Recycling Waste Gypsum in Soil Stabilization Applications

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ABSTRACT
Solid waste management is a serious problem worldwide as amounts of produced wastes are increasing annually. For example, the disposal of gypsum waste plasterboard, widely used as dry wall across North America, represents a serious environmental issue. Therefore, attention is focused on using and recycling such waste as an alternative material in construction applications. This can reduce the amount of wastes that are sent to landfills, and hence leads to environmental and economic benefits. This study examines the potential of reusing gypsum wastes as a stabilizer material for earthwork projects. Recycled gypsum, mixed with cement or lime at different ratios, was used as a stabilizer for soft fine grained soil. Compressive strength, secant moduli, unit weight, water content and Atterberg limits tests were conducted to evaluate the improvement in stabilized soil properties. The results indicate that the inclusion of gypsum-cement or gypsum-lime admixtures improved the mechanical properties of the stabilized soil, with higher admixture concentrations leading to greater improvement. Moreover, the soil specimens stabilized using gypsum-lime admixture exhibited higher strength gain rate and reduction in plasticity index and water content than those stabilized by gypsum-cement admixture. It is concluded that the proposed stabilizing technique can be advantageous for both waste management and construction industries.

RÉSUMÉ
La gestion des déchets solides est un problème mondial grave étant donné l’augmentation annuelle de la production de déchets. Par exemple, la disposition des panneaux de gypse (« placoplâtre »), largement utilisés en Amérique du Nord pour l’installation de cloison sèche, représente un enjeu environnemental sérieux. L’attention est alors portée vers l’utilisation et le recyclage de ces déchets comme une alternative dans le domaine de la construction. Ceci peut réduire la quantité de déchets qui sont envoyés dans les décharges, et par conséquent mener à des bienfaits environnementaux et économiques. Cette étude examine le potentiel de réutilisation des déchets du gypse comme un matériau stabilisant pour des travaux de stabilisation du sol. Du gypse recyclé, mélangé à du ciment ou de la chaux à différents ratios, a été utilisé comme un stabilisant pour des sols mous à grains fins. Les essais de résistance en compression, de module sécant, de poids volumique, de teneur en eau et des limites d’Atterberg ont été réalisés pour évaluer l’amélioration des propriétés d’un sol stabilisé. Les résultats indiquent que les inclusions de mélanges gypse-ciment ou gypse-chaux améliorent les propriétés mécaniques du sol stabilisé, avec une plus grande amélioration pour une plus grande concentration du mélange ajouté. De plus, les échantillons de sol stabilisé, utilisant un mélange gypse-chaux, ont démontrés un plus fort taux d’augmentation de la résistance, une réduction de l’indice de plasticité et de la teneur en eau que le sol stabilisé avec un mélange gypse-ciment. Il est conclu que la technique de stabilisation proposée peut être avantageuse pour les industries de la gestion des déchets et de la construction.

1 INTRODUCTION

Utilization of waste and recycled materials as alternative construction material in civil engineering projects has two major environmental advantages: 1) reducing the huge quantities of solid wastes, and 2) creating a balance for the shortage of natural resources. Accordingly, the government of Ontario has established targets to divert specified percentages of Ontario’s waste every year through the 3 R (Reduce, Reuse and Recycle) program to achieve the aforementioned environmental advantages, and to reduce the operation of landfills in Ontario. The major types of construction and demolition (C&D) wastes in Ontario comprise concrete, asphalt, wood, and gypsum plasterboards. Concrete and asphalt are reused in the construction market, while gypsum waste plasterboard is not recycled or reused effectively in Ontario. For example, 17% of the global production of wallboard/plasterboard in Ontario ends up as scrap gypsum annually (Merwe 2009). It is estimated that around 64% of all plasterboard waste comes from new construction projects (Merwe 2009; Binggeli 2008). The disposal of gypsum wastes in landfill sites is considered a serious environmental issue because it has an adverse effect on the environment. For example, the generation of hydrogen sulfide gas and the release of fluorine more than the permitted limits may cause soil contamination (Kamei and Horai 2008, Kamei et al. 2013a). Therefore, most of recent studies have been directed to protect the environment by using waste and recycled materials as alternatives in civil engineering applications instead of their disposal in landfill sites. In general, recycled gypsum is derived from gypsum waste plasterboards/wallboards has potential to be used as a stabiliser material in soil improvement applications (Kamei et al. 2013a, Ahmed et al. 2011a). This is because gypsum has a cementation property that makes it possible to achieve adequate bonding between the soil particles, which thereby increases the strength of the stabilised soil. The recycled gypsum produced from gypsum wastes has been utilised in soil stabilisation and road construction projects in Japan and other countries (Kamei et al. 2013a, WRAP, 2007). Previous studies have shown that gypsum wastes, after a special treatment, have been turned into useful stabiliser materials in soil stabilization projects (Kamei et al. 2013a,b, Ahmed et al. 2011a, Kamei and Shuku 2007). The application of recycled gypsum produced from gypsum wastes as a stabilising agent in soil stabilization has been performed on a limited number of soil types, including sand, silty sand, and clay soil (Kamei et al. 2013a, Ahmed et al. 2011a,b, Kamei and Shuku 2007, WRAP 2007). Using recycled gypsum produced from gypsum wastes as a binder in the stabilization of soft organic fine grained soil is limited. Actually, the most regular binders used in the stabilization of soft organic fine grained soil are cement and lime. However, other binders are also used for stabilization of soft organic fine grained soil including blast furnace slag, fly ash, silica fume, red gypsum, and gravel (Hinberg 2006, Kalantari et al. 2010, Hughes 2011, Kyambadde and Kevin 2012, Kolay and Pui 2010). Therefore, the objective of this work is to investigate the use of recycled gypsum, produced from gypsum wastes, as a stabiliser for soft organic fine grained soil with high moisture content based on the mechanical properties of the stabilized soil. The influence of using recycled gypsum as a stabilizer for soft organic fine grained soil on the geo-environmental properties was investigated and presented elsewhere.

2 MATERIALS AND METHODS

Soft organic fine grained soil samples were collected from a construction site. Characteristics of the tested soil were determined and are presented in Table 1. According to the unified soil classification system, (USCS), the tested soil can be classified as MH soil.

Table 1. Characteristics of tested soil

Characteristics	Content, (%)
Organic matter	17.60
Water content[1]	158.00
Liquid limit	100.00
Plastic limit	61.50
Plasticity Index	38.50
Sand	24.10
Silt	55.40
Clay	20.50

The recycled gypsum used in this project was retrieved from the gypsum waste plasterboards. The details of the procedure used for preparing recycled gypsum from gypsum waste plasterboards are presented in the previous work (Ahmed et al. 2011a). The recycled gypsum was mixed with cement or lime at different ratios of 1:1, 2:1 and 3:1 and the resulting admixtures were used as a stabilising agent to improve the strength of the tested soil. Four different admixture contents of 0, 7.5, 15, and 22.5% by weight were mixed with the tested soil to investigate their influence on the mechanical properties of the tested soil. First, dry recycled gypsum was mixed with 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 admixtures of 7.5, 15, and 22.5%, according to the testing program. An automatic mixer was used for the mixing process, which was prolonged for 10 minutes to obtain a homogenous mixture.

There are two types of solidification agents used in this study; namely, furnace cement and lime. The main reason for the use of solidification agents is to prevent the dissolution of the soil-gypsum mixture because gypsum is soluble in water (Kamei et al. 2013b, Kamei and Horai 2008, Zhang and Tao 2006). Furthermore, the addition of a solidification agent improves the environmental properties (Ahmed et al. 2011a, Kamei and Horai 2008) and durability (Kamei et al. 2013b) of the soil-gypsum mixture. Both cement (C) and lime (L) were added to recycled gypsum (B) at different ratios as mentioned above. First, dry recycled gypsum was mixed with 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 admixtures of 7.5, 15, and 22.5%, according to the testing program. An automatic mixer was used for the mixing process, which was prolonged for 10 minutes to obtain a homogenous mixture.

A series of physical tests, including unconfined compression tests and Atterberg limits tests, were conducted on samples treated with recycled gypsum. Unconfined compression tests were conducted on cylindrical soil specimens having 50 mm in diameter and 100 mm in height. To mould these specimens, soil mixture was placed in three-layer mould and pressed by a steel rod to prevent the formation of air bubbles. Subsequently, the soil sample was subjected to static compaction using a hydraulic jack based on the desired density value. Precautions were taken during sample preparation and extraction to produce homogenous samples. For each test, three different specimens were used and their average results are reported. The extracted samples were cured in a controlled room at 21±1 °C and humidity of more than 90% for different curing times of 3, 7 and 28 days prior testing. Water content was determined for each sample before and after testing.

For Atterberg limit tests the tested soil was mixed with the desired stabilisers according to testing program and then cured for 7 days under the same regime, which was used in the unconfined compression test. The cured samples were air-dried for a few days before testing. The dried soil samples were pulverised and particles passed from a No. 40 sieve for the Atterberg limits.

3 RESULTS AND ANALYSIS

When fine grained soil are mixed with cementation materials such as gypsum, cement and lime chemical reactions taking place between the materials and the tested soil particles. This chemical reaction produces an adequate bond between the soil particles resulting in the enhancement of the treated soil strength. The enhancement in the strength is controlled by two important parameters: unit weight and water content of the tested soil. The influence of admixtures on the unit weight and water content are presented in Figures 1 and 2, respectively.

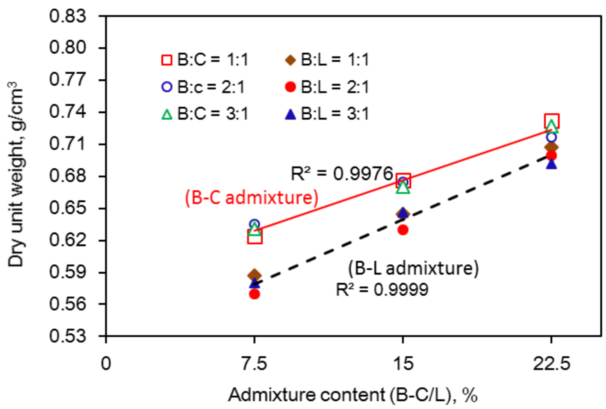


Figure 1. Effect of content and ratio of admixtures on dry unit weight.

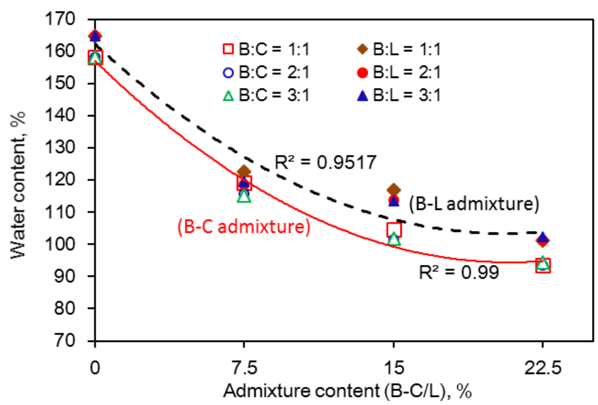


Figure 2. Effect of content and ratio of admixtures on water content.

Clearly, the addition of admixtures significantly reduced the water content and increased the dry unit weight. The increase of admixture content is associated with a decrease in the water content and an increase in the dry unit weight for both admixtures used. The decrease of water content is most likely related to the potential of gypsum to absorb the water from the tested soil. This occurred due to the ability of calcium sulphate hemi-hydrate to recover the three quarters of molecules of water that were missed during the manufacture process by heating and then water content reduces (Ahmed et al. 2011a). It is well known that the reduction in water content of the tested soil is associated with an increase in the unit weight as observed in this case. The decrease in the water content results in a reduction in the number of voids in the pores of soil particles and a decrease in the volume of soil mass all of which result in an increase in the dry unit weight. The increase in the unit weight is most likely attributed to the induced charge exchange between clayey soil particles and calcium, the main component of gypsum. Clay particles normally have two negative charges that attract calcium's two positive charges, allowing for the formation of a strong ionic bond. Accordingly, the flocculation between clayey soil particles takes place. Subsequently, clayey soil particles come close together and the volume of soil decreases. The reduction in the soil volume is associated with an increase in the unit weight because unit weight is a function of volume. There is no difference between the effect of the admixture ratio on the unit weight and the decrease of water content as presented in Figures 1 and 2, respectively. In contrast, an increase in admixtures content resulted in a significant increase in the unit weight and a decrease in the water content. This effect is related to an increase in the admixture content, which leads to an increase in the surface area of the particles in the admixture. As a result, the ability to absorb water is increased. Conversely, in the case of increasing admixture ratio, the surface area does not change so there is no significant increase in the ability of admixture to absorb water. The obtained results showed that there is no significant difference between the use of lime and cement as a solidification agent for soil-gypsum mixture on the increase in the unit weight and the decrease in the water content of stabilised soil gypsum samples.

The effect of adding admixtures on the tested soil temperature is shown in Figures 3 and 4. The temperature for the stabilised soil specimen was measured after the completion of mixing directly and the measuring time was prolonged up to 350 minutes or till the temperature keeps constant. The addition of admixtures does not exhibit a significant effect on the temperature of the stabilised soil gypsum particularly in the case of samples treated with the B-C admixture in comparison with the B-L admixture. In the case of samples treated with the B-L admixture, the temperature increased slightly for 30 minutes for an admixture ratio of 1:1. This result is possibly related to the increased concentration of lime in this admixture resulting in an increase in the temperature of soil-gypsum mixture. Figure 4 demonstrates that the temperature decreases and stays constant 2 hours after the mixing. This behaviour is related to the exothermic reaction between the lime and water in the clay soil, which takes place immediately followed by an increase in the temperature of the tested soil (Reeves et al. 2006). In addition, the hydration process for cement/lime in the presence of moist soil also produced heat, which accelerates the drying of the tested soil and improves the strength due to the reduction in the water content for the stabilised soil specimen.

Figure 5 shows the ultimate compressive strength for soil stabilised with different contents of admixtures at admixture ratio of 1:1 and different curing times. This figure indicates that ultimate strength improves with increasing content of B-C admixture in soil mixture. The same results are obtained in the case of B-L admixture. Similar to findings reported in previous studies (Ahmed et al. 2011b, Kamei et al. 2013a), the improvement in the compressive strength upon the addition of admixtures to the tested soil are attributed to dewatering, flocculation, reduced plasticity, and the formation of cementation compounds in the soil matrix. In particular, the reduction in plasticity of clayey soil plays an important effect on its strength (Reeves et al. 2006) and it will be presented hereafter.

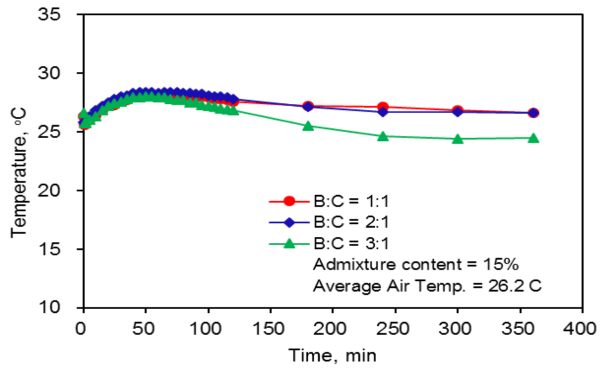


Figure 3. Effect B-C admixture on the temperature of stabilized soil.

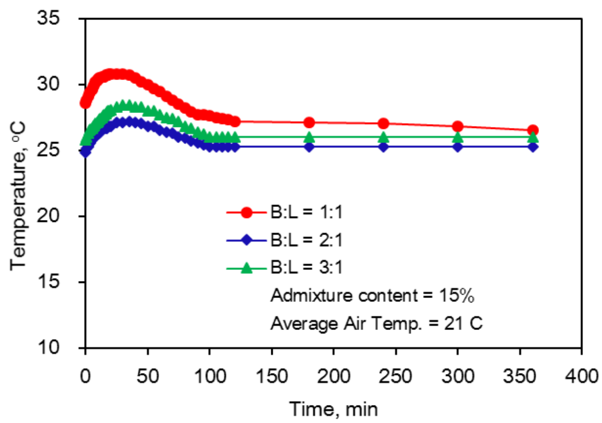


Figure 4. Effect B-L admixture on the temperature of stabilized soil.

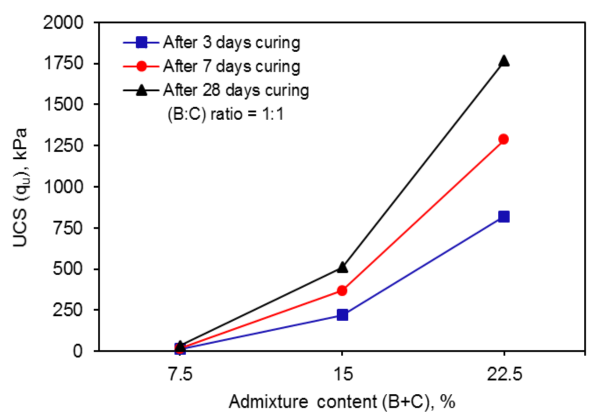
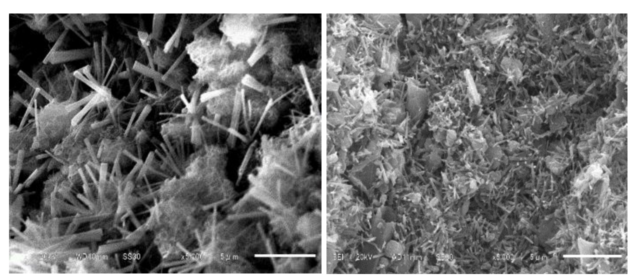


Figure 5. Effect B-C admixture content on the ultimate compressive strength of stabilized soil.

In addition, the formation of cementation compounds in the soil matrix has a significant effect on the permanent improvement in strength (Kamei and Shuku 2007, Kamei and Horai 2008). Ettringite is considered one of the most cementation compounds that increase the amount of hardening or binding of soil particles (Kamei and Horai 2008). The addition of admixtures to the tested soil produces ettringite and other cementation compounds as demonstrated by the SEM images provided in Figure 6. In the case of B-C admixture, ettringite is formed due to the reaction between the water in the moist soil and the calcium in gypsum and cement, sulphate in gypsum, silicate in both cement and soil, and alumina in both cement and soil. The increase of ettringite amount results in a significant increase in the strength of all samples treated with different admixtures in this study. This result is matching with the results presented in previous work, which proved that the addition of gypsum to clayey soil resulted in a significant formation of ettringite (Kamei and Horai 2008, Hinberg 2006). The developed of needle-shape ettringite prisms in soil matrix presented in Figure 6 contributes to reinforcing the soil structure, which supports the strength improvement (Hinberg 2006). It is important to note that the presence of ettringite in soil matrix has a negative effect on swelling properties of the tested soil although it has a positive effect on its strength. Previous results dealt with the use of recycled gypsum as a stabilizer in ground improvement proved that the incorporation of gypsum as a stabilizer with limited amounts and cooperated with solidification agent had no significant effect on the swelling (Kamei et al. 2013a,b). The formation of calcite within the soil matrix led to sufficient binding of soil particles, which is capable of mitigating the potential of swelling due to the formation of ettringite. Samples stabilised with B-L admixture exhibited clear impact on the formation of ettringite in comparison with samples stabilised with B-C admixture. This result is attributed to the higher calcium content in a B-L admixture in comparison with the B-C admixture. In fact, ettringite is not the only cementation compound that is produced in the stabilised soil; calcite (calcium carbonate) is also produced as evidenced by the XRD results (data not presented herein). Calcite is well known as hardening material that also leads to improved soil compressive strength. Therefore, ettringite is not the only main cementation compound responsible for the hardening of stabilised soil gypsum: the formation of calcite also has a significant effect on the improvement in the strength.



(a) B-C admixture (b) B-L admixture

Figure 6. SEM images for stabilized soil at admixture content 22.5% and ratio 1:1 after 28 days curing.

The effect of the admixture ratio on the ultimate compressive strength of soil stabilised with B-C admixture is presented in Figure 7. The increase in B-C admixture ratio has a negative effect on the improvement of strength and the same results are obtained in the case of B-L admixture. This result is most likely due to the decrease in proportion of cement or lime in the admixture. The strength decreases when the ratio of B-C admixture increases as presented in Figure 7, which can be attributed to the fact that cement or lime has a greater ability to bind soil particles compared to gypsum. In addition, the increase in the moisture content of the tested soil destroys the formation of links between the soil-gypsum mixtures because gypsum is soluble in water. In the case of the B-L admixture, the strength decreases gradually with an increase in the admixture ratio. This result is probably due to decreased lime proportion in the B-L admixture and reduced strength because lime is more likely to improve the soil cohesion compared to gypsum. The strength increase upon the addition of the B-L admixture to the tested soil is attributed to reactions on two different time scales: short-term and long-term. The strength improvement in the short-term reaction is mainly based on the ability of the stabiliser to absorb water from the moist soil, but it is temporary. Lime has a greater ability to absorb water from the moist soil compared with cement and this is why during the early curing stage, strength increases as a function of the B-L ratio. The strength improvement in the long-term reaction is mainly due to the potential of stabiliser to produce cementation compounds in the soil matrix. The decrease of the proportion of lime in the B-L admixture is associated with a decrease of the development of cementation compounds in soil matrix. The cementation compounds developed after the long-term reactions have more significant effect on the strength improvement in comparison to the short-term reaction effects such as dewatering. Subsequently, the increase in the B-L admixture ratio negatively impacts the permanent strength improvement and the same behaviour is observed in the case of samples stabilised with the B-C admixture.

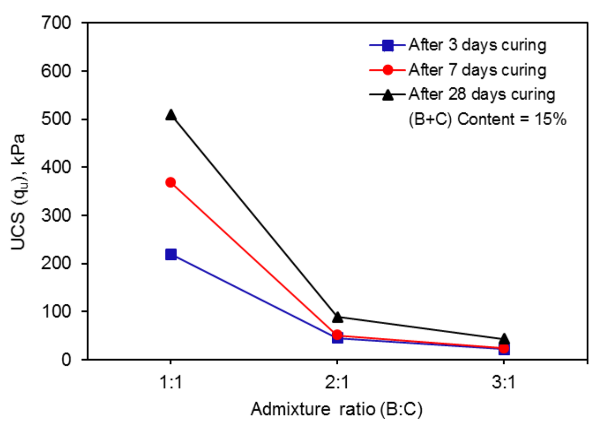


Figure 7. Effect B-C admixture ratio on the ultimate compressive strength of stabilized soil.

Figures 8 and 9 show the relationships between the secant modulus (E50) and the contents and ratios of admixtures. The secant modulus increases with increasing admixture content for the two admixtures used. This result reveals that the use of the investigated admixtures has a significant effect on the stiffness of stabilised soil specimens treated with recycled gypsum. This finding concurs with the results discussed in the previous work (Ahmed et al., 2011b) on the use of recycled gypsum to improve the secant modulus of silty sand soil. Additionally, it is clear from Figure 8 that using B-L admixture has a clear effect on improving the secant modulus compared to that of B-C admixture, especially in the case of low admixture content. This result is most likely related to the presence of cement in the soil-gypsum mixture, which increases the brittleness of stabilised soil specimens because cement is more brittle in comparison with lime. Figure 9 shows the effect of increasing the admixture ratio on the improvement of secant modulus. Clearly, the secant modulus decreases with increasing admixture ratio for both B-C and B-L. This result is in agreement with the observed effect of admixture ratio on the compressive strength due to the same reactions discussed earlier, in addition to the effect of increased brittleness in the case of cement. To summarise, the admixture ratio of 1:1 for the two admixtures used is the best ratio compared with other ratios for obtaining high strength and secant modulus. Subsequently, the recommended ratio and content for the admixture used in this project were 1:1 and 22.5%, respectively. It is important to report that the environmental impacts and durability of soil stabilised with recycled gypsum were also investigated and presented elsewhere.

Figures 10 and 11 show the plasticity index, based on the obtained results of Atterberg limits, for soil stabilised with different contents and ratios of admixtures. The results show that the addition of recycled gypsum admixtures lead to significant reduction in the plasticity index for all investigated soil samples. For soil stabilised with only recycled gypsum, the reduction in the plasticity index resulted from an increase in the plastic limit and the slight decrease in the liquid limit with increasing recycled gypsum content.

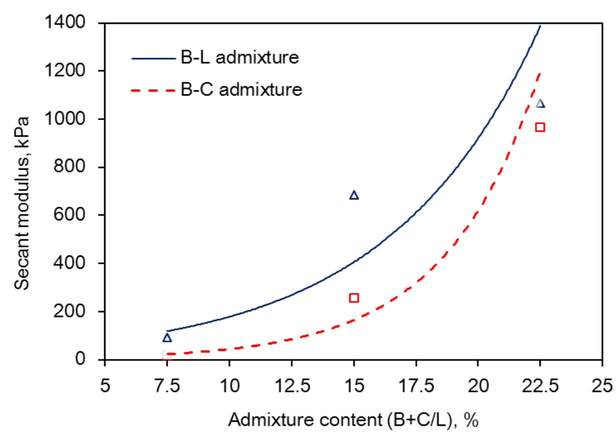


Figure 8. Effect admixture contents on the secant modulus for stabilized soil at admixture ratio of (1:1).

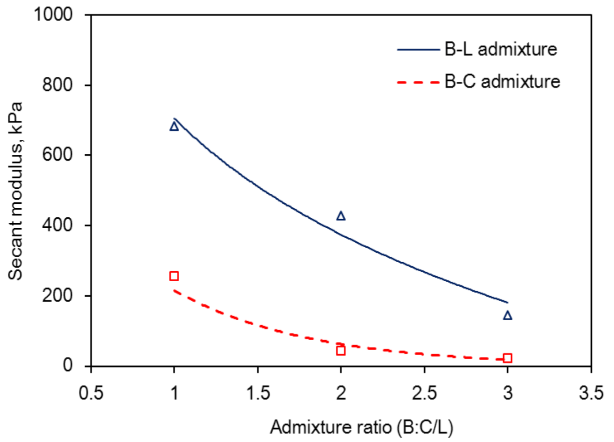


Figure 9. Effect admixture ratios on the secant modulus for stabilized soil with admixture content of 15%.

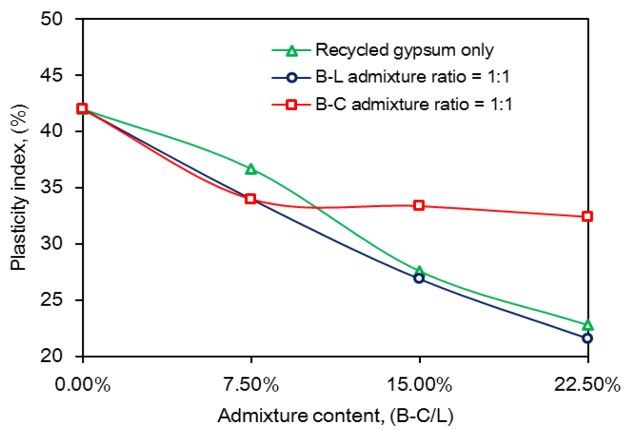


Figure 10. Effect of admixture contents on the plasticity index of stabilized soil.

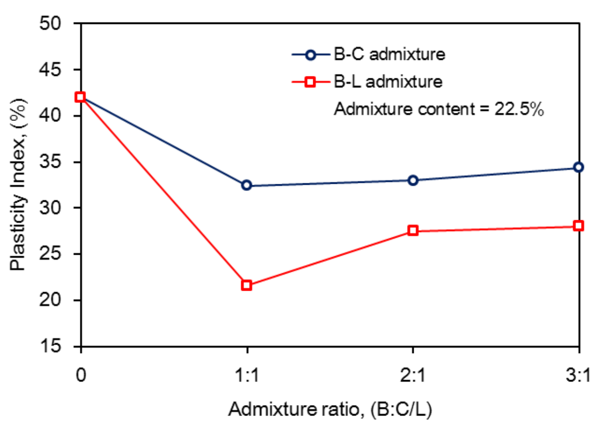


Figure 11. Effect of admixture ratios on the plasticity index of stabilized soil.

The effect of gypsum on the liquid limit is significantly lower than that of the plastic limit. For soil stabilised with the B-L admixture, the reduction in plasticity index is governed by the same effect as in the samples stabilised with recycled gypsum. For soil stabilised with the B-C admixture, the reduction in the plasticity index results from a decrease in liquid limit and a slight increase in the plastic limit. Generally, the main reason for the reduction in the soil plasticity when gypsum is introduced is related to the flocculation of clay soil particles in the presence of gypsum. All admixtures resulted in significant reduction on the plasticity index, as shown in Figure 10, which is attributed to increased flocculation of clay soil particles (Miller and Azad 2000). Furthermore, the addition of gypsum to the moist clay soil reduces the moisture content, and also reduces the plasticity index. Again, this is consistent with the results presented in previous work that demonstrated the significant effect of adding gypsum on reducing the index properties (Yilmaz and Civelekoglu 2009). Figure 11 indicated that there admixture with different ratio almost equally reduce the plasticity index, particularly in the case of the B-C admixture. It is also noted from Figure 11 that the B-L admixture reduces the plasticity index more than the B-C admixture. This may be attributed to the fact that the B-L admixture is rich in calcium compared to the B-C admixture. The presence of calcium in the saturated clay promotes cation exchange between the clay particles and calcium, which are found in lime and gypsum, resulting in a decrease in the plasticity. This reaction also affects the Atterberg limit for clayey soil depending on the nature of the cation exchange (Yilmaz and Civelekoglu 2009, Mathew and Narasimha 1997). Accordingly, a significant reduction in the plasticity index is observed for the optimal B-L admixture ratio of 1:1. In addition, this is consistent with the fact that an increase in the lime content in the soil decreases its plasticity properties (Miller and Azad 2000, Mathew and Narasimha 1997). In fact, the decrease in the tested soil plasticity when recycled gypsum is introduced plays an important role in the strength improvement because the soil strength increases with decreasing plasticity.

4 CONCLUSIONS

Recycled gypsum produced from gypsum wastes was investigated in the current study, along with furnace cement or lime, as a stabilizer material for soft organic fine grained soil. The mechanical properties of the tested soil were evaluated. The admixture of gypsum-cement/lime (B-C/L) can improve the strength, stiffness, mechanical properties and plasticity of the tested soil. The increase of admixture content is associated with significant increase of unit weight, strength, secant modulus, and stiffness of the tested soil. The increase in the admixture ratio has a negative effect on the compressive strength, especially in the case of the B-C admixture. The plasticity and water content decreases with increasing admixture content. The B-L admixture can reduce the soil plasticity more than the B-C admixture. For both admixture types, the different admixture ratios had almost the same effect on the plasticity index. Ultimately, the obtained results confirmed the potential use of recycled gypsum produced from gypsum wastes, in cooperation with solidification agent, as a stabilizer material in geotechnical projects.

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