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Stability of soft clay soil stabilised with recycled gypsum in a wet environment

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Abstract

This study investigates the effect of the soaking condition in a wet environment on the stability and durability of soft clay soil treated with recycled gypsum. Cement and lime are the two types of solidification agents used to improve the durability of the clay–gypsum mixture and to reduce the solubility of the gypsum in a wet environment because gypsum is soluble in water. The recycled gypsum was mixed with cement and lime in different ratios in the dry state, and different amounts of admixtures were mixed with the tested soil to explore the effect of the wet environment on the stability and durability of the stabilised gypsum–clay soil. Cylindrical stabilised soil specimens were cured for 3, 7, and 28 days and then soaked in water for different intervals up to 60 days. The soaked samples were evaluated based on the compressive strength, durability index, deformation changes, soil deterioration, and water absorption. The results show that increasing the content of both types of admixtures had a positive effect on the improvement of stability and durability for the tested soil in a wet environment, while the increase in the admixture ratio had a slightly negative effect on both the stability and the durability of the samples subjected to soaking. Short soaking times, up to 15 days, had a negative effect on the stability, durability, and changes in volume, and brought about a deterioration in the soluble soil and the water absorption compared with longer soaking times. The short curing times of 3 and 7 days exhibited a positive effect on the improvement of the stability, strength, and durability for the stabilised specimens subjected to soaking compared with the longer curing time of 28 days. Increasing the admixture content and soaking time had a significant effect on the water absorption and the soil deterioration of the tested soil. The effect of the soaking condition on the volume changes for the soil stabilised with the two admixtures was found to be insignificant, because the maximum volume change was found to be less than 0.15%.

Keywords: Soft clay soil; Soil stabilization; Recycled gypsum; Wet environment; Soaking durability; Solidification agent

1. Introduction

Recycled gypsum produced from gypsum waste plasterboards has been widely used as a stabiliser material in ground improvement projects in Japan (Ahmed et al., 2011, 2011a, 2011b, 2011c, 2010a; Kamei and Shuku, 2007; Kamei et al., 2007). The incorporation of waste materials as alternatives in the geotechnical field is considered one of the important ways to promote a sound environment (Vichan and Rachan, 2013;

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Horpibulsuk et al., 2013, Kamei et al., 2013a). Gypsum has the potential to bind soil particles and, as a result, to increase the strength of soil mixtures, especially in a dry environment. However, the use of recycled gypsum as a stabiliser material in a wet environment has many challenges due to the solubility of gypsum in water. Consequently, it is essential to use a solidification agent when recycled gypsum is incorporated into projects of ground improvement to prevent the solubility of gypsum and to improve the durability and stability of soil–gypsum mixtures (Kamei et al., 2013, 2011; Ahmed and Ugai, 2011; Ahmed et al., 2010b). The solubility of gypsum has a negative effect on stability due to the deterioration of the bonding within the soil–gypsum mixtures. Both stability and durability of stabilised soil are essential for all earthwork structures in order to avoid failure due to weathering conditions and to save on maintenance or repair costs. The main principle of ground improvement is to create sufficient stability for earthwork structures so they can resist weathering conditions, such as the exposure of stabilised soil to soaking due to rainfall or floods. Subsequently, information on the stability and durability of soft clay soil stabilised with recycled gypsum after soaking is essential to the production of sustainable structures. Durability is defined as the resistance of geotechnical materials to weathering conditions, such as freezing, wetting, soaking, and erosion. There are numerous durability tests in the geotechnical field, such as freeze–thaw, wet–dry, and soaking, which can be used to evaluate the durability of materials used in earthwork projects. Most of the previous studies in literature, that examined the effect of a wet environment or weathering conditions on soil stabilised with recycled gypsum, used wet–dry or freeze–thaw durability tests (Kamei et al., 2013; Kamei et al., 2011; Ahmed and Ugai, 2011; Ahmed et al., 2010b). Although wet–dry and freeze–thaw tests are important for exploring the influence of weathering conditions on the stability and durability of stabilised soil gypsum, the use of the soaking test is more important. This is because the exposure of stabilised soil gypsum to soaking simulates a critical situation that may occur in the field due to rainfall, flood, or seepage. Furthermore, to the best of the authors' knowledge, the effect of the soaking condition, otherwise known as a wet environment, on soft clay soil stabilised with recycled gypsum has not been reported in literature. There are limited studies on the behaviour and performance of soils based on gypsum, including fine-grained gypsiferous, gypsiferous subgrade, and gypsum sand in the presence of cyclic soaking (Ahmed et al., 2011d; Ismail and Hilo, 2008; Razouki et al., 2007; Razouki and Al-Azawi, 2003). The specific objective of this study, therefore, is to investigate the stability and durability of very soft clay soil stabilised with recycled gypsum after soaking. Accordingly, the recycled gypsum was mixed at different ratios with two types of solidification agents, furnace cement type-B and lime, and the resulting performance of the materials was evaluated with respect to stability and durability. In addition, the effect of the admixture contents and ratios, curing times, and soaking periods on the stability and durability of soft clay soil stabilised with recycled gypsum was investigated.

Table 1
Mechanical properties of the tested soil.

Property	Value	Property (mm)	Value
Specific gravity, G_s	2.46	D10	—
Liquid limit, LL %	100	D30	0.01
Plastic limit, PL %	61.5	D50	0.02
Plasticity index, Ip	38.5	D60	0.04

2. Materials and testing

2.1. Materials used

Very soft clay soil samples were collected from the construction site of an embankment project located in Gunma Prefecture, Japan. Soil samples were taken from a depth of 0.5–1 m below the original ground level. The samples were stored in a controlled room in plastic bags to maintain the water content until the samples were required for testing. The average water content was found to be $160 \pm 5\%$. Based on the hydrometer test results, the tested soil comprised 25.7% fine sand, 55.4% silt, and 18.9% clay. The tested soil can be classified as clay soil with high plasticity according to the unified soil classification system, (USCS). The physical properties of the tested soil are presented in Table 1.

The recycled gypsum (B) was produced from gypsum waste plasterboards by heating under a temperature ranging from 140 to 160 °C for a certain time. Details on the production of recycled gypsum from gypsum waste plasterboards have been provided in previous works (Ahmed et al., 2011c; Kamei et al., 2007). The process of recycled gypsum production was done by crushing gypsum waste to powder and then sieving the powder to remove any impurities or solid materials. The crushed gypsum waste was heated under a specific temperature for a certain time to produce the recycled gypsum. The main objective of the heating process was to remove three-quarters of the water molecules by evaporation from the gypsum waste, which is called calcium sulfate hydrate ($CaSO_4 \cdot 2H_2O$), to produce calcium sulfate hemi-hydrate ($CaSO_4 \cdot 1/2H_2O$), which is called recycled gypsum. The chemical composition of the used recycled gypsum is presented in Table 2. Recycled gypsum was mixed with cement (C) or lime (L) in a dry state at different ratios of 1:1, 2:1, and 3:1; then three different percentages of these admixtures of 7.5, 15, and 22.5% for each admixture type were mixed with the tested soil.

Two types of solidification agents are examined in this study, namely, furnace slag cement type-B (C) and lime (L). The objective of using solidification agents in this study is to prevent the solubility of gypsum, since gypsum is a soluble material in water (Kamei et al., 2011; Ahmed and Ugai, 2011). Moreover, the

Table 2
Chemical composition of the used recycled gypsum.

Chemical element	$CaSO_4 \cdot 1/2H_2O$	$CaSO_4 \cdot 2H_2O$	$CaSO_4$
Content (%)	92.6	2.1	5.3

addition of cement or lime improves the stability and durability of soil–gypsum mixtures (Ahmed and Ugai, 2011). In fact, recycled gypsum, which is hemi-hydrate calcium sulfate, has a solubility property when water is introduced (Ahmed and Ugai, 2011; Zhang and Tao, 2006). This issue is considered one of the most negative issues for the incorporation of recycled gypsum into ground improvement projects.

Furnace slag cement type-B is mainly produced as a by-product of Portland cement and some other waste. It has 30–60% blast furnace slag in its composition in accordance with JIS R5211 specifications (Kamei and Horai, 2008). The chemical composition of furnace cement type-B used in this study is presented in Table 3.

Local commercial lime was also used as a solidification agent in this study. The chemical composition of the lime is presented in Table 4. In general, many previous studies have been done on the use of lime or cement as a stabilizer to enhance the strength of soft soil (Kasama et al., 2012; Lin et al., 2007; Indratna, 1996; Bell, 1996). The role of cement or lime in this study is not to improve the strength of the tested soil, but to prevent the solubility of gypsum and to improve the durability against soaking.

2.2. Sampling and testing

The tested soil samples obtained from the construction site were used as-is and the recycled gypsum was mixed in the dry state with furnace cement or lime at different ratios of (B:C/L) 1:1, 2:1 and 3:1. Subsequently, the tested soil was mixed with the desired percentage based on the dry soil mass and the type of admixture (B:C/L) according to the testing program presented in Table 5. The mixing process was prolonged for 10 min using an automatic mixer to obtain as homogenous a mixture as possible and to ensure the uniformity of the mixture. Consequently, the mixture was placed in plastic moulds with internal dimensions of 50 mm in diameter and 100 mm in height. The mixture was placed in the moulds in three layers and each layer was pressed by a steel rod to prevent the formation of air bubbles. The specimens were extracted from the moulds after 24 h and then wrapped in plastic sheets. The specimens were cured for 3, 7, and 28 days in a controlled environment at a temperature of approximately 20 ± 1 °C and humidity of 100%. After completing the required curing time, the specimens were soaked in water for different interval times of 0, 4, 7, 15, 30, and 60 days and then examined in terms of unconfined compressive strength, volume change, soluble soil deterioration, and water absorption. Three different specimens were used for each test and the average of their results was considered to represent reliable data. It is important to mention that the selected soaking times in this study were determined based on the required design criteria and the time table for a ground improvement project using recycled gypsum as a stabilizing agent. This is because this study is part of a project to investigate the effect of a wet environment on the durability of soft clay soil stabilized with recycled gypsum. Consequently, the maximum soaking period was determined to be 60 days in this study to meet the required project time. Furthermore, the most significant effect of the soaking condition is observed in the early soaking times compared to the later soaking times, which will be presented in the soaking test results. That is why the maximum soaking time is limited in this study to 60 days. The main target of the soaking test is to investigate the effect of soaking conditions on the behaviour, strength loss, durability, and solubility of stabilised soil gypsum. Furthermore, the effect of the curing time on the durability and stability of stabilised soil gypsum under soaking is investigated. Volume changes, water absorption, and soil deterioration of the tested soil samples were reported after each soaking period to investigate the influence of soaking on the durability, stability, and solubility of the stabilised soil–gypsum specimens. Water absorption tests are done by immersing the soil samples in water for the required time and then weighing the samples after removing them from the water. The wet soil samples were dried and the percentage of water absorption was determined based on the difference in the dry soil weight before and after soaking. Furthermore, the specific purpose of the soaking tests herein is to study the ability of the stabilised soil–gypsum specimens to retain their strength under soaking in order to simulate critical cases that are expected to occur at project sites.

Unconfined compressive tests were carried out in accordance with ASTM 2166-66 (ASTM, 2007). The sample was placed in between the two blocks bearing the compression machine and then the load was applied with a strain rate of 1 mm/min up to failure or to a strain of 20%. The load was measured using an automatic load cell and the settlement was recorded using the Linear Vertical Displacement (LVD).

3. Soaking test results

3.1. Strength and durability results

The main drawback of using recycled gypsum in ground improvement projects is the deterioration of the soil–gypsum

Table 4
Chemical composition of the used lime.

Chemical element	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	P	S	CO_2
Content (%)	91.11	3.49	1.01	0.20	0.05	0.054	0.189	2.48

Table 3
Chemical composition of the used furnace cement type-B.

Chemical element	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	R_2O	TiO	P_2O	MnO	Cl	Ig. loss
Value (%)	26.30	8.70	1.90	54.10	3.70	2.00	0.26	0.42	0.54	0.69	0.08	0.28	0.01	0.80

Table 5
Testing program.

Admixture content (B–C/L)%	Admixture ratio (B:C/L)	Curing times (days)	Testing type/Soaking period																							
			Unconfined compression test						Volume changes						Soil deterioration						Water absorption					
			0 d	4 d	7 d	15 d	30 d	60 d	0 d	4 d	7 d	15 d	30 d	60 d	0 d	4 d	7 d	15 d	30 d	60 d	0 d	4 d	7 d	15 d	30 d	60 d
7.5%	1:1	28 d	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
15%			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
22.5%			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
15%	1:1	28 d	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	2:1		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	3:1		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
15%	1:1	3 d	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
		7 d	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
		28 d	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Note: The total number of tests for both admixture cases of B–C and B–L is 432.

materials when subjected to a wet environment because gypsum is soluble in water. The use of solidification agents, such as cement or lime, to prevent the solubility of gypsum is essential to improving the stability and durability of the stabilised soil gypsum in a wet environment. Subsequently, this section presents the effect of soaking on both the performance and the behaviour of stabilised soil gypsum in terms of strength, durability, water absorption, soil deterioration, and volume changes. Figs. 1 and 2 show the strength ratios as functions of the soaking time for soil specimens stabilised with 15% for B–C and B–L admixtures, respectively. These specimens were cured for different curing times of 3, 7, and 28 days before being subjected to soaking in water. The strength ratio is defined as the ratio of the strength of the sample subjected to a specified soaking time to the strength of an identical sample prior to soaking. These figures reveal that, the strength ratio increases significantly with an increase in soaking time up to 30 days, especially for samples subjected to curing times of 3 and 7 days. An increase in the strength ratio, in the case of specimens cured for 3 and 7 days, is most likely attributed to the following reasons. The chemical reaction between the B–C/L admixtures and the clay particles most likely requires more time to achieve the full improvement in strength, which may be more than 7 days. Subsequently, upon the exposure of the specimens cured for 3 and 7 days to soaking in water, the specimens gain additional curing time. This additional curing time allows the reaction between the stabilisers and the clay particles to finish; then the strength ratio increases with the increase in soaking time up to the specified time, which is 30 days in this case. After 30 days of soaking, the exposure of the specimens to soaking in water has no effect on the increase in strength ratio. This is because the chemical reaction between the clay particles and the stabilisers has already been completed. In addition, the soaking of the specimens in water for a long time weakens the bonding that has developed between the soil particles. It is clear from these figures that the increase in strength ratio, in the case of the samples stabilised with the B–L admixture, is obvious compared to the samples stabilised

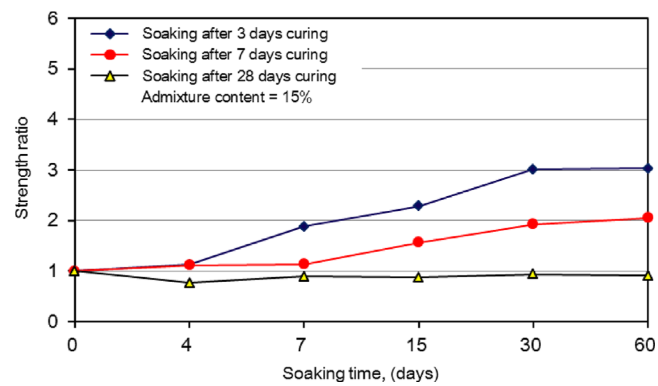

Fig. 1. Effect of soaking time on strength ratio of soil stabilized with B–C admixture subjected to different curing times before soaking.

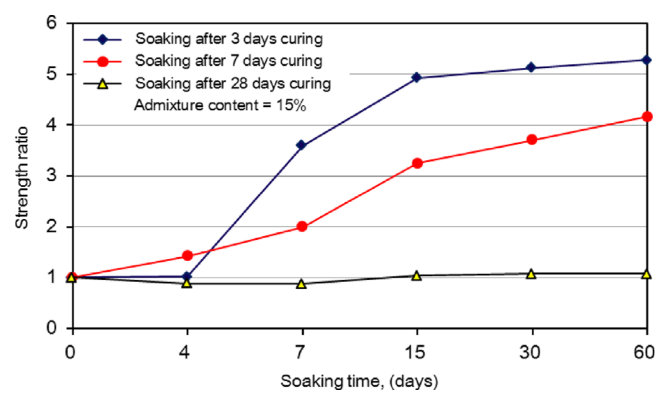

Fig. 2. Effect of soaking time on strength ratio of soil stabilized with B–L admixture subjected to different curing times before soaking.

with the B–C admixture. This occurred only in the case of the samples cured for 3 and 7 days. These results are most likely related to the improvement in strength of the samples stabilised with the B–L admixture for a short amount of time in comparison with those stabilised with the B–C admixture. Thus, samples stabilised with the B–L admixture can gain more additional curing time, and thus, the effect of the soaking time leads to a significant increase in the strength ratio. For samples cured for 28 days and then subjected to soaking, the strength ratio decreases with the increasing soaking time up to 15 days, whereas the increase in the soaking time after 15 days does not exhibit a significant effect on the strength ratio. These results are most likely attributed to the fact that 28 days of curing is enough to complete the reaction between the admixture and the clay particles, and thus, an additional curing period is not necessary. In addition, after the 28 days of curing, the stabilised specimen nearly reached the dry state. Subsequently, the expose of the dry specimens to soaking destroys the bonding between the soil particles resulting in a decrease in strength, as mentioned above. This occurs for both admixtures used.

For a better illustration of the effect of soaking on the durability of stabilised soil gypsum specimens, the relation between the durability index and the soaking time is provided in Fig. 3. The durability index is defined as the ratio between the strength of the samples cured for 28 days and then subjected to a specified soaking time to the strength of the samples prior to soaking. As expected, the durability index decreases with an increasing soaking time for all samples stabilised with different admixtures, as shown in Fig. 3. The durability index decreases significantly up to 15 days of soaking and then increases slightly or stays the same. The early soaking time has a negative effect on the durability index; this is most likely related to the following reasons. Firstly, the rate of water absorption during the early soaking time is greater than that of the later soaking time. Subsequently, the reduction in durability index or strength increases with an increasing rate of water absorption. The penetration of water for stabilised soil specimens results in a disturbance of the existing bonding between soil particles, changing the soil structure and decreasing the durability. These results are in agreement with those presented in the previous works for studying the effect of wet–dry cycles and soaking conditions on stabilised cement soil (Ahmed and Ugai, 2011; Oti et al., 2009; Khattab et al., 2008; Masato et al., 2005). Secondly, the structure of the stabilised specimens after 15 days may rearrange again to accommodate the new environment due to the slippage of particles in the structure of stabilised soil. Subsequently, the durability improves slightly after 15 days of soaking due to the gain in additional curing time for the stabilised specimens during the soaking process.

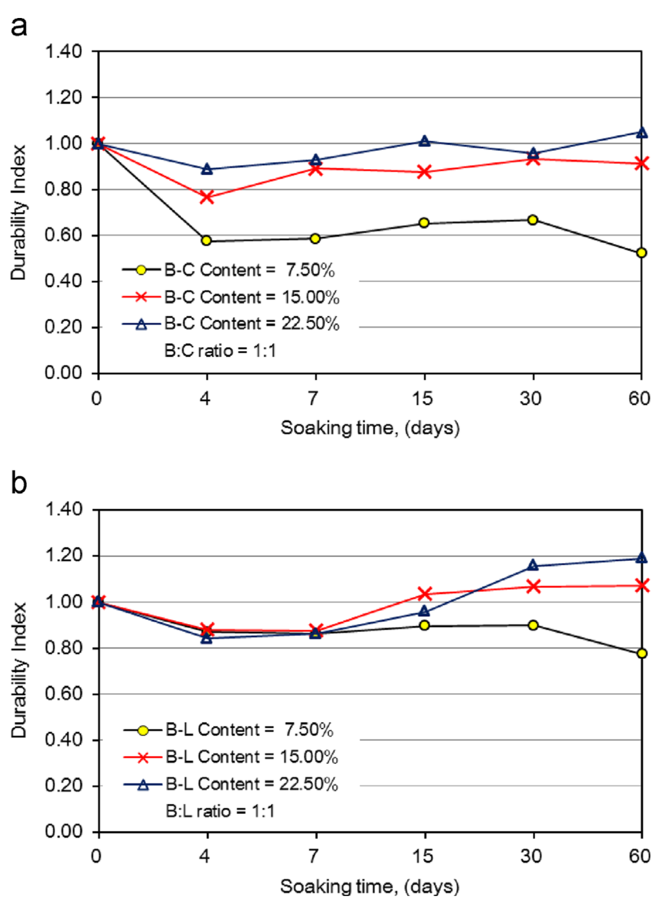

Fig. 3. Effect of soaking time on durability index of soil specimens stabilized with different B–C/L admixture contents. (a) In case of B–C admixture. and (b) In case of B–L admixture.

The figure demonstrates that the admixture content has a significant effect on the improvement of durability especially in the case of the B–C admixture compared with the B–L admixture. The increase in the B–C admixture is associated with an enhancement in durability. This result is most likely related to the increase in the proportion of cement in the soil mixture which results in adequate hardening between the soil particles that, in turn, leads to an improvement in durability. In the case of the B–L admixture, no difference in durability between the different contents was observed. The stabilised soil specimens with a low content of B–L admixture are more durable than the samples stabilised with the same amount of B–C admixture. This is most likely related to the improvement in strength of the samples treated with a small amount of B–L admixture due to its enhanced water absorption (dewatering) in addition to the development of cementation compounds. Therefore, the use of a low content of B–L admixture has a significant and immediate effect on the strength compared to the B–C admixture, because lime has a greater potential than cement to absorb water. Subsequently, the durability of the specimen stabilised with a small amount of B–L is high compared to the specimen stabilised with the same amount of B–C admixture.

The effect of soaking on the durability of the soil stabilised with different admixture ratios is shown in Fig. 4. For a better understanding and illustration, the strength values of different B/C and B/L ratios at a curing time of 28 days and an admixture content of 15% are presented in Fig. 6, which shows the stress–strain relationship. The increase in the admixture ratio is associated with a decrease in durability of both admixtures. This result is most likely related to the decrease in the proportion of solidification agents, cement, or lime, in the soil mixture, which decreases the ability of the stabilised soil gypsum to resist the effect of soaking. In fact, the solidification agent in the stabilised soil gypsum is considered to be the main factor responsible for the resistance to soaking as well as for the improvement in durability, because gypsum is a soluble material in water. It is clear from this figure that the effect of soaking on the durability is much more

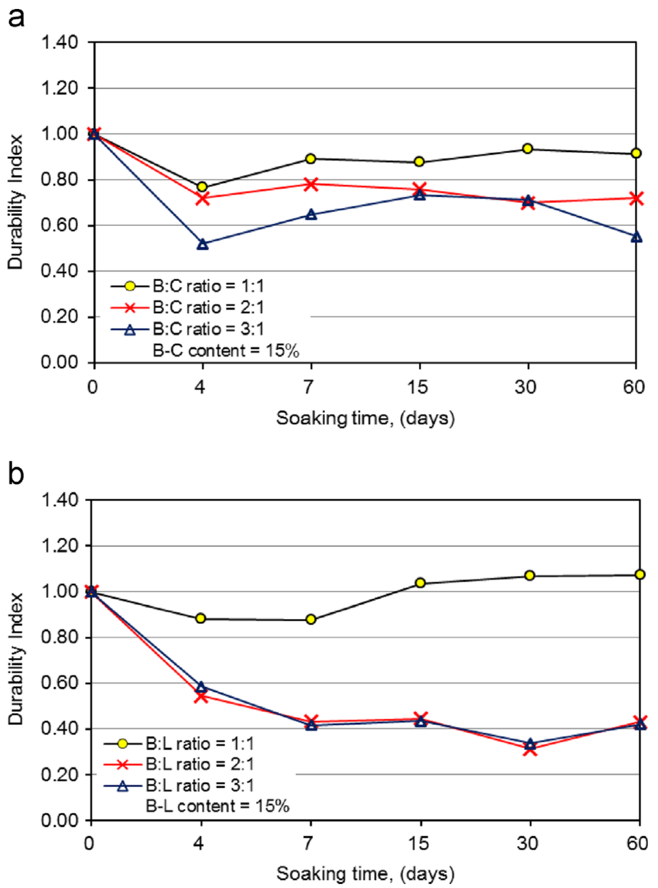

Fig. 4. Effect of admixture ratio on durability of soil specimens stabilized with different B–C/L admixture ratios. (a) In case of B–C admixture. and (b) In case of B–L admixture.

pronounced for the early soaking times. For more than 15 days of soaking, the durability improves slightly in some cases or stays the same. This result is consistent with the results obtained when evaluating the effect of the admixture content on durability. For admixture ratios of 2:1 and 3:1, the effect of the soaking condition is more negative on the durability index than for samples stabilised with B–L compared with the samples stabilised with B–C. It is related to the fact that the solidification of cement is higher than that of lime so a decrease in the proportion of lime has a significant effect on the durability of the soil mixture. Generally, it is important to report that improvements in the stress–strain relationship increase with an increasing admixture content and a decreasing admixture ratio for both admixtures used, as presented in Figs. 5 and 6. These figures show the effect of the admixture content and ratio on the stress–strain relationships for the samples stabilized with the two admixtures of B–C and B–L without the soaking condition at the curing time of 28 days. It is obvious from these figures that the B–L admixture has a significant effect on the improvement of the stress–strain relationship compared to the samples stabilized with the B–C admixture.

3.2. *Deformation (swelling–settlement) changes*

Deformation changes in this study are used to examine the settlement or the swelling, and are represented as the difference

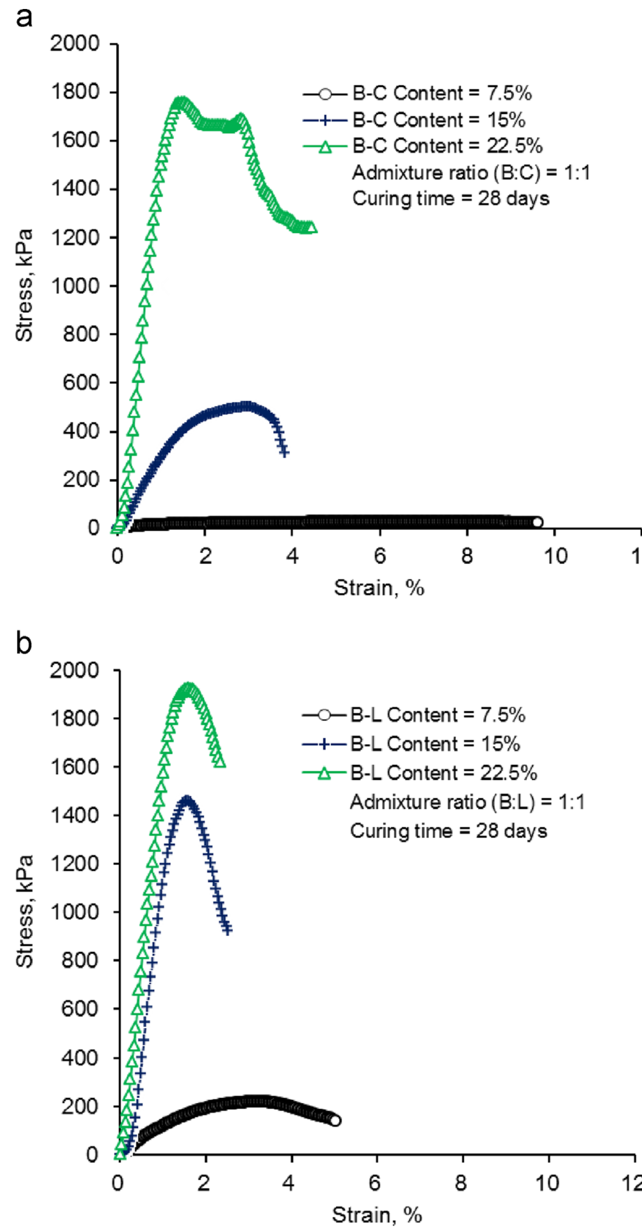

Fig. 5. Effect of admixture content on stress–strain relationship for samples stabilized with B–C/L admixtures. (a) In case of B–C admixture. and (b) In case of B–L admixture.

between the displacement measurements for the tested soil before and after soaking. Positive deformation refers to swelling, while negative deformation refers to the settlement of the tested sample. To study the effect of the soaking conditions on the changes in deformation of the tested specimens, a micrometre with high sensitivity was used and the measurements were performed through two fixed points. The following are the main reasons for the investigation of the effect of the soaking condition on the deformation of the stabilised soil gypsum. (1) When stabilised soil gypsum is subjected to soaking, the dissolution of gypsum may occur because gypsum is soluble in water. Subsequently, the soil structure may change in terms of the magnitude and the direction of the vertical movement of the soil (Ismail and Hilo,

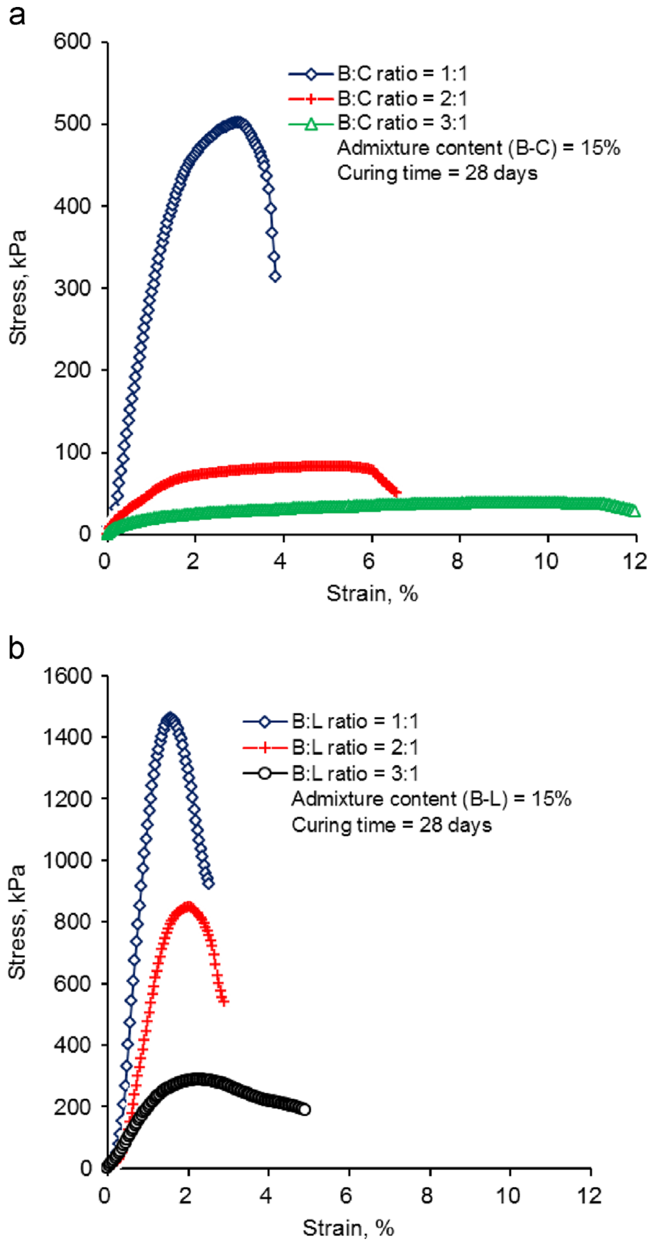

Fig. 6. Effect of admixture ratio on stress–strain relationship for samples stabilized with B–C/L admixtures. (a) In case of B–C admixture. and (b) In case of B–L admixture.

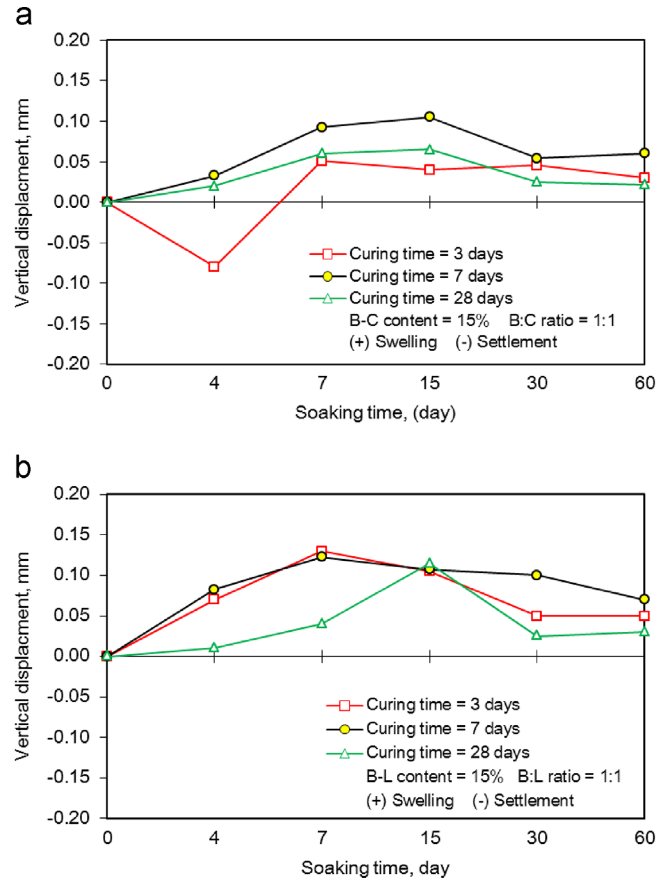

Fig. 7. Effect of soaking conditions on deformation changes of stabilized specimens cured for different times before soaking. (a) In case of B–C admixture. and (b) In case of B–L admixture.

2008). (2) The presence of sulphates in the chemical composition of gypsum may also promote swelling during its reaction with clay minerals that have a tendency to cause swelling, such as montmorillonite. (3) It is well known that when gypsum is subjected to water, some expansion may occur. The magnitude of this expansion depends mainly on the fineness of the gypsum powder, the amount of added water, and the presence of other added materials, such as sand, lime or accelerators with gypsum (Karni and Karni, 1995).

The vertical displacements of the samples cured for different times and subjected to soaking are presented in Fig. 7. It is clear from this figure that, in most cases, a small amount of swelling is observed and that this amount decreases gradually for soaking longer than 15 days. The slight induced swelling is attributed to the tendency of gypsum to expand when it is exposed to water. For a short curing time, as in the case of 7 days of curing, a significant swelling is observed in comparison with the longer curing time of 28 days for samples stabilised with the two admixtures. This result is attributed to the fact that the expansion of gypsum starts with the commencement of setting that takes several days to complete. Subsequently, compared with the samples cured for a long time, the expansion is extensive in samples subjected to a short curing time before soaking, because the setting process is still on-going, and therefore, is not complete. In contrast, the sample cured for 3 days, stabilised with the B–C admixture, settles during the beginning of the soaking time and then starts to swell, as shown in Fig. 7a. This result is attributed to the hardening between soil particles that need more time to develop compared with the samples stabilised with the B–L admixture, as mentioned previously. Subsequently, the sample in this case is softer, and when subjected to soaking, it settles suddenly. By increasing the soaking time for samples subjected to the small curing times of 3 and 7 days, the samples may gain extra strength, as presented in Figs. 1 and 2. The improvement in strength in this case may be related to the indirectly gained curing time due to the subjection of the samples to soaking. Afterwards, the chemical reaction between the soil particles and the stabilisers occurs and the sample begins to swell due to the presence of gypsum in the soil mixture.

Fig. 8 shows the effect of the admixture content on the changes in deformation of the stabilised soil specimens cured for 28 days and then subjected to soaking. Generally, no significant difference was observed between the different admixture contents for the two admixtures. The effect of soaking on the swelling of B–C admixtures decreased after 7 days of soaking and the samples begin to settle gradually afterwards. This result is attributed to the presence of cement in the soil–gypsum mixture, which resists swelling up to specified cement content, because cement has a shrinking property and decreases the ability of gypsum to swell. Subsequently, the reaction between the gypsum and the soil particles, which causes swelling, is constrained. Then, the swelling declines with an increase in soaking time. In contrast, in the case of the B–L admixture, the swelling increases slightly with an increasing soaking time up to 15 days and then declines slightly or stays constant, as shown in Fig. 8b. This result is most likely related to the presence of lime that reduces the swelling of the gypsum–soil mixture because lime has been used as a stabiliser to mitigate the potential of swelling. The activity of lime reduces the potential swelling (Akcanca and Aytekin, 2012; Al-Mukhtar et al., 2010, 2012), which will be more pronounced if the soil contained minerals that cause swelling, although this is not the case herein. The figure indicates that the use of the B–C admixture has a slight effect on the induced swelling compared with the samples stabilised with the B–L admixture. This is most likely related to the fact that cement exhibits more shrinkage during the solidification process than lime. Thus, the activity of lime in reducing the swelling through shrinkage is low because the tested soil has no minerals that are sensitive to swelling. Generally, the effect of soaking on the changes in volume for soil stabilised with the B–C/L admixtures is not significant because the maximum deformation change for all the tested samples is found to be less than 0.15%. This confirms that the use of recycled gypsum, treated with lime or cement for the stabilisation of soft clay soil within the investigated limits, is durable against the effect of soaking with respect to the changes in deformation.

The effect of the admixture ratio on the deformation changes of the soil specimens stabilised with B–C/L admixtures is provided in Fig. 9. As observed previously, for the effect of the admixture content and curing time on the deformation changes, the induced swelling decreases gradually after 15 days of soaking for all different admixture ratios investigated. In the case of the B–C admixture, the increase in the admixture ratio increases the swelling, as shown in Fig. 9a. This result is most likely related to the increase in the proportion of gypsum in the soil mixture, promoting the tendency of stabilised soil specimens to swell. In contrast, in the case of the B–L admixture, no difference in deformation changes was observed for the

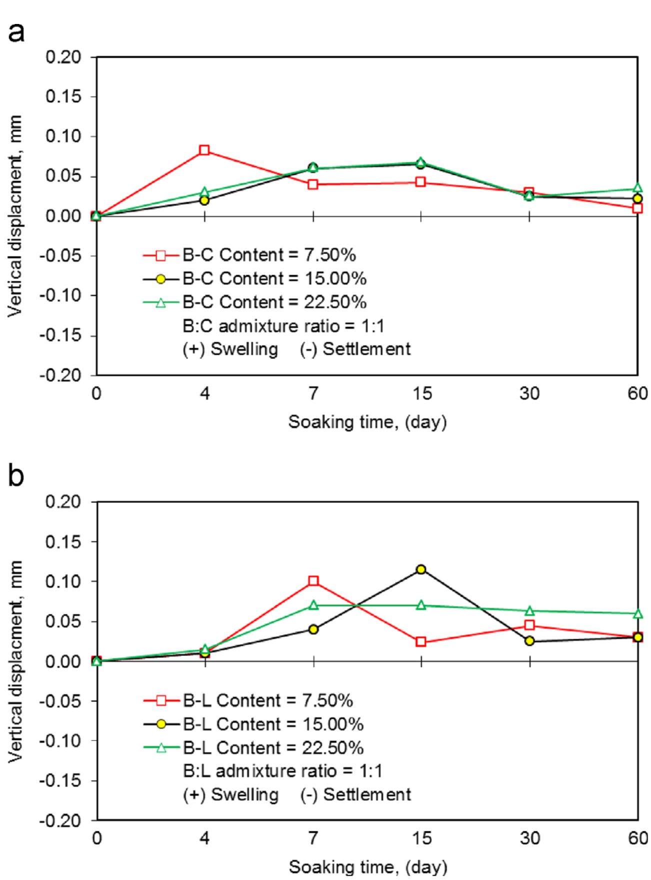

Fig. 8. Effect of admixture content on deformation changes for stabilized samples subjected to soaking. (a) In case of B–C admixture. and (b) In case of B–L admixture.

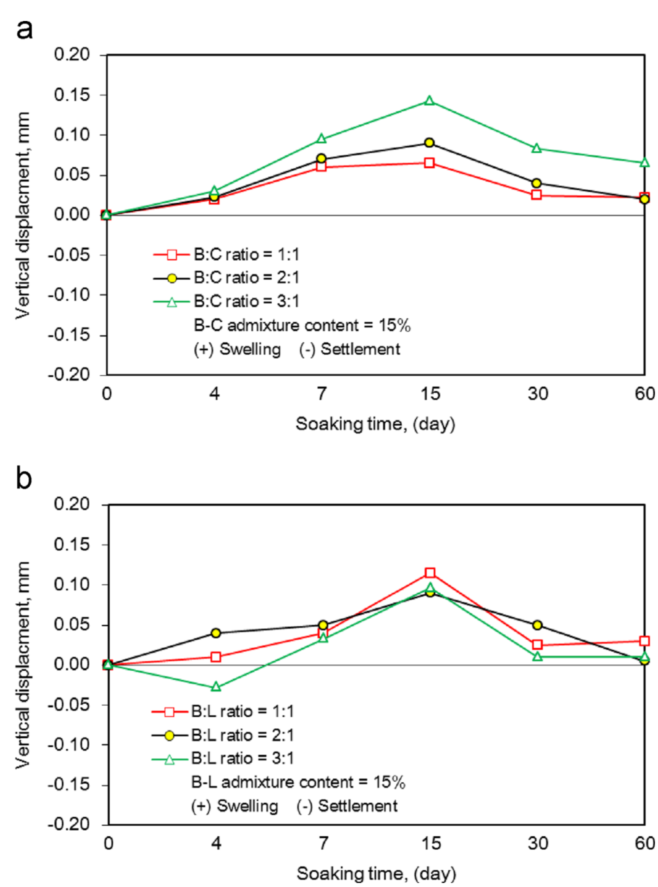

Fig. 9. Effect of admixture ratio on deformation changes for stabilized samples subjected to soaking. (a) In case of B–C admixture. and (b) In case of B–L admixture.

different admixture ratios, as shown in Fig. 9b. This figure demonstrates that for the admixture ratio of 3:1, a small amount of settlement at the early soaking days is observed and then the sample starts to swell gradually. This is most likely related to the increase in the proportion of gypsum in the soil mixture compared with that of lime. Subsequently, the potential for solidification is reduced compared with the other investigated ratios. Subsequently, when the stabilised soil with a B–L admixture ratio of 3:1 is subjected to soaking, sudden dissolution of the particles of the gypsum–soil mixture, which causes a sudden settlement during the early stage of soaking, may occur. Afterwards, the B–L admixture reacts with the clay particles and the stabilised sample begins to swell again, as shown in Fig. 9b.

3.3. Percentage of soil deterioration

The percentage of deteriorated soil soluble particles in stabilised soil gypsum subjected to soaking was determined based on the dry soil mass before and after soaking. It is defined as the difference between the initial and the final dry soil masses for soil samples before and after soaking divided by the initial soil mass before soaking. Fig. 10 shows the effect of the admixture content on the percentage of soluble soil

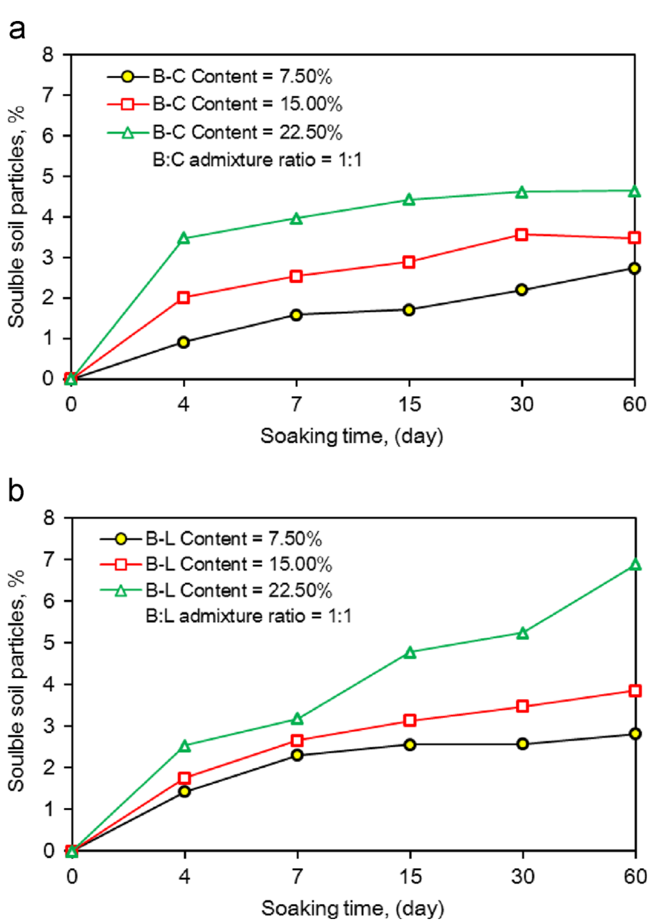

Fig. 10. Effect of admixture content on deterioration of soil for stabilized samples subjected to soaking. (a) In case of B–C admixture. and (b) In case of B–L admixture.

particles for stabilised soil specimens with B–C/L admixtures subjected to soaking. Generally, increasing the soaking time increases the percentage of soluble soil particles up to soaking of 15 days for both admixtures. Thereafter, the percentage of deteriorated soil stays constant and no more soil deteriorates from the tested specimens in the case of the samples stabilised with the B–C admixture. This result is related to the increase in water absorption that occurs during the early stage of soaking that affects the percentage of soil deterioration. This may be due to a change in the structure of the soil induced by the absorption of water. The highest percentage of soil deterioration occurred with an admixture content of 22.5% compared with the other contents used. In general, an increase in the admixture content is associated with an increase in the percentage of soil deterioration. This is most likely related to an increase in the admixture content in the soil mixture, which increases the likelihood of gypsum particles dissolving in water that, in turn, leads to an increase in the degree of soil–gypsum deterioration. The highest accumulative deterioration percentages in the case of B–C and B–L admixtures were found to be 4.64 and 6.88%, respectively. It is evident that cement has a greater solidification capacity that allows for the prevention of the dissolution of gypsum, in comparison to lime, especially for prolonged soaking times. It is important to mention that the results presented in this study are only valid for the limitations of the soaking period, which is 60 days, and for the ratios and the contents of gypsum–cement/lime admixtures investigated in this project.

Fig. 11 reveals the effect of the admixture ratio on the percentage of deteriorated soluble soil particles in stabilised soil specimens treated with the B–C/L admixtures and then subjected to soaking. Generally, the increase in soaking time is associated with an increase in the percentage of soil deterioration. No difference in the effect of different rations is observed with respect to soil deterioration. This result is attributed to the fact that the suggested amount of cement or lime proportion used in the soil–gypsum mixture to resist the effect of soaking is enough, because the specimens were not subjected to any external stress, such as brushing, as in the case of the wet–dry tests. Furthermore, the main role of the cement/lime in the soil–gypsum mixture is to prevent the solubility and not to improve the strength. In fact, the increase in the cement or lime fraction in the soil–gypsum mixture is associated with an increase in strength, as observed earlier. In contrast, for soil deterioration, the stabilised soil specimens were not subjected to any external stress except their own weight. The minimum proportion of cement or lime, which is found in the admixture ratio 3:1, is 25% from the entire admixture content. Accordingly, it should be noted that, the acceptable admixture ratio that can prevent solubility and reduce the percentage of soil deterioration in a soil–gypsum mixture should be greater than 3:1. In Fig. 11b, the percentage of soil deterioration for samples stabilised with the B–L admixture increases slightly after 15 days of soaking compared to samples stabilised with the B–C admixture. The diversity between the two results is most likely attributed to the growth of cementation between the soil particles. The B–C admixture is stronger than the B–L

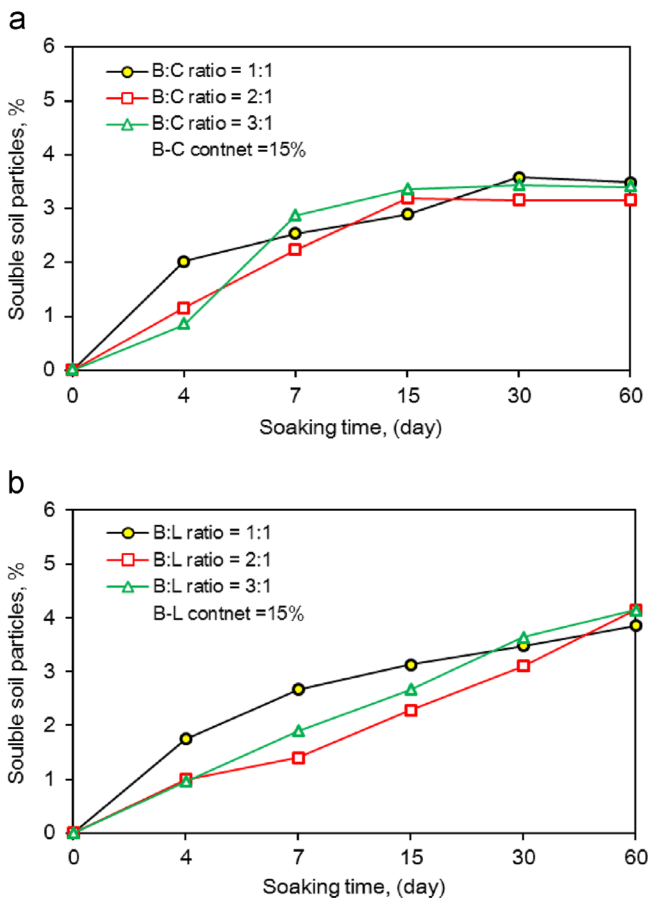

Fig. 11. Effect of admixture ratio on deterioration of soil for stabilized samples subjected to soaking. (a) In case of B–C admixture. and (b) In case of B–L admixture.

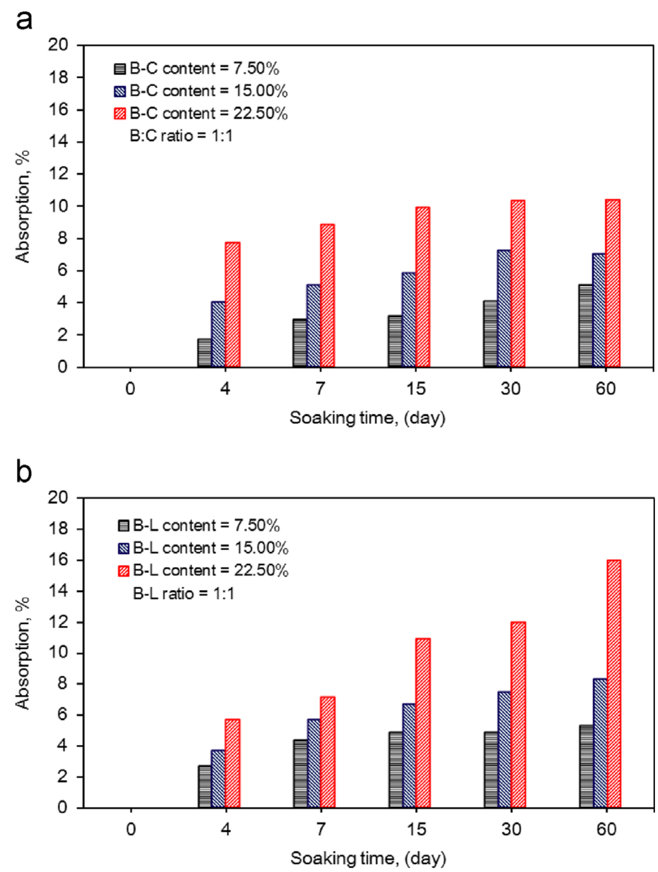

Fig. 12. Effect of admixture content on water absorption for stabilized samples subjected to soaking. (a) In case of B–C admixture. and (b) In case of B–L admixture.

admixture. This finding is consistent with the fact that cement has the highest cementation property among solidification agents.

3.4. Water absorption

The results of the water absorption for stabilised soil specimens are due the presence of voids in the soil matrix or due to the chemical reactions between the soil particles and the stabilisers that consume water. The percentage of water absorption is evaluated based on the dry weight for stabilised soil specimens. Fig. 12 shows the effect of the admixture content on the percentage of water absorption for stabilised soil specimens subjected to soaking. An increase in the admixture content results in a significant increase in the water absorption of the stabilised soil samples for both admixtures. This figure demonstrates that the B–L admixture has a greater ability to absorb water in comparison with the B–C admixture. The same behaviour is observed for different admixture ratios, as shown in Fig. 13. This result is attributed to the fact that lime has a greater tendency to absorb water from moist soil than cement (Reeves et al., 2006). That is why the water absorption stays constant after 15 days of soaking for the B–C admixture for all admixture amounts, as shown in Fig. 12a. It is well known that the reaction between cement and clay soil particles, which is called the hydration process, consumes more water. This

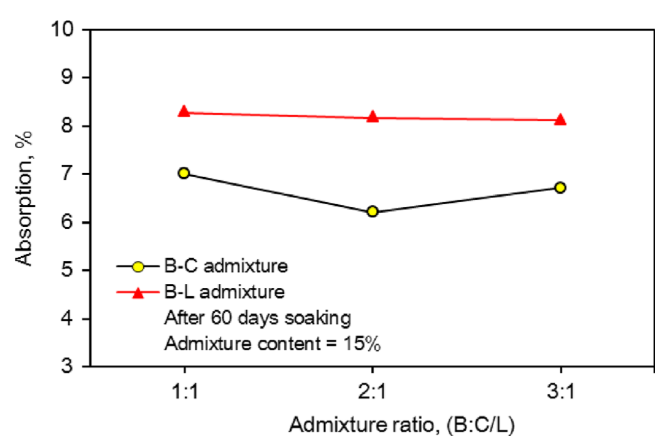

Fig. 13. Effect of admixture ratio and type on water absorption for stabilized samples after 60 days soaking.

reaction is responsible for the growth of bonds between the soil particles and the admixture. The bonding between soil particles is linked through water molecules and a high temperature is needed to remove these water molecules. The standard temperature used for the determination of the water content is 105 °C. Subsequently, this temperature may not be high enough to allow all the absorbed water from the samples stabilised with the B–C admixture to be removed. The water content stays constant after 15 days of soaking. In contrast, in the case of the B–L admixture, the water absorption does not stay constant after 15 days of soaking, and instead, increases slightly with an increasing soaking time. This behaviour is most likely related to the developed links between the lime and the soil particles which are easily destroyed at 105 °C compared to the case of samples stabilised with the B–C admixture. The effect of the B–C/L admixture ratio on the water absorption of stabilised soil specimens subjected to soaking is shown in Fig. 13. This figure indicates that no difference for the admixture ratios was observed for the percentage of water absorption. The B–L admixture has a clear effect on the percentage of water absorption in comparison with the B–C admixture. This result is related to the fact that lime has higher capacity to absorb water than cement.

4. Conclusions

The ratios and percentages of two admixtures investigated in this study demonstrated acceptable stability and reasonable durability in terms of strength, volume change, soil deterioration, solubility, and water absorption. The main purpose of this research was to confirm the potential use of recycled gypsum as a co-stabiliser material in ground improvement projects. It will help to cut down the cost of disposal, reduce the cost of ground improvement projects, and improve the sustainability of the environment. Based on the results of tests on strength, durability, deformation changes, soil deterioration, and water absorption, the following conclusions can be drawn:

1. The amount of admixture has a significant effect on the durability in samples treated with the B–C admixture in comparison with the B–L admixture. An increase in the B–C admixture content is associated with an increase in the durability, whereas no difference was observed for different amounts of admixture for B–L admixtures.
2. Stabilised soil specimens with a low content of the B–L admixture are more durable than the same samples stabilised with the B–C admixture.
3. For B–C/L admixtures, the increase in the admixture ratio is associated with a decrease in the durability index, whereas an improvement in the durability was observed with an increasing admixture content.
4. The effect of the soaking time on the durability was much more pronounced during the early stage of soaking. After 15 days of soaking, the durability improved or stayed constant. The curing time has a positive effect on the durability of the stabilised soil, especially during the early stages of 3 and 7 days compared to the longer curing time of 28 days.
5. The effect of soaking on the volume changes of stabilised soil is not significant because the maximum change in deformation for all the samples was found to be less than 0.15%. This proves that the use of recycled gypsum, solidified with cement or lime in ground improvement projects within the investigated limits, is resistant to the effect of soaking actions in terms of deformational changes.
6. For both admixtures, an increase in the soaking time increased with the percentage of soluble soil deterioration up to 15 days. Subsequently, the percentage of deteriorated soil stayed constant and no more soil deteriorated from the specimens. The results demonstrate that no difference is observed with respect to the percentage of the deteriorated soil for different admixture ratios.
7. An increase in the admixture content and soaking time is associated with an increase in the water absorption for both admixtures. Both the content and the ratio of the B–L admixture had a more significant effect on the rate of water absorption than the content and the ratio of the B–C admixture.
8. Based on the stability and durability results, the B–C admixture with a content of 22.5% and a ratio within 1:1 to 2:1 is recommended for preparing a stabiliser material that achieves sustainable durability. Generally, the use of furnace cement type-B as a solidification agent is recommended because it leads to an improvement in the stability and durability of soft clay soil stabilised with recycled gypsum and can prevent solubility.

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