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INVESTIGATING THE SWELLING CHARACTERISTICS OF COMPACTED HIGH PLASTICITY CLAYS

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Abstract. Impermeable layers consist of compacted clay mixtures, synthetic membranes or combinations of clay mixtures and synthetic membranes. When compacted clay liners are employed, they are required to have low hydraulic conductivity, high swelling characteristics, good radionuclide adsorption capacity and good self-sealing capacity. Investigation of the factors affecting the swelling behavior of zeolite-bentonite mixtures (ZBMs) is of great importance for controlling the stability and permeability of landfill sites. In this study, the effect of bentonite content in ZBMs on swelling behavior of compacted high plasticity clays were investigated. For this aim, two types of ZBMs containing 20% and 30% bentonite were prepared. 100% bentonite (pure bentonite) specimens were also tested. Compaction tests were performed on specimens of the ZBMs and pure bentonite, and compaction values were determined. Swelling tests were conducted at optimum water contents of the specimens of ZBMs and pure bentonite. The specimens of ZBMs were loaded under effective vertical stress levels of 1, 2.5, 5, 12.5, 25, and 50 kPa. Pure bentonite specimens were additionally subjected to 100 kPa effective vertical stress. Swelling was observed on ZBM specimens under all effective stress levels. Pure bentonite specimens exhibited limited swelling at 100 kPa effective vertical stress. Swelling of ZBMs increases with increasing bentonite content. The swelling behavior of compacted high plasticity clays was interpreted in terms of bentonite content and final void ratio.

Keywords: Swelling, bentonite, zeolite, effective vertical stress, final void ratio.

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1 Introduction

Regular solid waste landfill sites are constructed by selecting suitable areas in big cities. The most important problem encountered in regular landfill sites is the infiltration of leachate to ground water through the soil. In order to avoid this infiltration, soil layers with high impermeabilities are required at landfill sites. In landfills it is primordial to prevent the contamination of the groundwater by leachates percolating through the liner and to keep the wastes in a safe manner. In order to prevent or minimize the percolation of the leachates from wastes to groundwater, liners with no or low hydraulic conductivities are needed. The value of hydraulic conductivity should not exceed 1×10^{-9} m/s (Kayabali & Kezer, 1998).

The most appropriate impermeability values can be provided by clays. Since clay in the soil absorbs water, it creates a tendency to lower the hydraulic conductivity of the layer (Oren, 2007). Impermeability characteristics are related to high swelling capacity. While clayey soil swells by absorbing water, its hydraulic conductivity decreases. Therefore, investigating the swelling behavior of impermeable liners containing clays is very important in solid waste landfill sites. High plasticity clays have low hydraulic conductivity, high swelling potential, and high adsorption capacity. At solid waste landfill sites where liners containing high plasticity clays are used, the required impermeability can be obtained (Kaya & Durukan, 2004; Oren, 2007). Clay liners are natural materials that can be obtained easily, they are able to resist for longer periods when compared to synthetic liners, i.e. HDPE or other polymer liners (Cho et al., 1999; Oren, 2007). They are cheap, they swell when they are wet and they shrink when they are dried. This is an important characteristic of the high plasticity clays. In landfill liner, geosynthetic clay liner, and nuclear waste liner applications, swelling is expected to achieve the best performance (Daniel & Benson, 1990; Kenney et al., 1992; Korner et al., 1995; Komine & Ogata, 1999; Sun et al., 2009). The preferred way of prevention from the leachates is to use compacted clay barriers in landfills. Bentonite is the most preferred clay type with the lowest hydraulic conductivity. Sodium bentonite is generally preferred due to its high swelling capacity and its very low hydraulic conductivity (Boran, 2017). Sand-bentonite mixtures (SBMs) can be also applied in landfill sites to obtain the required hydraulic conductivity (Oscarson et al., 1990; Kenney et al., 1992; Alawaji, 1999; Komine & Ogata, 1999; Gueddouda et al., 2008; Mukherjee & Mishra, 2019; Biju & Arnepalli, 2020; Tan et al., 2021). However, they cannot afford to prevent leachates from flowing into ground water as required due to the lack of adsorption capacity of sand (Kleppe & Olson, 1985). In order to eliminate this disadvantage, zeolite, which is a natural material having granular structure, has begun to be used as an alternative to sand (Boran, 2017). The bentonite content should be minimized to meet the required hydraulic conductivity, to reduce expanding, and to prevent shrinkage cracking (Mollins et al., 1996). The use of zeolite instead of sand yields a desirable result by preventing radioactive materials from infiltrating through the liner. Also, there are very rich zeolite reserves in Turkey, notably in Bigadiç-Balikesir, Gediz and Emet-Kutahya, and Gordes-Manisa locations (Kaya & Durukan, 2004). Turkey is the third country having the largest zeolite reserves in the World (Boran, 2017).

The studies have been made on zeolite-bentonite mixtures (ZBMs) yield that the hydraulic conductivity of ZBMs is higher than that of SBMs (Oren et al., 2011). Swelling occurs at the mixture with adding water, and voids between sand grains are filled with the bentonite particles. Thus, the hydraulic conductivity decreases (Srikanth & Mishra, 2016). There is at least one order of magnitude difference between the hydraulic conductivity values of ZBMs and SBMs (Oren et al., 2014).

As mentioned above, there has not been enough studies in the literature about the change of swelling behavior by using zeolite instead of sand. Therefore, the aim of this study is to make a significant contribution to understand swelling behavior of ZBMs and the mechanism leading to swelling more comprehensible.

2 Materials and Methods

2.1 Materials

The materials used in this study, zeolite and bentonite, were collected at Soil Mechanics Laboratory of Department of Civil Engineering, Dokuz Eylul University. The grain size distribution of zeolite and bentonite performed in accordance with ASTM D 422-63, and obtained curves are shown in Fig. 1. Some physical and mineralogical properties of zeolite and bentonite are given in Table 1.

The specific gravity was determined according to ASTM D 854. The liquid limit of bentonite was determined by using cone penetrometer (fall cone method) in accordance with BS 1377. The plastic limit and plasticity index of bentonite were obtained according to ASTM D 4318. Zeolite was determined as non-plastic material. Results of the specific gravity and consistency limits are given in Table 1, as well.

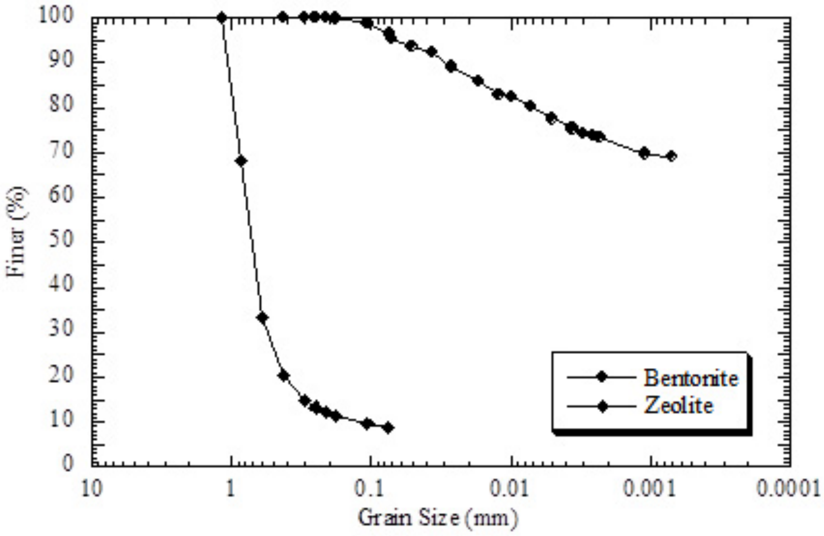

Figure 1: Grain size distribution of bentonite and zeolite (Boran, 2017)

Table 1: Some geotechnical and mineralogical properties of zeolite and bentonite (Boran, 2017)

Geotechnical Properties	**Zeolite**	**Bentonite**
Specific gravity	2.31	2.71
Liquid limit	NP	405%
Plastic limit	-	57%
Plasticity index	-	348%
Mineralogical Components	**Zeolite**	**Bentonite**
Smectite ($^{\beta}$)	1%	77%
Cristobalite	-	10%
Quartz	-	4.5%
Illite	-	2.5%
Clinoptilolite	58%	-
Mordenite	41%	-
Minor components	-	6%

The chemical compounds were determined by using X-ray diffraction method. Results were compared with the catalogues of trading firms from which bentonite and zeolite had been obtained. Similar ratios were given in the catalogues of the firms.

2.2 Methods

2.2.1 Compaction Tests

Proctor compaction tests were applied on ZBMs with bentonite contents of 20% and 30%. Mixtures were prepared in dry condition (air-dried under laboratory conditions), afterwhich some water was added, and thoroughly mixed in order to obtain a homogeneous structure. The wet samples were sealed in a plastic bag and left for curing for 24 hours. The next day, they were compacted by applying Standard Proctor compaction energy in accordance with ASTM D 698. The mixture with 80% zeolite and 20% bentonite was named as ZBM-1, and the one with 70% zeolite and 30% bentonite was named as ZBM-2.

Compaction curves of zeolite-bentonite mixtures and the zero-air-void curve are shown in Fig. 2. According to this figure, there is not a meaningful difference between compaction values of ZBM-1 and ZBM-2 mixtures. The maximum dry density of 20% ZBM (ZBM-1) is 1.08 Mg/m^3, and its optimum water content is 42%, whereas the maximum dry density of 30% ZBM (ZBM-2) is 1.09 Mg/m^3, and its optimum water content is 41%. Literature review on characteristics of zeolite-bentonite mixtures revealed that maximum dry unit weight and optimum water content values were in accordance with those in the literature Oren et al. (2011); Srikanth & Mishra (2016); Oren et al. (2014).

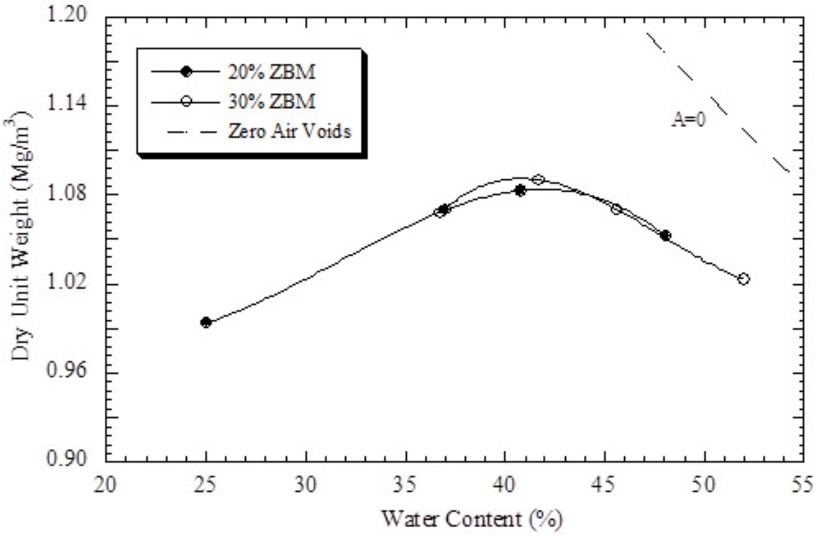

Figure 2: Compaction curves of zeolite-bentonite mixtures and the zero-air-void curve (Boran, 2017)

2.2.2 Swelling Test

Swelling tests were conducted on ZBM-1 and ZBM-2 as well as 100% (pure) bentonite specimens. ZBM-1 and ZBM-2 samples were prepared at their optimum water content and maximum dry unit weight values, and they were placed in the rings with 19 mm height. Then the ring was placed in the oedometer cell using porous stones and filter papers at the bottom and top of the specimen (Fig. 3). Since swelling capacity of bentonite is extremely high, pure bentonite specimens were prepared in the rings with 19 mm height, but the height of specimens was 3 mm in these rings. The reason of the height of the specimen is rather thin (3 mm) than the height of the consolidation ring (19 mm) is to prevent the excessive expansion of pure bentonite during swelling process at low effective vertical stresses. Pure bentonite specimens were prepared by tamping method by applying 10 and 25 number of blows (impacts) on specimens in the consolidation rings (Fig. 4).

Swelling tests on ZBM-1, ZBM-2 and pure bentonite samples were conducted under the effective vertical stresses of 1, 2.5, 5, 12.5, 25, and 50 kPa according to ASTM D 2435. Pure bentonite specimens were additionally subjected to 100 kPa effective vertical stress. All swelling tests were performed by using the oedometers in DEU Soil Mechanics Laboratory shown in Fig. 3.

The initial effective vertical stress was applied as 1 kPa according to ASTM D 4546-08. The water level in the cell was continuously monitored during each test. The height of specimen was constantly recorded until swelling was completed. The final void ratio was determined from the initial void ratio, and change in the specimen volume was calculated.

(a) **(b)**

Figure 3: Consolidation cell (a) and oedometers in DEU Soil Mechanics Laboratory (b)

(a) **(b)**

Figure 4: Sample preparation of pure bentonite for swelling tests: Tamping method (a), and the height of specimen (b)

3 Results and Discussion

3.1 Swelling Behavior of Zeolite-Bentonite Mixtures

Swelling tests were conducted on zeolite-bentonite mixtures with 20% and 30% bentonite content in order to determine the swelling behavior of ZBMs. The data obtained from swelling tests of ZBMs with 20% and 30% bentonite content under various effective vertical stress levels are given in Fig. 5 and Fig. 6, respectively.

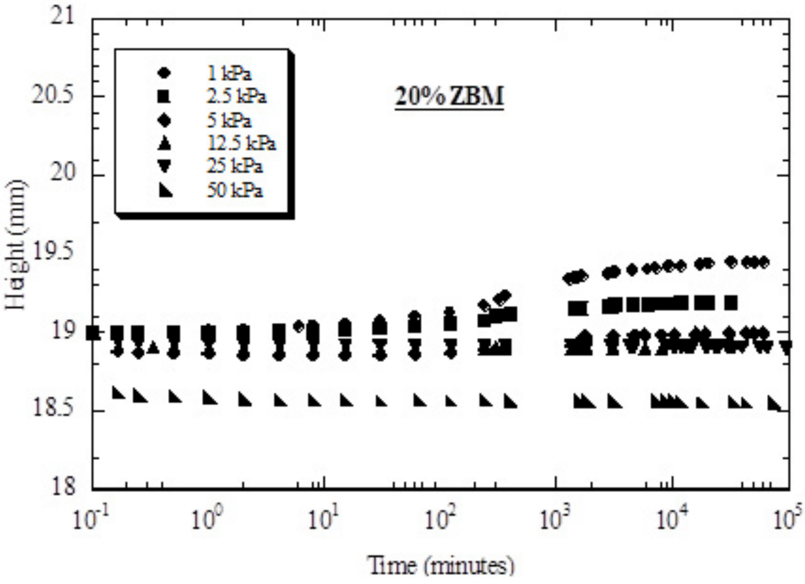

Figure 5: Swelling-time curves of 20% ZBM (Boran, 2017)

When swelling-time curves of 20% ZBMs and 30% ZBMs are compared, it can be easily seen that the amount of swelling increases with the increase of bentonite content in the mixture.

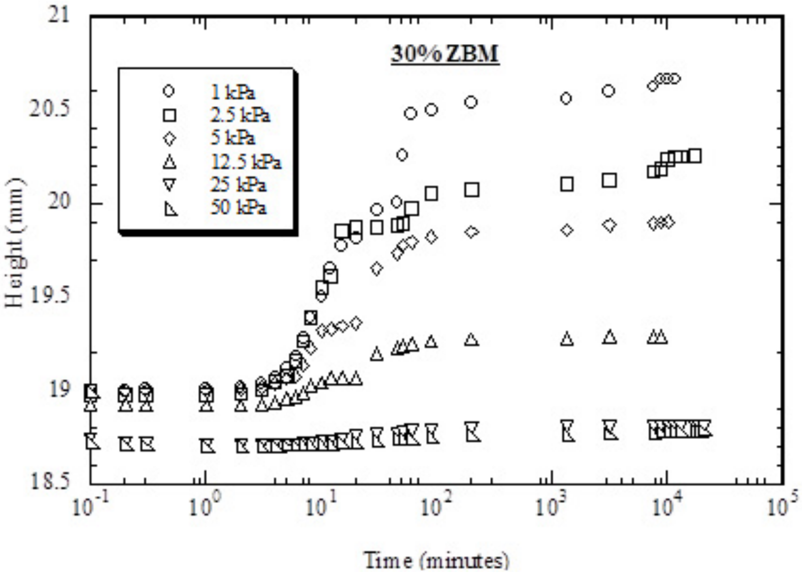

Figure 6: Swelling-time curves of 30% ZBM (Boran, 2017)

30% ZBMs swelled more for each effective vertical stress level when they are compared with 20% ZBMs. Bentonite can easily enter the voids between zeolite particles when the effective stress is low. Thus, the amount of swelling increases (Boran, 2017). When the effective stress is high, the bentonite can penetrate into the zeolite grains much, and it fills the voids less, because the zeolite grains in the mixture are in close contact to each other. The 20% ZBMs indicate swelling behavior under the effective stresses 1 and 2.5 kPa, while the 30% ZBMs show swelling under the effective stresses 1, 2.5, and 5 kPa. The 20% ZBMs and 30% ZBMs did not show enough swelling under the effective stresses 12.5, 25, and 50 kPa because bentonite could not penetrate into the zeolite grains.

3.2 Swelling Behavior of Pure Bentonite Specimens

Due to high swelling capability of bentonite, swelling tests on pure bentonite specimens were completed in approximately 8 weeks. The swelling amounts and the height of the specimen-time relationships of pure bentonite specimens for various effective stress levels are given in Fig. 7.

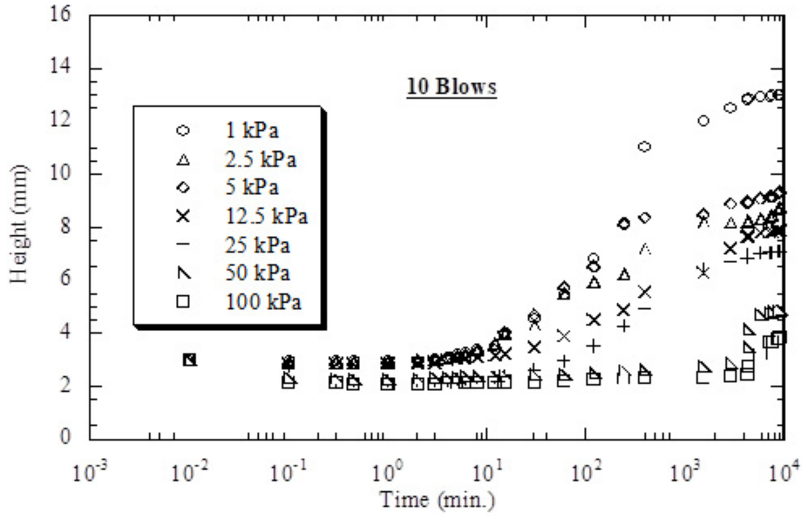

Figure 7: Swelling-time curves of pure bentonite specimens (Boran et al., 2017)

According to Fig. 7, swelling occurred rapidly in the first 24 hours, and then slowed down as the time passed. The height of specimen reached approximately to threefold or fourfold of its initial value (i.e. swelling strain reached the values of 250-350%). Generally, as the effective vertical stress increased, the amount of swelling decreased. The height of specimen reached from 3 mm to 4 mm (slightly swelling), and the swelling strain increased by 33% for 100 kPa effective vertical stress. It was mentioned that pure bentonite specimens do not show any swelling or compression for 400 kPa effective vertical stress (Cui et al., 2012).

When pure bentonite specimens were compacted by applying 25 number of blows (impacts) in the consolidation rings, similar amounts of swelling were obtained. The compactive effort (compaction energy) did not affect the swelling behavior, significantly. This finding is in accordance with the study of Mollins et al. (1996).

Final void ratio (e_c) values of ZBMs and pure bentonite were calculated and their relationship with effective vertical stress ($\sigma\prime_v$) is shown in Fig. 8. The relationships between these parameters give an exponential relationship on the semi-logarithmic scale. This finding is in accordance with the final void ratio-effective vertical stress relationship of the pure bentonite specimens used in the studies of Mollins et al. (1996) and Sun et al. (2013).

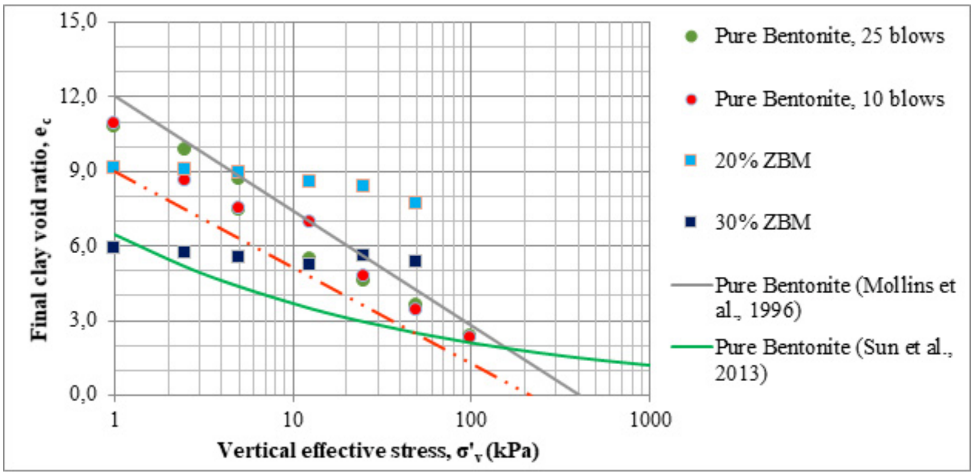

Figure 8: Final clay void ratio-effective vertical stress ($e_c - \sigma_v^{'}$) relationship for ZBMs and pure bentonite specimens

4 Conclusion

In this study, the swelling characteristics of zeolite-bentonite mixtures (ZBMs) and pure bentonite were investigated. Bentonite content is an important parameter controlling the swelling behavior of bentonite containing mixtures. In order to prove this effect scientifically, swelling tests were applied on ZBMs with 20% and 30% bentonite contents. Swelling-time curves of ZBMs were obtained, and the findings in this study were compared to the results of the studies in the literature. Besides, the swelling characteristics of 100% (pure) bentonite were investigated. The following conclusions were reached from the findings of the compaction and swelling tests.

The compaction values (the optimum water content and the maximum dry unit weight) of ZBMs in this study are almost the same as those of the ZBMs in the literature. However, the optimum water content was 2.5 times higher, and the maximum dry unit weight was 1.5 times lower than those of sand-bentonite mixtures (SBMs) in the literature. This difference can be explained by lower specific gravity and the porous crystalline structure of zeolite than sand, and the water uptake of zeolite. The principal factor affecting the swelling behavior of high plasticity clays is the bentonite content in the mixture. The amount of swelling of ZBMs increases when the bentonite content increases. Swelling was observed at all effective vertical stresses from 1 kPa to 50 kPa. Pure bentonite specimens continued to the limited swelling although the effective vertical stress was 100 kPa. Swelling was determined on pure bentonite specimens which were prepared in tamping method by applying 10 or 25 number of blows (impacts) in the similar range. The difference of swelling amount was negligible when the number of blows changed.

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