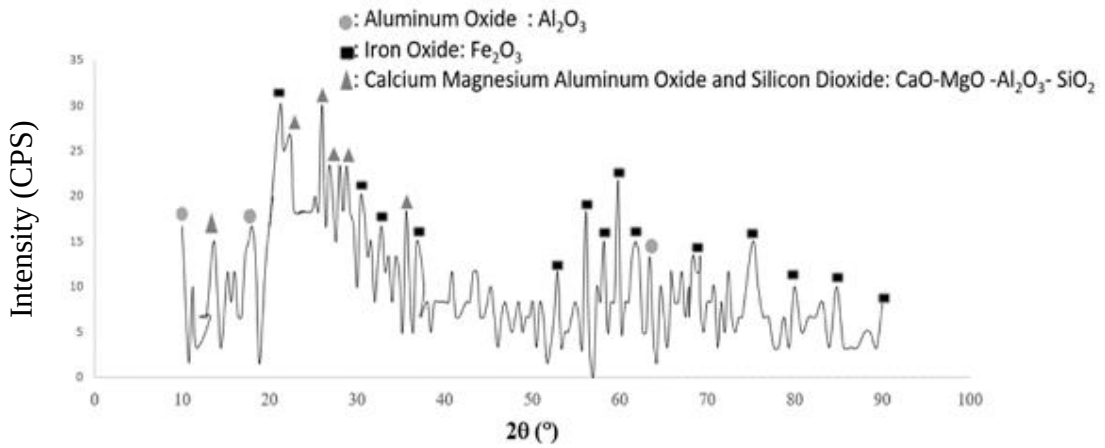

Figure 3.7 XRD analysis results of perlite sample

3.2 Methods

3.2.1 Sample Preparation

In the tests different additive contents were used according to the additive type. For example, pumice and perlite were added in 5% and 10%, however fiberglass was used in 0.5% or 1.0% contents. The samples were weighted depending on their dry weights and mixed homogenously. The sample mixtures to be used for the tests and their abbreviations are shown in Table 3.3. While naming the samples, sand was abbreviated as “S”, bentonite as “B”, zeolite as “Z”, kaolin as “K”, perlite as “PE”, pumice as “PU” and fiberglass as “FG”. For example, 5PE-19B-76Z mixture contains 5% perlite, 19% bentonite and 76% zeolite.

Table 3.3 Abbreviated names of the samples

	Sample abbreviation		
	Perlite	Pumice	Fiberglass
Bentonite – Zeolite Mixtures		20B-80Z	
	5PE-19B-76Z	5PU-19B-76Z	0.5FG-19.9B-79.6Z
	10PE-18B-72Z	10PU-18B-72Z	1.0FG-19.8B-79.2Z
Sand – Kaolin Mixtures		20S-80K	
	5PE-19S-76K	5PU-19S-76K	0.5FG-19.9S-79.6K
	10PE-18S-72K	10PU-18S-72K	1.0FG-19.8S-79.2K

3.2.2 Test Set-up

In this study, compaction, direct shear, consolidation, hydraulic conductivity and thermal conductivity experiments were conducted in the presence of perlite, pumice and fiberglass on the zeolite-bentonite and sand-kaolin mixtures. Direct shear, consolidation and hydraulic conductivity tests were performed at both room temperature and high temperature (80 °C). It is predicted that the hydraulic conductivity of sand-kaolin mixtures will be high and the flow will be fast. In this case, they will not have the desired barrier values. For this reason, hydraulic conductivity experiments were not performed for sand-kaolin mixtures. The experimental set-up is shown in Table 3.4.

Table 3.4 Test set-up

Sample	Compaction tests	Direct Shear/Consolidation tests		Hydraulic Conductivity tests		Thermal Conductivity measurements
		Room Temperature	80 °C	Room Temperature	80 °C	Room Temperature
20B-80Z	✓	✓	✓	✓	✓	✓
5PE-19B-76Z	✓	✓	✓	✓	✓	
10PE-18B-72Z	✓	✓	✓	✓	✓	✓
5PU-19B-76Z	✓	✓	✓			
10PU-19B-76Z	✓	✓	✓	✓	✓	✓
0.5FG-19.9B-79.6Z	✓	✓	✓	✓	✓	✓
1.0FG-19.8B-79.2Z	✓	✓	✓			
20K-80S	✓	✓	✓			✓
5PE-19K-76S	✓	✓	✓			
10PE-18K-72S	✓	✓	✓			
5PU-19K-76S	✓	✓	✓			
10PU-19K-76S	✓	✓	✓			✓
0.5FG-19.9K-79.6S	✓	✓	✓			✓
1.0FG-19.8K-79.2S	✓	✓	✓			

3.2.3 Compaction Tests

Standard Proctor compaction tests were performed in accordance with ASTM-D 698-12 (2012). The soil mixtures and additives were mixed homogenously in the trays. Then, water was added by spraying method according to the predetermined water content, and the mixture was mixed slowly while adding water. The samples were kept in plastic bags for 24 hours. The Standard Proctor Test Compaction Energy was converted to two layers. As a result of these 43 blows were applied to each layer. Then, the samples were compacted into 2 layers of 43 impacts in a standard mold. These processes were performed at four different water contents. The maximum dry unit weight and optimum water content values were determined.

3.2.4 Direct Shear Tests

Direct shear tests were performed according to ASTM D3080 (2018). For direct shear experiments, dry materials were mixed in a container at certain proportions until became homogeneous. After the mixture became homogeneous, water (w_{opt}+2%) was added. After adding water, the mixture was mixed with a spatula to ensure homogeneity. The mixed mixture was placed in a square (6 cm x 6 cm) mold with a dry unit weight value corresponding to the (w_{opt}+2%) value obtained as a result of the compaction experiments. The prepared sample was kept in a water-filled tray for one day. A weight is placed on the sample to prevent swelling. (Fig. 3.8a and b).

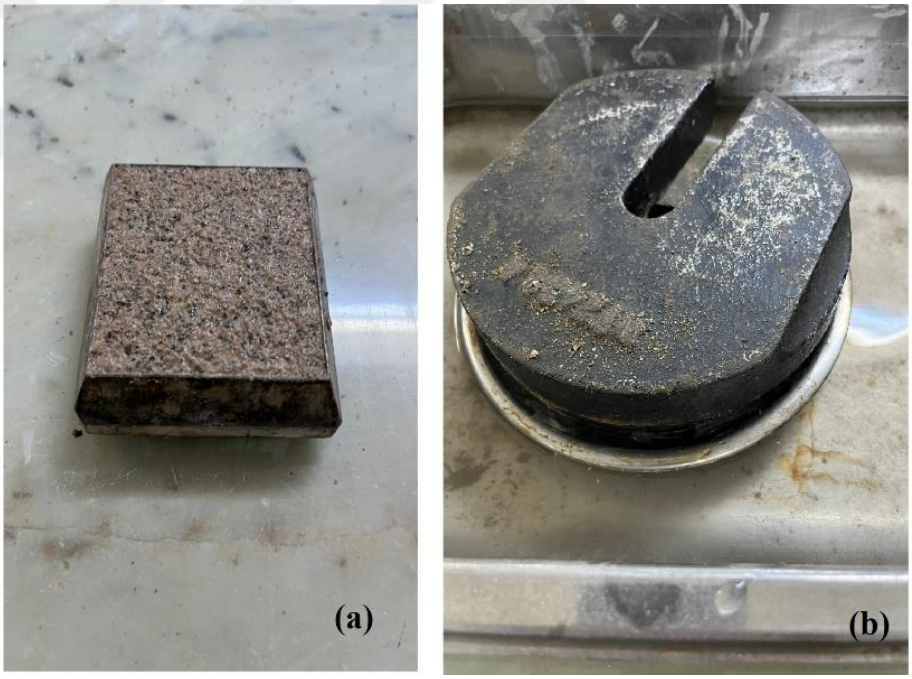

Figure 3.8 Sample preparation for direct shear tests, a) compacted sample b) submerged sample into water and weight on it (Personal archive, 2022)

After one day, the sample was taken out of the mold and placed in the shear box. Direct shear tests were performed under three different normal stresses (49, 98, 196 kPa). The samples were consolidated and sheared at a shear rate of 0.5 mm/min.

The direct shear experiments were performed at both room and high temperature (80 °C). In the experiments performed under high temperature, the heating of the shear box assembly was supplied with the help of a heat rod. (Fig. 3.9a). The water temperature in the shear box was kept at 80 °C with the help of thermostat (Fig. 3.9b). The temperatures of the mixture and water were measured with the help of two separate K-type thermocouples (Figure 3.9c) and a digital thermometer (Figure 3.9d). The thermal direct shear test system is shown in Figure 3.10. At the end of each experiment, the sample was placed in an oven (105 °C) to determine the final water content.

Figure 3.9 Equipment used in the thermal direct shear tests a) Heat rod, b) Thermostat, c) K-type thermocouple and d) Digital thermometer (Personal archive, 2022)

Figure 3.10 Thermal direct shear test device (Personal archive, 2022)

3.2.5 Consolidation Tests

Consolidation experiments were performed according to ASTM D2435 (2011) standard. The test mixtures were prepared at dry unit weight values corresponding to 2% wet side of the optimum water content (w_{opt}+2%) which were obtained from compaction tests. The mixtures were mixed homogeneously in dry condition before adding water. After adding water to the mixture, which was mixed homogeneously in the dry state, it was mixed with the help of a spatula until it became homogeneous. The homogeneously mixed sample was compacted into the metal rings with the help of a wooden mallet. After the sample was prepared, it was kept under pressure of 6.86 kPa for 24 hours. Then, loadings as 24.5, 49, 98, 196, 392, and 784 kPa were applied, respectively. When loading

stages completed, the unloading stage was started by unloading from 784 kPa to 196 kPa and then 49 kPa, consecutively.

For the experiments performed under high temperature (80 °C), a specially designed circular heat rod and thermostat system were placed into oedometer cell. The water in the cell was increased until 80 °C. The temperature inside the cell was increased after applying a settlement pressure of 6.86 kPa for 24 hours. With the help of the thermostat, the temperature inside the oedeometer was controlled and the temperature kept constant at 80 °C. In order to prevent evaporation that may occur in the experiments, the upper part of the oedeometers was covered with the help of a thick rubber membrane. In order to keep the water level inside the cell constant against evaporation, water flow was supplied into the cell at low speed with the help of a water tank. Since the water flow was very slow, it did not cause any temperature fluctuations. The temperatures inside the cell were continuously controlled by connecting to a digital thermometer with the help of a K-type thermocouple. The schematic representation of the thermal consolidation test system is shown in Figure 3.11.

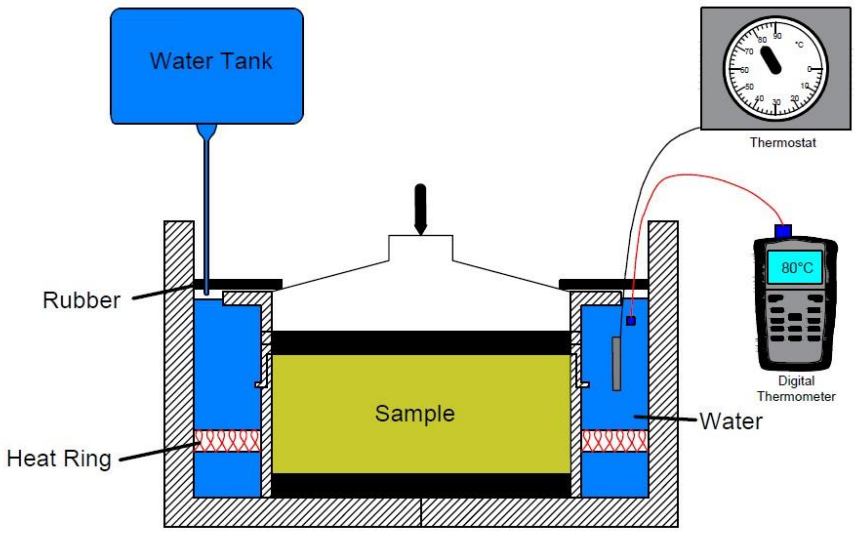

Figure 3.11 Schematic of thermal consolidation test set-up

3.2.6 Hydraulic Conductivity Tests

Hydraulic conductivity tests were performed according to ASTM D5084-16a (2016). In these experiments, flexible-walled permeameters were used and hydraulic conductivity values were determined by the falling-head method. In the experiments, the mixtures were prepared with a water content of w_{opt}+2% and a dry unit weight corresponding to this value. The samples prepared for the experiment were kept in airtight bags for 24 hours, and the samples were compacted with Standard Proctor energy and carefully removed from the mold with the help of a hydraulic jack.

In order to perform experiments under high temperature, permeameters made of aluminum material, which are resistant to high temperatures, were specially designed (Fig. 3.12). The lower and upper caps which sample comes into contact also made of aluminum material. At the top of the permeameter, there were three separate holes for the heat rod, the thermostat and the thermocouple (Figure 3.13). In order to perform the experiments at high temperatures, the water was heated with the help of 400-watt heat rod, and the water temperature was kept at the desired temperature with the help of the thermostat. The temperature of the water in the cell was measured with the help of a digital thermometer by a K-type thermocouple passing through the upper hole. The holes opened in the upper part were also closed with a heat-resistant liquid gasket in order to avoid leakage problems.

Figure 3.12 Aluminum cell designed for experiments under high temperature (Personal archive, 2022)

Figure 3.13 The top plate of the permeameter a) Heat rod, b) Heat rod, thermostat, and K-type thermocouple holes (Personal archive, 2022)

In the experiments, geotextiles with a diameter of 15 cm were used instead of porous stone on the top and bottom of the sample. After the sample was placed, a latex membrane is placed to prevent leakage that may occur in the sample, and then three O-rings were attached to the upper and lower caps. The permeameter cell was closed and the permeameter was filled with water. A hole with a diameter of thermocouple was drilled on the bottom geotextile to measure the temperature of the sample while performing the experiments under high temperature. K-type thermocouple was passed through a valve of the permeameter cell and a hole was opened on the geotextile and contact with the sample was ensured. In this way, the temperature of the sample could be measured during the experiments.

In the experiments, water flow was supplied from top to bottom from 50 ml glass burettes and the effluent was collected in 100 ml glass cylinders. The hydraulic conductivity value is expressed as the flow amount (PVF) in terms of the void volume of the soil. For the experiments, the cell pressure was applied as approximately 50 kPa. To run the experiments, cell pressure was applied, then the air in the pipes was removed and flow was started.

Hydraulic conductivity experiments were first started at room temperature (Cell: 25 °C - Sample: 20 °C), then the temperature was increased to 50 °C (Cell: 50 °C - Sample: 40 °C) and the experiments were continued until the steady flow. In the next step, the experiment was continued by increasing the temperature to 80 °C (Cell: 80 °C - Sample: 60 °C). After performing the hydraulic conductivity test at high temperature, the temperature was decreased to 50 °C and then to room temperature, and the test was terminated. The thermal hydraulic conductivity test set-up is shown in Figure 3.14.

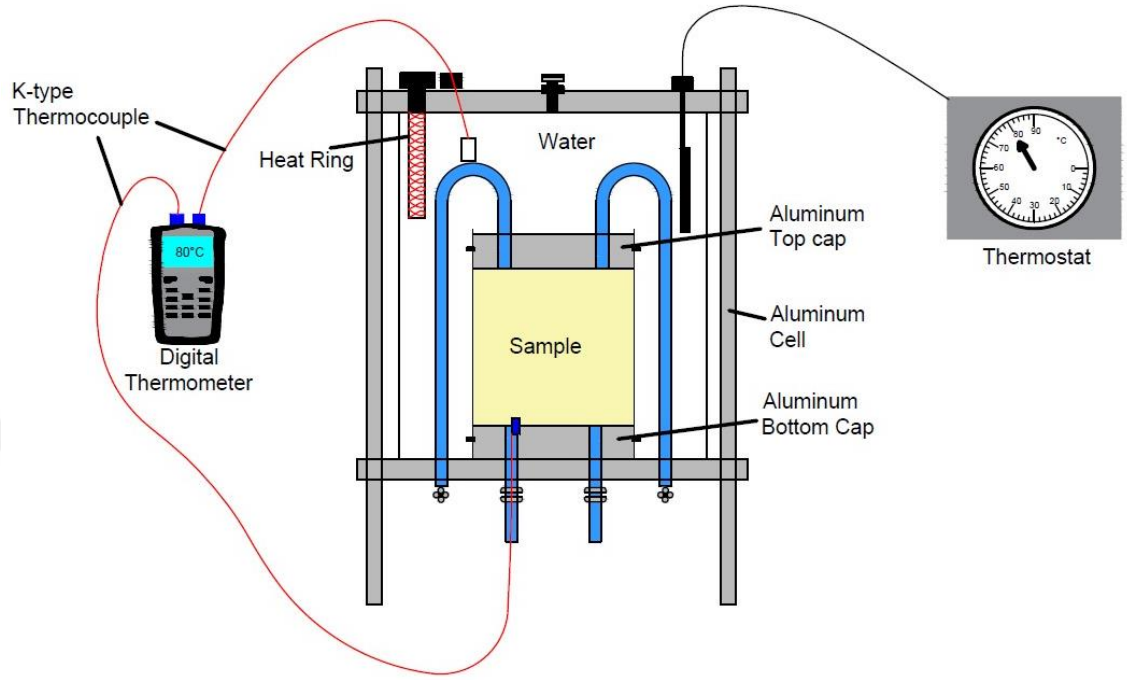

Figure 3.14 Schematic representation of thermal hydraulic conductivity test set-up

3.2.7 Thermal Conductivity Tests

The thermal conductivity of values of zeolite-bentonite and sand-kaolin mixtures were determined in the presence of pumice, perlite and fiberglass additives. It is known that the thermal conductivity of porous composite soils depending on the dry unit weight, porosity, water content, fine content, mineralogy, and organic matter (Abu-Hamdeh, N. H., & Reeder, R. C., 2000). Since the effect of void ratio and water content are the most important factors on the thermal conductivity both the void ratio and saturation degree of the samples were kept constant.

The samples were placed in specially produced square-section wooden molds with dimensions of 12 cm x 12 cm x 4 cm (Figure 3.15). The number of impacts was determined by trials in order to maintain desired dry unit weight value, and they were compacted in four layers.

Figure 3.15 Specially manufactured wooden sample mold (Personal archive, 2022)

The samples were first mixed homogeneously in dry state in the plastic container. Then the water content was added and homogeneity was ensured with mixing the help of a spatula. After the mixture became completely homogeneous, the sample was kept in an airtight bag for 24 hours. The samples were compacted in the wooden molds with the determined number of blows. The Shotherm QTM instrument was used for thermal conductivity measurements (Figure 3.16). For each sample, measurements were made on the right, left, top, bottom and diagonal regions of the sample. The measurement places are shown in Figure 3.17.

Figure 3.16 Shotherm QTM thermal conductivity instrument (Personal archive, 2022)

Figure 3.17 Measurement places on the sample (Personal archive, 2022)

CHAPTER 4
COMPACTION TEST RESULTS and VOLUME DEFORMATION UNDER HIGH TEMPERATURE

The experimental results performed in the scope of the thesis are presented in this section. The Standard Proctor test results and the results of consolidation, direct shear and hydraulic conductivity tests conducted at room temperature and high temperature are also given. Finally, the thermal conductivity measurement results are presented.

4.1 Compaction Test Results

4.1.1 Compaction of Sand-Kaolin Mixtures

The compaction parameters of sand-kaolin mixtures were determined in the presence of 5-10% pumice and perlite, 0.5% and 1.0% glass fiber additives. Compaction experiments were conducted by applying Standard Proctor energy according to ASTM: D698 (2012e2).

The compaction curve of the sand-kaolin mixture is shown in Figure 3.1. The optimum water content and maximum dry unit weight of the 20K-80S mixture was determined to be 11.2% and 18.93 kN/m^3, respectively. Within the scope of the thesis, the effect of perlite, pumice and glass fiber additives on 20B-80S mix is shown.

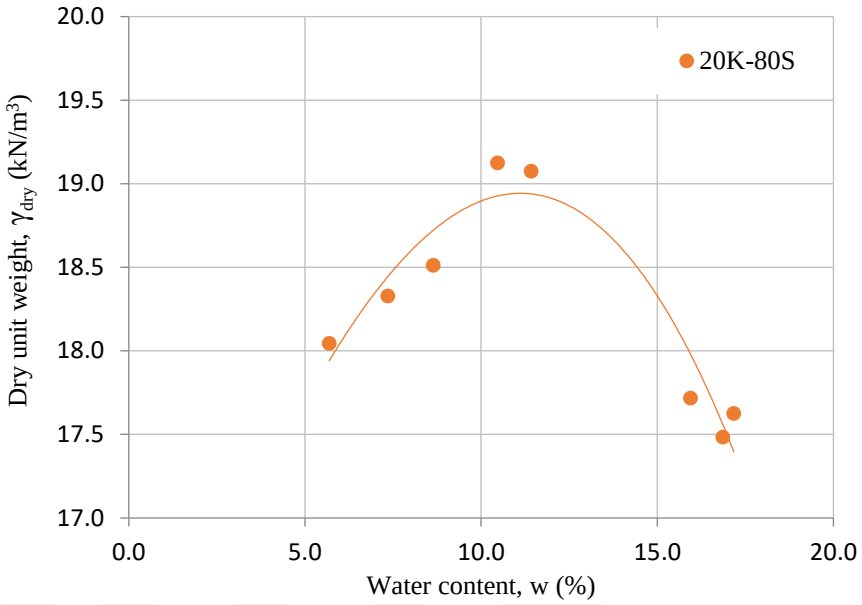

Figure 4.1 Sand-kaolin mixture compaction curve

4.1.1.1 Compaction of Sand-Kaolin Mixtures with Perlite

Figure 4.2 shows the obtained compaction curves of sand-kaolin mixtures in the presence of 5 and 10% perlite additives. The optimum water content of the 5PE-19K-76S mixture was found to be 16.5% and the maximum dry unit weight value was 15.25 kN/m^3. The optimum water content value of the 10PE-18K-72S mixture was found to be 27.2% and the maximum dry unit weight value was found to be 13.13 kN/m^3. When 5-10% perlite was added to the 20B-80S mixture, the optimum water content of the KSMs increased, while the maximum dry unit weight value decreased. The increase in optimum water content was observed due to the higher water holding capacity of perlite than sand and kaolin. The decrease in the maximum dry unit weight value was due to the lower specific gravity value of perlite compared to sand and kaolin.

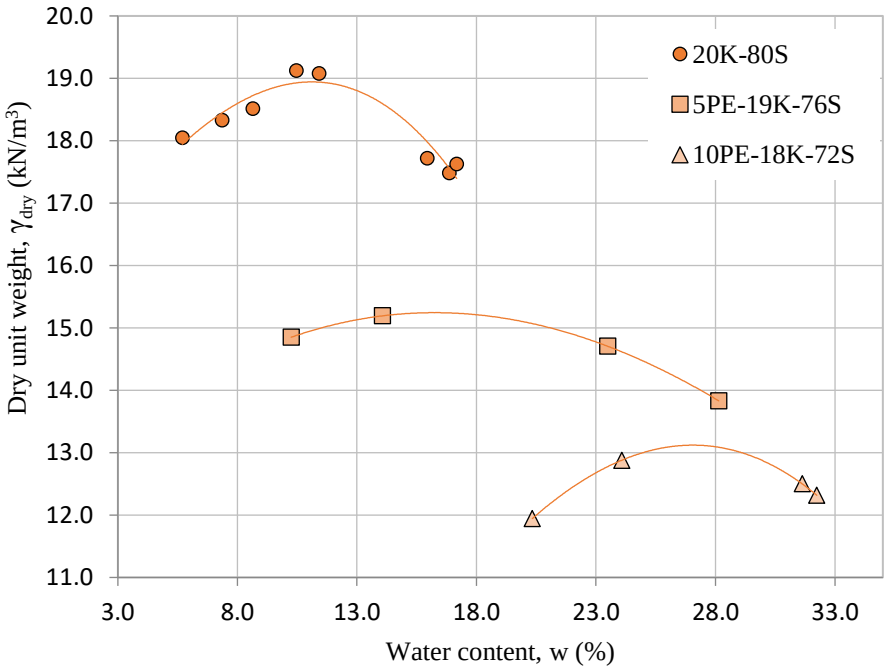

Figure 4.2 Compaction curves of perlite added sand-kaolin mixtures

4.1.1.2 Compaction of Sand-Kaolin Mixtures with Pumice

Figure 4.3 shows the compaction curves of sand-kaolin mixtures with 5% pumice and 10% pumice. The optimum water content of the 5PU-19K-76S mixture was found to be 11.5% and the maximum dry unit weight value was 19.01 kN/m^3. The optimum water content and maximum dry unit weight values of the 10PU-18K-72S mixture was found to be 11.0% and 18.53 kN/m^3, respectively. When 5% pumice was added optimum water content and maximum dry unit weight values increase slightly, while the optimum water content and maximum dry unit weight values decreased in the presence of 10% pumice.

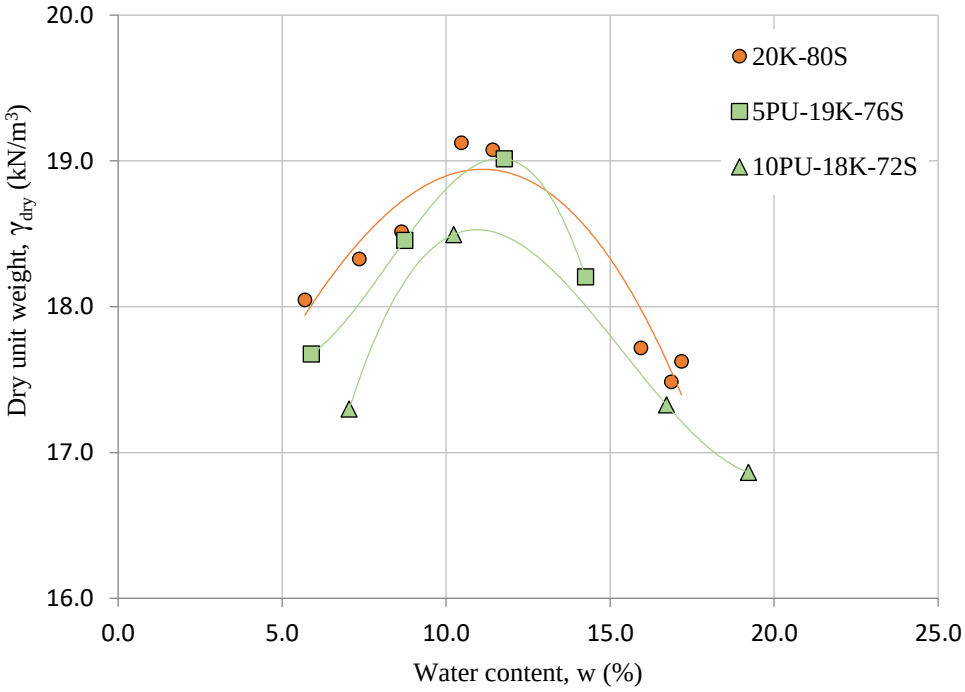

Figure 4.3 Compaction curves of pumice added sand-kaolin mixtures

4.1.1.3 Compaction of Sand-Kaolin Mixtures with Fiberglass

The compaction curves of the KSMs with 0.5-1.0% fiberglass are shown in Figure 3.4. The optimum water content of 0.5FG-19.9K-79.6S mixture was found to be 11.2% and the maximum dry unit weight value was 18.93 kN/m^3. It was observed 0.5 and 1% fiberglass did not change the optimum water content and maximum dry unit weight values significantly. The reason why the optimum water content and maximum dry unit weight values are approximately similar is due to the proportionally small amount of fiberglass additive material in the mixture.

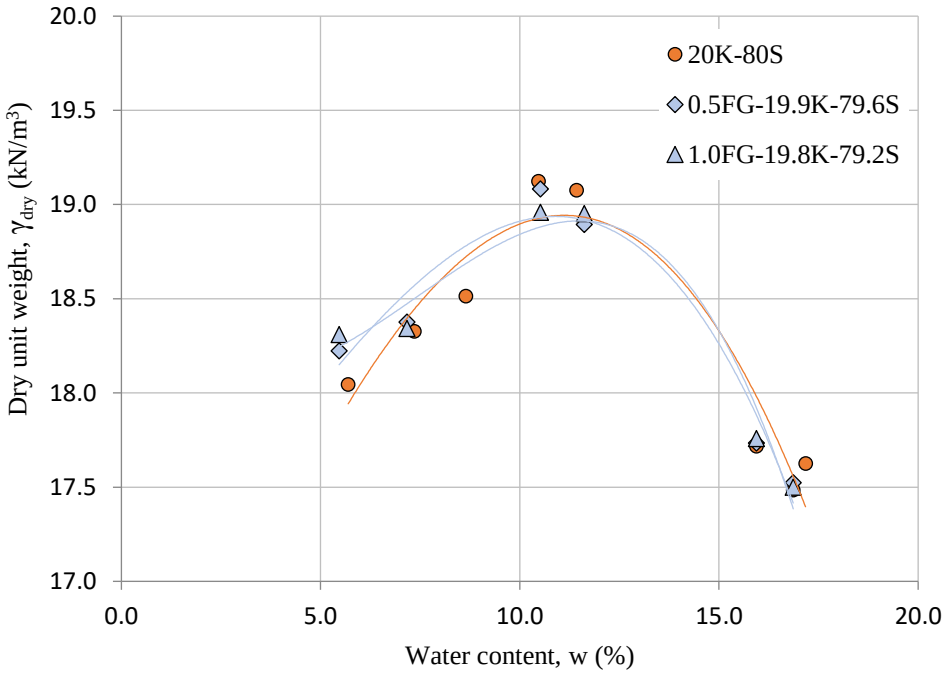

Figure 4.4 Compaction curves of fiberglass added sand-kaolin mixtures

The compaction parameters of sand-kaolin mixtures in the presence of perlite, pumice and fiberglass additives are summarized in Table 4.1.

Table 4.1 Compaction parameters of sand-kaolin mixtures in the presence of pumice, perlite and glass fiber additives

Sample	**$\gamma_{d,max}$ (kN/m^3)**	**w_{opt} (%)**
20K-80S	18.93	11.2
5PU-19K-76S	19.01	11.5
10PU-18K-72S	18.53	11.0
5PE-19K-76S	15.25	16.5
10PE-18K-72S	13.13	27.2
0.5FG-19.9K-79.6S	18.93	11.2
1.0FG-19.8K-79.2S	18.93	11.2

4.1.2 Compaction of Zeolite-Bentonite Mixtures

The compaction parameters of zeolite-bentonite mixtures were determined in the presence of 5-10% pumice and perlite and 0.5-1.0% fiberglass additives. According to the results, the optimum water content value of the 20B-80Z mixture was determined to be 40.0% and the maximum dry unit weight value was found to be 10.88 kN/m^3 (Figure 4.5).

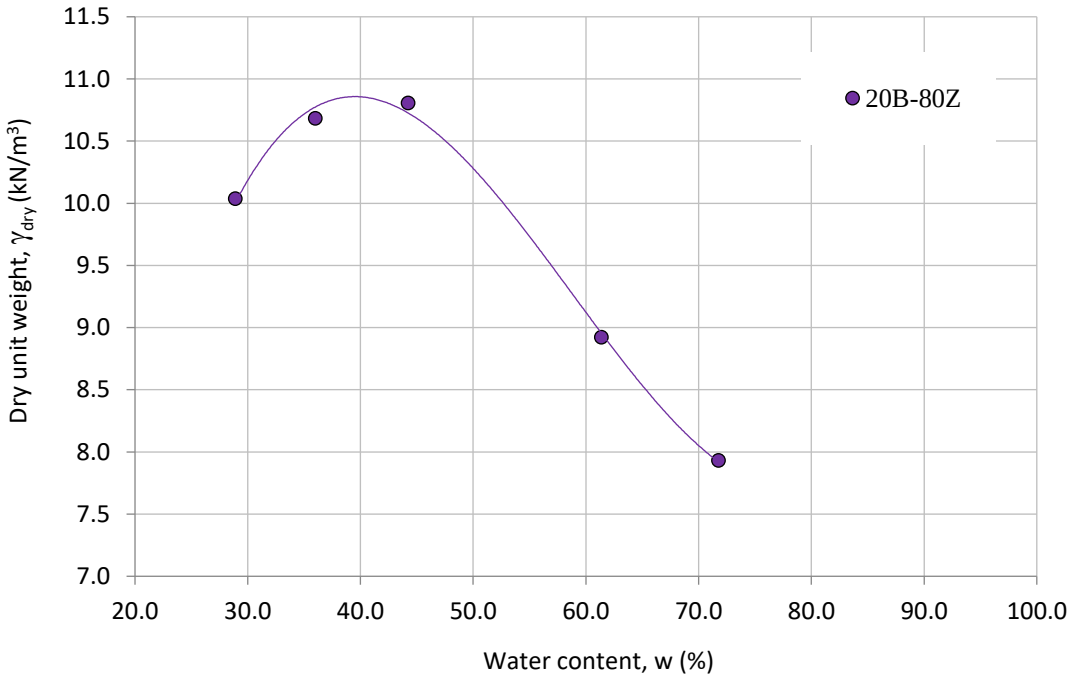

Figure 4.5 Compaction curve of zeolite-bentonite mixture

4.1.2.1 Compaction of Zeolite-Bentonite Mixtures with Perlite

Figure 4.6 shows the compaction curves of zeolite-bentonite mixtures with 5 and 10% perlite additives. The optimum water content of the 5PE-19B-76Z mixture was determined as 42.5% and the maximum dry unit weight value was 9.96 kN/m^3. The optimum water content value of the zeolite-bentonite mixture increased from 42.5 to 45.5% and the maximum dry unit weight value decreased from 9.96 to 8.98 kN/m^3 in the presence of

10% perlite when compared with 5% perlite additive. When 5 and10% perlite were added to the 20B-80Z mixture, the optimum water content increased, while the maximum dry unit weight value decreased. The increase in optimum water content was observed due to the decrease in the content of zeolite and the addition of perlite with high water retention capacity. The decrease in the maximum dry unit weight value was due to the lower specific gravity value of perlite compared to bentonite and zeolite.

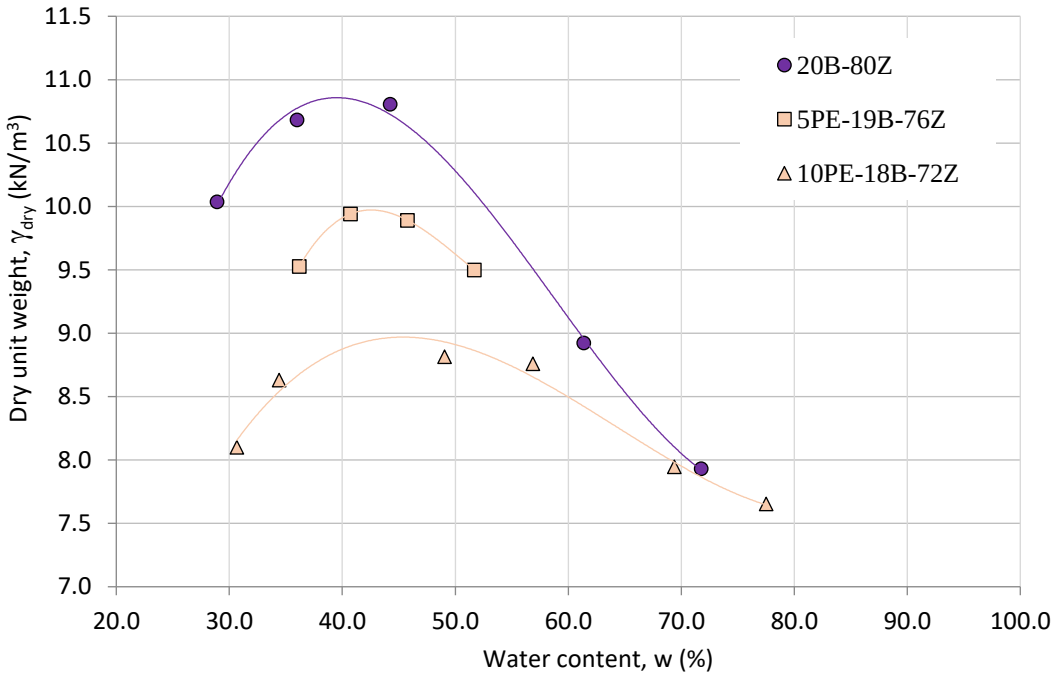

Figure 4.6 Compaction curves of perlite added zeolite-bentonite mixtures

4.1.2.2 Compaction of Zeolite-Bentonite Mixtures with Pumice

Figure 3.7 shows the compaction curves of zeolite-bentonite mixtures with 5 and 10% pumice. The optimum water content of the 5PU-19B-76Z mixture was found to be 38.5% and the maximum dry unit weight value was 11.22 kN/m^3. The optimum water content value of the 10PU-18B-72Z mix was found to be 37.0% and the maximum dry unit weight value was found to be 11.52 kN/m^3. When 5 and 10% pumice was added to the 20B-80Z

mixture, the optimum water content values of decreased, while the maximum dry unit weight values increased. The decrease in the optimum water content is due to the fact that the water retention capacity of pumice is less than bentonite. The increase in the maximum dry unit weight value is due to the addition of pumice material instead of zeolite material, which has a lower specific gravity than pumice.

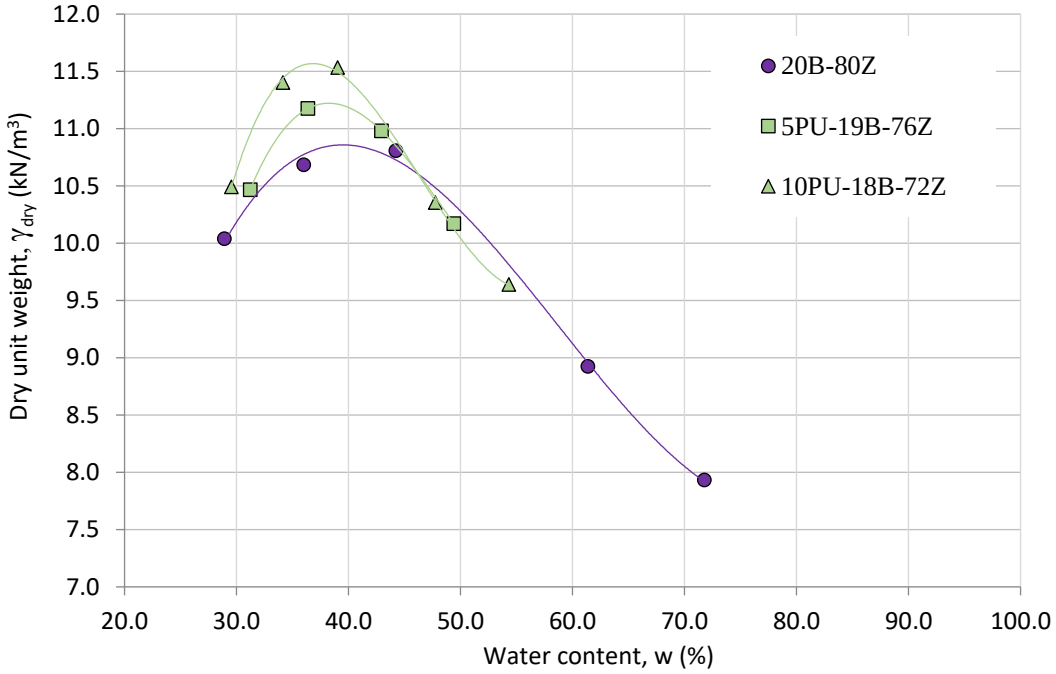

Figure 4.7 Compaction curves of pumice added zeolite-bentonite mixtures

4.1.2.3 Compaction of Zeolite-Bentonite Mixtures with Fiberglass

The compaction curves of the ZBMs with 0.5 and 1.0% fiberglass are shown in Figure 4.8. The optimum water content of 0.5FG-19.9B-79.6Z mixture was found to be 40.5% and the maximum dry unit weight value determined as 10.85 kN/m^3. The optimum water content value did not change in the presence of 1% fiberglass, the maximum dry unit weight (10.83 kN/m^3) did not change as well. According to the results, the 0.5 and 1%

fiberglass had no effect on the compaction parameters of the zeolite-bentonite mixture. The reason of this can be explained by the low content of the fiberglass in the mixtures.

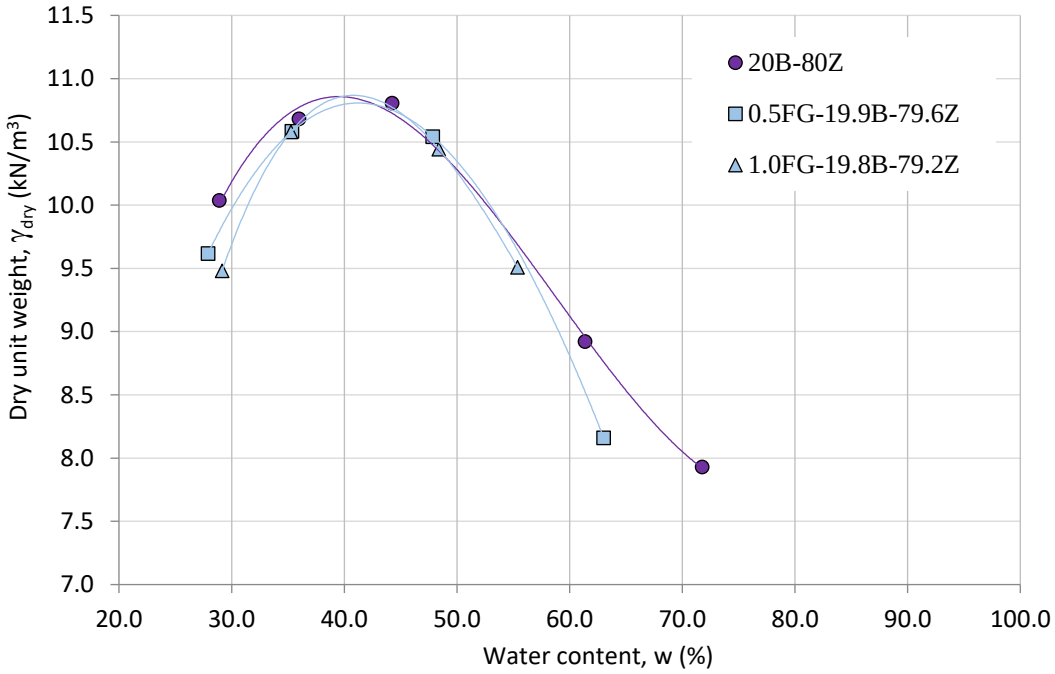

Figure 4.8 Compaction curves of fiberglass added zeolite-bentonite mixtures

The compaction parameters of zeolite-bentonite mixtures in the presence of perlite, pumice and fiberglass additives are summarized in Table 4.2.

Table 4.2 Compaction parameters of zeolite-bentonite mixtures obtained from standard proctor tests in the presence of pumice, perlite and fiberglass additives

Sample	$\gamma_{d,max}$ (kN/m^3)	w_{opt} (%)
20B-80Z	10.88	40.0
5PU-19B-76Z	11.22	38.5
10PU-18B-72Z	11.52	37.0
5PE-19B-76Z	9.96	42.5
10PE-18B-72Z	8.98	45.5
0.5FG-19.9B-79.6Z	10.85	40.5
1.0FG-19.8B-79.2Z	10.83	40.5

According to the compaction test results of sand-kaolin and zeolite-bentonite mixtures (Figure 4.9 and Figure 4.10), the optimum water content of the mixtures increased as the amount of perlite increased, while the maximum dry unit volume weight values decreased. The fact that perlite increases the optimum water content while increasing the maximum dry unit weight is due to its fine grain content. Because it has been shown in the literature that as the fine grain content increases, the dry unit weight value generally decreases and the optimum water content increases (Isik and Ozden, 2013). In addition, another reason why perlite additive significantly changes the water content is due to the high-water absorption capacity of perlite (LL: 375%).

The pumice additive did not show a general trend in sand-kaolin mixtures, but it increased the maximum dry unit weight of zeolite-bentonite mixtures while decreasing the optimum water content. In general, the addition of bentonite to soils resulted in a decrease in the maximum dry unit weight and an increase in the optimum water content (Mitchell and Soga, 2005). Therefore, when bentonite was replaced by pumice in the mixture, the maximum dry unit weight increased while the optimum water content decreased.

Fiberglass additive did not generally change the compaction parameters of sand-kaolin and zeolite-bentonite mixtures. This may be due to the use of 0.5% and 1.0% fiberglass additives in the mixture.

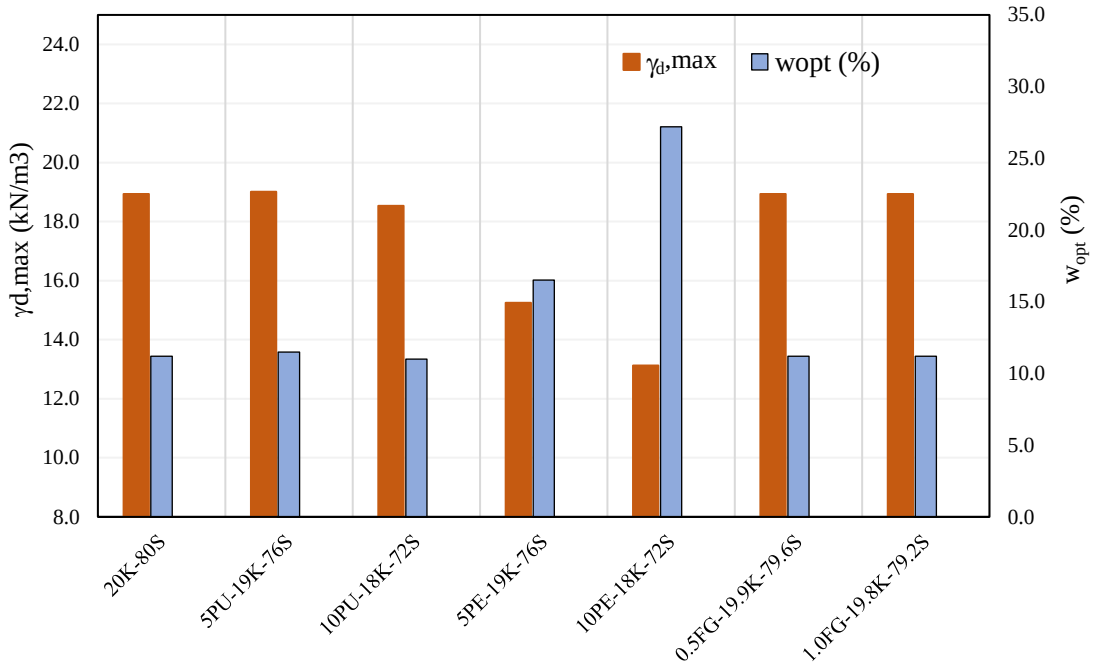

Figure 4.9 Compaction parameters of sand-kaolin mixtures

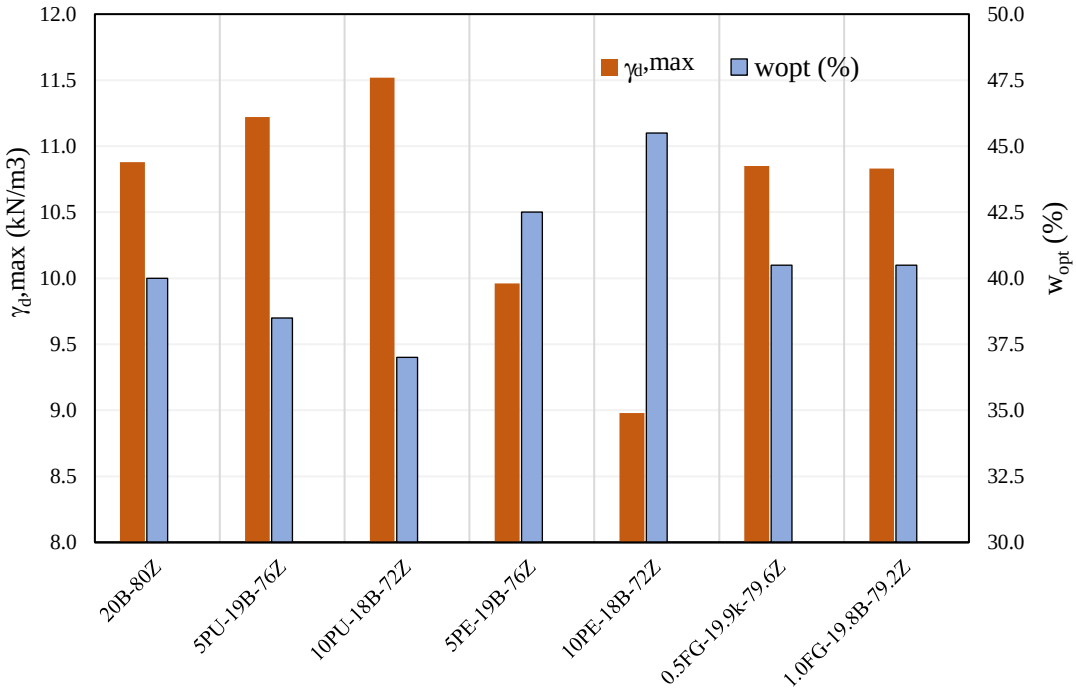

Figure 4.10 Compaction parameters of zeolite-bentonite mixtures

4.2 Consolidation Test Results

Consolidation tests were performed at both room temperature (RT) and high temperature (80 °C) in order to determine the effect of high temperature on the compression and swelling behaviors. The effect of pumice, perlite and fiberglass additives on the compression and swelling behaviors of the sand-kaolin and zeolite-bentonite mixtures were investigated at both room and high temperatures. Consolidation tests were performed according to ASTM D2435 (2011) standard.

4.2.1 Compression and Swelling Behavior of Sand-Kaolin Mixtures

The compression and swelling behaviors of sand-kaolin mixtures were determined under both room temperature and high temperature.

4.2.1.1 Compression and Swelling Behavior of Sand-Kaolin Mixtures Under Room and High Temperatures

The effective stress-vertical deformation graphs of the sand-kaolin mixtures (SKMs) at room temperature and high temperature are given in Figure 4.11. The vertical deformation value of the sand-kaolin mixture was 3.72% at room temperature and increased slightly to 3.98% under high temperature (80 °C). The effect of the high temperature was insignificant on the sand-kaolin mixtures. However, the effect of the high temperature was more significant on the swelling behavior. The swelling deformation value was 0.66% under room temperature increased to 0.80% under high temperature. Generally, the compression and swelling deformations of SKMs increased under 80 °C.

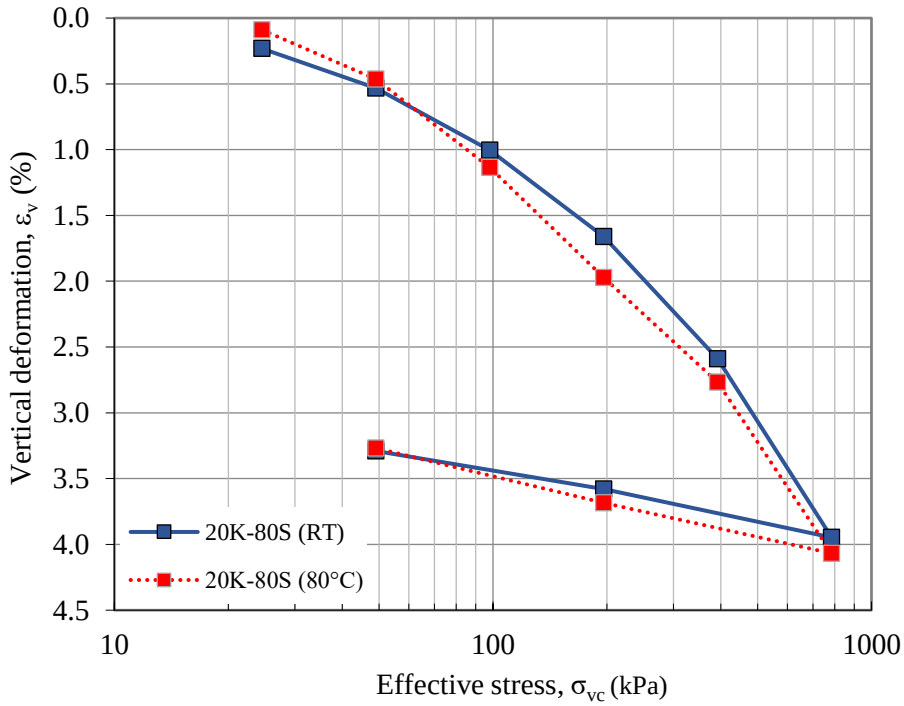

Figure 4.11 Compression and swelling curves of 20K-80S mixture under room and high temperatures (80 °C)

4.2.1.2 Compression and Swelling Behavior of Pumice Added Sand-Kaolin Mixtures Under Room and High Temperatures

The effect pumice on the compression and swelling behavior of SKMs were investigated by performing one-dimensional consolidation tests. The effective stress-vertical deformation graphs of sand-kaolin mixtures with 5 and 10% pumice additives at room and high temperatures are shown in Figure 4.12. When 5% pumice was added to the sand-kaolin mixture at room temperature, compression deformation increased from 3.72 to 4.43%, however the compression deformation decreased from 3.72 to 3.57% in the presence of 10% pumice. Similar to compression behavior 5% and 10% pumice contents have totally different effects on the swelling behavior. In the presence of 5% pumice the swelling deformations increased (from 0.66 to 0.76%) and decreased with 10% pumice from 0.66 to 0.55%. Depending on the content of pumice, the effects on the compression and swelling behavior changed under room temperature.

When 5% pumice was added to the sand-kaolin mixture at high temperature (80 °C), the compression decreased from 3.98 to 3.56% which is different from room temperature. However, in the presence of 10% pumice, the amount of compression increased from 3.98 to 4.32% under the effect of high temperature. Both pumice contents decreased the swelling deformation amounts from 0.80 to 0.59% and from 0.80 to 0.68% in the presence of 5 and 10% pumice, respectively. While the compression value of 5PU-19K-76S mixture was 4.43% at room temperature, it decreased to 3.56% under high temperature (80 °C). It means that pumice has positive effects on the compression behavior under high temperature.

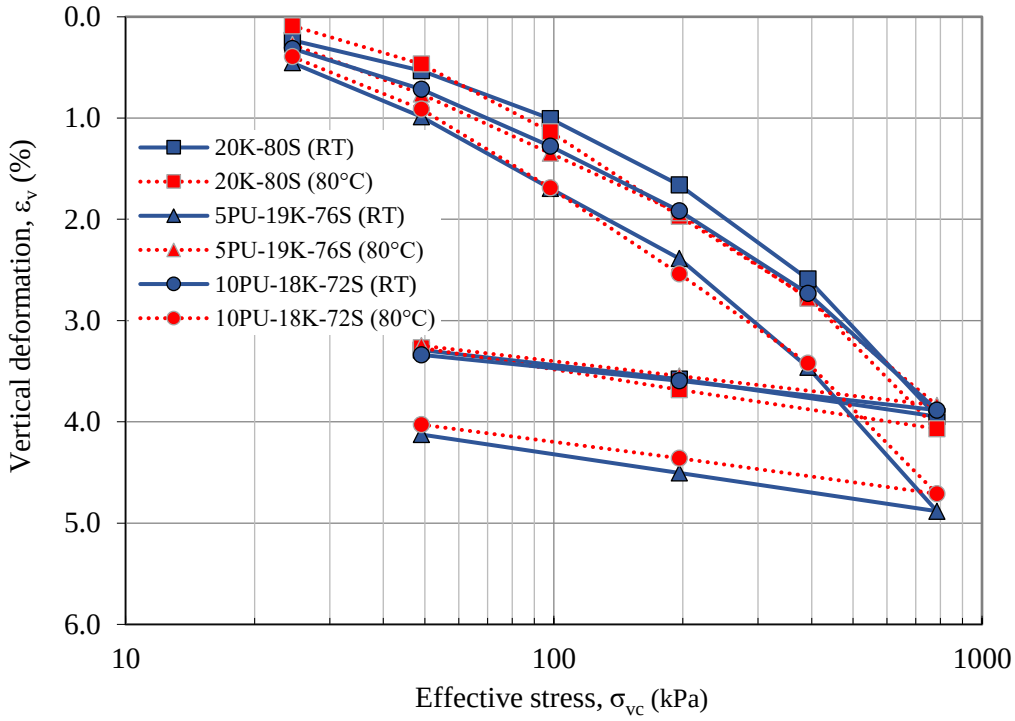

Figure 4.12 Compression and swelling curves of pumice added sand-kaolin mixtures under room and high temperatures (80 °C)

4.2.1.3 Compression and Swelling Behavior of Perlite Added Sand-Kaolin Mixtures Under Room and High Temperatures

Figure 4.13 shows the effective stress-vertical deformation graphs of sand-kaolin mixtures at room and high temperatures in the presence of 5 and 10% perlite additives. In the presence of 5% perlite additive, the compression of the sand-kaolin mixture increased from 3.72 to 5.14%, and the increase in content perlite to 10% increased the compression deformation amounts. The effect of perlite on the compression deformation amounts was determined in the increasing direction. In the presence of 5% perlite additive under high temperature (80 °C), still the compression deformation increased from 3.98 to 4.30%. The 10% perlite additive increased compression deformations as well. Similarly, swelling deformation amounts increased in the presence of perlite under room temperature. The

swelling decreased from 0.80 to 0.73%; however swelling increase with 10% perlite from 0.80 to 1.08%.

The compression deformations of 5PE-19K-76S mixture decreased from 5.14% at room temperature to 4.30% under high temperature (80 °C). The swelling deformations decreased with the effect temperature from 0.88 to 0.73% under high temperature (80 °C). The compression of the 10PE-19K-76S mixture increased from 3.57% at room temperature to 4.32% under 80 °C. It was observed that 5 and 10% perlite additives increased the amount of compression both at room temperature and under high temperature. When the swelling deformations values are compared, 5% perlite additive decreased the swelling deformations slightly under high temperature.

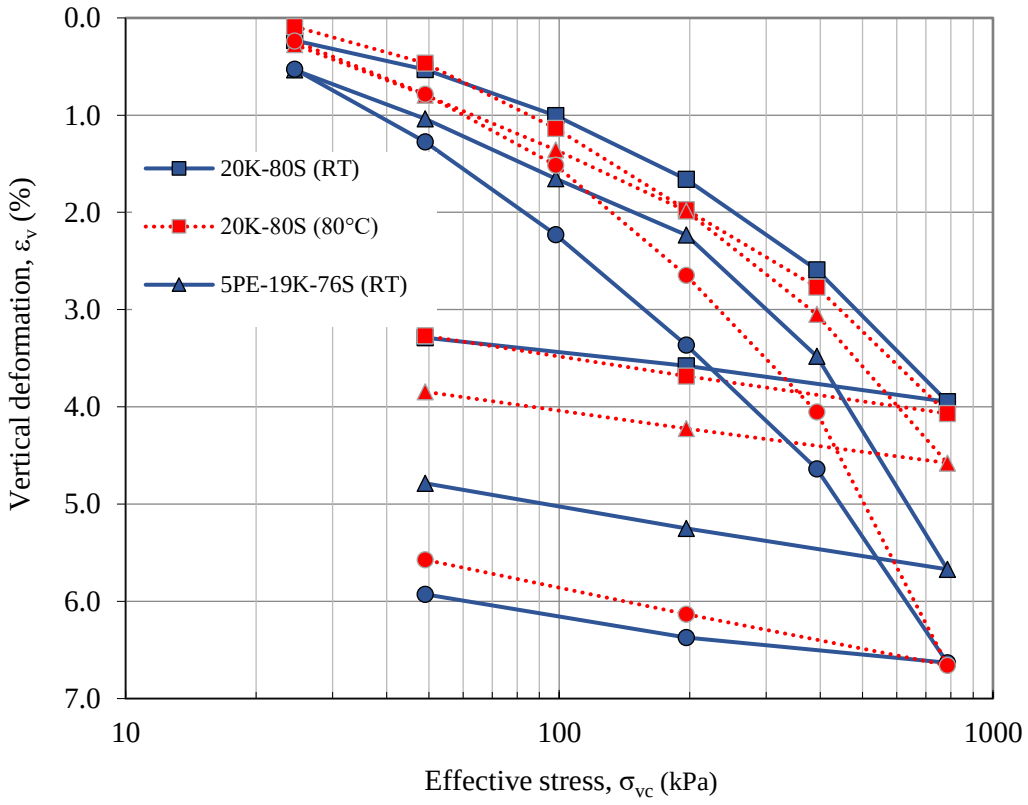

Figure 4.13 Compression and swelling curves of perlite added sand-kaolin mixtures under room and high temperatures (80 °C)

4.2.1.4 Compression and Swelling Behavior of Fiberglass Added Sand-Kaolin Mixtures Under Room and High Temperatures

The compression and swelling behavior of SKMs were determined in the presence of 0.5 and 1.0% fiberglass additives. The results have shown that the compression deformations increased of the sand-kaolin mixture from 3.72 to 4.13 and 4.29%, respectively (Figure 4.14) in the presence of 0.5 and 1.0% fiberglass. Similar to compression deformations, the swelling deformations increased in the presence of fiberglass under room temperature.

In the presence of 0.5% fiberglass the amount of compression of the sand-kaolin mixture increased from 3.98 to 4.18% under high temperature, and the deformation values attained to 4.31% with 1.0% fiberglass content. The fiberglass addition could not prevent the vertical deformations even under high temperature. The 0.5% fiberglass addition decreased the amount of swelling decreased from 0.80 to 0.73%. The fiber structure of fiberglass decreased the rebounds in the soil. However, in the presence of 1.0% fiberglass swelling deformations did not change when compared with lower content of fiberglass.

The compression of SKMs did not change significantly in the presence of 0.5 and 1.0% fiberglass additives under 80 °C. The swelling value decreased slightly under 80 °C. In general, the compression deformation values increased in the presence of fiberglass additive under both room temperature and high temperature. At room temperature, fiberglass additive increased the swelling deformations. Total compression and swelling deformation values of the sand-kaolin mixtures at room temperature and high temperature in the presence of perlite, pumice and fiberglass additives are given in Table 4.3.

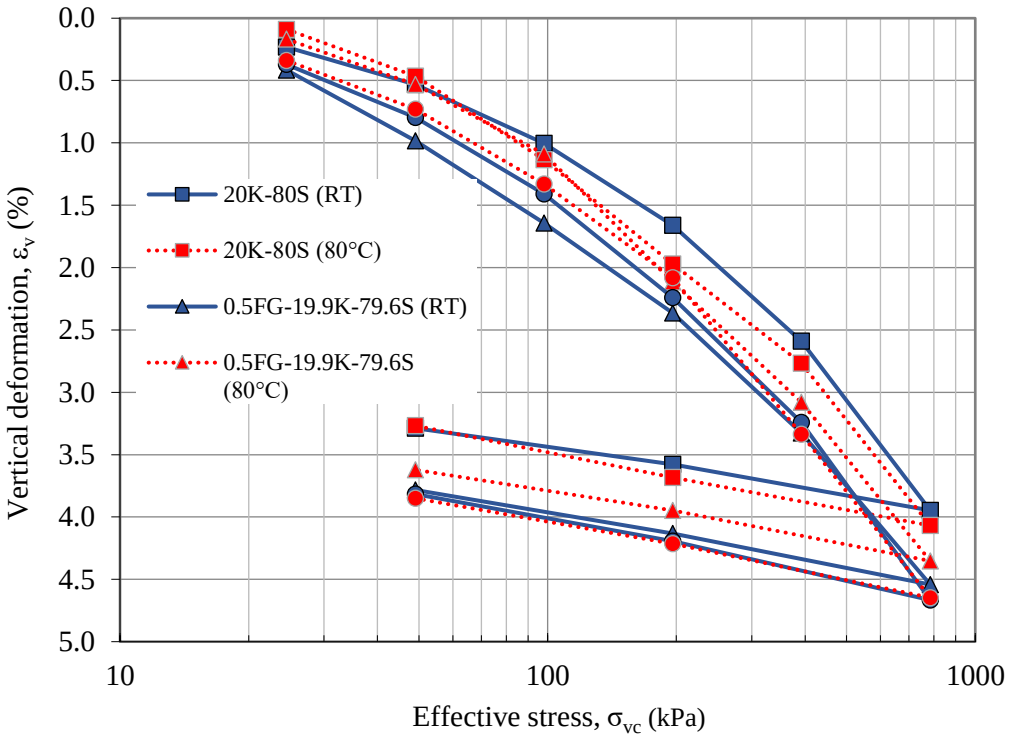

Figure 4.14 Compression and swelling curves of fiberglass added sand-kaolin mixtures under room and high temperature (80 °C)

Table 4.3 Total compression and swelling deformation values of sand-kaolin mixtures in the presence of pumice, perlite and fiberglass additives

Sample	Room Temperature		80 °C	
	Total vertical deformation (%)	Total swelling deformation (%)	Total vertical deformation (%)	Total swelling deformation (%)
20K-80S	3.72	0.66	3.98	0.80
5PU-19K-76S	4.43	0.76	3.56	0.59
10PU-18K-72S	3.57	0.55	4.32	0.68
5PE-19K-76S	5.14	0.88	4.30	0.73
10PE-18K-72S	6.11	0.71	6.42	1.08
0.5FG-19.9K-79.6S	4.13	0.76	4.18	0.73
1.0FG-19.8K-79.2S	4.29	0.85	4.31	0.80

4.2.2 Compression and Swelling Behavior of Zeolite -Bentonite Mixtures

The compression and swelling behaviors of the zeolite-bentonite mixtures in the presence of pumice, perlite and fiberglass additives at both room temperature and high temperature were investigated in order to determine the contribution of these additives to the vertical deformation behavior under high temperature.

4.2.2.1 Compression and Swelling Behavior of Zeolite-Bentonite Mixtures Under Room and High Temperatures

The effective stress-vertical deformation graphs of zeolite-bentonite mixtures (ZBMs) at room temperature and high temperature (80 °C) are given in Figure 4.15. The vertical deformation (compression) value of the 20B-80Z mixture increased from 10.23% at room temperature to 11.19% at 80 °C. While the swelling deformations decreased from 2.09 to 1.93% under the effect of high temperature (Figure 4.15). High temperature increased the vertical deformation values; however decreased the swelling deformation amounts in the zeolite-bentonite mixtures.

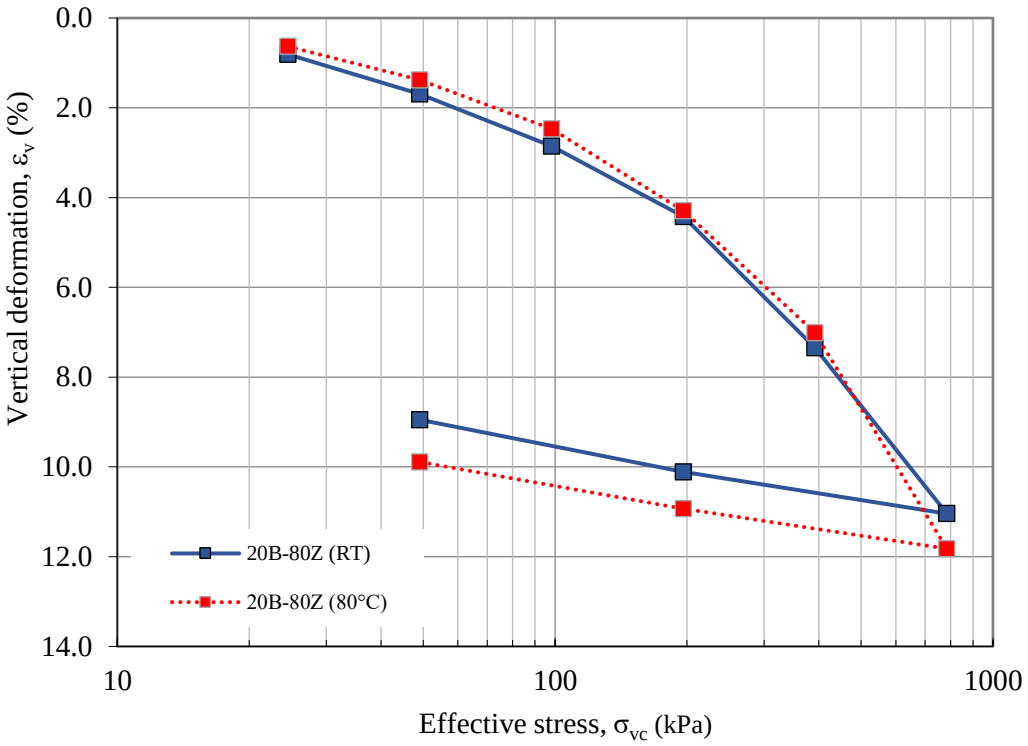

Figure 4.15 Compression and swelling curves of 20B-80Z mixture under room and high temperatures (80 °C)

4.2.2.2 Compression and Swelling Behavior of Pumice Added Zeolite-Bentonite Mixtures Under Room and High Temperatures

The effective stress-vertical deformation graphs of zeolite-bentonite mixtures at room temperature and high temperature in the presence of 5 and 10% pumice additives are shown in Figure 4.16. When 5 and 10% pumice were added to the zeolite-bentonite mixture compression deformations decreased from 10.23, 10.07 and 9.25%, respectively. Similar to compression the swelling deformations decreased in the presence of fiberglass.

Similar to room temperature, the compression deformations decreased under high temperature. When 5% pumice was added to the zeolite-bentonite mixture under high temperature, the amount of compression decreased from 11.19 to 9.66%. While the

compression value of 5PU-19B-76Z mixture was 10.07% at room temperature, it decreased to 9.66% under high temperature (80 °C). The pumice decreased the swelling deformations 1.93 to 1.47% with 10% pumice under high temperature. 5PU-19B-76Z mixtures swelling deformation values decreased from 2.02 to 1.84% under high temperature (80 °C) (Figure 4.16). The pumice additive decreased the vertical deformation values under high temperature which is a positive contribution of the pumice.

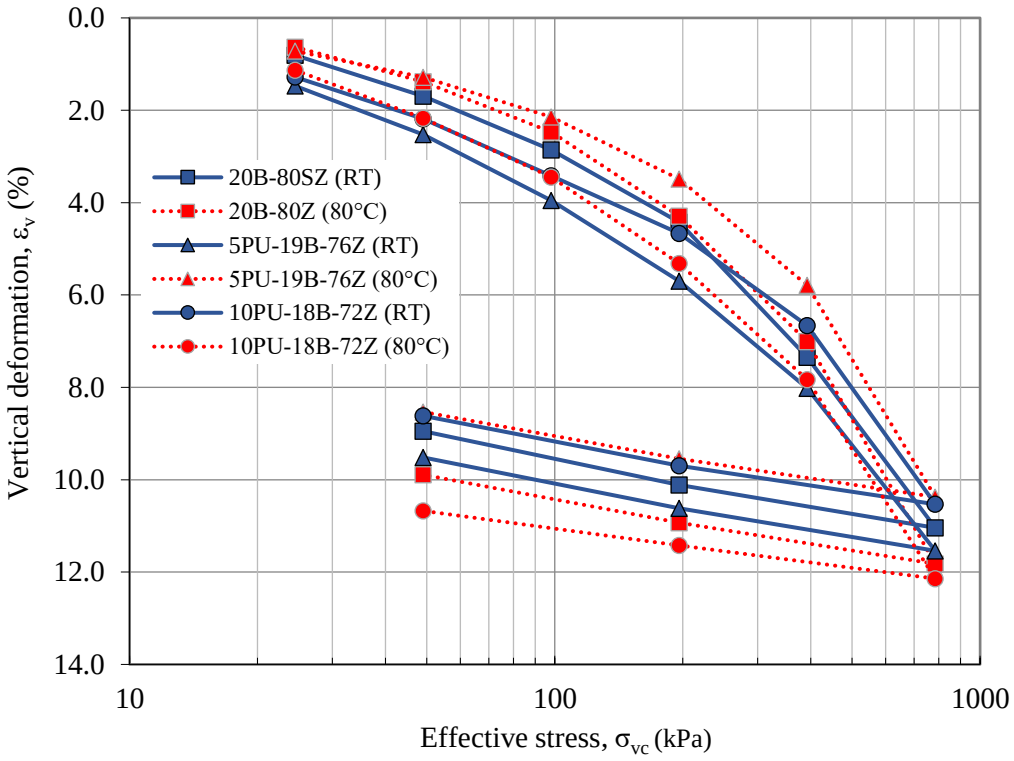

Figure 4.16 Compression and swelling curves of pumice added zeolite-bentonite mixtures under room and high temperatures (80 °C)

4.2.2.3 Compression and Swelling Behaviors of Perlite Added Zeolite-Bentonite Mixtures Under Room and High Temperatures

Figure 4.17 shows the effective stress-vertical deformation graphs of zeolite-bentonite mixtures at room temperature and high temperature in the presence of 5 and 10% perlite

additives. In the presence of 5% perlite additive, the compression of the zeolite-bentonite mixture did not change under room temperature. However, in the presence of 10% perlite additive, the compression decreased from 10.23 to 10.03%, insignificantly. The swelling deformations decreased with both contents of perlite.

In the presence of 5% perlite additive under high temperature (80 °C), the compression of the zeolite-bentonite mixture decreased from 11.19 to 8.94%. Similar to the results those of under room temperature, the swelling deformations decreased from 1.93 to 1.65% in the presence of 5% perlite (Figure 4.17). When the zeolite-bentonite mixtures in the presence of perlite additives were examined, it was observed that the compression and swelling behavior at room temperature and high temperature were in the decreasing direction.

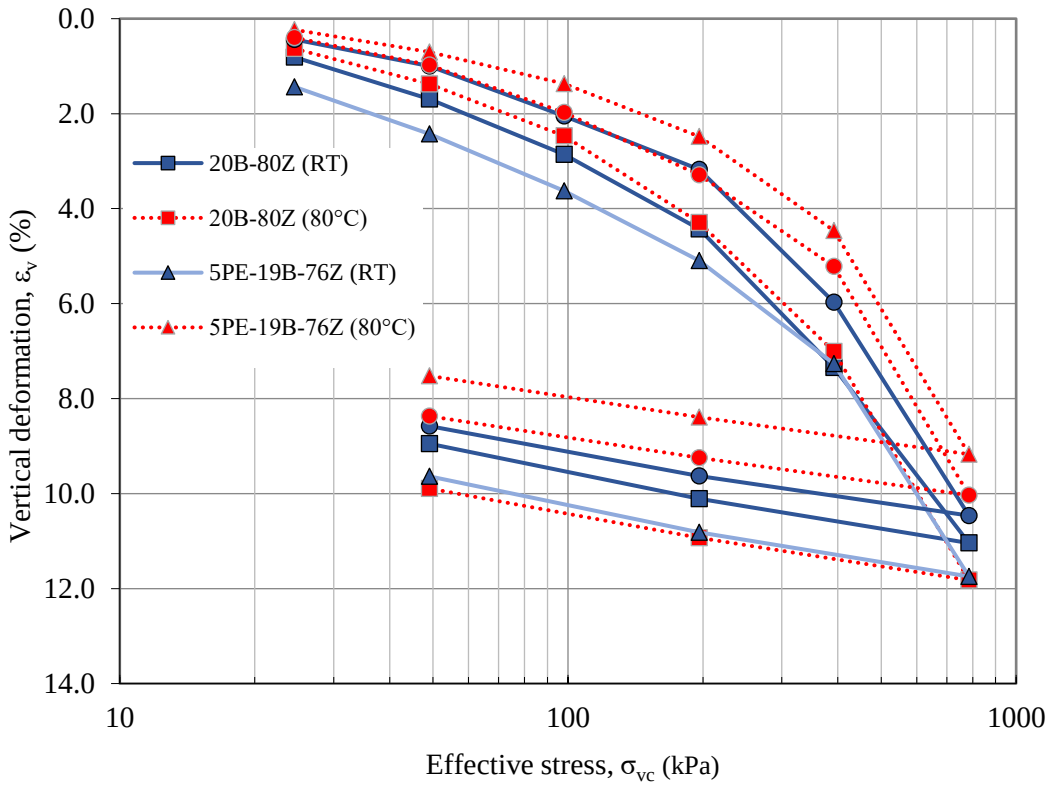

Figure 4.17 Compression and swelling curves of perlite added zeolite-bentonite mixtures under room and high temperature (80 °C)

4.2.2.4 Compression and Swelling Behavior of Fiberglass Added Zeolite-Bentonite Mixtures Under Room and High Temperatures

The 0.5 and 1.0% fiberglass additive increased the compression deformations of the zeolite-bentonite mixture from 10.23 to 11.25 and 11.35%, respectively. The swelling deformations decreased at room temperature in the presence of 0.5% fiberglass (Figure 4.18).

In the presence of 0.5% fiberglass additive under high temperature (80 °C), the compression of the zeolite-bentonite mixture decreased from 11.19% to 10.79%. However, the compression increased with 1.0% fiberglass content in the mixture. It should be noted that swelling deformations decreased with fiberglass.

When the effect fiberglass on the compression behavior of zeolite-bentonite mixtures was examined, the results of have shown that the amount of compression decreased and the amount of swelling increased at room temperature. Under high temperature, 0.5% fiberglass additive decreased the amount of compression, while 1% fiberglass additive increased the amount of compression. The swelling deformations under high temperature decreased when fiberglass additive was added.

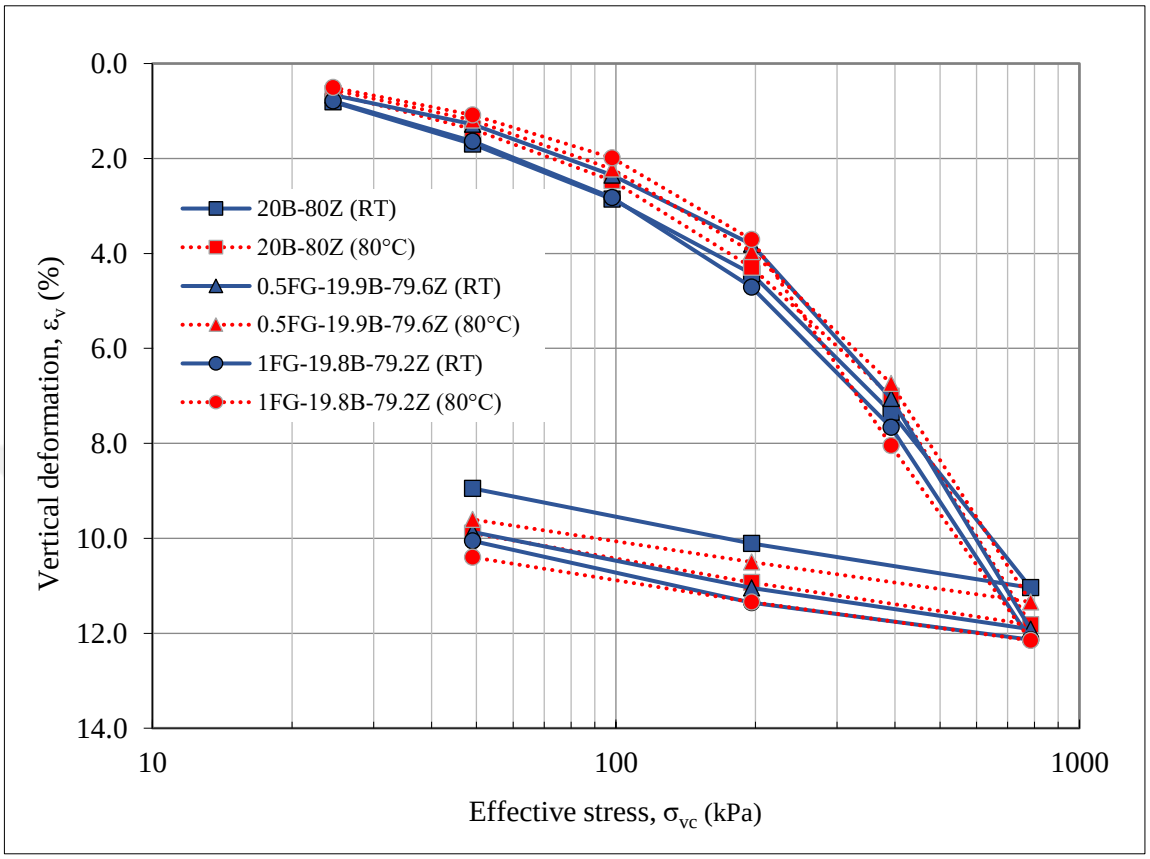

Figure 4.18 Compression and swelling curves of fiberglass added zeolite-bentonite mixtures under room and high temperatures (80 °C)

Total compression and swelling deformation values of zeolite-bentonite mixtures in the presence of perlite, pumice and fiberglass additives at room temperature and high temperature are given in Table 4.4.

Table 4.4 Total compression and swelling values obtained from consolidation tests of zeolite-bentonite mixtures in the presence of pumice, perlite and fiberglass additives

Sample	Room Temperature		80 °C	
	Total vertical deformation (%)	Total swelling (%)	Total vertical deformation (%)	Total swelling (%)
20B-80Z	10.23	2.09	11.19	1.93
5PU-19B-76Z	10.07	2.02	9.66	1.84
10PU-18B-72Z	9.25	1.92	11.01	1.47
5PE-19B-76Z	10.31	2.11	8.94	1.65
10PE-18B-72Z	10.03	1.88	9.63	1.66
0.5FG-19.9B-79.6Z	11.25	2.05	10.79	1.74
1.0FG-19.8B-79.2Z	11.35	2.08	11.65	1.75

An increase in the amount of compression of 20B-80Z and 20K-80S mixtures was observed with increasing temperature without any additive. Former studies have shown that the thermally induced volume change depends on the stress history. Soil exhibits contraction behavior as it moves from the normally consolidated to the over consolidated state and exhibits expansion behavior beyond a certain OCR value (Abuel Naga et al., 2007). In this thesis, the samples were found to be over consolidated with preloading applied at Standard Proctor energy. When the temperature increases, the over consolidated soil exhibits only irreversible contraction. The initial expansion of over consolidated soils is due to thermal expansion of soil minerals and can be reversed by temperature (Delage et al., 2000). The effect of temperature on the mechanical properties of the soil depends on the rate of over consolidation, plasticity, expansivity and compaction water content (Baldi et al. 1988; Romero et al. 2001). Since the samples were over-consolidated in the present study, there is a certain OCR ratio in order to see expansion behavior. For that reason, the samples were contracted under applied stresses. For example, in the presence of fiberglass additives, the amount of compression of sand-kaolin and zeolite-bentonite mixtures was generally increased both at room temperature and high temperature. It was

noted that the molecules with increased energy become more active and the bonds weaken more, resulting in an increase in the amount of compression in the soil (Gupta 1964; Jarad 2016).

When perlite-added sand-kaolin mixtures performed under high temperature and room temperature were investigated, perlite additive increased the amount of compression of the mixtures. Since the perlite produced under high temperature is coarse perlite, the void ratio is high and the strength of the material decreases as the void ratio increases (KTÜ, Lecture Notes). The increase in the amount of compression of perlite under high temperatures can be explained as an increase in the void ratio. The vertical deformation values of sand-kaolin mixtures in the presence of perlite, pumice and fiberglass additives are shown in Figure 4.19.

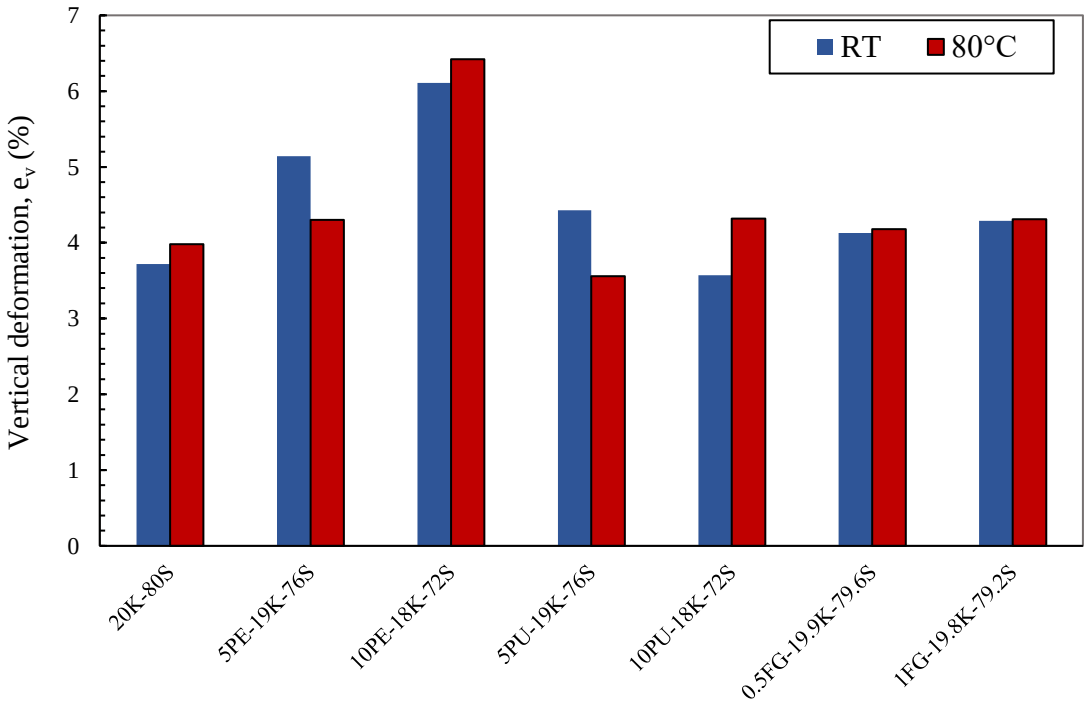

Figure 4.19 Vertical deformation values of sand-kaolin mixtures

Figure 4.20 shows the vertical deformation values of zeolite-bentonite mixtures in the presence of perlite, pumice and fiberglass additives. A decrease in the amount of compression of zeolite-bentonite mixtures was noted in the presence of perlite and pumice additives under room temperature and high temperature (Figure 4.20). It was reported that when the temperature increases, the viscosity of the adsorbed water decreases and the porosity decreases and accordingly the amount of compression will decrease (Wang et al., 2017). Similarly, it was observed that with increasing temperature, the ability to resist deformation is acquired and the compression index decreases (Tsutsumi and Tanaka, 2012). When the temperature was increased to 75 °C, the amount of compression increased of sand-bentonite mixtures (Sinha and Kusakabe, 2008). This situation was explained by the shrinkage of the clay grains and the decrease in volume due to less space in the diffuse double layer. Similar the studies in the literature, the amount of compression increased as temperature increased which is parallel to the literature. However, the perlite has positive contribution under high temperature by decreasing the amount of compression. In terms of swelling, it was observed that generally the swelling deformation values decreased with/without additives. It should be noted that, the effect of some additives for example %10 pumice can be more pronounced between other additives on the swelling behavior of ZBMs (Figure 4.21).

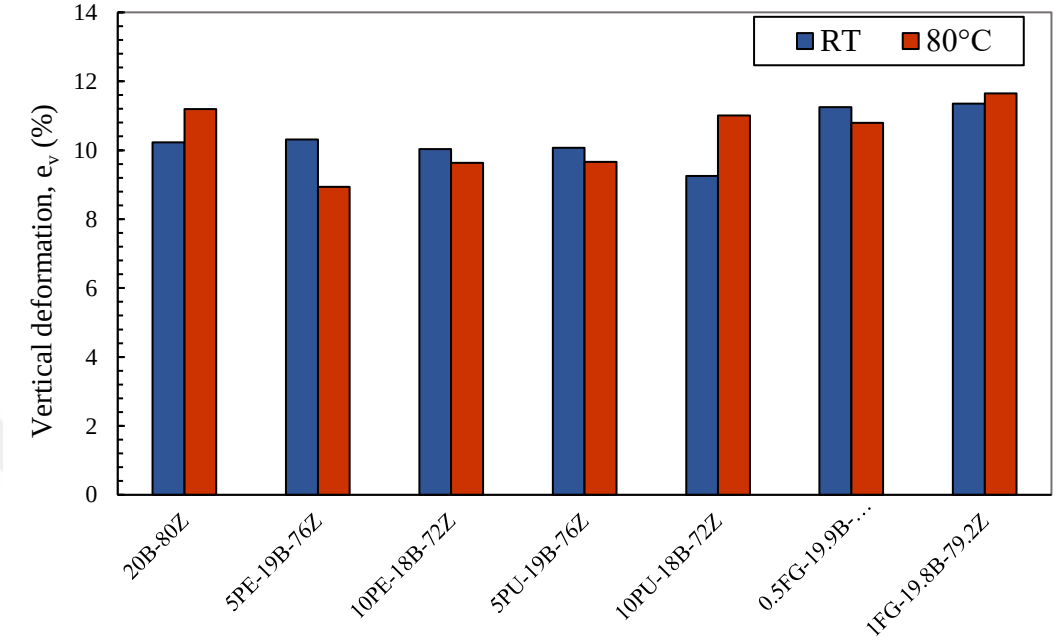

Figure 4.20 Vertical deformation values of zeolite-bentonite mixtures

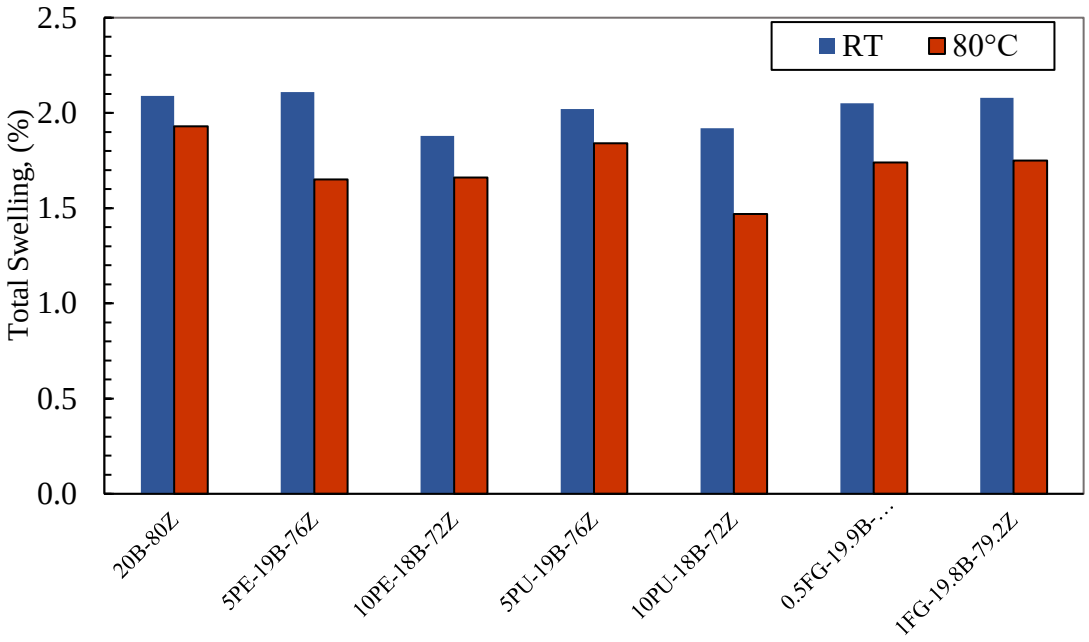

Figure 4.21 Total swelling values of zeolite-bentonite mixtures

CHAPTER 5
SHEAR STRENGTH BEHAVIOR UNDER HIGH TEMPERATURE

Direct shear tests were performed at both room temperature (RT) and high temperature (80 °C). The shear strength behavior of sand-kaolin and zeolite-bentonite mixtures in the presence of pumice, perlite and fiberglass additives were investigated. The shear strength values of the mixtures under a normal stress of 196.1 kPa were compared. Shear stress versus normal stress relationship graphs were plotted to obtain the drained internal friction angle and cohesion values. Direct shear tests were performed according to ASTM D3080 (2018).

5.1 Shear Strength of Sand-Kaolin Mixtures

The effect of pumice, perlite and fiberglass additives on the shear strength behavior of sand-kaolin mixtures under both room and high temperatures were investigated.

5.1.1 Shear Strength Behavior of Sand-Kaolin Mixtures Under Room and High Temperatures

Figure 5.1 shows the shear stress-strain relationships of sand-kaolin mixtures at room temperature and high temperature (80 °C). Under high temperature, shear strength of 20K-80S mixture increased compared to room temperature. The maximum shear stress value of 20K-80S mixture increased from 116.09 kPa to 128.91 kPa when temperature was increased to 80 °C.

Figure 5.2 shows the shear stress-normal stress relationship of 20K-80S mixtures. According to the results when temperature was increased there was no significant change in the angle of internal friction, while the cohesion value increased from 34.3 kPa to 40.0 kPa.

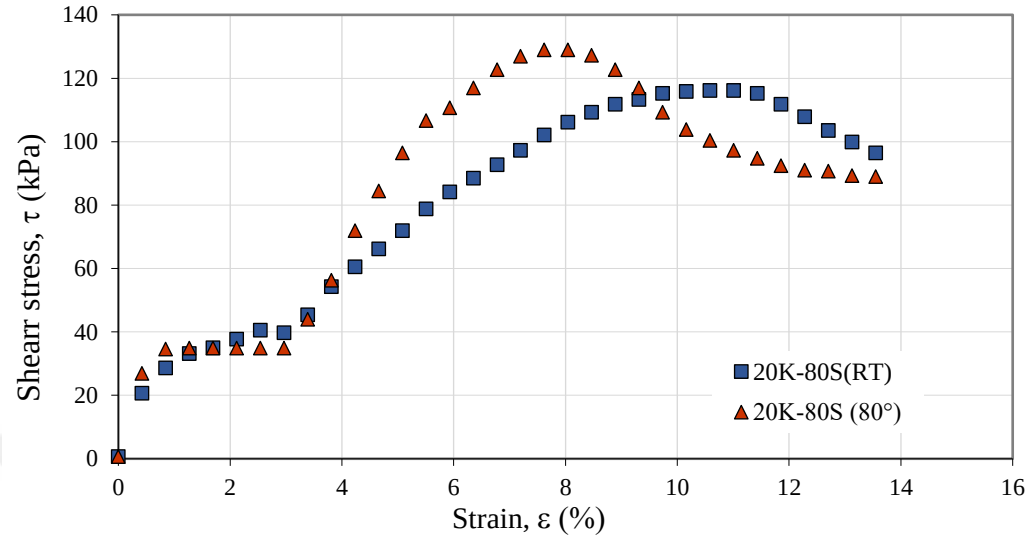

Figure 5.1 The shear stress-strain of 20K-80S mixtures at room and high temperatures (80 °C)

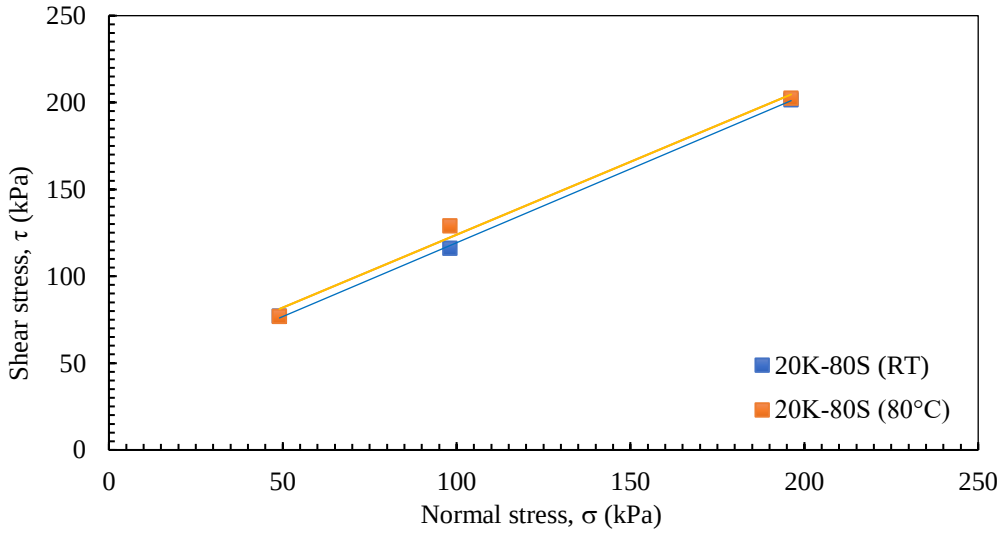

Figure 5.2 Shear stress-normal stress relationship of sand-kaolin mixtures under room and high temperatures (80 °C)

5.1.2 Shear Strength Behavior of Pumice Added Sand-Kaolin Mixtures Under Room and High Temperatures

Figure 5.3 shows the shear stress-strain relationship of sand-kaolin mixtures at room and high temperatures (80 °C) in the presence of 5 and 10% pumice. When the maximum shear stress values (under a vertical stress of 196.1 kPa) were compared, the highest shear strength value was obtained under high temperature as 128.91 kPa for additive-free sample under high temperature. In general, under room temperature and high temperature, pumice additive caused a decrease in the maximum shear stress values.

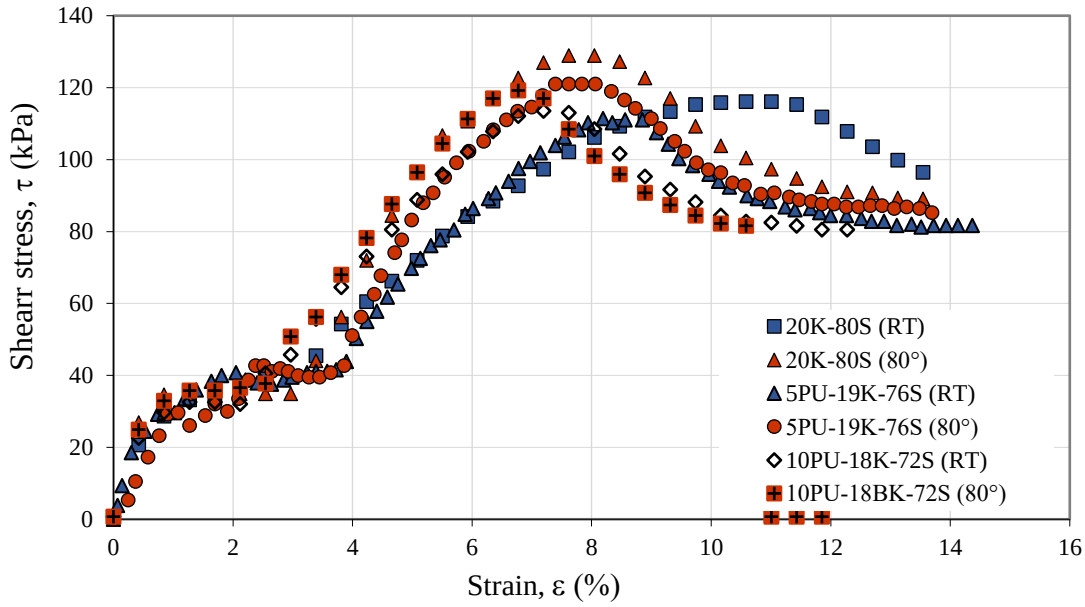

Figure 5.3 Shear stress-strain relationship of pumice added sand-kaolin mixtures at room and high temperatures (80 °C)

Shear stress-normal stress relationships of sand-kaolin mixtures at room temperature and high temperature (80 °C) in the presence of pumice are given in Figure 5.4. For the 20K-80S mixture, the angle of internal friction increased from 40.4° to 44.6° when 5% pumice additive was added at room temperature. Under high temperature (80 °C), the

angle of internal friction increased from 40.0° to 42.0° with 5% pumice and from 40.0° to 42.5° when 10% pumice was added.

At room temperature, the cohesion value decreased in the presence of pumice additives. The cohesion values decreased from 34.3 kPa to 13.5 kPa in the presence of 5% pumice additive. Similar to room temperature results under high temperature cohesion values decreased significantly.

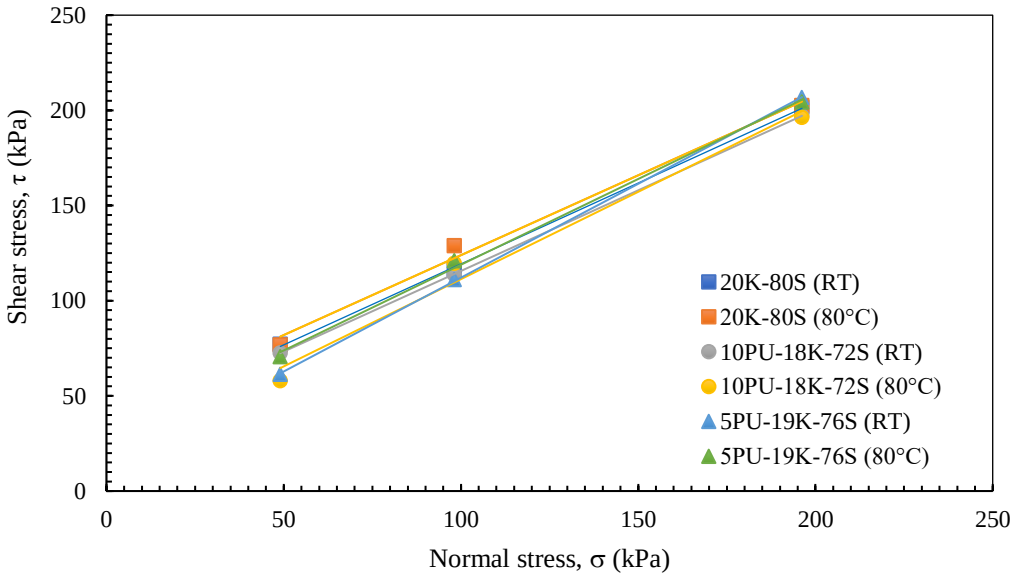

Figure 5.4 Shear stress-normal stress relationships of pumice added sand-kaolin mixtures at room and high temperatures (80 °C)

5.1.3 Shear Strength Behavior of Perlite Added Sand-Kaolin Mixtures Under Room and High Temperatures

Figure 5.5 shows the shear stress-strain relationships of sand-kaolin mixtures at room and high temperatures (80 °C) in the presence of 5 and 10% perlite additive. When the maximum shear stress values (under a vertical stress of 196.1 kPa) are analyzed, the highest value was obtained with 20K-80S mixture under high temperature with 128.91

kPa. The lowest value was obtained in 5PE-19K-76S mixture with 111.0 kPa. Perlite decreased the shear strength of sand-kaolin mixtures under room temperature and high temperature.

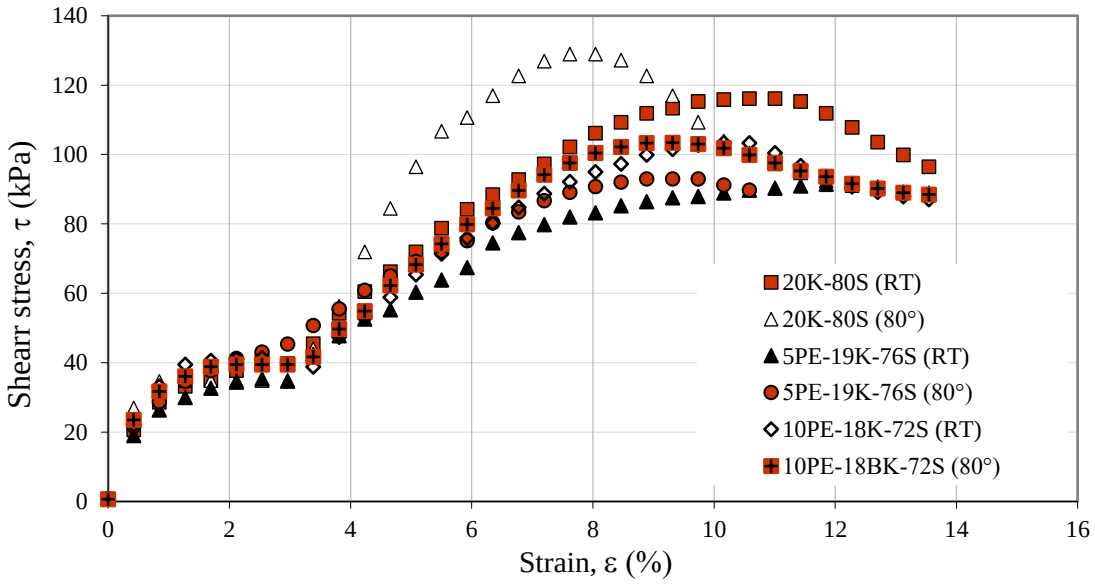

Figure 5.5 Shear stress-strain relationships of perlite added sand-kaolin mixtures at room and high temperatures (80 °C)

Shear stress-normal stress relationships of sand-kaolin mixtures at room temperature and high temperature (80 °C) in the presence of perlite additive are given in Figure 5.6. The angle of internal friction decreased from 40.4° to 39.7° and 36.7° in the presence of 5 and 10% perlite additives, respectively under room temperature. Under high temperature, the angle of internal friction decreased from 40.0° to 37.0° with 5% perlite, while there was no change in the angle of internal friction when 10% pumice was added.

At room temperature, the cohesion value of the sand-kaolin mixture decreased from 34.3 kPa to 10.0 kPa in the presence of 5% perlite additive. The decreasing trend in cohesion with perlite additives continued even under high temperature.

The cohesion value of 5PE-19K-76S mixture increased from 10.0 kPa to 23.4 kPa with temperature, while the cohesion value of 10PE-18K-72S mixture decreased from 28.2 kPa to 17.2 kPa. When the internal friction angles were analyzed, the value of 5PE-19K-76S mixture decreased from 39.7° to 37.0° when the temperature increased, while the angle of internal friction value of 10PE-18K-72S mixture increased to 40.0°.

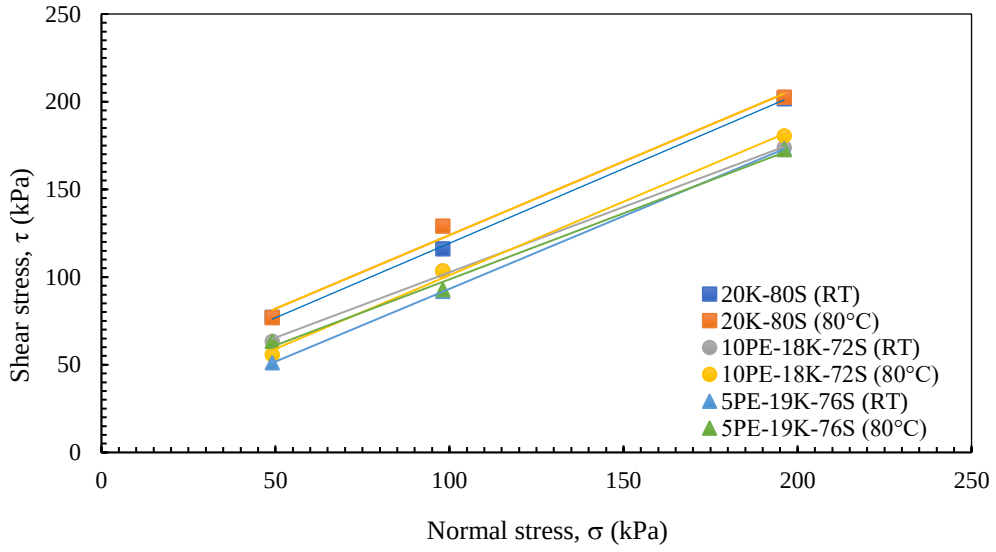

Figure 5.6 Shear stress-normal stress relationships of perlite added sand-kaolin mixtures at room and high temperatures (80 °C)

5.1.4 Shear Strength Behavior of Fiberglass Added Sand-Kaolin Mixtures Under Room and High Temperatures

The shear stress-strain relationships of sand-kaolin mixtures at room temperature and high temperature in the presence of 0.5 and 1% fiberglass. When the maximum shear stress values (under a vertical stress of 196.1 kPa) were compared, the highest value (128.91 kPa) belonged to 20K-80S mixture under high temperature (Figure 5.7). The lowest value was obtained with 1.0% fiberglass. In the presence of fiberglass additive,

the shear strength of sand-kaolin mixtures increased at room temperature, while a decrease was observed under high temperature.

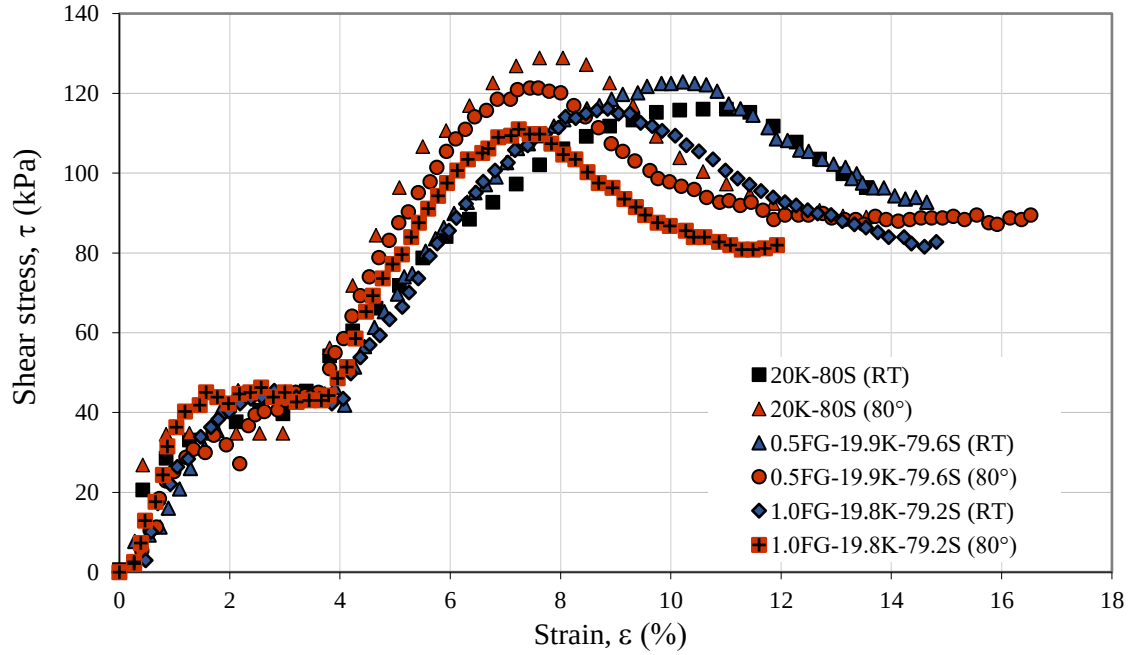

Figure 5.7 Shear stress-strain relationships of fiberglass added sand-kaolin mixtures at room and high temperatures (80 °C)

Shear stress-normal stress relationships of sand-kaolin mixtures at room temperature and high temperature (80 °C) in the presence of fiberglass additive are given in Figure 3.29. For the 20K-80S mixture, the angle of internal friction increased from 40.4° to 46.4° and 45.2° in the presence of 0.5 and 1.0% fiberglass, respectively under room temperature. Under high temperature (80 °C), the internal friction angle insignificantly increased from 40.0° to 41.4° and 41.3° when 0.5 and 1.0% fiberglass were added.

At room temperature, the cohesion value of the sand-kaolin mixture decreased from 34.3 kPa to 20.8 kPa in the presence of 0.5% fiberglass and from 34.3 kPa to 14.7 kPa in the presence of 1% fiberglass additive. Under high temperature, the cohesion values decreased too.

The cohesion value of 0.5FG-19.9K-79.6S mixture increased from 20.8 kPa to 35.5 kPa and the cohesion value of 1FG-19.9K-79.6S mixture increased from 14.7 kPa to 22.4 kPa with increase in temperature. When change in internal friction angles were analyzed, the value of 0.5FG-19.9K-79.6S mixture decreased from 46.4° to 41.4° when the temperature increased, and the value of 1FG-19.9K-79.6S mixture decreased from 45.2° to 41.3° when the temperature increased.

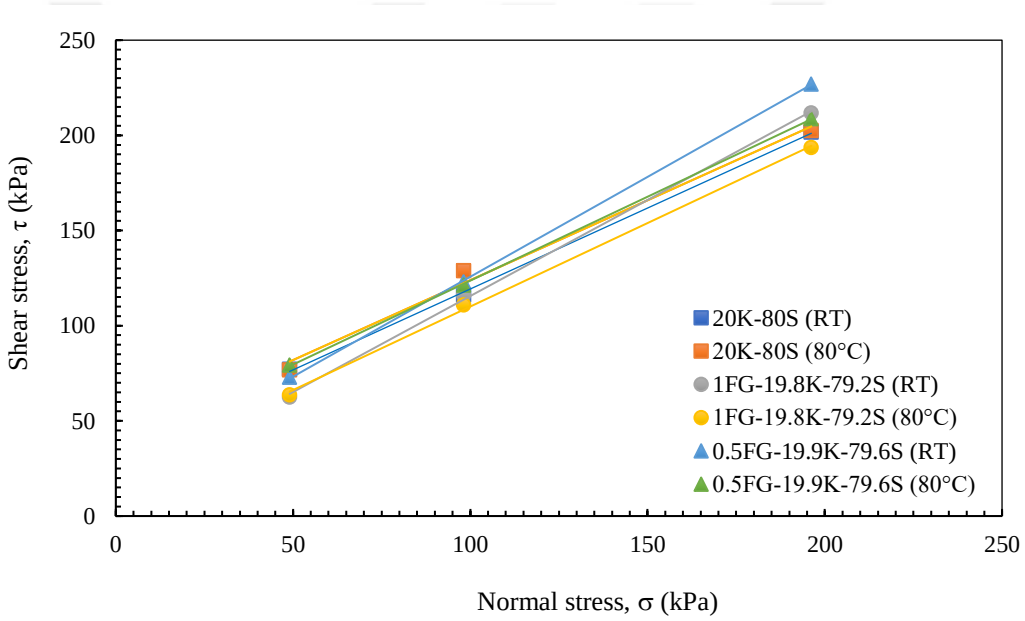

Figure 5.8 Shear stress-normal stress relationships of fiberglass added sand-kaolin mixtures at room and high temperatures (80 °C)

The shear strength parameters obtained from direct shear tests of perlite, pumice and fiberglass added sand-kaolin mixtures are given in Table 5.1.

Table 5.1 Shear strength parameters of sand-kaolin mixtures in the presence of pumice, perlite and fiberglass additives obtained from direct shear tests

Sample	Room Temperature		80 °C	
	ϕ' (°)	**c' (kPa)**	**ϕ' (°)**	**c' (kPa)**
20K-80S	40.4	34.3	40.0	40.0
5PU-19K-76S	44.6	13.5	42.0	28.8
10PU-18K-72S	42.0	30.9	42.5	19.7
5PE-19K-76S	39.7	10.0	37.0	23.4
10PE-18K-72S	36.7	28.2	40.0	17.2
0.5FG-19.9K-79.6S	46.4	20.8	41.4	35.5
1.0FG-19.8K-79.2S	45.2	14.7	41.3	22.4

5.2 Shear Strength of Zeolite -Bentonite Mixtures

The effect pumice, perlite and fiberglass additives on the shear strength behavior of zeolite-bentonite mixtures under both room temperature and high temperature is shown.

5.2.1 Shear Strength Behavior of Zeolite-Bentonite Mixtures Under Room and High Temperatures

Figure 5.9 shows the shear stress-strain relationships of zeolite-bentonite mixtures under room and high temperature. Under high temperature, the shear strength of 20B-80Z mixture increased compared to room temperature. The maximum shear stress value increased from 61.77 kPa to 75.71 kPa (under a vertical stress of 196.1 kPa).

Figure 5.10 shows the shear stress-normal stress relationship of 20B-80Z mixtures. According to the results when the temperature increased, the angle of internal friction value increased from 19.4° to 24.2°, while the cohesion value decreased from 24.2 kPa to 17.2 kPa.

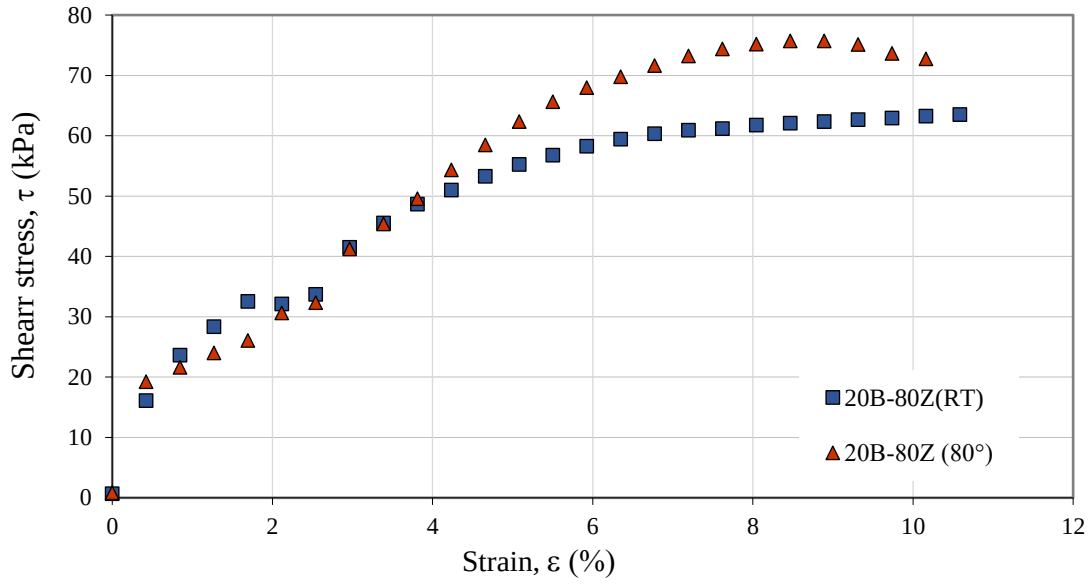

Figure 5.9 The shear stress-strain relationships of 20B-80Z mixtures at room and at high temperatures (80 °C)

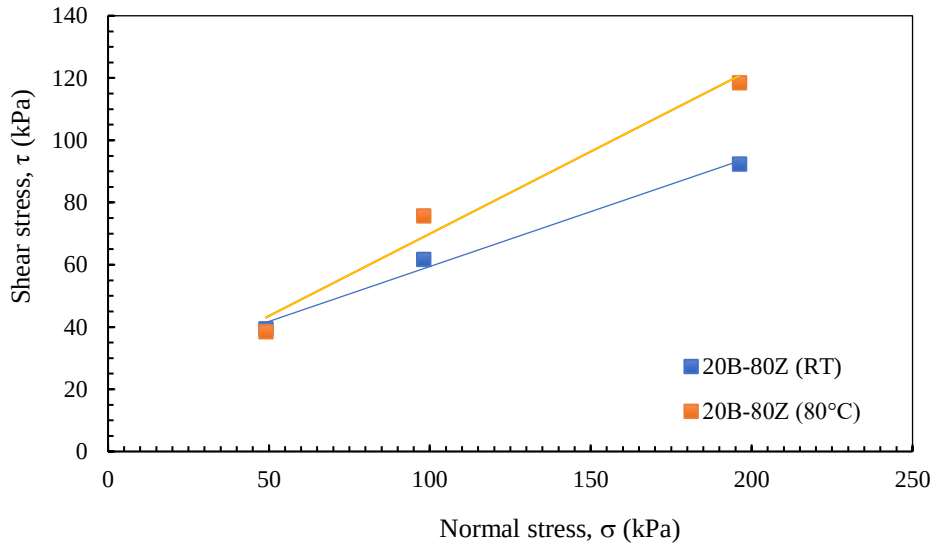

Figure 5.10 The shear stress-normal stress relationship of 20B-80Z mixtures at room and high temperatures (80 °C)

5.2.2 Shear Strength Behavior of Pumice Added Zeolite-Bentonite Mixtures Under Room and High Temperatures

The shear stress-strain relationships of zeolite-bentonite mixtures under room and high temperatures (80 °C) in the presence of 5 and 10% pumice additive. When the maximum shear stress values were compared under room temperature, the highest and lowest values belonged to 5PU-19B-76Z and 20B-80Z mixtures, respectively (Figure 5.11). Pumice increased the shear strength of zeolite-bentonite mixtures under room and high temperatures.

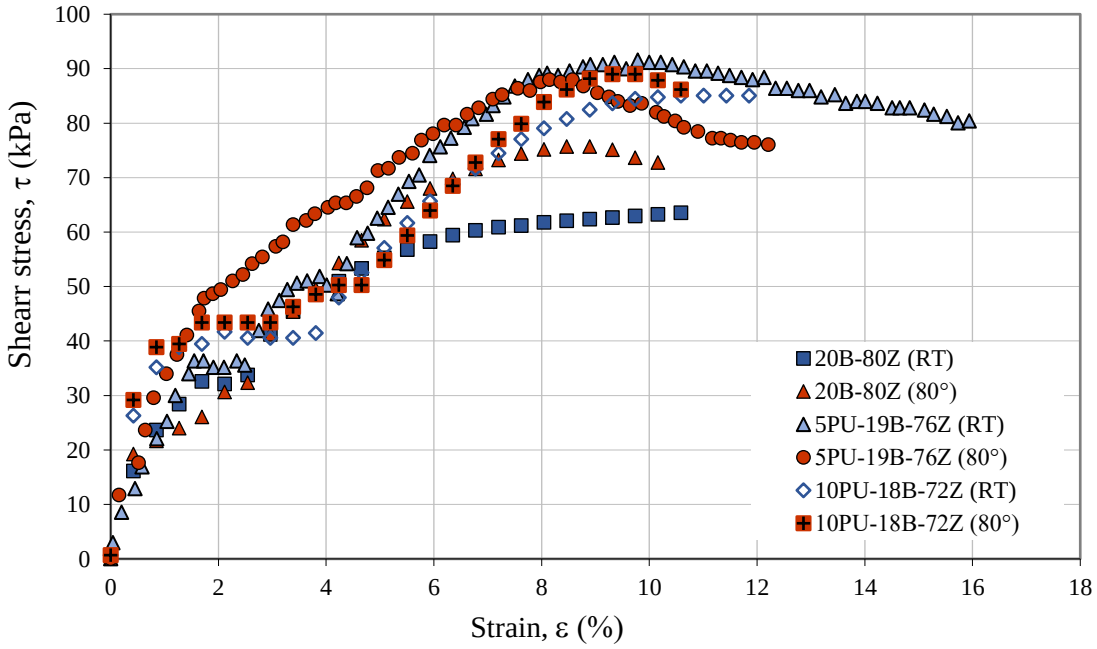

Figure 5.11 Shear stress-strain relationships of pumice added zeolite-bentonite mixtures at room and high temperatures (80 °C)

Shear stress-normal stress relationships of zeolite-bentonite mixtures at room and high temperatures (80 °C) in the presence of pumice are given in Figure 5.12. For the 20B-80Z mixture, the angle of internal friction increased from 19.4° to 25.2° when 5% pumice was

added at room temperature and from 19.4° to 24.6° when 10% pumice was added. Under high temperature (80 °C), the internal friction angle increased from 27.8° to 29.4° and 31.4° when 5 and 10% pumice were added, respectively.

At room temperature, the cohesion value of the zeolite-bentonite mixture increased from 24.2 kPa to 31.9 kPa in the presence of 5% pumice additive, while no significant change in cohesion value was observed in the presence of 10% pumice additive. Under high temperature, addition of pumice increased the cohesion values with both contents.

The cohesion value of 5PU-19B-76Z mixture decreased from 31.9 kPa to 25.8 kPa and the cohesion value of 10PU-18B-72Z mixture decreased from 24.3 kPa to 23.3 kPa under high temperature. Regarding the internal friction angle values, the values increased significantly under high temperatures.

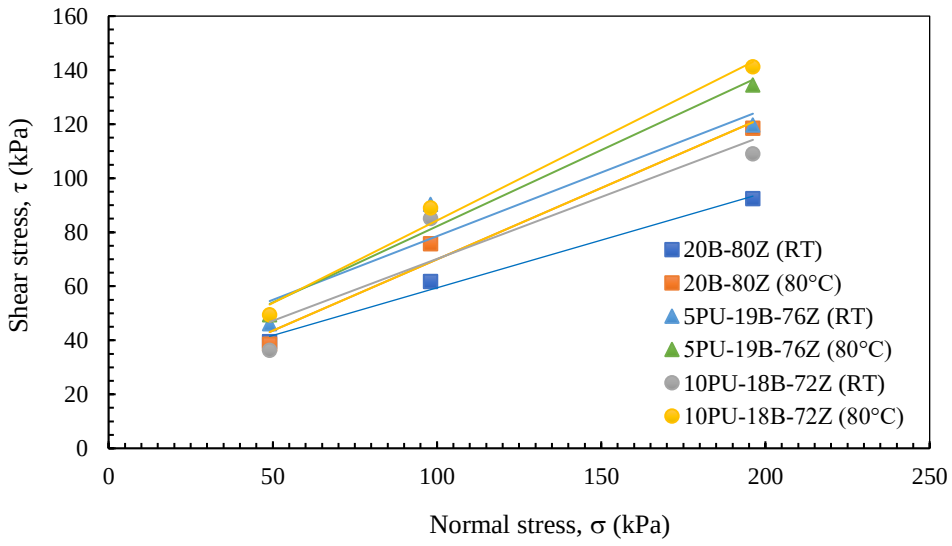

Figure 5.12 Shear stress-normal stress relationships of pumice added zeolite-bentonite mixtures at room and high temperatures (80 °C)

5.2.3 Shear Strength Behavior of Perlite Added Zeolite-Bentonite Mixtures Under Room and High Temperatures

Figure 5.13 shows the shear stress-strain relationships of zeolite-bentonite mixtures under room and high temperatures (80 °C) in the presence of 5 and 10% perlite. When the maximum shear stress values were compared, the highest value was obtained in 5PE-19B-76Z mixture at room temperature as 110.9 kPa. The lowest value was obtained in the 20B-80Z mixture at room temperature as 61.8 kPa. Perlite significantly increased the shear strength of zeolite-bentonite mixtures under room and high temperatures.

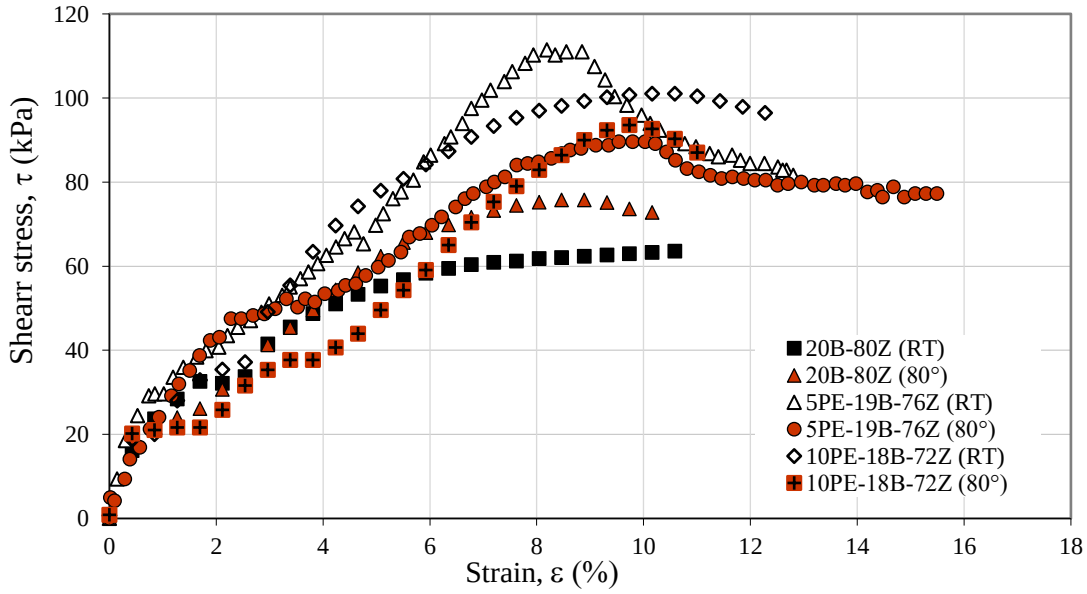

Figure 5.13 Shear stress-strain relationship of perlite added zeolite-bentonite mixtures at room and high temperatures (80 °C)

Shear stress-normal stress relationships of zeolite-bentonite mixtures at room and high temperatures (80 °C) in the presence of perlite are given in Figure 5.14. For the 20B-80Z mixture, the angle of internal friction value increased from 19.4° to 30.5° when 5% perlite was added at room temperature and from 19.4 to 27.9° when 10% perlite was added.

Under high temperature (80 °C), the internal friction angle increased from 27.8° to 31.1° and, 32.3° in the presence of 5 and 10%, respectively.

At room temperature, the cohesion value of the zeolite-bentonite mixture increased with perlite. Similarly, cohesion values increased under high temperature. The cohesion value of 5PE-19B-76Z mixture decreased from 40.7 kPa to 28.6 kPa with temperature, while the cohesion value of 10PE-18B-72Z mixture decreased from 33.7 kPa to 25.4 kPa. Regarding the internal friction angles, there was no significant change in the presence of 5 and 10% perlite when the temperature increased.

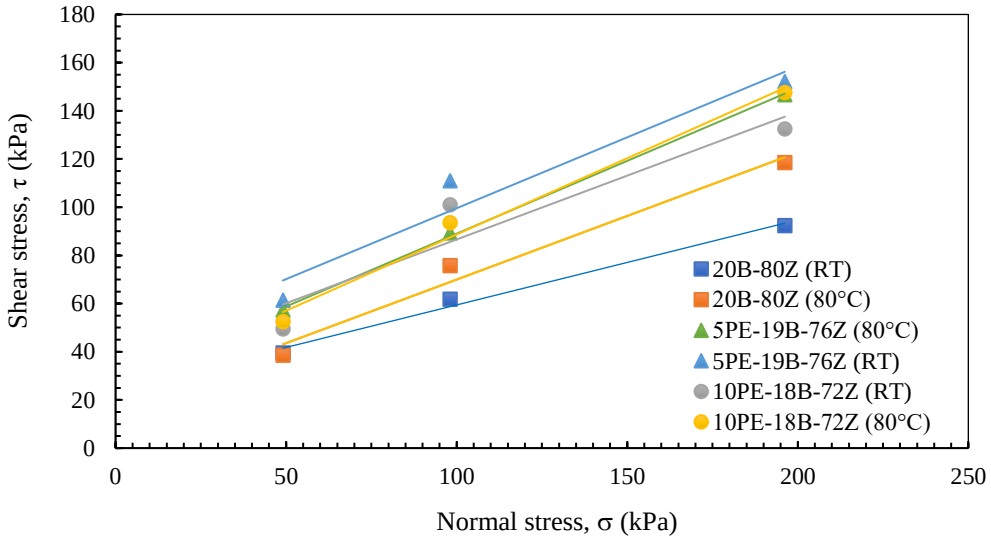

Figure 5.14 Shear stress-normal stress relationships of perlite added zeolite-bentonite mixtures at room and high temperatures (80 °C)

5.2.4 Shear Strength Behavior of Fiberglass Added Zeolite-Bentonite Mixtures Under Room and High Temperatures

Figure 5.15 shows the shear stress-strain relationship of zeolite-bentonite mixtures at room and high temperatures (80 °C) in the presence of 0.5 and 1.0% fiberglass. The highest shear stress value was obtained with 1.0FG-19.8B-79.2Z mixture under high

temperature as 81.0 kPa. Fiberglass additive significantly increased the shear strength of zeolite-bentonite mixtures under room and high temperatures.

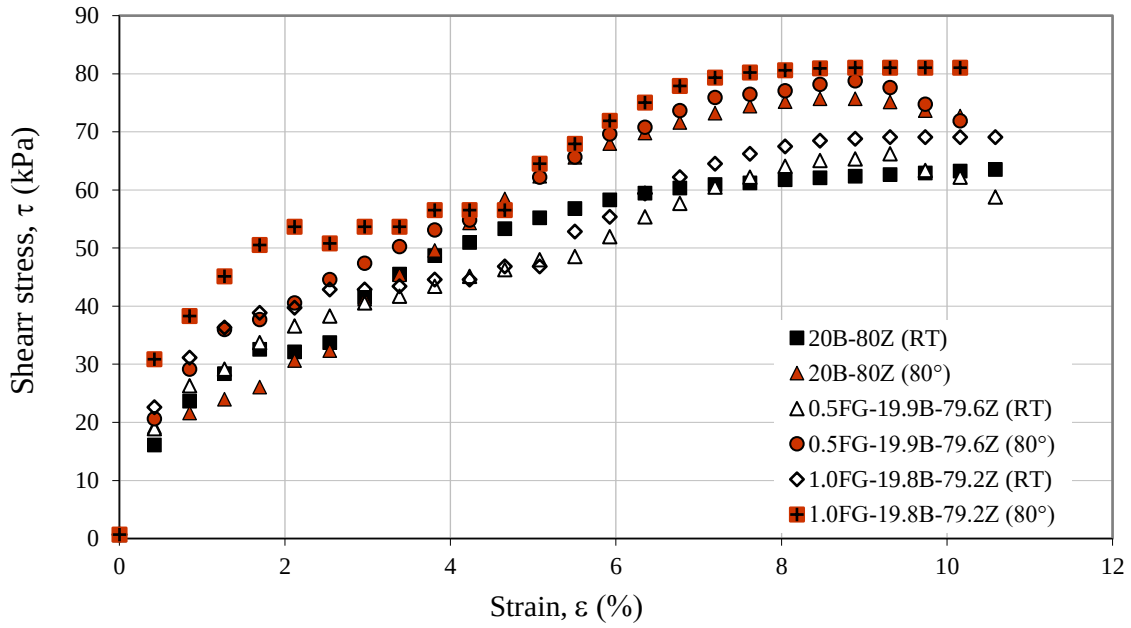

Figure 5.15 Shear stress-strain relationships of fiberglass added zeolite-bentonite mixtures at room and high temperatures (80 °C)

Shear stress-normal stress relationships of zeolite-bentonite mixtures at room and high temperatures (80 °C) in the presence of fiberglass are given in Figure 5.16. For the 20B-80Z mixture, the internal friction angle increased from 19.4° to 24.0° when 0.5% fiberglass.

At room temperature, the cohesion values of the zeolite-bentonite mixture decreased in the presence of fiberglass insignificantly. Under high temperature, the cohesion values increased from 17.2 to 23.2 and 25.5 kPa in the presence of 0.5 and 1% fiberglass. When the change in internal friction angles were examined with high temperature, it is seen that increase from 24.0° to 28.1° 0.5FG-19.9B-79.6Z in the mixture, increase from 24.2° to 28.3° in the mixture 1FG-19.8B-79.2Z were observed.

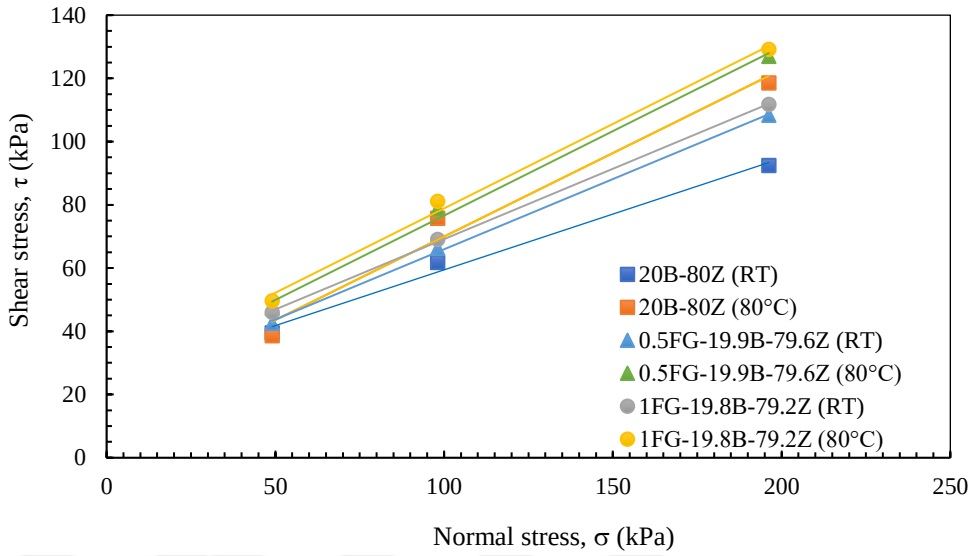

Figure 5.16 Shear stress-normal stress relationships of fiberglass added zeolite-bentonite mixtures at room temperature and high temperature (80°C)

Shear strength parameters obtained from direct shear tests for sand-kaolin mixtures are given in Table 5.2.

Table 5.2 Shear strength parameters of zeolite-bentonite mixtures in the presence of pumice, perlite and fiberglass additives obtained from direct shear tests

Sample	**Room Temperature**		**80 °C**	
	ϕ' (°)	**c' (kPa)**	**ϕ' (°)**	**c' (kPa)**
20B-80Z	19.4	24.2	27.8	17.2
5PU-19B-76Z	25.2	31.9	29.4	25.8
10PU-18B-72Z	24.6	24.3	31.4	23.3
5PE-19B-76Z	30.5	40.7	31.1	28.6
10PE-18B-72Z	27.9	33.7	32.3	25.4
0.5FG-19.9B-79.6Z	24.0	21.5	28.1	23.2
1.0FG-19.8B-79.2Z	24.2	24.7	28.3	25.5

According to the direct shear test results, the shear strength of sand-kaolin mixtures generally increased with increasing temperature. This can be explained by the viscous shear resistance of adsorbed water and texture changes due to temperature increase (Alpaydın, 2019). It was noted that buffer properties may change with cementation and illitization when the temperature approaches 100 °C (Liu, Cai, & Wang, 2017). However, as a result of the direct shear test, the cementation effect did not occur and the shear strength decreased. In addition, the shear strength of clays with increasing temperature depends largely on the volume change caused by the increasing temperature (Hong et al., 2013).

In the presence of additives in sand-kaolin mixtures, the shear strength generally decreased. It is well known that the shear strength would increase with increasing sand content as the friction between sand grains increased. In the presence of additives, it can be said that the shear strength decreases due to the decrease in the amount of sand. The vertical shear strength values of sand-kaolin mixtures in the presence of perlite, pumice and fiberglass additives are shown in Figure 5.17.

Figure 5.18 shows the shear strength of zeolite-bentonite mixtures in the presence of perlite, pumice and fiberglass additives. The shear strength increased in the presence of perlite additive- both at room temperature and under high temperature of the ZBMS. This is due to the presence of silanol (Si-OH) groups on the surface of perlite in the literature and the silanol group binds to hydroxyl groups in clay slabs (Ogawa et al., 1998). For this reason, perlite is attached to the clay surface and increases the shear strength.

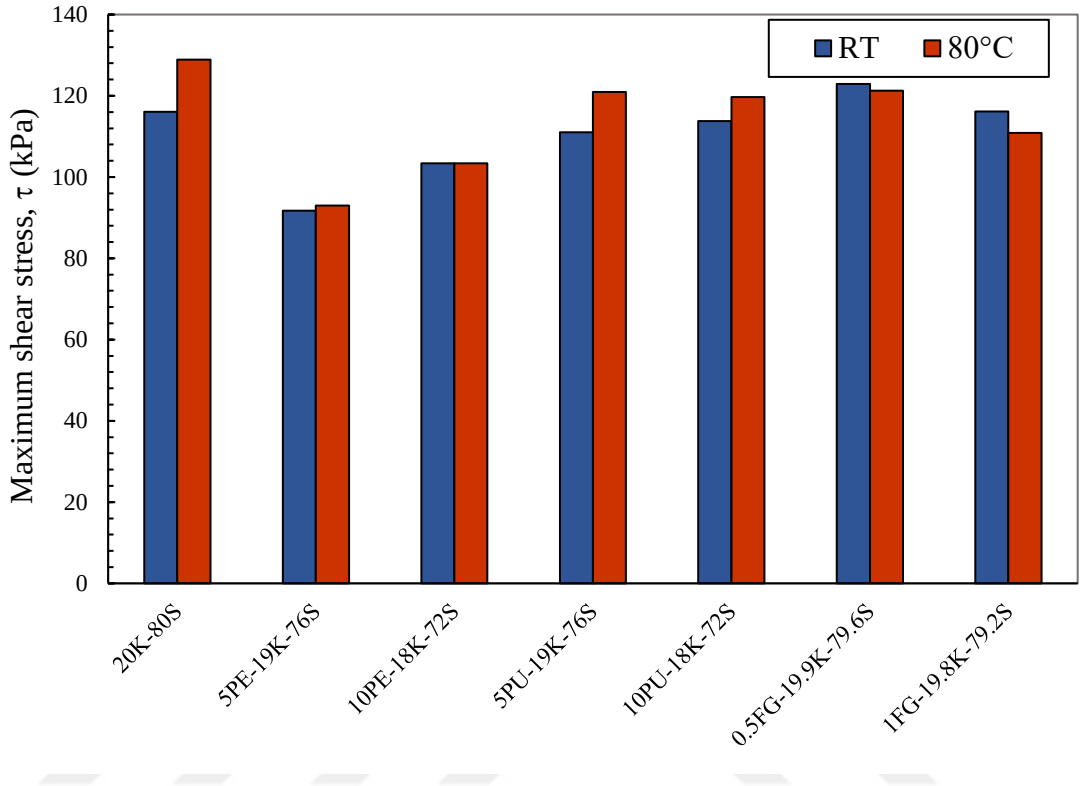

Figure 5.17 Shear strength values of sand-kaolin mixtures

In general, the shear strength of bentonite-zeolite mixtures decreases with increasing temperature except for the mixture with fiberglass additives. An increase in temperature causes thermal expansion of soil grains and pore water, which reduces the strength (Gu et al., 2014).

Figure 5.19 shows the shear strength parameters of zeolite-bentonite mixtures in the presence of perlite, pumice and fiberglass additives. When zeolite-bentonite mixtures are examined, an increase in the angle of internal friction is generally observed with increasing temperature, while there is a decreasing trend in the cohesion value. These results are consistent with the increase in the angle of internal friction with increasing temperature and decrease in the cohesion value with temperature as described by Wang, Benway and Arayssi (1990) in the literature.

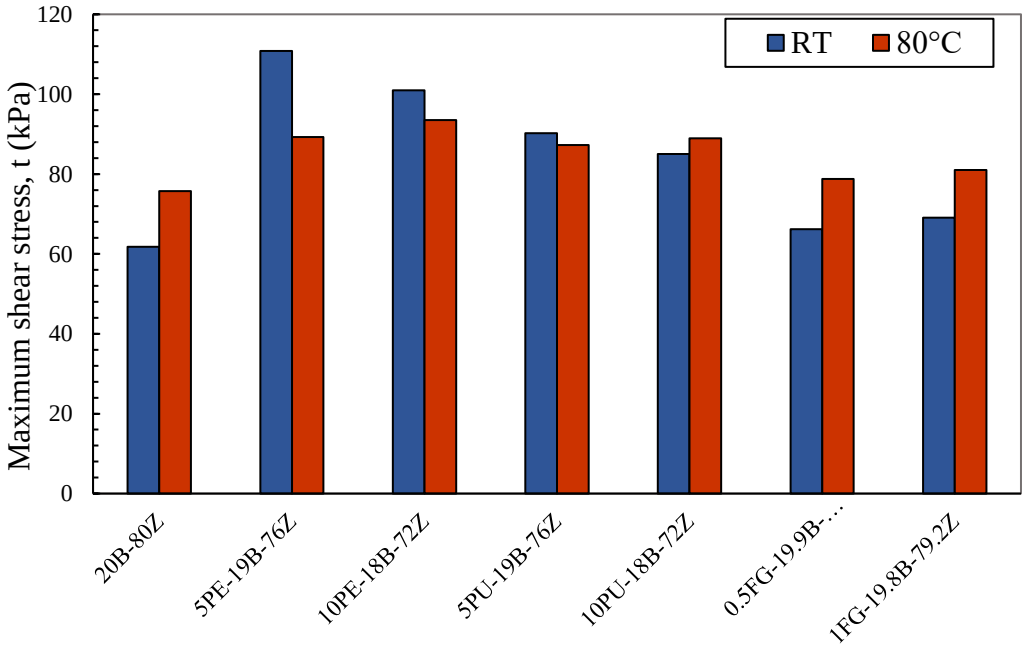

Figure 5.18 Shear strength values of zeolite-bentonite mixtures

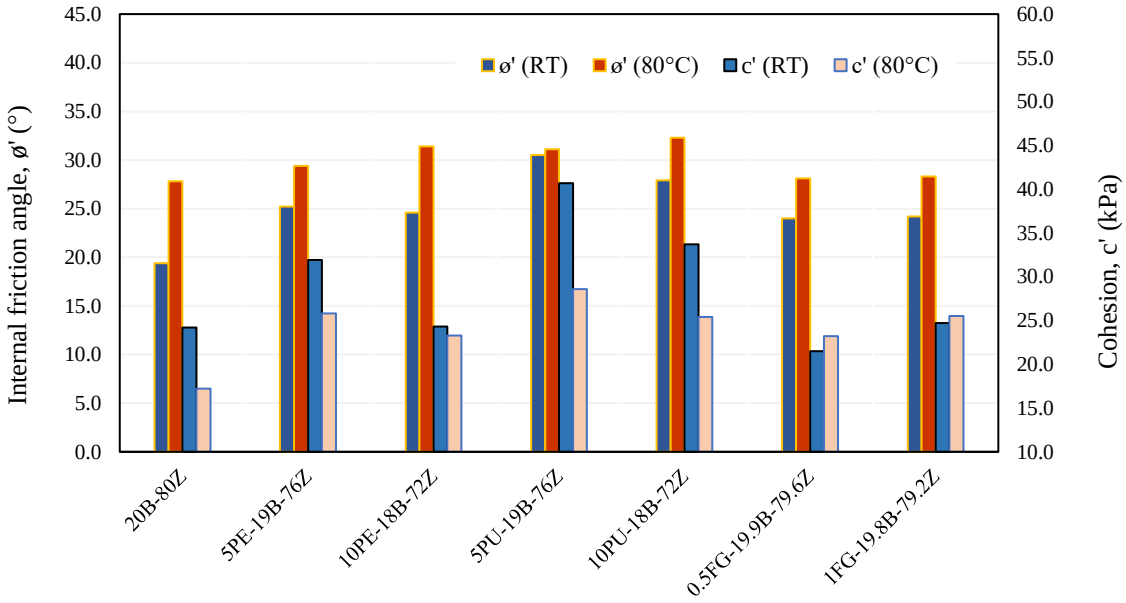

Figure 5.19 Shear strength parameters of zeolite-bentonite mixtures

CHAPTER 6
HYDRAULIC CONDUCTIVITY BEHAVIOR UNDER HIGH TEMPERATURE and THERMAL CONDUCTIVITY MEASUREMENTS

6.1 Hydraulic Conductivity Test Results

Hydraulic conductivity values were determined with performing flexible wall permeameters under different temperatures. The hydraulic conductivity tests results of zeolite-bentonite mixtures in the presence of perlite, pumice and fiberglass additives are given in this section.

6.1.1 Hydraulic Conductivity of Zeolite -Bentonite Mixtures

The hydraulic conductivity values of the zeolite-bentonite mixture were determined under different thermal conditions. The temperature was increased in the cell from room temperature to 50 and 80 °C, respectively. Hydraulic conductivity test results of 20B-80Z mixture are shown in Figure 6.1. The hydraulic conductivity value of 20B-80Z mixture was determined as $3.9x10^{-9}$ m/s at room temperature. There was no significant change was observed in the hydraulic conductivity value when cell temperature increased to 50 °C. However, when the temperature was increased to 80 °C, the hydraulic conductivity value increased to $5.4x10^{-10}$ m/s. Cooling was applied after this temperature level. While the hydraulic conductivity value was similar when cooled from 80 °C to 50 °C, however the hydraulic conductivity value decreased when cooled from 50 °C to 25 °C. The hydraulic conductivity values are given in Table 6.1.

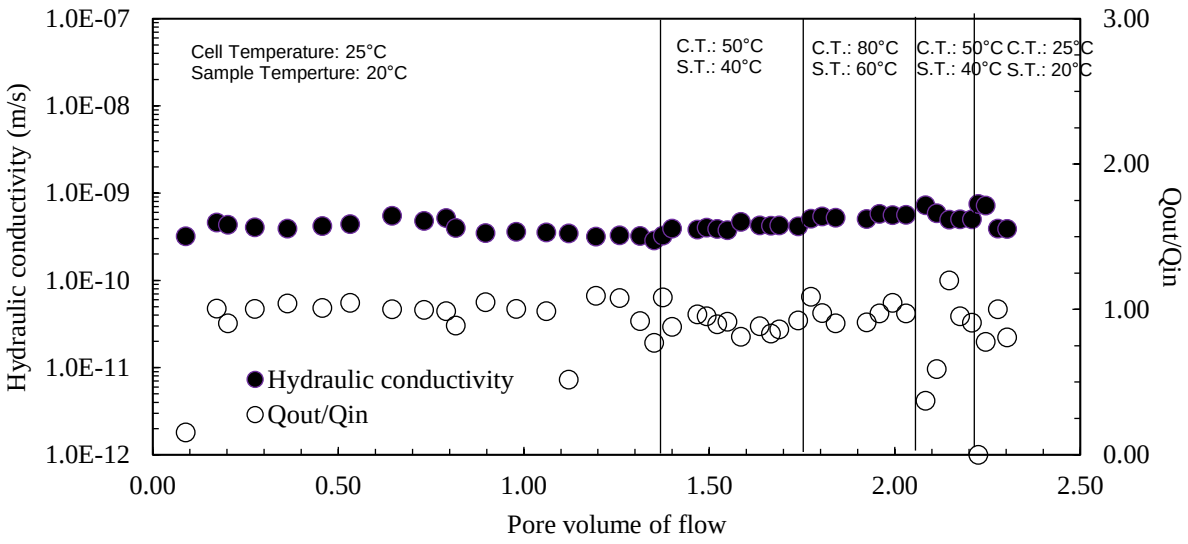

Figure 6.1 Hydraulic conductivity-pore volume of flow of 20B-80Z mixture

Table 6.1 Temperature dependent hydraulic conductivity values of 20B-80Z mixture

Temperature (°C)	k (m/s)
25	$3.9x10^{-10}$
50	$4.1x10^{-10}$
80	$5.4\ x10^{-10}$
50	$5.2x10^{-10}$
25	$3.9x10^{-10}$

6.1.1.1 Hydraulic Conductivity of Pumice Added Zeolite-Bentonite Mixtures

The hydraulic conductivity values of the zeolite-bentonite mixture in the presence of pumice were determined by experiments performed at room and high temperatures. Figure 6.2 shows the hydraulic conductivity test results of the pumice added zeolite-bentonite mixture. The hydraulic conductivity value of the 10PU-18B-72Z mixture was determined as $7.2x10^{-10}$ m/s at room temperature. As the cell temperature increased to 50 °C, the

hydraulic conductivity value increased 2.1 times and reached $1.5x10^{-9}$ m/s. When the cell temperature was increased to 80 °C, there was no significant increase in the hydraulic conductivity value. While the hydraulic conductivity value was similar when cooled from 80 °C to 50 °C, a slight decrease in the hydraulic conductivity value was observed when the temperature decreased from 50 °C to 25 °C. In addition, the hydraulic conductivity value of the mixture did not return to its initial value at the end of the cycle. The hydraulic conductivity values are given in Table 6.2.

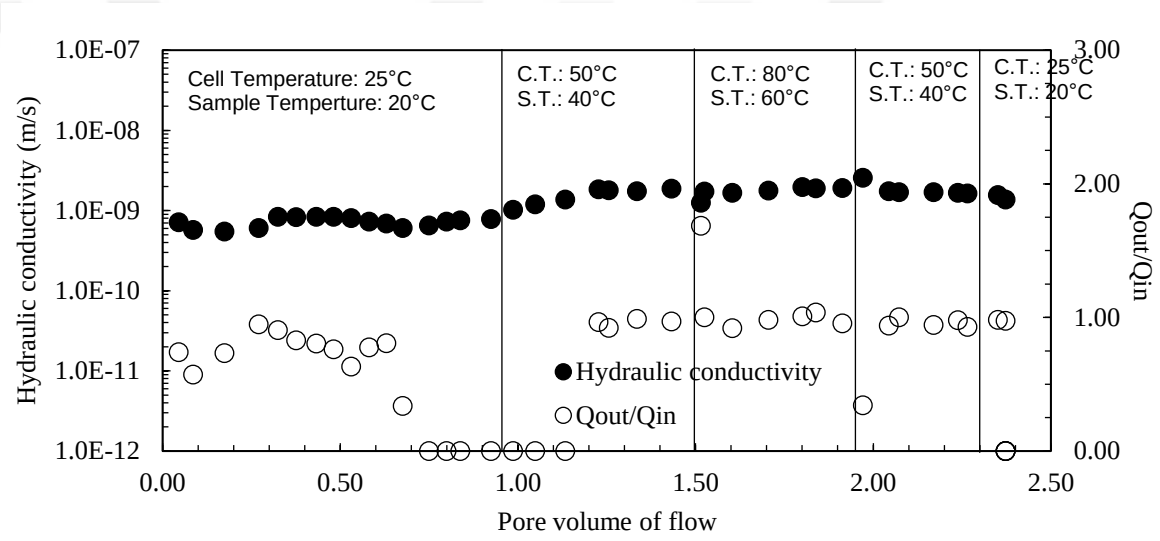

Figure 6.2 Hydraulic conductivity-pore volume of flow of 10PU-18B-72Z mixture

Table 6.2 Temperature dependent hydraulic conductivity values of mixtures

Temperature (°C)	**k (m/s)**	
	20B-80Z	10PU-18B-72Z
25	$3.9x10^{-10}$	$7.2x10^{-10}$
50	$4.1x10^{-10}$	$1.5x10^{-9}$
80	$5.4\ x10^{-10}$	$1.7\ x10^{-9}$
50	$5.2x10^{-10}$	$1.7x10^{-9}$
25	$3.9x10^{-10}$	$1.5x10^{-9}$

6.1.1.2 Hydraulic Conductivity of Perlite Added Zeolite-Bentonite Mixtures

The hydraulic conductivity values of the zeolite-bentonite mixture in the presence of 5 and 10% perlite were determined by experiments performed at different temperatures. Figure 6.3 shows the hydraulic conductivity test results of 5% perlite added zeolite-bentonite mixture. The hydraulic conductivity value of 5PE-19B-76Z mixture was determined as $1.2x10^{-8}$ m/s at room temperature. An increase of approximately 7 times in the hydraulic conductivity value was observed when the cell temperature was increased from 25 °C to 50 °C. When the cell temperature was increased from 50 °C to 80 °C, it was observed that the hydraulic conductivity value increased approximately 1.3 times. The hydraulic conductivity values are given in Table 6.3.

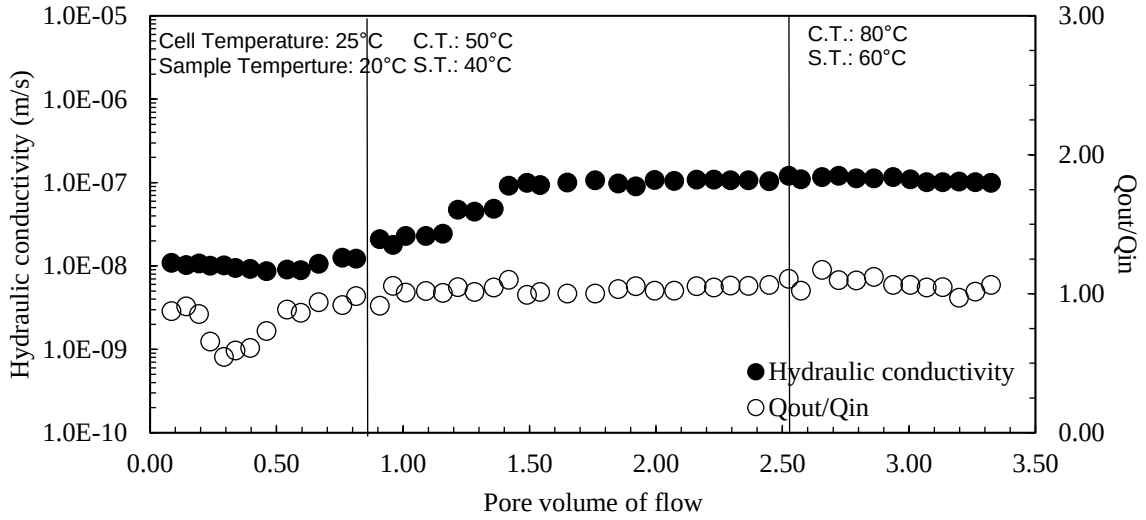

Figure 6.3 Hydraulic conductivity-pore volume of flow of 5PE-19B-76Z mixture

The hydraulic conductivity test results of zeolite-bentonite mixture with 10% perlite additive are shown in Figure 6.4. The hydraulic conductivity value of the 10PE-18B-72Z mixture was determined as $1.4x10^{-7}$ m/s at room temperature and no significant change was observed as the cell temperature increased from 50 and 80°C. When temperature decreased no significant change was observed in the hydraulic conductivity values.

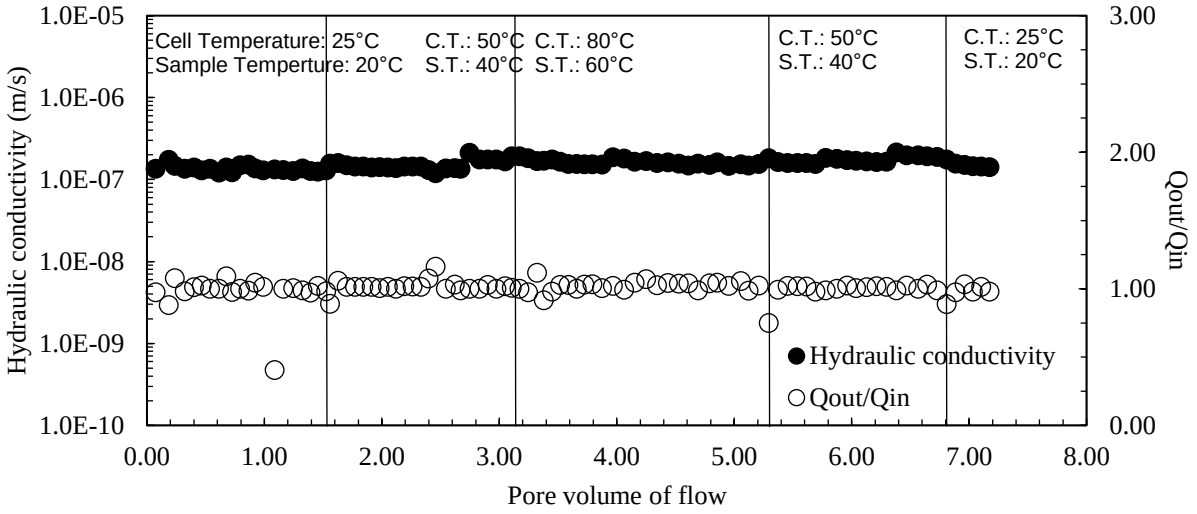

Figure 6.4 Hydraulic conductivity-pore volume of flow graph of 10PE-18B-72Z mixture

Table 6.3 Temperature dependent hydraulic conductivity values of zeolite-bentonite mixtures

Temperature (°C)	**k (m/s)**		
	20B-80Z	5PE-19B-76Z	10PE-18B-72Z
25	$3.9x10^{-10}$	$1.2x10^{-8}$	$1.4x10^{-7}$
50	$4.1x10^{-10}$	$8.5x10^{-8}$	$1.5x10^{-7}$
80	$5.4\ x10^{-10}$	$1.1x10^{-7}$	$1.6x10^{-7}$
50	$5.2x10^{-10}$	-	$1.8x10^{-7}$
25	$3.9x10^{-10}$	-	$1.5x10^{-7}$

6.1.1.3 Hydraulic Conductivity of Fiberglass Added Zeolite-Bentonite Mixture

The hydraulic conductivity values of the zeolite-bentonite mixture in the presence of fiberglass were determined under high temperatures. The hydraulic conductivity test results of glass fiberglass added zeolite-bentonite mixture are given in Figure 6.5. The hydraulic conductivity value of 0.5FG-19.9B-79.6Z mixture was determined as $8.4x10^{-10}$ m/s at room temperature. As can be seen in Table 6.4, the hydraulic conductivity remained

approximately same as the cell temperature increased to 50 °C. When the cell temperature was increased to 80 °C, the hydraulic conductivity value increased 1.9 times. The results of the hydraulic conductivity tests are given in Table 6.4.

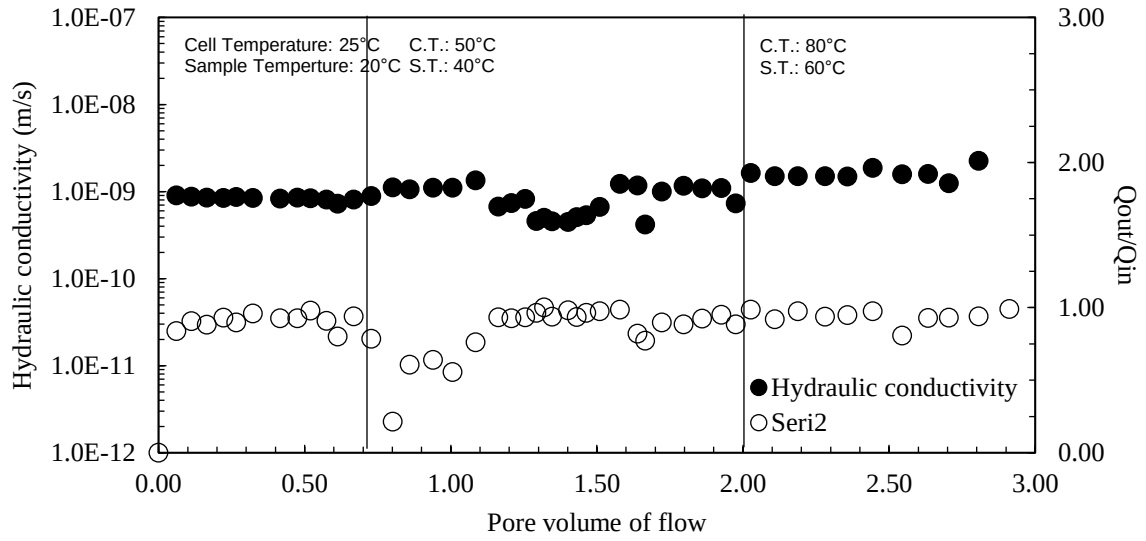

Figure 6.5 Hydraulic conductivity-pore volume of flow graph of 0.5FG-19.9B-79.6Z mixture

Table 6.4 Temperature dependent hydraulic conductivity values of 0.5FG-19.9B-79.6Z mixture

Temperature (°C)	**k (m/s)**
25	$8.4x10^{-10}$
50	$8.4x10^{-10}$
80	$1.6x10^{-9}$

The hydraulic conductivity values of zeolite-bentonite mixtures are shown in Figure 6.6. When the hydraulic conductivity values of zeolite-bentonite mixtures were compared, an increase in hydraulic conductivity values was observed with the increase in temperature. The reason for this is that the viscosity of water increases with increasing temperature (Tsutmumi and Tanaka, 2012). It was noted that the viscosity of pore water decreased due

to high temperature and this effect increased the hydraulic conductivity value (Cho et al., 2002). It was noted that at a certain temperature, adsorbed water molecules do not move and free water flow occurs through the confined channels, thus reducing the water layer thickness and increasing the hydraulic conductivity value (Habibagahi, 1977).

Similar to former studies, it was observed that the hydraulic conductivity value of bentonite-zeolite mixture increased in the presence of perlite, pumice and fiberglass additives. The decrease in the hydraulic conductivity value as the amount of bentonite increases is due to the fact that bentonite has a high specific surface, adsorbs more water and has a high swelling capacity (Kumar and Yong, 2002). For this reason, when additives were added to the mixtures, the hydraulic conductivity value increased due to the decrease in the amount of bentonite.

Fiberglass additive material increased the hydraulic conductivity value of zeolite-bentonite mixture at high temperature while it was similar at room temperature. It was noted in the literature that 0.5% fiberglass additive maintained the hydraulic conductivity value and was at acceptable levels (Miller et al., 2004). None of the additives could contribute to the hydraulic conductivity values at regulations level (1×10^{-12} m/sec). For that reason, in order to reach the hydraulic conductivity regulations level, the bentonite content can be increased in the mixtures.

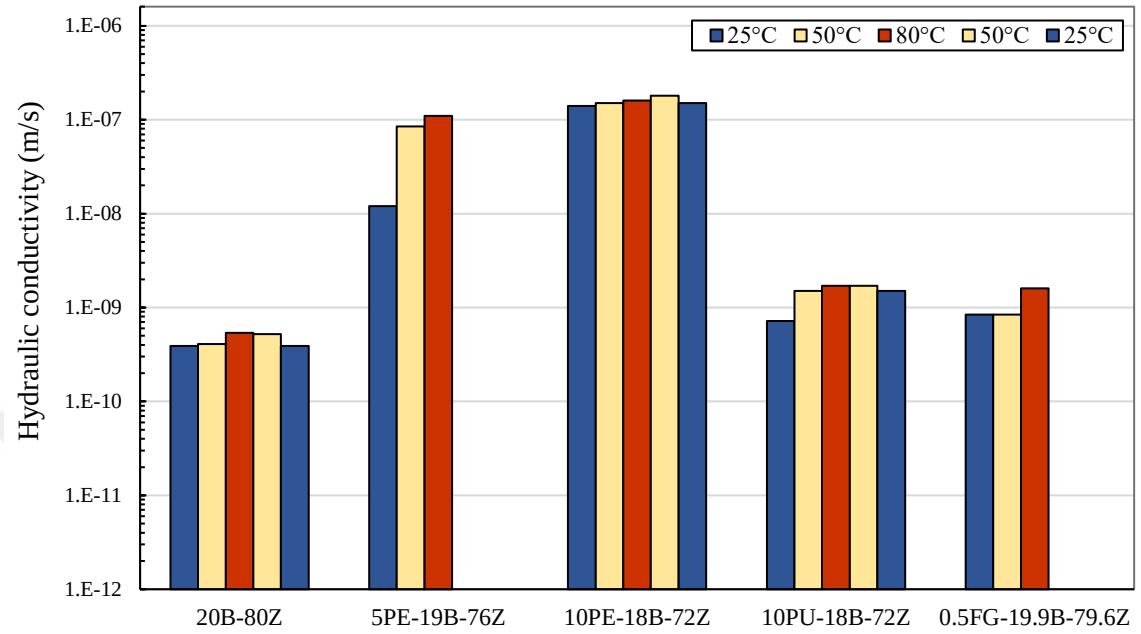

Figure 6.6 Hydraulic conductivity values zeolite-bentonite mixtures

6.2 Thermal Conductivity Test Results

The thermal conductivity values of zeolite-bentonite mixtures in the presence of perlite, pumice and fiberglass are given in this section.

6.2.1 Thermal Conductivity of Sand-Kaolin Mixtures

The change in thermal conductivity of the sand-kaolin mixture in the presence of pumice and fiberglass is presented in this section. As shown in Table 6.5, the thermal conductivity value of the 20B-80Z mixture was found to be 2.345 W/m.K. In the presence of 5 and 10% pumice additive, the thermal conductivity values of the sand-kaolin mixture decreased to 2.215 W/m.K and 2.311 W/m.K, respectively. In general, pumice and fiberglass decreased the thermal conductivity of sand-kaolin mixtures.

Table 6.5 Thermal conductivity values of sand-kaolin mixtures with pumice and fiberglass additives

Sample	Thermal Conductivity (W/m.K)
20K-80S	2.345
10PU-18K-72S	2.215
0.5FG-19.9K-79.6S	2.311

6.2.2 Thermal Conductivity of Zeolite -Bentonite Mixtures

The change in the thermal conductivity of the sand-kaolin mixture in the presence of pumice, perlite and fiberglass additives were determined by thermal conductivity measurements. As shown in Table 6.6, the thermal conductivity value decreased from 0.970 to 0.953 W/m.K when 10% pumice additive was added to the zeolite-bentonite mixture, from 0.970 W/m.K to 0.863 W/m.K when 10% perlite additive was added. In the presence of 0.5% fiberglass, the thermal conductivity decreased, too. In general, the thermal conductivity values of zeolite-bentonite mixtures decreased in the presence of pumice, perlite and fiberglass.

Table 6.6 Thermal conductivity values of zeolite-bentonite mixtures with pumice, perlite and fiberglass

Sample	Thermal Conductivity (W/m.K)
20B-80Z	0.970
10PE-18B-72Z	0.863
10PU-18B-72Z	0.953
0.5FG-19.9B-79.6Z	0.958

When the thermal conductivity test results of sand-kaolin and zeolite-bentonite mixtures were investigated, it was observed that the additives decreased the thermal conductivity values. The three factors that significantly affect the thermal conductivity

value were noted as dry density, water content and fine grain ratio (Becker & Fricke, 1997). In a study in the literature, it was noted that the addition of expanded perlite and pumice decreased the thermal conductivity value (Demirboğa, R., & Gül R., 2003).

CHAPTER 7
CONCLUSIONS

7.1 CONCLUSIONS

The engineering behavior of sand-kaolin and zeolite-bentonite mixtures, which are buffer material candidates, were investigated under high temperature (80 °C) in the presence of pumice, perlite and fiberglass additives. In this context, compaction, consolidation, direct shear, hydraulic conductivity and thermal conductivity tests were performed on the mixtures. The results obtained as a result of the thesis are summarized below:

The summary of the compaction tests results is given below:

- The $\gamma_{d,max}$ values decreased in the presence of pumice and perlite of sand-kaolin mixtures, w_{opt} values decreased with pumice, increased with perlite because of high water holding capacity of perlite.
- In the presence of pumice additive in zeolite-bentonite mixtures, $\gamma_{d,max}$ value increased while w_{opt} value decreased.
- In the presence of perlite additive, $\gamma_{d,max}$ value of zeolite-bentonite mixtures decreased while w_{opt} value increased.
- Fiber glass additive did not cause significant changes in $\gamma_{d,max}$ and w_{opt} values of zeolite-bentonite and sand-kaolin mixtures.

The summary of the sand-kaolin mixtures consolidation tests results is given below:

- Perlite and fiberglass increased compression of sand-kaolin mixtures under room and high temperatures, while no trend was observed for pumice additive.
- At room temperature, perlite and fiberglass additives increased the amount of swelling.

- Under high temperature, fiberglass and pumice additives decreased the amount of swelling, while no trend was observed for perlite additive.

The summary of the zeolite-bentonite mixtures consolidation tests results is given below:

- Pumice and perlite additives generally decreased the amount of compression and swelling under room and high temperatures.
- Fiberglass additive increased the amount of compression at room temperature, while no trend was observed under high temperature.
- The lowest compression values were obtained under high temperature in the presence of perlite additive.

The summary of the sand-kaolin mixtures direct shear tests results is given below:

- When the shear strength behavior was investigated in the presence of perlite, pumice and fiberglass additives and under 196.1 kPa vertical stress, the maximum value was obtained in the 20K-80S mixture under high temperature. The minimum value was obtained in 5PE-19K-76S mixture at room temperature.
- The test results which were performed under room temperature, perlite and pumice additives decreased the maximum shear stress value, while fiberglass additives slightly increased the shear stress value.
- Perlite additive decreased the internal friction angle and cohesion value under room temperature and high temperature.
- Pumice and fiberglass additives increased the angle of internal friction and decreased the cohesion value under both temperatures.

The summary of the zeolite-bentonite mixtures direct shear tests results is given below:

- In zeolite-bentonite mixtures, the maximum shear strength under 196.1 kPa vertical stress was obtained at room temperature for the 5PE-19B-76Z mixture,

while the minimum value was obtained at room temperature for the 20B-80Z mixture.

- The shear stress value increased in the presence of perlite, pumice and fiberglass additives for the experiments performed under room temperature and high temperature for zeolite-bentonite mixtures.
- A general decrease in the shear stress value in the presence of perlite and pumice was observed with increasing temperature, while an increase in the shear stress value was observed in fiberglass doped mixtures.
- Perlite, pumice and fiberglass additives increased the internal friction angle and cohesion values under room temperature and high temperature.

The summary of the hydraulic conductivity tests results is given below:

- The perlite, pumice and fiberglass additives increased the hydraulic conductivity value.
- Hydraulic conductivity values of all mixtures increased with increasing temperature.
- When the mixtures were reduced to room temperature after high temperature, 20B-80Z and 10PE-18B-72Z mixtures returned to the initial hydraulic conductivity value.

The summary of the thermal conductivity tests results is given below:

.

- Pumice and fiberglass additives decreased the thermal conductivity of zeolite-bentonite and sand-kaolin mixtures.
- While perlite additive decreased the thermal conductivity value of zeolite-bentonite mixture, the sand-kaolin mixture experiment could not be performed in the presence of perlite additive because the required compaction could not be obtained.

According to the results of the thesis, it can be concluded that the most appropriate additive is pumice for the energy geo-resources field applications. The optimum content of 5% can be considered.

7.2 FUTURE STUDIES

In order to increase the performance of energy geo-structures resistant soil materials under high temperature is needed. For that reason, different additives for example steel and ferrochrome slags can be used. The effects of slags should be investigated under high temperatures. The suitability of different soil mixtures for buffer materials such as zeolite-sand-bentonite mixtures should be investigated for better performance of energy geo-structures. In order to attain hydraulic conductivity regulations for nuclear energy waste repositories, the bentonite content should be increased in the mixtures. The engineering behavior of these mixtures should be investigated under high temperatures.

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