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CHANGES IN THERMAL PROPERTIES OF SATURATED SOIL BASED ON FINE FRACTION

SUYA DOYGUN ZEMİNLERDE İNCE DANE ORANINA BAĞLI OLARAK TERMAL ÖZELLİKLERİN DEĞİŞİMİ

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ÖZET

Bu çalışmada kum-bentonit karışımlarının ısıl iletkenlik, ısıl özdirenç, özgül ısı kapasitesi ve ısıl yayılma özellikleri incelenmiştir. Zeminlerin ısıl özelliklerinin termal iğne metodu ile nasıl ölçüldüğü ve ve bu metod ile çalışan termal analiz cihazı Tempos hakkında bilgi verilecektir. Son olarak ince dane oranına bağlı olarak suya doygun zeminin ısıl özelliklerinin değişimine değinilecektir.
Anahtar Kelimeler: *zemin ısıl özellikleri, zeminin termal analizi, kum-bentonite karışımları*

ABSTRACT

In this study, thermal conductivity, thermal resistivity, specific heat capacity and thermal diffusivity of sand-bentonite mixtures were investigated. Information will be given about how the thermal properties of soils are measured by the thermal needle method and about the thermal analysis device Tempos that works with this method. Finally, the change of the thermal properties of the saturated soil will be discussed depending on the fine fraction.
Keywords: *soil thermal properties, soil thermal analysis, sand-bentonite mixtures*

1. INTRODUCTION

One of the physical properties of the soil is its thermal properties. Thermal properties vary depending on the void ratio, porosity, water saturation, mineralogy, effective stress on the soil, and density of the soil. Contact between soil particles is important in conduction and heat transfer. The wider contact area between the grains, soil grains will conduct heat more easily (Ahn & Jung, 2017).

The thermal conductivity of the soil is defined as the amount of heat passing through a unit soil area per unit time. If the thermal conductivity is high, heat conduction will be easy. Thermal conduction takes place by means of conduction, convection and radiation. Since there is no convection and radiation phenomena on the soils, it can be assumed that heat is transmitted only by conduction (Hamdhan & Clarke, 2010). Thermal conductivity is usually denoted by the symbol "λ" or "K" and its unit is $\frac{w}{m.K}$. In soils, thermal conductivity increases as water saturation and effective stress increase, and decreases as the void ratio increases.

The thermal resistivity of the soil is the temperature difference between the two faces of a unit cubed soil when 1 watt of heat is transferred. It is the opposite of thermal conductivity and its unit is $\frac{m.K}{w}$.

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The specific heat capacity of the soil is the amount of energy required to heat the soil in a given volume by 1 degree. It is denoted by C, its unit is $\frac{J}{kg.K}$. The specific heat capacity of the soil increases linearly as the water content increases.

The thermal diffusivity of the soil is the ratio of the thermal conductivity of the soil to the specific heat capacity of the soil. It is an indicator of how quickly the temperature change spreads during thermal conduction. If the thermal diffusivity is high, the temperature variation within the ground spreads rapidly. It is denoted by k and its unit is $\frac{m^2}{s}$.

In this study, the thermal properties of the soil was investigated depending on the fine content by using sand-bentonite mixtures. This study was part of developing a method that could predict soil class by making thermal measurements of saturated soils.

2. MATERIALS AND METHOD

2.1. Materials

In this study, sand and bentonite were used by mixing in certain proportions. The sand was taken from a facility in the Izmir region. The sand is close to a clean sand. The fine fraction in it is around 3%. The specific gravity of the sand is 2.65. A calcium bentonite activated with sodium bicarbonate was obtained from Ünye Madencilik. All of the bentonite passes through the sieve no 200. The specific gravity of bentonite is 2.60. The grain size distribution curve of the sand is shown in Figure 1. As can be seen from the graph, the sand is clean sand.

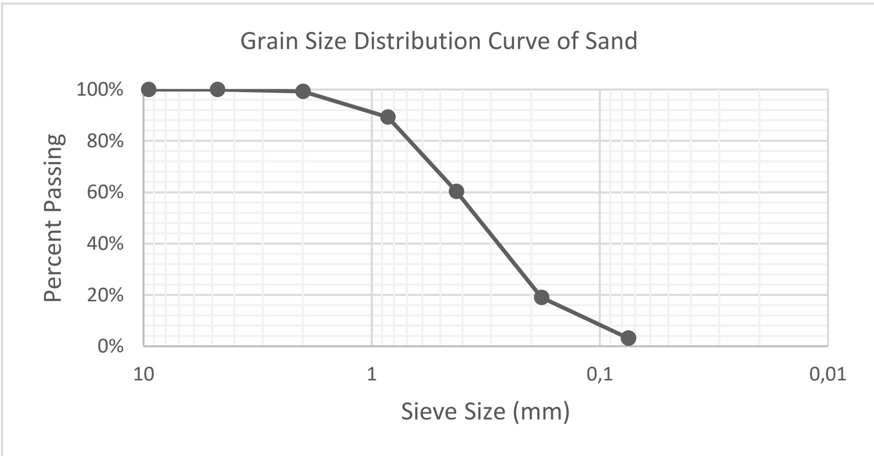

Figure 1. Grain size distribution of sand

Six different samples were prepared by mixing sand with 5%, 10%, 15%, 20%, 25% and 30% bentonite by dry weight, respectively. Sample names and proportions are shown in table 1. All samples were prepared and compacted at water contents between 8% and 26%. Thermal conductivity properties were measured from all samples at each water content.

Table 1. Proportions of samples

Name	Sand (%)	Clay (%)
S95.C05	95	5
S90.C10	90	10
S85.C15	85	15
S80.C20	80	20

S75.C25	75	25
S70.C30	70	30

2.2. Method and Equipments

In order to determine the dry unit weight and optimum water content of the samples, they were compacted in accordance with ASTM-D698 standard. To determine the optimum water content, each sample was compacted at 4 different water contents. The thermal properties of the samples were measured at each of these 4 points.

The thermal properties of the samples were measured in accordance with the ASTM-D5334 standard. It is a guide that determination of thermal conductivity of soil and soft rock by thermal needle probe procedure. The thermal needle method consists in placing a probe with a certain resistance through which a known amount of direct current flows, into the soil sample. The electrical current applied to the resistor inside the probe increases the temperature of the probe. The heat flux is constant. The heating rate of the soil sample is determined and the measurement is taken depending on time. As a result, it is possible to determine whether there is an increase or decrease in the temperature of the soil sample. A mathematical solution to the problem based on the assumption of an infinitely long and infinitely thin heat source was developed by Carslaw & Jaeger (1959).

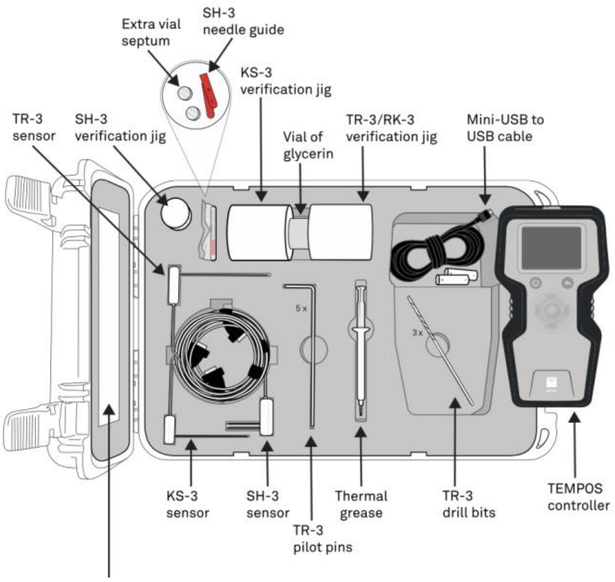

Figure 2. Tempos Thermal Analyzer (Tempos User Manual)

Tempos Thermal Analyzer was used for the measurements. The Tempos Thermal Analyzer is suitable for many materials that can measure thermal conductivity, thermal diffusivity and specific heat capacity using the thermal needle method. The sensor's performance should be validated before beginning each series of measurements by measuring the thermal conductivity of certified reference material given by the manufacturer. The test process can be carried out on soil samples if the verification result is valid. This device, which works with the principle described below, is shown in the Figure 2.

The needle sensor should be properly put in the sample's center. In all directions, a minimum of 2 cm of material should be allowed parallel to the sensor. The sensor should be fully inserted into the soil being measured. Thermal paste must be used to increase interaction between soil and needle. The sensor location should not be modified once it has been put within the specimen to ensure the best possible thermal contact between the sensor and the measured medium. It is recommended that you wait 15 minutes before starting the measurement to allow the samples and sensor to reach temperature equilibrium (Ryzynski & Zerun, 2020).

Each sample was subjected to 5-6 measurements in accordance with the technique. The placement of the probe was not modified during or between readings. The sensor-sample temperature equilibrated best with a fifteen-minute wait between observations. Different types of thermal probes should be chosen depending on the physical qualities of the substance being evaluated. The TR-3 sensor is used to determine the thermal properties of soft soils, while the RK-3 is recommended for rock and concrete.

Basically, there are two types of thermal needles that are compatible with the soil. One of these needles is "TR-3 single needle". Thermal conductivity values are measured with this needle. It is the best needle for wet soils, dry soils and granular materials. It is 10 cm long and 2.4 mm in diameter. It calculates the thermal conductivity value in the range of 0.1-4.0 w/m.K with 10% accuracy. Second of these needles is "SH-3 double needle" measures thermal conductivity, thermal diffusivity and specific heat capacity. It can be used for wet floors, dry floors and granular materials. It consists of two needles with a diameter of 1.3 mm, a length of 3 cm and a gap of 6 mm between them. It measures the thermal conductivity value in the range of 0.02-2.00 w/m.K with 10% sensitivity. It can calculate thermal diffusivity values in the range of 0.1-1.00 mm^2/s with 10% sensitivity. It finds the specific heat capacity in the range of 0.5-4.2 MJ/m^3 with 10% sensitivity.

3. RESULTS AND DISCUSSION

The compaction curves obtained for clay ratios of 5%, 10%, 15%, 20%, 20%, 25% and 30% respectively are shown in Figure 3. It is observed that the maximum dry unit weight decreases as the clay content increases in sand-bentonite mixtures. As can be seen in the graph, the amount of water required for the best compressibility increased with increasing clay content. It is known that denser materials conduct heat better. In this case, the higher the γ_{dry}, the more conductive the soil is. However, as γ_{dry} decreased, water content also increased. As the water content of soils increases, their thermal conductivity also increases. While the thermal conductivity of quartz mineral, which is a sand mineral, is 7.7-8.4 w/m.K, the thermal conductivity of clay minerals is between 1.6-2.6 w/m.K (Zhang et al., 2016). A decrease in thermal conductivity is expected when sand consisting of more conductive minerals is mixed with less conductive bentonite. In summary, it is very difficult to observe a thermal conductivity change depending only on the clay ratio in this study. (Simpson & Evans, 2015)

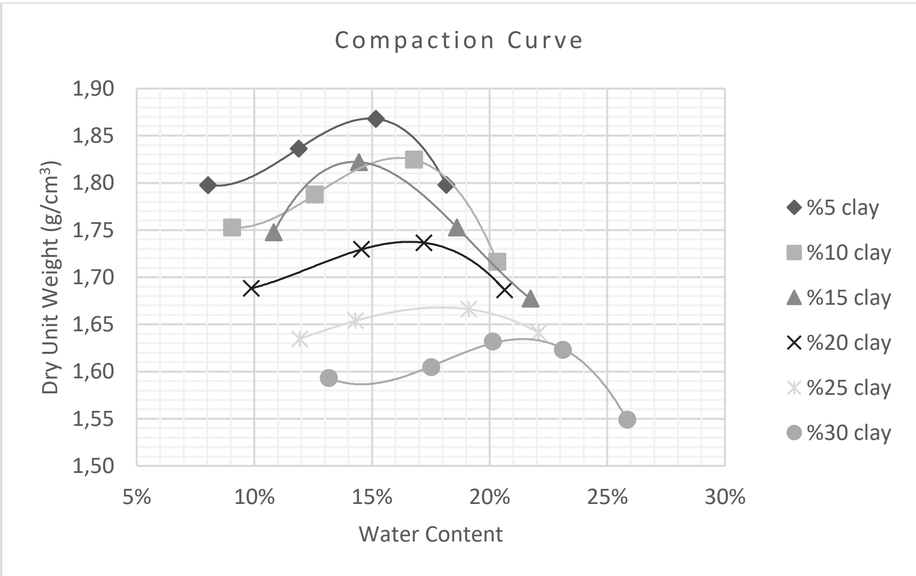

Figure 3. Compaction curve of sand-bentonite mixtures

Figure 3. was obtained when the most similar soil parameters were analyzed in the water saturated condition. In the water saturated state, the closest values of γ_{dry} and γ_{wet} were selected. Soil consists of three phases: grain, water and air. The soil structure is porous and filled with air or water. Since the thermal conductivity of water (0.56 W/m.K) is about 25 times higher than that of air (0.026 W/m.K), an increase in the degree of saturation causes an increase in thermal conductivity (Yun & Santamarina, 2007). In this case, when only fully saturated samples are compared, the effects of this situation can be minimized and only the change due to the fine ratio can be better

examined. If two soils of different dry unit weights are present in a fixed volume, the soil with the higher dry unit weight will have lower porosity and a larger contact surface between the grains. Since the thermal conductivity of soil grains is higher than that of water and air, an increase in γ_{dry} will lead to an increase in thermal conductivity. In this case, the effects of this situation were minimized as samples with close dry weights were examined.

In Figure 4, measurements with the TR-3 sensor are shown with the K' index and measurements with the SH-3 sensor are shown with the K" index. Recall that the TR-3 sensor has a single needle and had the best thermal conductivity measurement accuracy. The SH-3 sensor, on the other hand, has a dual needle and was more suitable for specific heat capacity and diffusivity measurements. The measurements taken with both sensors were similar to each other. The increase in clay content caused a significant decrease in thermal conductivity values. This can be explained by the fact that the clay mineral has a lower thermal conductivity value than the sand mineral. As the clay content increases, clays will come into contact with clays instead of sands coming into contact with sands. In this case, even if there is thermal contact, the thermal conductivity will decrease because the material itself has low conductivity. If the soil was not saturated with water, an increase of 5-10% in the clay content could cause the soil to be better graded and more in contact, which could lead to some increase in thermal conductivity, but since the soil is saturated with water, maximum thermal contact is already achieved.

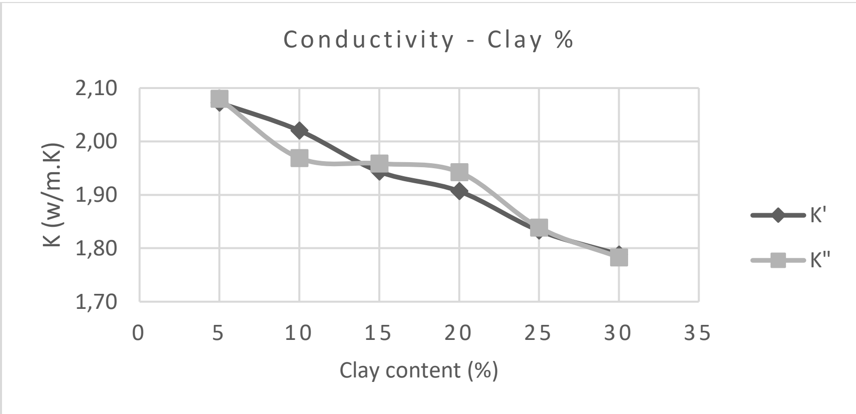

Figure 4. Thermal conductivity variation depending on clay content

Zhang et al. (2016) developed a general model for the thermal conductivity of sand-kaolin mixtures. Similar results were observed with the experiments performed in this study. The sand-clay mixtures were prepared 0%, 5%, %10, 20%, 20%, 30% and 100% clay by weight, respectively. As can be seen from the Figure 5, as the clay content increases, a decrease in thermal conductivity is observed even at each water saturation level.

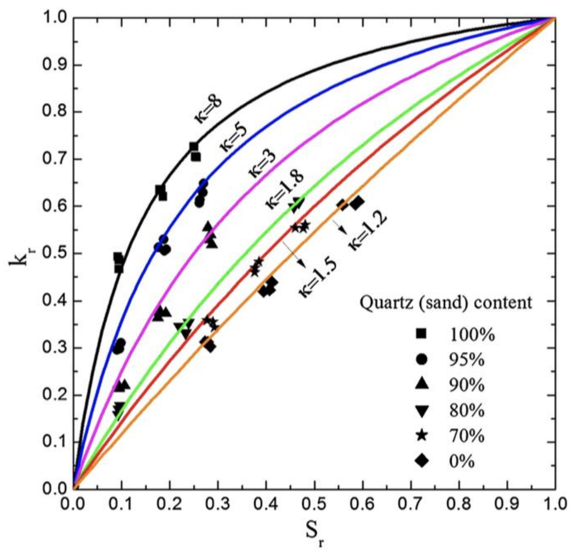

Figure 5. Normalized thermal conductivity (k_r) and degree of saturation (S_r) (Zhang et al., 2016)

Changes in thermal properties of saturated soil based on fine fraction

Although the increase in thermal conductivity due to water saturation rather than clay content was examined more in the study, it is clearly seen that there is a significant decrease in thermal conductivity as the clay content increases. In the study, it was observed that the thermal conductivity increased in each mixture as the water saturation increased. The apparent increase in thermal conductivity due to water saturation in pure sand is due to the formation of a thermal bridge of voids with water films. As the clay content increases in the mixture, the water films do not form a thermal bridge and are present in the clay due to the clay's affinity of water. This shows that the increment in thermal conductivity decreases with higher saturation levels in sand-clay mixtures. The decrease in thermal conductivity due to clay content can also be explained by the increase of clay minerals with low thermal conductivity in the solid phase of the soil.

4. CONCLUSION

As a result, as the clay content increased in sand-bentonite mixtures, the water requirement of the soil increased due to the water affinity of bentonite. Therefore, it was observed that the optimum water content required for compaction increased depending on the clay content. The dry unit weight of the soil decreased as the clay content increased. When saturated sand-bentonite mixtures were examined in terms of thermal properties, a more insulating soil was obtained when more conductive sand mineral was mixed with less conductive clay. In summary, it was observed that thermal conductivity decreased as the clay content increased in saturated sand-bentonite mixtures.

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