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Durability of soft clay soil stabilized with recycled Bassanite and furnace cement mixtures

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Abstract

This study examines the wetting–drying durability of soft clay soil stabilized with recycled Bassanite, produced from gypsum waste. Specifically, this study focuses on an investigation of the effects of the moisture conditions on the strength performance and durability of very soft clay soil stabilized with Bassanite and furnace cement mixtures during the wetting–drying cycles, referred to as weathering conditions in this study. Cylindrical stabilized soil specimens were produced and then cured for 28 days. The cured specimens were subjected to different numbers of wetting–drying cycles, and then tested for unconfined compressive strength. The results show that the compressive strength increased with an increase in the Bassanite content for the different wetting–drying cycles investigated. The increase in the Bassanite content is associated with the increase in the dry unit weight, as well as in the decrease in the moisture content of the stabilized specimens for the different wetting–drying cycles investigated. The compressive strength of the soil stabilized with the Bassanite and furnace cement mixtures gradually decreases with an increase in the number of wetting–drying cycles, and the earlier cycles are seen to have a more negative effect on durability than the later cycles. Generally, the influence of the wetting–drying cycles on changes in the strength, durability and volume of the soft clay soil stabilized with Bassanite and furnace cement mixtures is not significant. This is evidence that the use of recycled Bassanite, produced from gypsum waste to stabilize soft clay soil, achieves acceptable durability, raises the strength performance and improves the engineering properties of soft clay soil in a wet environment. In addition, the effective use of gypsum waste contributes to the development of a sustainable society by reducing the huge quantity of solid waste and establishing a sound environment.

Keywords: Soil stabilization; Soft clay soil; Wetting-drying durability; Compressive strength; Recycled Bassanite; Gypsum waste

1. Introduction

Due to the high economic growth in Japan, which started in 1970, the construction industry increased rapidly; and thus, large amounts of construction and demolition waste were, and continue to be, generated annually. For example, the amount of construction and demolition waste increased from 30 million tons in 1980 to 66.85 million tons in 1992; this means the amount doubled within 12 years (MLIT) Gypsum plasterboard is one of the

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most widely used construction materials in the building sector, and approximately 1.6–1.7 million tons of gypsum plasterboard waste are generated every year in Japan (Ahmed et al., 2010, 2011a, 2011b; Kamei et al., 2007). Plasterboard is made from gypsum sheets covered on both sides with paper sheets. The waste from gypsum plasterboard creates a serious problem in Japan because the cost of disposing this waste in landfill sites is high. As a result, hazards increase when gypsum waste is sent to landfill sites due to the emission of hydrogen sulfide and a decrease in the area specified for landfill sites. Researchers are attempting to find an alternative way to use gypsum plasterboard waste in ground-improvement projects instead of disposing it in landfill sites; this is a recent issue of importance in Japan. In order to facilitate the use of recycled Bassanite, derived from gypsum plasterboard waste, as a stabilizing agent in ground-improvement projects, it is essential to know the durability of the soil stabilized with recycled Bassanite. It is well-known that recycled Bassanite can achieve acceptable levels of strength and stiffness under dry conditions, but it has trouble both achieving and sustaining an adequate level of strength to maintain the required loads in a wet environment, because Bassanite is a soluble material in water. Thus, there is a need to better understand the strength performance and durability of very soft clay soil stabilized with Bassanite in wet environments to avoid any negative effect when such waste is introduced in ground-improvement projects. Durability is the property of a geotechnical material that reflects its performance under freeze-thaw and wetting–drying cycles. Freeze-thaw tests should be conducted in areas that are subject to freezing conditions, such as cold regions, while wetting–drying cycles should be conducted in all geographic areas (Zhang and Tao, 2006). In general, Japan is considered one of the countries subjected to rainfall in all seasons. As such, an investigation of the wetting–drying durability of soil stabilized with recycled Bassanite is essential to facilitating the incorporation of recycled Bassanite in ground-improvement projects.

The main objective of this study is to investigate the effect of a wet environment, wetting–drying cycles in this study, on the strength, the performance and the durability of very soft clay soil specimens stabilized with recycled Bassanite and type-B furnace cement. For this purpose, the 28-day cured stabilized soil specimens were subjected to different numbers of wetting–drying cycles and then tested for unconfined compressive strength and volume change.

2. Previous research

The disposal of solid waste is a major problem throughout the world. Therefore, a lot of attention is being directed nowadays to protecting the environment by using recycled and waste materials as alternative materials in civil engineering applications instead of disposing them in landfill sites. Increasing the use of waste and recycled materials in earthwork projects has created the necessity for a better understanding of the durability and strength performance of these materials against weathering conditions. In general, there are several scholars who have examined the utilization of different types of waste and recycled materials as a stabilizing agent to enhance the strength of weak soil (Attom and Al-Sharif, 1998; Miller and Azad, 2000; Arora and Aydilek, 2005; Jha and Gill, 2006; Lin et al., 2007; Kamei et al., 2007; Khoury and Zaman, 2007; Maslehuddin et al., 2008; Khattab et al., 2008; Ahmed et al., 2009, 2010, 2011a; Chen and Lin, 2009). The use of recycled Bassanite, which is derived from gypsum waste, was started recently in Japan (Kamei et al., 2007, Ahmed et al., 2010, 2011a, 2011b). Thus, as far as the authors of this paper know, the wetting–drying durability of very soft clay soil stabilized with recycled Bassanite has not been previously studied or reported in literature. Subsequently, this section presents a brief summary of previous investigations dealing with the durability of soil stabilized with different types of waste and recycled materials. The effect of the weathering conditions, in terms of freeze-thaw and wetting–drying cycles for silty sand soil stabilized with recycled gypsum, was investigated. Four different contents, ranging from 0 to 20% of recycled gypsum and treated with different quantities of cement, were used. Cylindrical specimens of stabilized soil were compacted and cured for 7 days before being subjected to freeze-thaw and wetting–drying cycles; then they were tested for compressive strength, loss of soil weight and volume change. The results show that the cycles of freeze-thaw had a significantly more negative effect on the durability than the cycles of wetting–drying. Both the recycled gypsum and the cement content had a significant effect on the improvement of durability. Samples stabilized with recycled gypsum, and without treatment by the addition of cement, were not able to survive the actions of the weathering conditions (Ahmed and Ugai, 2011). The wet durability of the soil stabilized with industrial waste lime was investigated in terms of unconfined compressive strength. The tested soil was stabilized with different contents of industrial waste lime, ranging from 0 to 8%. The 7-day cured stabilized soil specimens were immersed in water for 2 days; after that, the specimens were tested for compressive strength. The results indicate that a more limited reduction in compressive strength was obtained for the samples stabilized with industrial waste lime than those stabilized with lime (Khattab et al., 2008). The effect of the wetting–drying cycles on the strength and durability of black cotton clay soil, stabilized with different contents of lime and fly ash, was investigated. The 28-day cured samples were subjected to 14 cycles of wetting–drying and then tested for splitting tensile strength. The results show that the durability and tensile strength improved with an increase in the fly ash content (Soni and Jain, 2008). In addition, the effect of the wetting–drying cycles on the aggregate stabilized with C-type fly ash was examined. The tested samples were cured for 3 and 28 days; after that, the samples were subjected to different numbers of wetting–drying cycles and then tested for unconfined compressive strength. The results show that the wetting–drying had a more negative effect on the samples cured for 28 days than on those cured for 3 days (Khoury and Zaman, 2002). The durability of a lime stone aggregate, stabilized with cement kiln dust (CKD), was examined under different numbers of wetting–drying and freeze-thaw cycles in terms of a resilient modulus. The results show that the effect of the wetting–drying cycles on the durability of samples stabilized with cement kiln dust was less than that of the freeze-thaw cycles (Zaman et al., 1999). The durability of aggregates stabilized with cement kiln dust, fly ash and fluidized bed ash was examined by subjecting the samples to wetting–drying cycles. Cylindrical specimens were produced and then cured for 28 days before applying the wetting–drying cycles. The results show that the durability of the stabilized samples depends on the type of stabilizing agent (Khoury and Zaman, 2007). In summation, an exploration of the weathering effect, for example, in terms of wetting–drying cycles, on the durability of soil stabilized with recycled and waste materials, should be considered before introducing these materials in ground-improvement projects in order to avoid any negative effect that may occur, particularly for long-term performance, since the properties of waste materials vary from site to site.

3. Materials and methods

3.1. Materials used

The materials used in the present study were Kaolin clay soil, type-B furnace slag cement and recycled Bassanite. The tested soil was Kaolin clay; it was acquired from the SINO Industrial Clay Company in Japan. The tested clay soil had a clay content of 64.7% and a silt content of 35.3%. The physical and mechanical properties of the tested soil are presented in Table 1, while the chemical composition is tabulated in Table 2. According to USCS (the unified soil classification system), the soil type was classified as clay with high plasticity (CH).

The type-B furnace slag cement was acquired from the Local Cement Company in Japan. This type of cement is mainly produced from waste materials and by-product Portland cement; it has a furnace slag content of about 30–60%. The main reason for using cement in this research is to prevent the solubility of the recycled Bassanite by developing solidification for the soil-Bassanite mixture. Furthermore, the presence of cement will improve the durability of the stabilized clay soil and decrease the leaching effect of the heavy metals due to the use of recycled Bassanite (Kamei and Horai, 2008; Ahmed and Ugai, 2011). Two cement–soil (C/S) ratios of 5% and 10%, based on the dry soil mass, were used.

The recycled Bassanite used in this research was produced from gypsum plasterboard waste. More details about the production of recycled Bassanite from gypsum plasterboard waste can be found in previous works (Ahmed et al., 2010, 2011a; Kamei et al., 2007). In brief, air-dried gypsum plasterboard waste was brought from some landfill sites in Japan and then pulverized to obtain the crushed gypsum waste in powder form that is called hydrate calcium sulfate ($CaSO_4$. $2H_2O$). The crushed gypsum waste was sieved to remove any solid portions and paper; subsequently, the gypsum waste powder was heated for a certain time at a specified temperature to produce the recycled Bassanite that is called hemi-hydrate calcium sulfate ($CaSO_4 \cdot 1/2H_2O$). The chemical composition of the recycled Bassanite used in this research is presented in Table 3. Fig. 1 shows the particle size distribution curve for the Bassanite.

For each cement–soil ratio of 5% and 10%, four different Bassanite–soil (B/S) ratios, 0, 10, 20 and 40, were used to investigate the effect of the Bassanite-cement mixtures on the strength performance and durability of the tested soil subjected to different numbers of wetting–drying cycles.

3.2. Specimen preparation

Distilled water was added to the oven-dried soil to achieve a water content (W/S) of 140% for the tested soil; subsequently, the tested soil became very soft clay soil, which was the target required in this research. The tested soil was mixed with water using an automatic mixer. The mixing process was prolonged for a long time in order to obtain homogenous and isotropic clay soil. The main reason for selecting the water content of 140% is attributed to the soft clay soil found in some locations in Japan, which is very soft and has approximately the same water content as that of the soil used in this study. This type of

Table 1
Physical properties of Kaolin clay soil.

Property	ρ_s (gm/cm^3)	LL (%)	PL (%)	I_P	Sand (%)	Silt (%)	Clay (%)
Value	2.679	73.10	36.70	36.40	0.00	35.30	64.70

Table 2
Chemical composition of Kaolin clay soil.

Element	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2	Na_2O
Content (%)	8.10	24.80	0.14	0.15	0.02	0.02	1.54	0.56

Table 3
Chemical composition of recycled Bassanite.

Element	CaO	H_2O	SO_3
Content, (%)	38.63	6.21	55.16

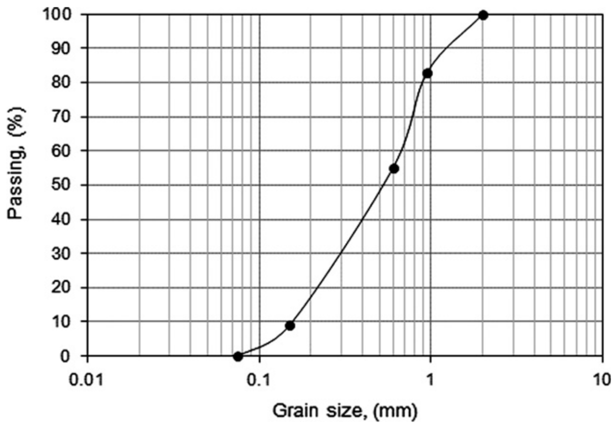


Fig. 1. Grain size distribution curve for Bassanite.

very soft clay soil is spread especially around the Haneda Airport area. The water content of this soil type, 140%, was recorded in several in situ and case studies in Japan (Nakase and Kamei, 1984).

The desired contents for the recycled Bassanite and furnace cement were mixed by hand under a dry state. Stabilized soil samples were prepared by mixing the tested soil with four different contents of recycled Bassanite (B/S), 0, 10, 20 and 40%, and two cement contents (C/S), 5 and 10%, based on the weight of the tested soil, as previously mentioned. The required amount of recycled Bassanite and furnace cement mixture was added to the tested soil using the automatic mixer, and the mixing process was prolonged for 30 min to ensure the uniformity of the mixture. After that, the samples were placed in cylindrical steel molds having internal dimensions of 50 mm in diameter and 100 mm in height. The molds were lubricated, before placing the samples in them, to avoid any friction between the soil samples and the inner sides of the molds that might develop during the extraction of the samples. The samples were placed in the molds in five layers, and the blow of a rubber hammer was applied to each layer to remove any bubbles from within the soil matrix. The molds were placed in polyethylene bags and kept in a controlled room at a temperature of 20 °C for 24 h. The specimens were extracted from the molds with special care after 24 h. Then, the specimens were wrapped in polyethylene plastic sheets and kept in the controlled room for 28 days at a temperature of 20 °C until they were required for the testing. In order to achieve reliability in the test results, at least three different specimens were prepared for each test and the average was reported in certain cases; in other cases, the results for all three specimens were plotted on curves to represent the results of one sample. The unit weight of each tested sample was determined based on the weight of the sample and the volume of the mold.

3.3. Durability tests

The cycles of wetting and drying were used to evaluate the strength performance and durability of the clay samples stabilized with recycled Bassanite. Wetting–dying durability tests were conducted in this research according to the procedure for wetting–drying cycles provided by the Japanese Highway Society (JHS, 2001). These tests were proposed to examine the durability of geotechnical materials used in road and highway construction against the actions of weathering conditions in Japan. The procedure used in this test is approximately similar to that presented in the ASTM specifications for tests with the same type of expectation regarding the number of cycles, the curing time and the soil loss. In brief, after completing the curing time of 28 days, the specimens were air dried for 24 h at room temperature and then completely immersed in water for another 24 h. This process represented one cycle of wetting–drying, which requires 48 h. After completing the required cycles of wetting–drying, the specimens were tested for unconfined compressive strength, and the water content was measured for each tested specimen to determine any change in moisture content. With knowledge of the water content, the dry unit weight for the tested specimens could be determined based on the value of the bulk density which had been previously determined. The volume change was determined after each wetting–drying cycle by measuring the dimensions of the sample (diameter and height). The volume change was also determined based on the calculated value of the dry unit weight using the value of the moisture content for the tested samples after the samples had been subjected to the desired numbers of wetting–drying cycles. To better understand the effect of the wetting–drying cycles on the strength performance and durability of the stabilized specimens, the durability index of the stabilized specimens was considered. This index is determined by dividing the ultimate compressive strength of a specimen, $q_{u(n=1,3,5)}$, after the desired number of wetting–drying cycles, by the ultimate compressive strength of an identical specimen, subjected to only 28 days of curing, $q_{u(n=0)}$.

3.4. Unconfined compressive strength Tests

Unconfined compressive strength tests were used in this research to evaluate the strength performance and durability of the clay soil stabilized with recycled Bassanite subjected to cycles of wetting–drying. Using the compressive strength is considered to be one of the most popular methods for evaluating the performance of soil stabilization, and the compressive strength is one of the main parameters applied in the design of earthwork projects (Yarbasi et al., 2007). In addition, it is used to evaluate the durability of stabilized soil subjected to weathering conditions (Zhang and Tao, 2008; Ghazavi and Roustaie, 2010). For these reasons, the unconfined compressive strength was selected in this study to evaluate the durability of clay soil stabilized with recycled Bassanite. Unconfined compressive strength tests were conducted in accordance with ASTM D 2166-66 (Bowles, 1992). The load was applied to each specimen at a displacement rate of 1 mm/min and the loading was continually applied until the failure of the sample.

4. Results and discussion

Variations in stress versus strain for samples treated only with furnace cement contents ($C/S = 5\%$ and 10%) and without the addition of Bassanite ($B/S = 0$), and subjected to wetting–drying cycles, are presented in Fig. 2, while the stress–strain relationships for the samples treated with different contents of Bassanite (B/S) at cement contents (C/S) of 5% and 10%, and subjected to wetting–drying cycles, are shown in Figs. 3 and 4, respectively. The values for the ultimate compressive strength of the stabilized soil samples, subjected to different numbers of wetting–drying cycles, are presented in Table 4. In general, as shown in these figures and in Table 4, the unconfined compressive strength decreases gradually with an increase in the number of wetting–drying cycles for most of the different specimens investigated. It is important evidence that the samples treated with the cement content of $C/S = 10\%$ had a much higher compressive strength before the wetting–drying cycles than identical samples treated with the cement content of $C/S = 5\%$, as presented in Fig. 2. In addition, the sustained compressive strength for the samples treated with $C/S = 10\%$, after the application of the wetting–drying cycles, is more compared to the samples

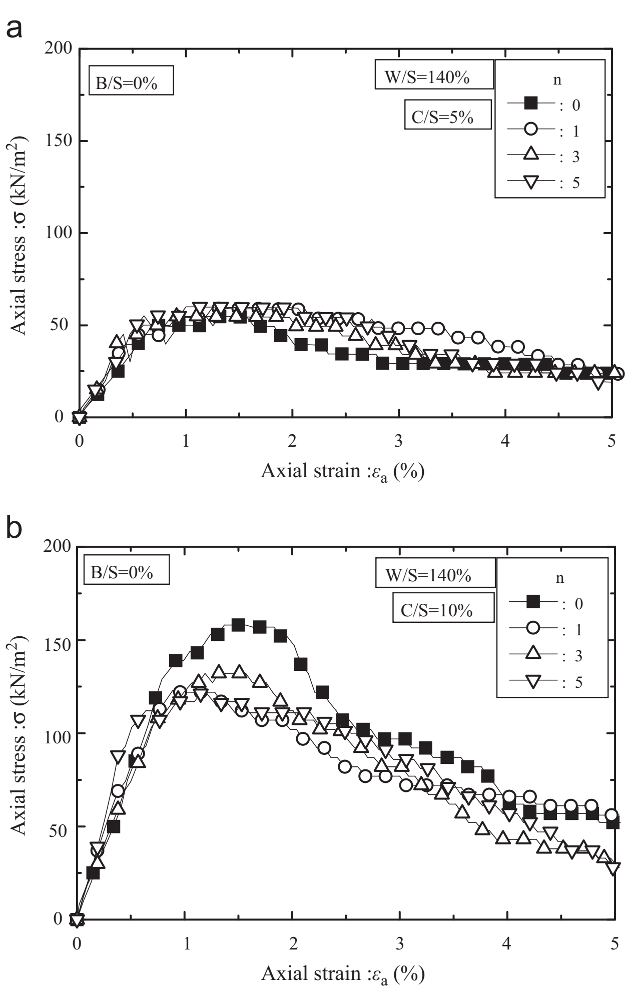


Fig. 2. Stress–strain relationships for samples stabilized with only furnace cement and subjected to wetting–drying cycles (n). (a) In case of cement–soil ratio (S/C) of 5% and without Bassanite ($B/S = 0$). (b) In case of cement–soil ratio (S/C) of 10% and without Bassanite (B/S = 0).

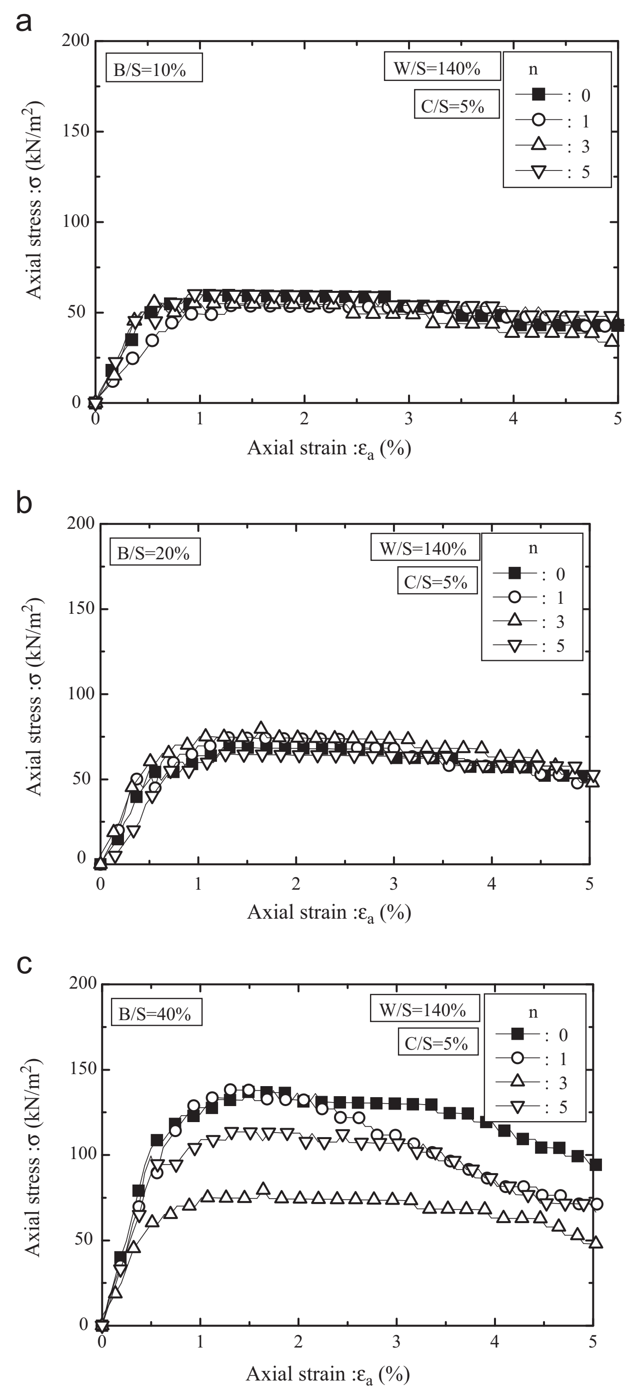


Fig. 3. Stress–strain relationships for soil samples stabilized with different Bassanite–soil ratios (B/S) at cement–soil ratio (C/S) of 5% and subjected to wetting–drying cycles (n). (a) In case of Bassanite–soil ratio (B/S) of 10%. (b) In case of Bassanite–soil ratio (B/S) of 20%. (c) In case of Bassanite–soil ratio (B/S) of 40%.

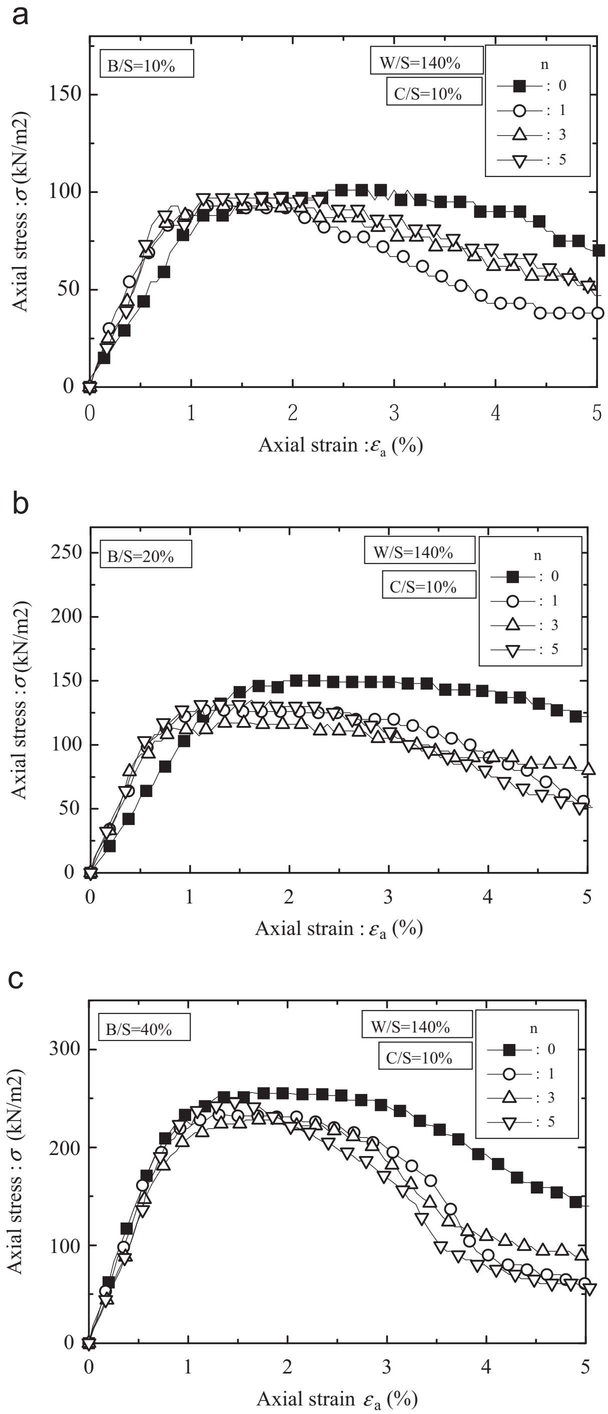


Fig. 4. Stress–strain relationships for soil samples stabilized with different Bassanite–soil ratios (B/S) at cement–soil ratio (C/S) of 10% and subjected to wetting–drying cycles (n). (a) In case of Bassanite–soil ratio (B/S) of 10%. (b) In case of Bassanite–soil ratio (B/S) of 20%. (c) In case of Bassanite–soil ratio (B/S) of 40%.

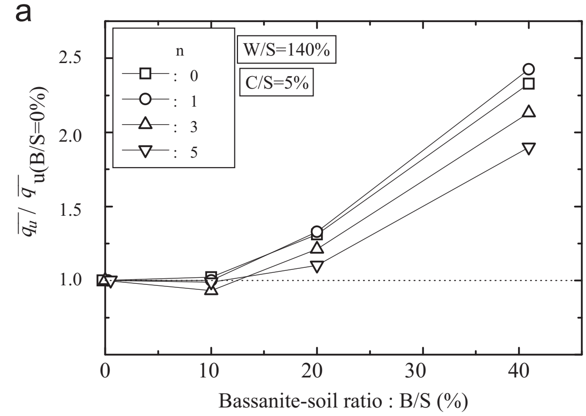
Table 4
Values of ultimate compressive strength for stabilized soil samples subjected to different numbers of wetting–drying cycles.

Number of wetting–drying cycles, (n)	Ultimate compressive strength, (kPa) Bassanite–soil ratio (B/S), (%)							
	Cement–soil ratio (C/S=5%)				Cement–soil ratio (C/S=10%)			
	0%	10%	20%	40%	0%	10%	20%	40%
0	55	58	70	131	150	100	155	255
1	54	50	74	130	125	92	126	230
3	56	57	74	75	130	85	126	220
5	55	58	67	113	120	90	123	240

treated with $C/S=5\%$. The wetting–drying cycles have a large effect on the decrease in unconfined compressive strength in the case of the samples treated only with the 10% cement content compared to the samples treated only with the 5% cement content, as presented in Fig. 2. The percent decrease in the compressive strength of the samples subjected to 5 cycles of wetting–drying and treated with cement contents of (C/S) 10% and 5% was found to be 20% and 0%, respectively. The strength of the sample treated with $C/S=10\%$, after 5 wetting–drying cycles, was found to be 120 kPa, while it was found to be 50 kPa for an identical sample treated with $C/S=5\%$. This proves that although the percent decrease in strength for the sample treated with $C/S=10\%$ is high, compared to the case of the sample treated with $C/S=5\%$, the sustained strength of the sample treated with $C/S=10\%$ is better. This behavior is attributed to the increase in cement content, associated with the increase in bonding between the soil particles due to the induced chemical reactions between the cement and the soil particles, and to the strength which then increases with an increase in cement content. Furthermore, the tested samples treated with the 10% cement content reached an approximate dry state, compared to those treated with the 5% cement content, due to the consumption of water found in the tested soil during the process of hydration for cement. Subsequently, the effect of the wetting–drying cycles on the dry soil samples is significant, while the effect of the cycles on the wet soil samples is not significant. This can probably be attributed to the samples in a wet state, which already contained an adequate amount of water, and to the fact that their tendency to absorb more water was limited because the voids in the soil matrix were already full of water. Thus, the effect of the wetting–drying cycles on the samples treated with a low content of cement is not significant. On the contrary, the immersing of the dry samples in water during the wetting phase has a significant effect on the de-acceleration of the chemical reactions induced between the stabilizers and the soil particles. Subsequently, the bonding which develops between the soil particles, produced by the chemical reactions, is reduced by the increase in the number of wetting–drying cycles, due to changes in the condition of the chemical reactions between the stabilizers and the soil particles. For all the investigated specimens, treated with Bassanite-cement mixture and cement alone, the wetting–drying cycles have a much more pronounced effect on the decrease in compressive strength, especially in the first three cycles. Afterward, this effect decreases with an increase in the number of wetting–drying cycles. This phenomenon can be explained by the exposure of the samples to the first wetting–drying cycles. This exposure causes a rearrangement of the soil particles and possible changes in the structure of the stabilized soil. Subsequently, the strength of the samples deteriorates with an increase in the number of wetting–drying cycles up to the third cycle. This concept concurs with the results obtained in previous works which reported that the strength decreased with an increase in the rate of water absorption due to the expose of the samples to the wetting–drying cycles (Oti et al., 2009; Bin-Shafique et al., 2009). After some specified number of wetting–drying cycles, 3 cycles in this case, the effect of an increasing number of cycles on the deterioration in strength is not significant. It is probably related to most of the chemical reactions between the stabilizers and the soil particles, and may be completed early or before the third cycle; then the effect of wetting on the de-accelerating of the chemical reactions is reduced. Therefore, the effect of the wetting–drying cycles on the decrease in strength after the third cycle is not significant.

As the presence of furnace cement in the soil mixture plays an important role in the enhancement of the compressive strength, as illustrated in Fig. 2(b), the presence of Bassanite in the soil mixture also has a positive effect on the enhancement of the compressive strength, as illustrated in Figs. 3 and 4(c). It is important to report the fact that cement has more potential to improve the strength of the tested soil than Bassanite, because cement has a higher cementation property. To better illustrate the effect of the addition of Bassanite on the enhancement of the durability for the different wetting–drying cycles investigated, the relationship between the durability index and the Bassanite–soil ratio is determined and presented in Fig. 5. Clearly, the increase in the Bassanite–soil ratio increases the durability index for the different samples stabilized with the different Bassanite and cement contents used. These results can probably be attributed to the increasing content of recycled Bassanite in the soil mixture and to the sufficient hardening which develops for the stabilized samples. Subsequently, the samples can resist the actions of the wetting–drying cycles. The hardening which develops between the soil particles, when recycled Bassanite is introduced, is most likely related to the exchange of charges between the calcium ion in the Bassanite, which has two positive charges, and the clay particles, which have two negative charges. Thus, the clay minerals flocculate to form stronger blocks of clay fractions that help to delay the water distribution within the soil matrix. Furthermore, a chemical reaction takes place among the calcium, the silica and the alumina, that already existed in the tested clay (as presented in Table 2 for the clay composition), to produce complex aluminates and silicates that improve the strength and durability of the tested soil. Previous studies reported that soils stabilized with certain cementation materials, which have a calcium component, experienced an improvement in strength, especially in the case of cohesive soil

a



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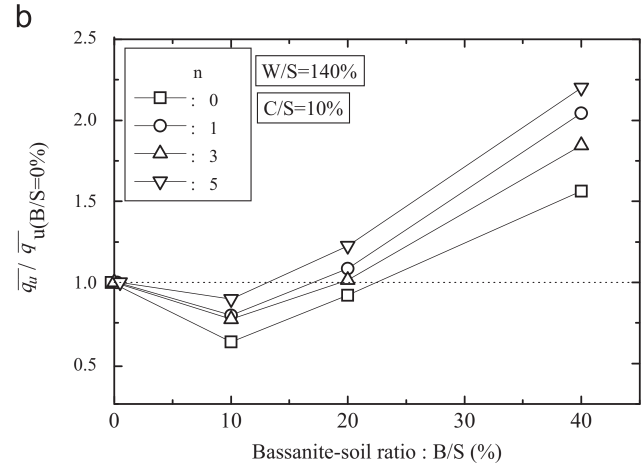

Fig. 5. Effect of Bassanite–soil ratios (B/S) for each cement–soil ratio used on durability index for stabilized soil samples subjected to wetting–drying cycles. (a) In case of cement–soil ratio (C/S) of 5%. (b) In case of cement–soil ratio (C/S) of 10%.

(Rogers and Glendinning, 1997; Kinuthia et al., 1999; Oti et al., 2009). The compressive strength and durability index of the samples treated with a Bassanite content of 10% and a cement content of 10% decreased compared to the other stabilized samples, as presented in Figs. 4(a) and 5(b), respectively, whilst this reduction in strength and durability was diminished with an increase in the Bassanite content to more than 10%, as presented in Fig. 5(b). Better enhancement of both strength and durability was obtained when a greater percentage for the Bassanite–soil ratio was introduced. The same behavior was provided in a previous work that investigated the effect of the recycled Bassanite content on the enhancement of soft clay soil. Kamei and Shuku (2007) explained that this behavior, based on C_3A (Tri-calcium aluminate–$Ca_3Al_2O_4$), which is one of the main components of cement, occurs or reacts at high hydration heat by a hydration reaction. In this case, Bassanite is used as the heat control agent; it acts to reduce the strength, as observed in Fig. 4(a). This reduction in strength is probably attributed to the activity of C_3A, which is one of the parameters most responsible for the hardening or the setting of the cement; it may be reduced by some chemical reactions taking place between the Bassanite and the cement (Kamei and Shuku, 2007), as occurred in this case with a Bassanite content of 10%. The effect of the number of wetting–drying cycles on the durability index of the stabilized soil specimens is illustrated in Fig. 6. It can be argued that the action of wetting–drying cycles has no significant effect on the durability of the samples stabilized with Bassanite-cement mixtures. This is most likely attributed to the main reason mentioned previously, namely, the contents of cement and Bassanite used herein are capable of resisting the actions of the wetting and drying cycles. Samples treated with different Bassanite–soil ratios, at a cement–soil ratio of 10%, achieved small durability (Fig. 6(b)) compared to those samples treated with the same Bassanite–soil ratios at a cement–soil ratio of 5% (Fig. 6(a)). This behavior coincides with that of the unconfined compressive strength, which was previously explained. However, the durability in the case of samples treated with different Bassanite–soil ratios, at a cement–soil ratio of 10%, enhanced significantly after the third cycle of wetting–drying, as presented in Fig. 6(b). Generally, it can be stated that soft clay soil, stabilized with recycled Bassanite, is durable against the actions of wetting–drying cycles.

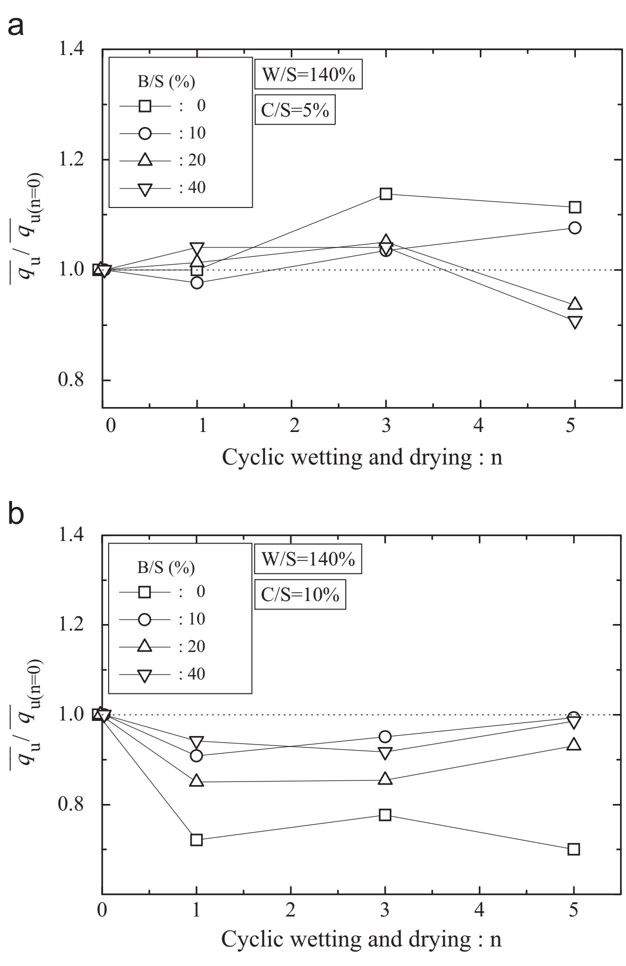

Fig. 6. Influence of number of wetting–drying cycles (n) on durability index for soil samples stabilized with different Bassanite–soil ratios (B/S) for each cement–soil ratio (C/S) used. (a) In case of cement–soil ratio (C/S) of 5%. (b) In case of cement–soil ratio (C/S) of 10%.

The effect of the Bassanite–soil ratio on the dry unit weight and water content of the stabilized soil specimens, subjected to different numbers of wetting–drying cycles, is shown in Figs. 7 and 8, respectively. These figures clearly show that the increase in the Bassanite–soil ratio decreases the water content and increases the dry unit weight for all the investigated wetting–drying cycles. This is most likely related to the Bassanite, which is hemi-hydrate calcium sulfate ($CaSO_4 \cdot 1/2H_2O$), absorbing the water from the moist clay soil because it has a chemical property linked to the water molecules to change to hydrate calcium sulfate ($CaSO_4 \cdot 2H_2O$). This reaction takes place because the hydrate calcium sulfate attempts to recover three-quarters of the molecules of water, which were previously missing during the heating process, to change to hemi-hydrate calcium sulfate. Subsequently, the increase in the Bassanite content in the soil mixture decreases the water content. The decrease in water content results in an increase in the dry unit weight of the stabilized soil specimens. This occurs because the relation between the water content and the dry unit weight is the reverse relationship, according to the general formula for dry unit weight (Bowles, 1992). These results coincide with the results provided in previous works (Ahmed et al., 2010, 2011a). It is evident that the same behavior was obtained for all the different numbers of wetting–drying cycles applied. This phenomenon is most likely related to the stabilized samples, when subjected to the drying process, helping the Bassanite retrieve its chemical property in absorbing the water again. In addition, it can be explained that this behavior is the result of the occurrence of flocculation for the tested soil due to the addition of Bassanite. Flocculation results in the stronger agglomeration of clay soil particles and blocks the voids between the fine soil particles. Subsequently, it causes a constraining of the water penetration inside the fine soil particles; and thus, the influence of the wetting–drying cycles on changes in the water content and dry density has no effect. This is due to the fact that the chance of water penetrating into the stabilized soil particles decreases with an increase in the Bassanite–soil ratio. The results shown in

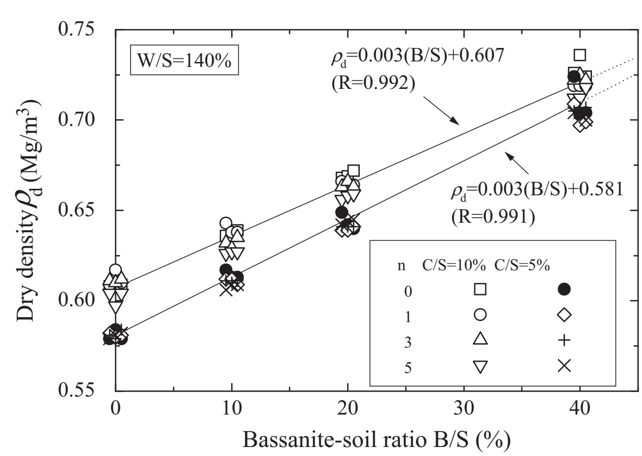

Fig. 7. Influence of Bassanite–soil ratios (B/S) for each cement–soil ratio (C/S) used on dry unit weight of stabilized soil specimens subjected to wetting and drying cycles (n).

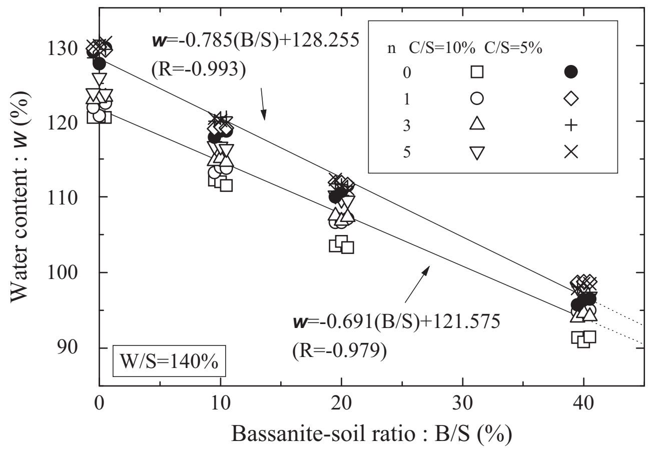

Fig. 8. Influence of Bassanite–soil ratios (B/S) for each cement–soil ratio (C/S) used on water content of stabilized soil specimens subjected to wetting and drying cycles (n).

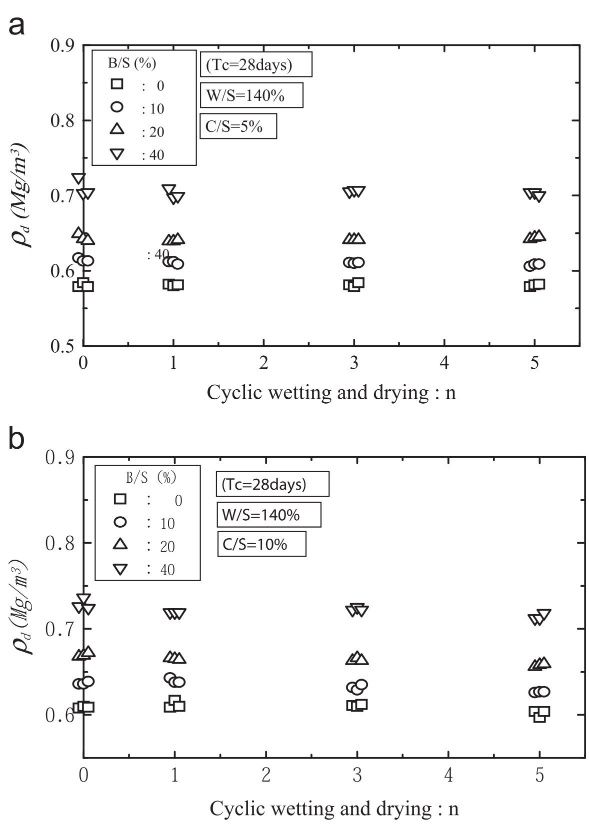

Fig. 9. Influence of wetting–drying cycles (n) on dry unit weight of soil specimens stabilized with different Bassanite–soil ratios (B/S) for each cement–soil ratio (C/S) used. (a) In case of cement–soil ratio (C/S) of 5%. (b) In case of cement–soil ratio (C/S) of 10%.

Figs. 9 and 10, which present the influence of the wetting–drying cycles on the dry unit weight and the water content, respectively, prove the above discussions. It can be stated that the wetting–drying cycles have no significant effect on changes in the water content or dry density of the stabilized clay soil

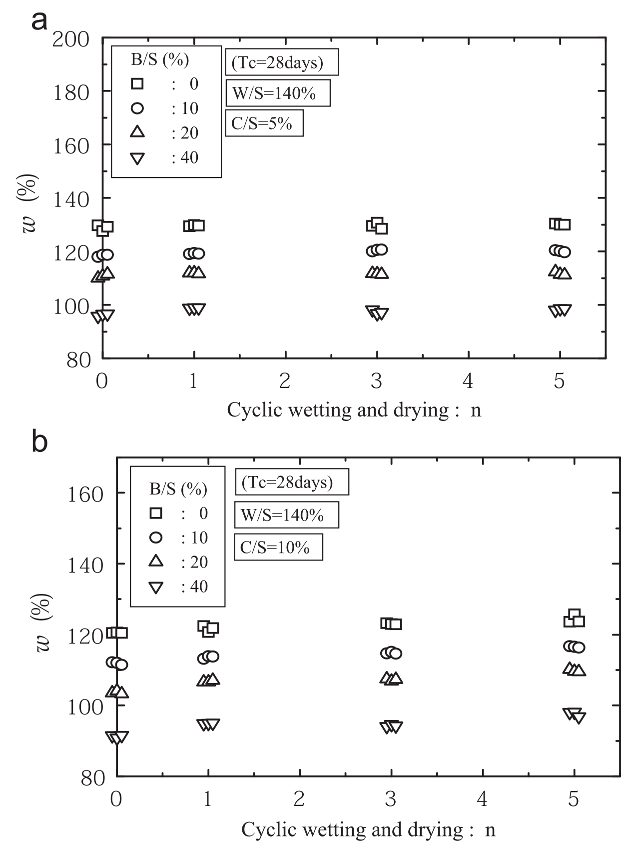

Fig. 10. Influence of wetting–drying cycles (n) on water content of soil specimens stabilized with different Bassanite–soil ratios (B/S) for each cement–soil ratio (C/S) used. (a) In case of cement–soil ratio (C/S) of 5%. (b) In case of cement–soil ratio (C/S) of 10%.

with Bassanite–furnace cement mixtures. Therefore, cycles of wetting–drying have no effect on changes in the volume of the soil specimens stabilized with the recycled Bassanite, because the dry unit weight does not change. The average values for the swelling and shrinkage of the soil specimen stabilized with Bassanite, based on the dimensions of the sample after subjecting the samples to wetting–drying cycles, was found to be 0.01%. These results confirm the results obtained from the influence of the wetting–drying cycles on the water content and dry unit weight of the soil sample stabilized with Bassanite. This behavior is attributed to the reason discussed above. Furthermore, the major component of the tested soil is a kaolin mineral and it has no components which are sensitive to swelling in its composition, such as montmorillonite or nontronite minerals, while the little increase in the volume change for the stabilized soil with Bassanite is probably related to the common expansion for the Bassanite/gypsum when it starts to set.

5. Conclusions

The application of recycled Bassanite, produced from gypsum waste, in combination with furnace cement, as a stabilizer material for very soft clay soil, achieved acceptable levels of durability and strength in a wet environment. The main conclusions of the test results can be drawn as follows:

1. Both the compressive strength and the wetting–drying durability of very soft clay soil improved with the addition of Bassanite–cement mixtures. The durability index and compressive strength increased with an increase in the Bassanite–soil ratio in the soil mixtures for stabilized specimens subjected to different numbers of wetting–drying cycles.
2. The effect of the Bassanite–soil ratio on the enhancement of the durability and strength of the soft clay soil was found to be much more significant in the case of the samples treated with a cement–soil ratio of 5% compared to identical samples treated with a cement–soil ratio of 10%.
3. The strength of treated and untreated soil samples decreased with an increase in the number of wetting–drying cycles by an average value of 10–15%.
4. Increasing the number of wetting–drying cycles was associated with a decrease in strength and durability up to the third cycle, and afterward, the increase in the number of cycles had no effect on either the strength or the durability. The earlier cycles of wetting–drying had a negative effect on the durability of the stabilized soil specimens compared to the effect of the later cycles of wetting–drying.
5. By increasing the Bassanite–soil ratio, the water content decreased and the dry unit weight of the stabilized soil increased for all the different numbers of wetting–drying cycles investigated.
6. The cycles of wetting–drying had no significant effect on the water content, the dry unit weight or the volume change for the soil stabilized with Bassanite–furnace cement mixtures.

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