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Research Article

Comparative Study of Swelling Pressure in Expansive Soils considering Different Initial Water Contents and BOFS Stabilization

İnan Keskin,[1] **Mahdi Salimi**,[2] **Eylem Özge Ateyşen**,[1] **Selman Kahraman**,[1] **and Amir Hossein Vakili**[3,4]

[1]*Karabük University, Faculty of Engineering, Civil Engineering Department, Karabük 78050, Turkey*
[2]*Faculty of Engineering, Hamedan Branch, Islamic Azad University, Hamedan, Iran*
[3]*Department of Environmental Engineering, Faculty of Engineering, Karabük University, Karabük 78050, Turkey*
[4]*Department of Civil Engineering, Faculty of Engineering, Zand Institute of Higher Education, Shiraz, Iran*

Correspondence should be addressed to Amir Hossein Vakili; amirvakili@karabuk.edu.tr

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In terms of geotechnical engineering, swelling soils are among the most important soil groups whose characteristics should be determined in detail before design studies. These types of soils cause significant damage to engineering structures. For this reason, it is expected that the swelling behavior of the soils will be known in advance to minimize the damage that may occur in the structures. Within the scope of this study, the swelling pressures of bentonite clay with 10 different water content were determined by keeping all conditions the same to reveal the effect of water content on soil swelling behavior. In this context, bentonite-type (montmorillonite content) clay, which has a very swelling property when it comes in contact with water, was used in the experiments. The fixed volume swelling pressure test method was used in the experiments and all samples were compressed at the same rate and placed in the swelling test device. In all samples left to swell with pure water, measurements were made for 10 days and the effects of swelling pressures on the initial water content were discussed. Thereafter, another swelling soil was stabilized using basic oxygen furnace slag (BOFS) during different curing times, and after performing the swelling pressure test, the results were compared with the findings obtained from different initial water contents. According to the results, while the swelling pressures increase in the regions close to optimum water content, significant decreases are observed in swelling pressure values in wetter and drier regions than in optimum water content. Finally, the results indicated that the application of BOFS, albeit small, after the proper curing time can significantly affect the swelling behavior of bentonite, even more than changing the initial water content.

1. Introduction

Determining the swelling properties of soils is of great importance in terms of explaining soil behavior. Drnevich et al. [1] described swelling pressure as the pressure required to keep the soil volume constant when water is added. It can be listed as the expansion caused by the elastic stretching of crystals because of unloading and the swelling caused by the pressure in the compressed air during the progress of wetting in the soil [2–5]. As these soils increase in volume as they get wet, their volume decreases as they dry [6, 7]. Clay soils with swelling properties cause deformations in engineering structures depending on the change in stress conditions [8–11]. Estimates in the literature that the annual cost of damages caused by swelling soil could reach billions of dollars worldwide [12–15]. While settlements occur on the soils due to the increase in stress conditions, swelling may be observed as a result of the decrease in stress. The changes in the volume of the soil mass that occur due to the settlement and swelling properties are the most effective factors in the design of the projects related to the soil.

For this reason, it is extremely important to determine the swelling characteristics of the soil in the buildings to be built on it and to make the necessary precautions by stabilizing before the application phase [14, 16]. Therefore, one of the geotechnical engineering fields of study is knowing how the soil and structure will be affected by different loading and environmental conditions of the soils [17]. One of the most important stages of these evaluations is to determine the swelling properties of clay soils, where large volume changes may occur. In this context, it is necessary to determine and predict the swelling potential of the clayey soil, the maximum pressure level that will occur because of swelling, and the amount of swelling that will occur on the soil surface. When the interaction of clays with water is examined in detail, the predicted problems can be controlled by taking necessary measures [18, 19].

Most engineering structures built on clay soils cause moisture changes in the clay due to the stresses they apply, degrading the natural water content in the clay [20, 21]. Clay swelling occurs as a result of balancing the interaction forces between the clay surface, ions, and water [22, 23]. Due to the increase in the water content of dry soil, the clay grains move away from each other and increase in volume, and as a result, the thrust force occurs [24, 25].

Many factors such as clay percentage, the mineralogical structure of clay, dry unit weight, stress conditions, external loads, water content, and climate conditions can affect the swelling of clay soils [26–30]. Although clays tend to swell more at lower water content than optimum water content, the amount of swelling is negligibly small at water content above optimum [31]. David and Komornik [32] suggested that the swelling pressure increased as the water content decreased. Chen [33] stated in his studies that volumetric swelling decreased due to the increase in water content. Warkentin [34] stated that clayey soils have a significant effect on swelling behavior, and swelling decreases due to the increase in water content. David Suits et al. [35] investigated the effect of curing time on the swelling behavior of soil with a liquid limit of 100%. Samples were kept for 7, 15, 30, and 90 days in glass desiccators with different concentrations of sulfuric acid to maintain different relative humidity conditions. One-dimensional oedometer swelling tests were performed on these samples. They observed that the increase in the waiting time caused a decrease in the swelling potential. In the study, it is stated that the initial saturation degree and water content affect aging. It was emphasized that the aging effect increases as a result of the increase in water content for the same dry unit weight, and the effect becomes more important with the increase in the degree of saturation at constant water content. McCormack and Wilding [36] examined the relationship between soil swelling and clay content by keeping all other parameters constant and emphasized that clay percentage is a parameter that affects the swelling potential in illite-dominated soils. Schafer and Singer [37] explained that the change in the swelling potential of the soil is related to the percentage of swelling clay.

The swelling properties of expansive soils are generally determined by two different techniques. The first of these is the estimation method, which is made by using some soil parameters such as swelling potential, density, Atterberg limits, and clay fraction, known as the indirect method. The other is the method that quantitatively determines the swelling potential of the soil by performing the oedometer test, free swelling test, or swelling index test. Determining the swelling characteristics of the expansive soils directly takes a long time and is costly due to complex laboratory studies [34]. Indirect assessment of swelling requires only a few simple routine laboratory tests. Therefore, it is a usual practice to give a preliminary estimate for the swelling potential using mostly indirect methods, and further tests such as odometers are preferred after problems [38].

There are studies in the literature that examine the effect of cyclic wetting and drying on the swelling behavior of soils [35, 39–47]. In addition, Nordquist and Bauman [48], Obermeier [49], and Popescu [50] emphasized that the swelling ability increases with the number of drying and wetting repeats. Some researchers [42, 51, 52] stated that the swelling potential will decrease if soils are repeatedly subjected to swelling and then allowed to dry (partial shrinkage) to the initial water content [40]. Osipov [39] showed that the potential for swelling increases after the first cycle when the stabilized swelling soil is allowed to dry completely to or below the shrinkage limit (full shrinkage).

On the other hand, the cycling effect on the swelling potential of lime-stabilized soils has been reported to increase the swelling potential when the lime-stabilized soil is subjected to a wetting and drying cycle. Basma et al., Chaney et al., and Alonso et al. [42–44] stated that the drying method has a significant effect on the swelling properties of the swelling soil. Chen et al. [53] stated that swelling pressure is exponentially dependent on dry density but independent of the initial water content of the clay. He found that the swelling capacity is mainly affected by the vertical load at which saturation occurs and it increases with the initial dry density but decreases as the initial water content increases. Besides the water content, the chemistry of the pore water is important in the swelling behavior of soils. In general, as the salinity of the pore water increases, the swelling pressure of bentonite decreases. Also, Di Maio et al. [54] and Castellanos et al. [55] stated that chemical conditions and initial stress state play a very important role in the swelling behavior of compressed bentonite.

In this study, the effect of water content on the swelling property of soils was assessed. In the literature, the effect of wetting conditions of compacted bentonite and bentonite-aggregate mixtures on swelling pressure has been investigated by various researchers [45–47]. However, as in this study, no discussion was made regarding the optimum water content based on wet conditions. For this purpose, clay which has a high swelling capacity, the industrial name of which is bentonite, was used. Within the scope of the study, the Atterberg limit values of bentonite clay were first determined, and then the compaction test was performed to determine the optimum water content. Bentonite clay with optimum water content was prepared at different water contents determined below and above the optimum and the effect of initial water content on swelling pressure was investigated by measuring swelling pressures for 10 days for each sample. In the next step of this study, for comparison, another type of bentonite was stabilized using base oxygen furnace slag (BOFS) and swelling pressure tests were performed on the samples after up to 90 days of curing times, and finally, the results were compared with the previous findings.

2. Materials and Methods

Bentonite is part of the montmorillonite family and is a clay mineral with a liquid limit value of 500% or higher. They are formed as a result of chemical decomposition or degradation of volcanic ash, tuff, and lava rich in aluminum and magnesium content. In commercial terms, any clay with advanced liquid absorbent and colloidal properties is called bentonite [56]. Bentonites swell more or less when they come in contact with water. Bentonites can be classified into three groups according to their sodium-calcium ions, as they are divided into over, medium, and low swelling bentonites according to their swelling ability. The geological features of these bentonites differ in their formation. Among these, sodium bentonite is commercially important. However, sodium bentonite has little reserves in nature. Therefore, calcium and sodium-calcium bentonites that do not show much swelling feature are converted to sodium bentonite by various chemical methods [57].

The bentonite samples used in the experiments were obtained from KarBen Inc in Tokat (Turkey) (B1) and Naeen city in Isfahan (Iran) (B2). These natural bentonites were used in the experiments by sieving under the 40 sieves to release the lumps before starting the experiments. The physical and chemical properties of bentonite soils used in the study are listed in Table 1. The consistency limits of raw bentonites (B1 and B2) were determined as liquid limit (312 and 350.1%) and plastic limit (67 and 38.6%) according to ASTM D4318 (Table 1, Figure 1(a)). To determine the optimum water content, with the compaction tests as per ASTM D698, the optimum water contents of the clay samples for B1 and B2 were found to be 43% and 45.5%, respectively (Figures 1(b) and 2). In this study, basic oxygen furnace slag (BOFS) as a stabilizer was prepared by Iran Ferroalloys Industries Co. to enhance the swelling behavior of bentonite (B2).

After determining the optimum water content, in the case of B1, the soil samples were prepared from 0% to 100% water content (with an interval of 10%), and the swelling pressure of the samples was measured according to ASTM D4546 for 10 days with the swelling pressure test setup consisting of devices S type load cell and oedometer cell (Figure 3). This 4-channel data collection unit consists of a computer, and it can measure instantaneous swelling pressure with the software. The pressure that prevents the volume change that will occur as a result of the increase in the water content of swollen clay soil is called swelling pressure. Within the scope of this study, the pressure reached when the swelling did not occur with the device detailed above was found. In the case of B2, the soil was mixed with different amounts of BOFS (0, 2.5, 5, 10, 15, 20, and 30%) and tested after curing times of 1, 3, 7, 28, 45, and 90 days at a temperature of 25°C and with a relative humidity of 85%. In this study, the range of 0 to 30% was considered for BOFS in line with previous studies [58, 59] because this amount of BOFS can effectively change the engineering characteristics of the soil, thereby it is an acceptable range. The results of the XRF analysis and also a view of the BOFS used in this study are presented in Table 1 and Figure 4, respectively. It is worth noting that all tests were repeated twice and average values were measured to minimize changes.

3. Results and Discussion

3.1. Effect of Initial Water Contents on the Swelling Potential. Figure 5 shows that the swelling pressures of bentonite clay with 0% and 10% water content increase with time. In both conditions, the values showed a continuous increase, and it was seen that the maximum swelling pressure value was obtained within 10 days. It can be stated that the swelling pressure curve of bentonite clay with 10% water content has a sharper rise compared to that of 0% water content. In general, percentage changes depending on the time between two water contents are given in Table 2. It is seen that the swelling value of 10% water content at the last moment shows an increase of 57% compared to 0% water content.

The maximum swelling pressure value of bentonite clay kept at 20% water content for 10 days is higher than that of one kept at 10% water content. Based on this, it can be stated that the swelling in 20% water content is more than 0% water content. While the curve for 10% water content shows a steady increase, the curve at 20% water content was fixed after the 10000th minute as shown in Figure 6. As can be seen in Table 2, the percentage changes increased to about 50% by 8400 minutes, after which the rate decreased until the difference finally reached 16%.

Considering the swelling pressures of bentonite with 20% and 30% water content, it can be seen that both of them increase up to the 10000th minute depending on the time, and stabilize after this minute. It can be said that the swelling pressure for a 30% water content value is more than 20% water content. The maximum swelling pressure values for both occurred at the end of the experiment as shown in Figure 7. As can be seen in Table 2, the percentage change in the two water contents made a rapid decrease up to 37% until the 8400th minute, and then it was fixed at 23% as very little changes.

The optimum water content of bentonite clay used in the experiment is 40%, and the swelling pressure in this water content has the highest value when compared to the swelling pressure in other water contents. Swelling pressure values at 30% water content are close to the values at optimum water content. Considering Figure 8 and Table 2, it is seen that the curves approach each other, and the percentage change decreases with time.

As can be seen in Figure 9, the swelling pressure decreases in the water contents higher than the optimum value. At the beginning of the experiment, the swelling in clay with 50% water content shows a decrease of over 100% compared to 40% water content (Table 2). The maximum swelling

Table 1: Physical and chemical properties of raw bentonite.

Definition	B1	B2	BOFS
>75 μm	2.5% (by weight)	0% (by weight)	0% (by weight)
E (Methylene blue concentration (0.01 N))	310 ml	—	—
Montmorillonite content	75%	77%	—
SiO_2	61.28%	70.4%	15.6%
Al_2O_3	17.79%	12.1%	8.2%
$Fe2O_3$	3.01%	1.6%	20.9%
CaO	4.54%	2.2%	48%
MgO	2.10%	2.1%	3.4%
K_2O	1.24%	1.1%	<0.1%
Na_2O	2.70%	0.6%	0.2%
Liquid limit	312%	350.1%	—
Plastic limit	67%	38.6%	—

(a) (b)

Figure 1: (a) Liquid limit test. (b) Compaction test.

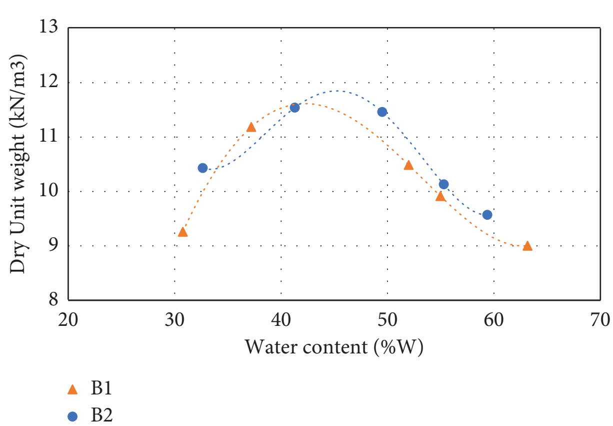

Figure 2: Compaction test results.

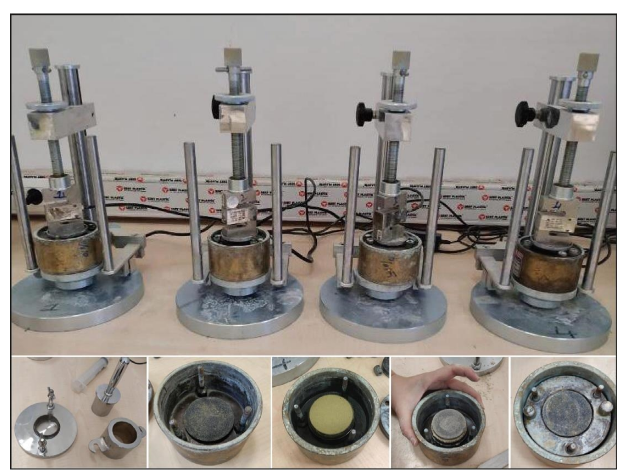

Figure 3: Stages of the swelling pressure test.

pressure value was obtained on the last day of the experiment (i.e., after the 10000th minute).

Comparing the swelling pressure values of bentonite clay with 50% and 60% water content, the swelling value at 60% water content is higher until the average 7000th minute, and then, the swelling value at 50% water content begins to increase compared to 60% water content. While the swelling pressure value of the clay with 60% water content shows steady progress after the 7000th minute, a constantly increasing curve is observed at 50% water content (Figure 10). It can be stated that the maximum swelling pressure values occur at the end of the 10th day.

According to Figure 11, similar results were obtained for the swelling behavior of bentonite clay with 60% and 70% water content. It can be seen that the curves continuously increase up to the 6000th minute, and the changes after this period progress at a minimum and reach the maximum inflation pressure value. The change in percentage after the 3600^{th} minute was fixed by the remaining 24% as shown in Table 2.

Figure 4: A view of BOFS used in this study.

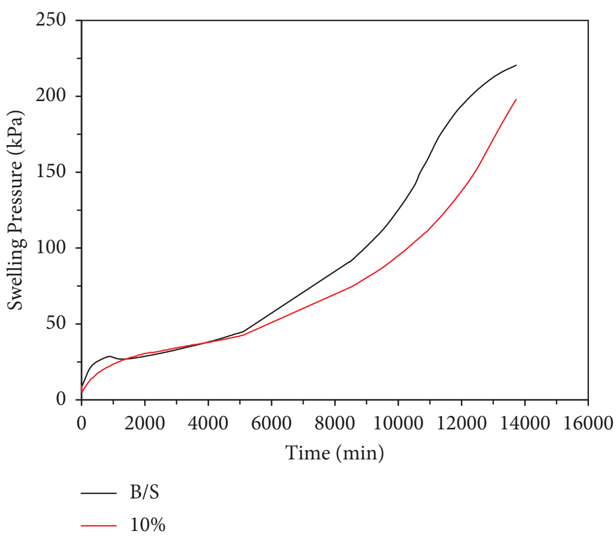

Figure 5: Comparison of swelling pressures of bentonite with 0% and 10% water content.

Considering Figure 12, it was observed that the swelling pressure of bentonite clay with 70% and 80% water content had similar changes to the swelling pressure of 60% and 70%. Generally, it can be stated that bentonite clay exhibits similar behavior in water contents greater than its optimum water content. It can be seen that the swelling pressure increased rapidly until the 6000th minute and then reached a constant value. Based on Table 2, the swelling pressure is 30% less than the 80% water content compared to the 70% water content, but this percentage change is fixed by coming to 11% depending on the time. When the previous conditions are compared with the current conditions, it is seen that the percentage change in 60% and 70% water content remained constant at 24% after the 4800th minute, and the percentage change in 70% and 80% water content continued for a while and stabilized at 11%. These indicate the importance of the percentage change in each water content in the studied soil.

Based on Figure 13, it is possible to say that after 80% water content, the soils can no longer show more swelling behavior and reach the highest swelling pressure they can show. In this context, it can be seen that the swelling pressure of the sample with 90% water content compared with samples prepared under different water content conditions reached the maximum value in a shorter time. While the clay with 80% water content reached a constant value after the 6000th minute, the swelling pressure of bentonite clay with 90% water content was fixed after the 4000th minute. As per Table 2, the percentage difference has reached a very high value, such as 41%, since the swelling pressure value is less at 90% water content.

In Figure 14, when the bentonite with 100% water content is compared with the bentonite with 90% water content, it was seen that they have similar changes and their swelling pressure values are one of the lowest values. As shown in Table 2, an average change of 20% was observed up to the 6000th minute and after that, it remained at around 13%.

Within the scope of this research, the swelling behaviors of bentonite clay depending on each 10% increase in water content were examined separately, and the swelling pressure changes for each condition were considered as a whole in the graphic given in Figure 15. Based on this, it can be stated that the most swelling pressure is at 40% water content, followed by 30% and 50% water content, respectively. It is observed that there is a continuous decrease in swelling values from 60% water content to 100% water content due to the increase in water content. The lowest swelling pressure values are found at 0% and 10% water content. In all cases, it is found that there is not much change in values after the 10000th minute.

3.2. Comparison of the Effect of Initial Water Content and BOFS Stabilization on Swelling Potential.

Figure 16 shows the results obtained from the swelling pressure test for two expansive soils under different initial water content as well as stabilized with different amounts of BOFS after different curing times. For a better comparison between the results, by defining the $\Delta P/P_0$ as a dimensionless parameter, a reasonable comparison was made in which the ΔP is equal to the difference in swelling pressure in each sample with that of the bentonite soil sample (P_0). As shown in Figure 16(a), the $\Delta P/P_0$ for bentonite soil under different water contents initially had an upward trend up to its optimum water content range (~42%-see Figure 2) and then decreased with increasing water content. It should be noted that positive values for the $\Delta P/P_0$ parameter mean that the swelling pressure is higher than the bentonite soil sample and negative values for $\Delta P/P_0$ indicates lower swelling pressure than the bentonite soil sample so that if in a sample the pressure is equal to −1, it indicates complete control of the swelling potential (swelling potential equal to zero).

As previous studies have reported [60], the engineering parameters of compacted clay soils on the dry and wet sides are significantly different from each other. Clay soils compacted on the dry side have a random fabric, while compaction on the wet side of optimum moisture content (OMC) leads to more particle orientation, resulting in more thoroughly developed double-layer water films.

In general, at a certain amount of energy for the compaction process, on the dry side, the specimens are flocculated and large voids are formed due to their random

Table 2: Percentage change of swelling pressures of bentonite with water content.

Water content/time (min) (%)	0 (%)	1200 (%)	2400 (%)	3600 (%)	4800 (%)	6000 (%)	7200 (%)	8400 (%)	9600 (%)	10800 (%)	12000 (%)	13200 (%)
0–10	−25	10	16	19	22	2	31	34	41	45	49	57
10–20	−50	−15	−11	5	26	43	49	57	55	47	36	16
20–30	66	71	75	73	69	60	51	37	26	24	23	23
30–40	40	55	51	46	33	19	13	8	5	4	3	3
40–50	−180	−204	−142	−103	−71	−49	−37	−23	−17	−13	−11	−10
50–60	12	44	34	23	16	10	1	−12	−16	−21	−23	−25
60–70	−18	−46	−38	−29	−25	−24	−23	−23	−23	−24	−24	−24
70–80	5	−35	−29	−27	−22	−13	−12	−12	−11	−11	−11	−11
80–90	−8	12	4	−6	−17	−34	−37	−40	−40	−41	−41	−41
90–100	−10	−27	−28	−24	−23	−20	−19	−12	−12	−13	−13	−15

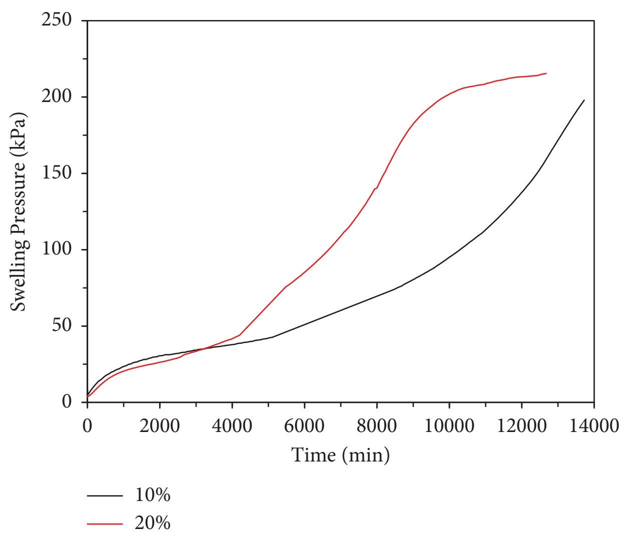

Figure 6: Comparison of swelling pressures of bentonite with 10% and 20% water content.

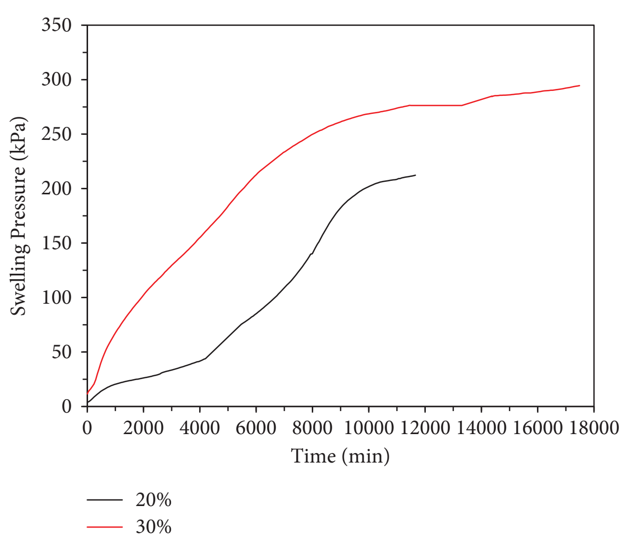

Figure 7: Comparison of swelling pressures of bentonite with 20% and 30% water content.

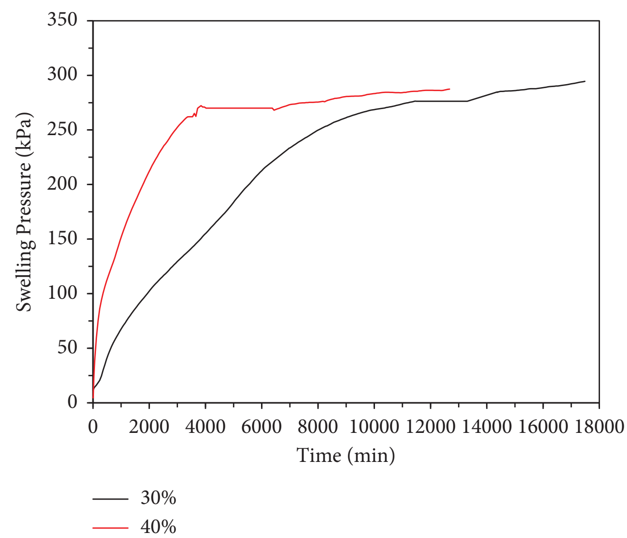

Figure 8: Comparison of swelling pressures of bentonite with 30% and 40% water content.

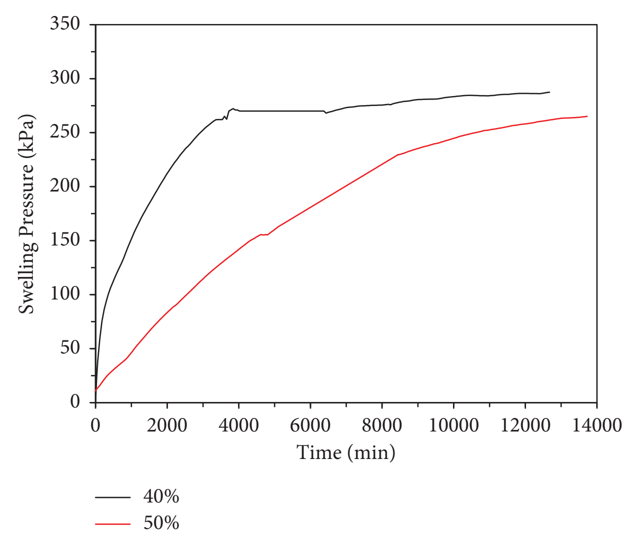

Figure 9: Comparison of swelling pressures of bentonite with 40% and 50% water content.

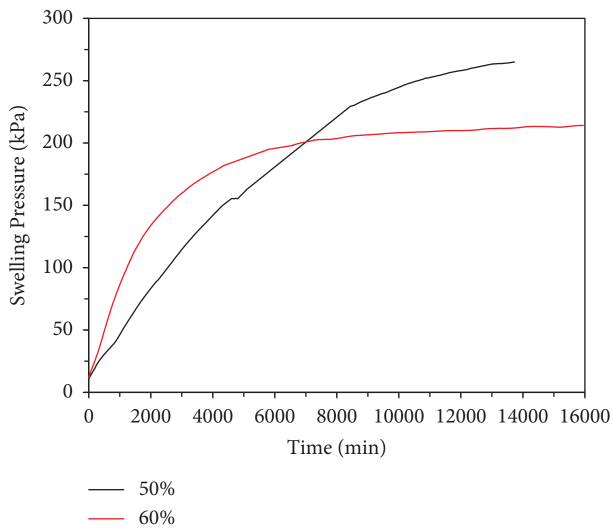

Figure 10: Comparison of swelling pressures of bentonite with 50% and 60% water content.

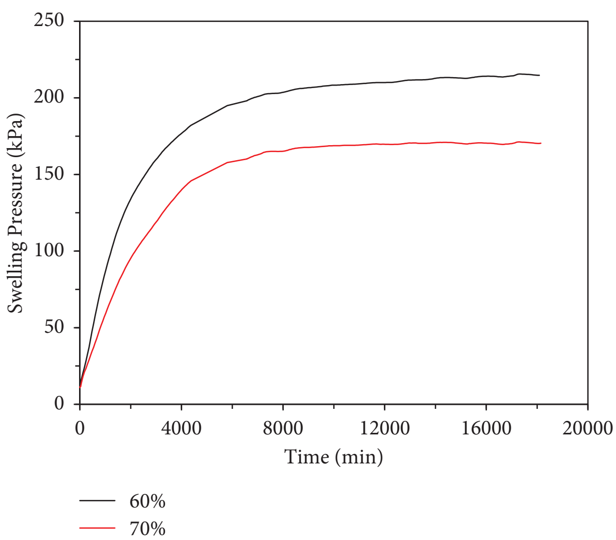

Figure 11: Comparison of swelling pressures of bentonite with 60% and 70% water content.

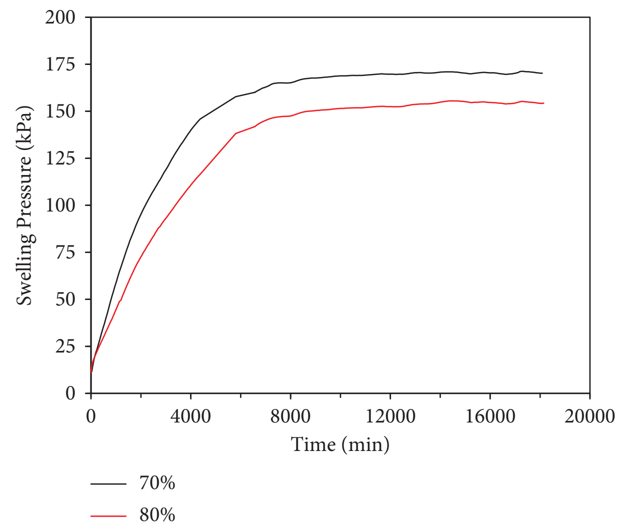

Figure 12: Comparison of swelling pressures of bentonite with 70% and 80% water content.

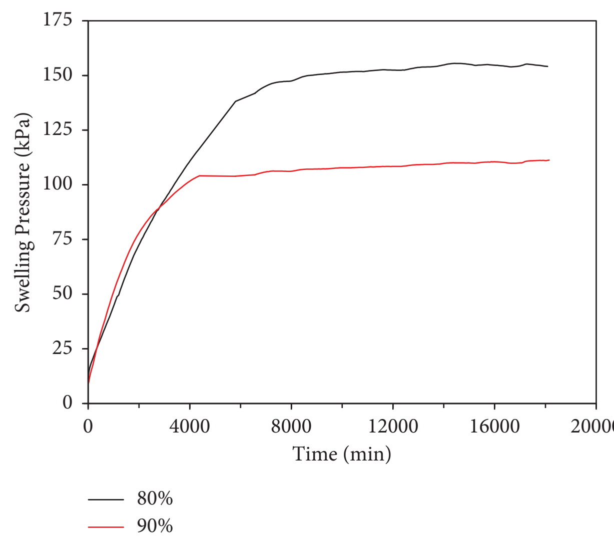

Figure 13: Comparison of swelling pressures of bentonite with 80% and 90% water content.

orientations, which usually have edge-to-edge or edge-to-face contacts. However, on the wet side of OMC, the orientation of soil particles is much higher than that of the dry side, and therefore, the quantity of face-to-face contact also increases. As shown in Figure 16(a), the $\Delta P/P_0$ value initially increased with increasing water content up to the optimum content range which is in good agreement with previous studies [61]. According to the earlier explanations, the reason for this can be attributed to the state of particle flocculation with the edge-to-face contact and large voids between particles. In this case, more water content can be placed between the particles. However, by adding the initial water content higher than the optimum range, the $\Delta P/P_0$ rate and swelling pressure have been reduced due to the different structures of clay particles, their oriented patterns, and face-to-face contact. It should be noted that under the specified dry density, samples with a lower initial water content have larger macro voids and therefore the interior space is largely sufficient to allow the soil to swell. As the initial water content increases, the amount of these voids decreases, and as a result, the swelling pressure increases due to the limited space (between the soil particles) to swell during the wetting procedure. According to Figure 16(a), with the addition of the initial water content, there was a threshold value for which the $\Delta P/P_0$ began to decrease. The reason for such a decrease in swelling pressure, as well as $\Delta P/P_0$, is that soil swelling with higher initial water content increases during the sampling process, and therefore, the $\Delta P/P_0$ decreases during the test. Hence, the maximum swelling pressure was obtained with the optimum moisture content range under the same dry density of samples.

Figure 16(b) shows the changes in the dimensionless $\Delta P/P_0$ parameter for different amounts of BOFS at up to 90 days of curing times. As can be seen, the $\Delta P/P_0$ decreased with

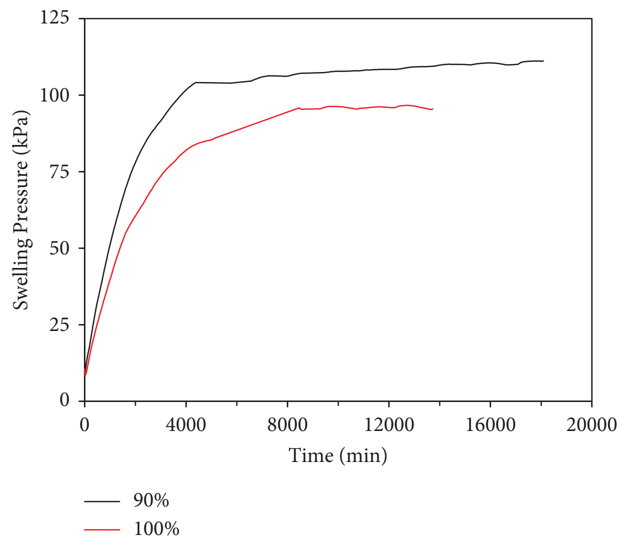

Figure 14: Comparison of swelling pressures of bentonite with 90% and 100% water content.

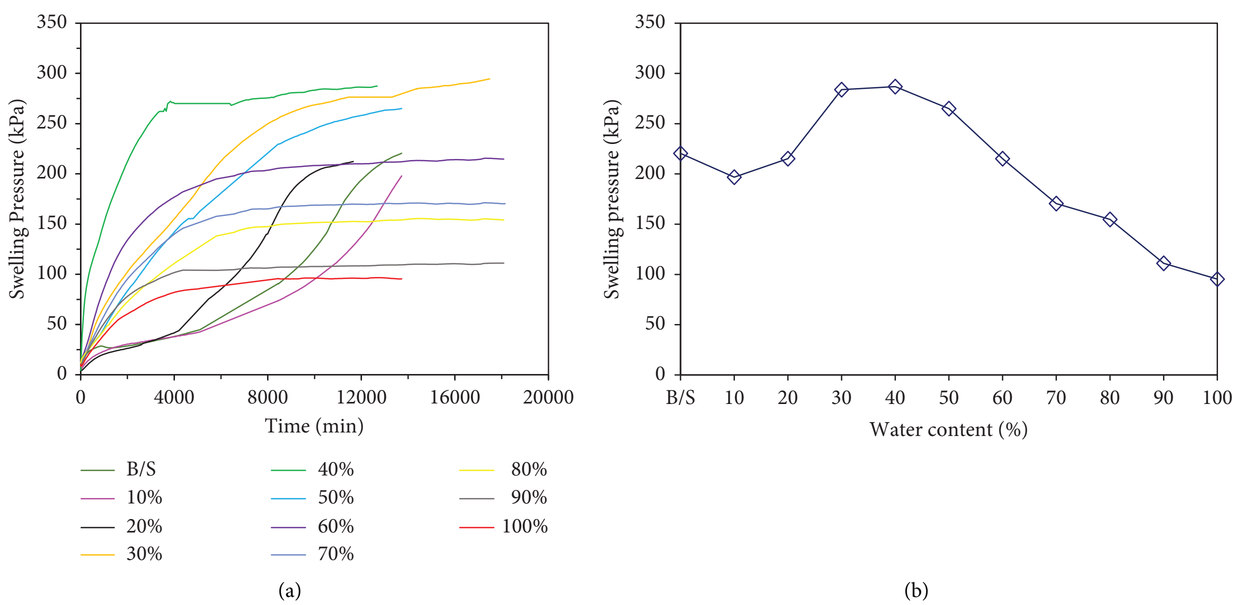

Figure 15: Swelling pressures of bentonite for all water contents: (a) in detail and (b) final swelling pressure.

increasing BOFS, which can be attributed to the positive effect of chemical additives in the stabilization of bentonite (B1). So, the reason for the decrease in $\Delta P/P_0$ is the short-term and long-term reactions between BOFS and soil particles. Comparing these two diagrams, it can be seen that 2.5 and 5% BOFS after 90 and 45 days of curing time, respectively, can greatly reduce the ΔP/P0, which is much lower than that of the initial moisture content of 100%. This indicates that the use of such an additive, albeit small, at the proper curing time can have a significant effect on the swelling pressure, even more than changing the initial water content. Therefore, in projects where complete control of

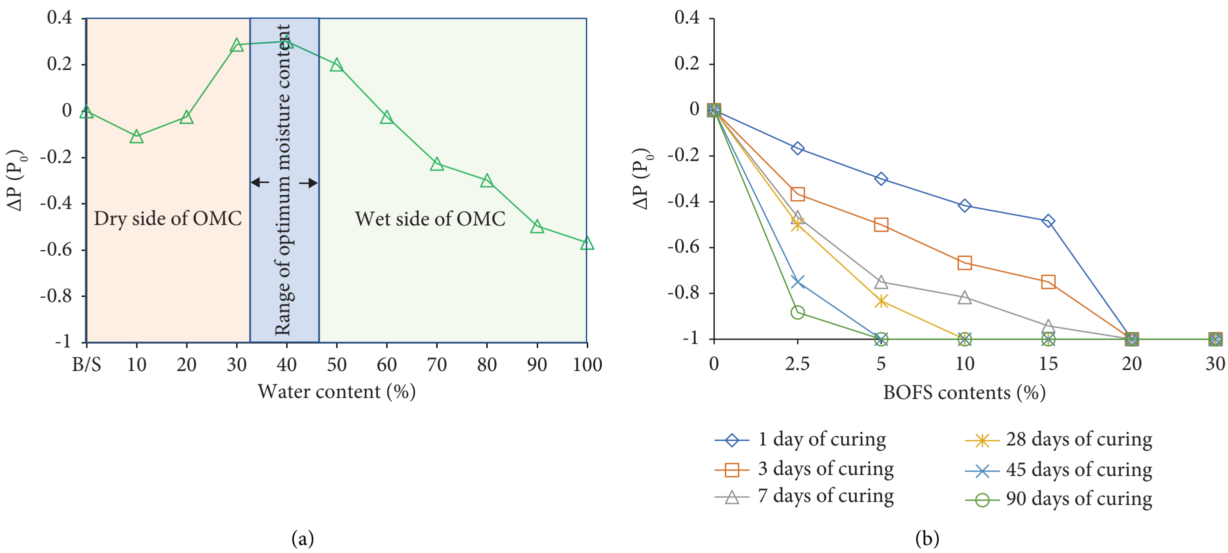

Figure 16: Swelling pressures of bentonite samples for different (a) initial water contents and (b) BOFS contents.

swelling pressure is considered, the use of additives such as BOFS can be very useful because it is not possible to achieve this goal by changing the initial moisture content.

4. Conclusions

Within the scope of the study, swelling pressure changes of bentonite clay depending on the changes in water content were investigated. Unlike the studies in the literature, it has been experimentally revealed how the swelling pressure will change for each 10% increase in water content. If a general evaluation is made on the swelling pressure graphs of bentonite clay prepared in different water contents, it can be summarized that the data obtained support the previous studies in the literature up to the optimum water content, but there is a relative decrease in swelling pressures after optimum water content.

Experimental studies have examined the change in swelling pressure of bentonite clay at different rates depending on each 10% increase in water content. Based on this, it can be stated that the most change occurs between 40% and 50% water content. The biggest change under optimum water content was observed with an average 75% increase in the transition from 20% to 30%. Above optimum, the maximum swelling pressure change occurred with a 40% increase between 80% and 90% water content. It was found that the swelling pressure values of the bentonite samples generally have been stabilized from the 5th and 6th days. Based on this data, it can be noted that bentonite shows the swelling property for a certain period, and then the swelling feature stops.

With this study, the swelling potential of the swelling clays in the soil improvements to be made in the geotechnical field was examined, depending on the water content, and it was evaluated that the results obtained would be effective in reducing swelling damages by reflecting on the application. However, the use of BOFS in soil stabilization significantly improved the swelling pressure of bentonites. Comparing these two techniques showed that despite the positive effect of initial water content on soil properties, it is impossible to fully control the swelling pressure. Therefore, in order to achieve the complete elimination of swelling and the resulting swelling pressure, it is necessary to include chemical stabilization methods in the projects.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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