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The Effect of Variation in Water Compaction and Blending Approach on the Performance of Gypsum-Based Soil Stabilized with Cement and Silica Fume

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تأثير نسبة الرطوبة وطريقة الخلط على أداء التربة الجبسية المثبتة بالأسمنت وغبار السيليكا

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Abstract:
The performance of chemical stabilization of gypseous soil, a conventional technique, relies on several aspects, i.e., soil structure, stibilzer combination, sulphate concentration, and water content etc. This research studies the impact of using various water contents and different mixing approaches on the behaviour of gypsum-based soil stabilized by varying proportions of cement (C) and silica fume (S). In this context, a series of gypseous soil samples was prepared by utilizing a blended combination of 7S-3S and 5C-5S, various water contents, and two blending approaches (dry-based blending (DM) and slurry-based blending approach (SM)). Then, the prepared gypseous soil samples were exposed to several engineering tests, entailing the compressive strength (UCS) and linear expansion invistigations. The outcomes revealed that utilizing SM in the fabrication of specimens led to a deteriorative impact on the UCS and swelling values. This deterioration is due to the clumping of cementitious compounds and the inhomogeneous distribution of hydrated materials produced during the chemical interaction. Conversely, the utilization of various water contents showed a deterioration in UCS values and an improvement in swelling values, possibly due to the extension of void geometry, thus reducing the hardness of soil against deformation and easing the faster ettringite growth.

Keywords: Heaving, Soil Stabilization, Lime, Cement, Strength.

الملخص
يعتمد أداء التثبيت الكيميائي للتربة الجبسية، وهي تقنية تقليدية، على عدة عوامل، تشمل معادن التربة، ومزيج المادة الرابطة، وتركيز الكبريتات، ومحتوى الرطوبة، إلخ. يدرس هذا البحث تأثير استخدام محتويات مائية مختلفة وطرق خلط مختلفة على أداء التربة الجبسية المعالجة بالإسمنت (C) وغبار السيليكا (S). في هذا السياق، تم تحضير سلسلة من عينات التربة الجبسية باستخدام مزيج ممزوج من S-3S7 وC-5S5، ومحتويات مائية مختلفة (31٪ و33٪)، وطريقتي خلط (الخلط الجاف (DM) وطريقة الخلط القائمة على الملاط (SM)). بعد ذلك، تعرضت عينات التربة الجبسية المحضرة لعدة اختبارات هندسية، تضمنت اختبار قوة الضغط غير المحصورة (UCS) واختبارات التمدد الخطي. كشفت النتائج أن استخدام SM أدى إلى تأثير تدهوري على قيم UCS والتورم. يُعزى هذا التدهور إلى تكتل المركبات الأسمنتية وعدم تجانس توزيع المواد المائية، بما في ذلك هيدرات سيليكات الكالسيوم (CSH) وهيدرات الومينات الكالسيوم (CAH). في

المقابل، أظهر استخدام أنواع مختلفة من المحتوى المائي تدهورًا في قيم معامل التمدد (UCS) وتحسنًا في قيم الانتفاخ، ربما بسبب اتساع هندسة الفراغات، مما يُقلل من صلابة التربة ضد الأحمال ويُسهّل نمو الإترينجيت.

الكلمات المفتاحية: الإترينجيت، تثبيت التربة، مُثبِّت قائم على الكالسيوم، المتانة، التمدد.

Introduction

Sulphate soil is an expansive soil susceptible to high volumetric changes, loss of strength capacity, and erosion, and is widespread in several countries, such as, USA, UK, IRAQ, and CHINA [1,2]. Therefore, several extensive studies have been conducted to improve its geotechnical characteristics, like strength and swelling potential [3–11]. One common method employed to enhance the geotechnical characteristics of sulphate-bearing soil is chemical treatment by using cement and lime [6,7,12]. Principally, the use of calcium-based stabilizer (cement and lime), upon mixing with expansive soil, leads to a series of chemical reactions [3,4,13,14]. These interactions include: 1) the hydration process occurring at the mixing of soil with the calcium-based stabilizer in presence of water, which responsible for elevating the alkalinity value, thus easing the silica and alumina release from the particles of soil and portlanadite (CaOH) from calcium-enriched stabilizer; 2) cation exchange, which encourages the soil particles flocculation, and responsible for improving the plasticity and workability of soil; and 3) pozzolanic process, the interaction between the released silica and alumina with the activating agent Ca^2 (from cement and lime), which promote the generation of cementitious materials (CSH and CAH) responsible for generating a hardened matrix.

However, the situation changes in the case of sulphate soil diametrically, where the impact of the agent of calcium-based stabilizer (like cement and lime) on treated soil is counterproductive. The essential reason behind this reversal effect is the existence of sulphate particles in the matrix of soil, such as calcium, sodium, potassium and magnesium sulphate [15–17]. This reversal effect was initially called a sulphate attack, where the first research on the effect of sulphate attack was on concrete by [16,18]. In such a study, it was inferred that the existence of high sulphate content in concrete leads to deterioration, decay, and cracking of the concrete structure. This deterioration is typically associated with ettringite nucleation and development [19]. Depending on the study conducted by [20], the ettringite can cause an increase in the natural volume of components from 30 to 800%. In the existence of soluble carbonates and at low temperatures below 15 °C, the ettringite may also transform into thaumasit, which can cause further deterioration in mortars and concretes [21]. The ettringite and thaumasite nucleation also appear in a treated gypseous soil with a calcium-based stabilizer [22,23]. In the regions where gypseous soil predominated, the economic losses from the deterioration of soil were reported in billions of dollars [14].

To overcome the deficiency of sulphate-bearing soil, several stabilizers have been evaluated. Nevertheless, the conventional treatment by employing calcium-based stabilizers (including cement and lime) as an independent stabilizer was not adequate for treating the collapse of sulphate-bearing soil [14,24]. This is because the nucleation of the ettringite between the particles of soil increases the swelling and deteriorates the strength of treated gypsum-based soil, which thus induces an adverse effect on the overlying facilities [22,25,26]. Therefore, to restrict this phenomenon, several researchers suggested limiting the usage of stabilizer rich in a high dosage of calcium because of its major role in the nucleation of ettringite, and the application of binder rich in silica and alumina compounds. This is to improve the interparticle bonds and suppress the ettringite formation process, thus declining the volumetric increases, and enhancing the strength [14,25].

Numerous studies used pozzolanic materials including S to improve the characteristics of cement-treated soil [27–29]. S is typically produced during the production process of silicon alloys in an electric furnace [30]. The particles of silica fume typically have a tiny spherical vitrified shape, a high specific surface area, and a superior characteristic of pozzolanic reaction. Therefore, it improves the cemented soil by increasing the bond force between particles of soil, resulting in filling voids, producing a hardened matrix [31]. Several studies conducted by [32–34] indicated that the addition of S into cemented soil leads to enhancing the UCS, flexural strength and restricting the volume increase of treated soil samples. To name a few, Ehwailat, Ebailila, Ezreig, and Aljoat [35] investigated the role of cement-silica fume (C-S) in controlling the strength and swelling perfoamnce of gypseous clay made with different mix ratios. The results indicated that 7C-3S was the optimum blend for improving the UCS, while 5C-5S is the optimum blend for restricting the swelling potential. However, such a study did not investigate the effect of moisture content and mixing method on the performance of sulphate soil stabilisation with cement and silica fume. Therefore, this study evaluated the influence of different mixing methods and moisture contents (31% and 33%) on the performance of gypseous soil treated with C-S blend, in which several soil samples were examined using UCS and linear expansion test to determine the optimum mixing method and the optimum moisture content.

Material and methods

The materials utilized in this study included one artificial gypseous soil (kaolin clay, mixed with 9% gypsum, K9G), two binding materials (C and S), and distilled water. Tables 1 and 2 illustrated, respectively, the oxides and physical properties of the raw ingredients used, while Figures 1 and 2 showed the X-ray diffraction of kaolin clay and particle size distribution of raw materials, respectively.

Table 1 Oxides of K, C and S.

Oxides	Kaolin	cement	Silica
CaO	-	61.49	-
MgO	0.1	3.54	-
SiO2	47.32	18.84	98.4
Al2O3	35.96	4.77	0.2
Na2O	0.07	0.02	-
P2O5	0.12	0.1	0.03
Fe2O3	0.69	2.87	0.01
Mn2O3	0.02	0.05	-
K2O	1.8	0.57	0.2
TiO2	0.02	0.26	-
V2O5	<0.01	0.06	-
BaO	0.07	0.05	-
SO3	0.01	3.12	0.1
LOI	0.09	4.29	0.5

Table 2 Physical properties of K, C and S.

Properties	K	C	S
Density	-	1400	300
Specific gravity	2.14	3.15	3.15
pH	5.38	13.41	6.9
Color	White	Grey	White

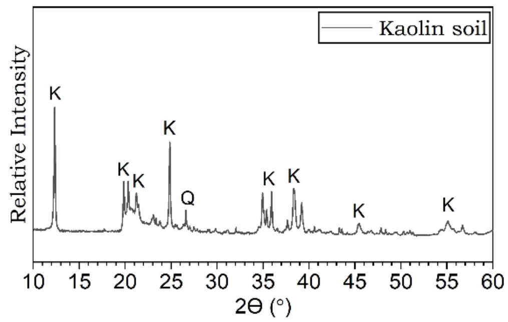

Figure 1: The XRD pattern of kaolin soil.

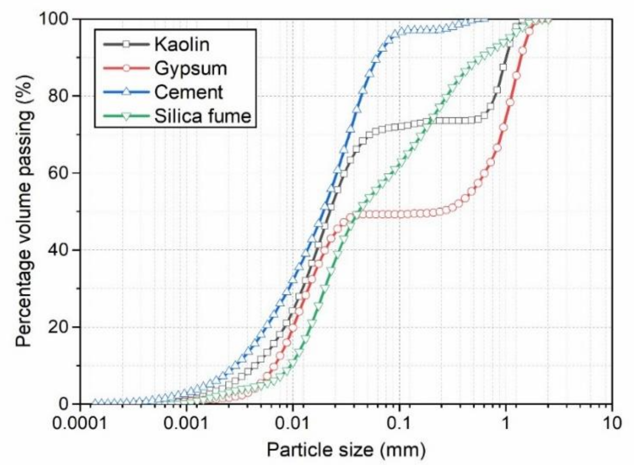

Figure 2: Size distribution of kaolin, gypsum, cement and silica fume.

The employed K was in powder form and was supplied by Potterycarfts Ltd, UK. The outcomes from the XRD investigation referred to the composition of K as kaolinite and quartz. The outcomes from the sieve testing revealed that the composition of K was 60% silt, 27% sand and 13% clay. The physico-properties investigations declare that K has a 56.7% liquid limit, 33.3% plastic limit and 23.4% plasticity index. According to these numbers, the classification of K is a sandy SILT. The employed G in this study was a calcium sulphate dihydrate, which was obtained from Fisher Scientific Ltd, UK. The C was in a fine grey form and was sourced from Premier Cement Limited, UK, under the name of Portland Cement. The S used was a light grey powder, containing 98.4% of silica oxide, and was purchased from Tarmac Cement and Lime Company, UK.

Mix design

To investigate the consequence of variation in liquid content and multiple blending methods on the gypsum-based soil treated by cement and silica fume, several mix designs as tabulated in Table 3 was designed using: 1) one artificial gypseous soil containing 9%-G: 2) a fixed stabilizer ratio of 10 wt% of soil specimen: 3) two fixed binder proportion ratio of cement-silica (7C-3C and 5C-5S); 4) two different water quantity, and 5) two various mixing approaches.

Table 3 Mix design of artificially gypsum-based kaolin stabilised with C-S blends.

Mix code	Mix composition					Mix method
	Gypseous soil		binder		MC (%)	
	K (%)	G (%)	C (%)	S (%)		
K9G-7C-3C	91	9	7	3	1.1	DM
K9G-7C-3C	91	9	7	3	1.1	SM
K9G-5C-5S	91	9	5	5	1.1	DM
K9G-5C-5S	91	9	5	5	1.1	SM
K9G-7C-3C	91	9	7	3	1.2	DM
K9G-5C-5S	91	9	5	5	1.2	DM

The blend ratios combination was prepared in two dosages (70% cement-30% silica fume) and (50% cemnet-50% silica fume), in line with the observation reported in [35]. The moisture content was adopted at 31% and 33%, which is equal to 1.1 and 1.2 of the optimum moisture content obtained using the standard proctor test. This moisture level was selected to verify that the soil materials are compacted as wet as the optimum moisture content (OMC), which is required for conformity with the essential condition to achieve the best durability behaviour [36].

The two selected mixing approaches were a dry mixing approach (DM) and a slurry mixing approach (SM), where the difference was in the order of the mixing procedure. In the DM approach, all the solid components were mixed first in dry form for three minutes, then the OMC was incorporated and re-mixed for an additional 3 minutes, to be ready for the compaction process. Nevertheless, in the SM approach, the stabilizing agent was blended with water first for 3min, then the gypseous soil added and mixed for an additional 3 min, to be ready for the compaction process.

Samples preparation

A total of 12 jack-compacted cylindrical samples in line with [11] were prepared for each mix combination; each sample has a measurement of 100mm length and 50mm diameter. Three samples were used to evaluate the swelling, while 9 samples were used to determine the UCS at varying ages (7, 28, and 90 days). According to each mix design, as illustrated in Table 3, the raw solid and liquid materials were mixed to prepare the samples. The admixture was then cast into the steel mould and compressed using a hydraulic jack to apply axial compression by aiding a short plunger [36], as presented in Figure 3. Thereafter, the produced specimens were held in the mould for 3 min to realize stability [36]. To extract the samples from the mould, a long plunger was used. Thereafter, the samples were covered in nylon film to reduce evaporation and carbonation. Ultimately, the samples were kept in a plastic container at a room temperature of 20∓ 2 ℃ until testing.

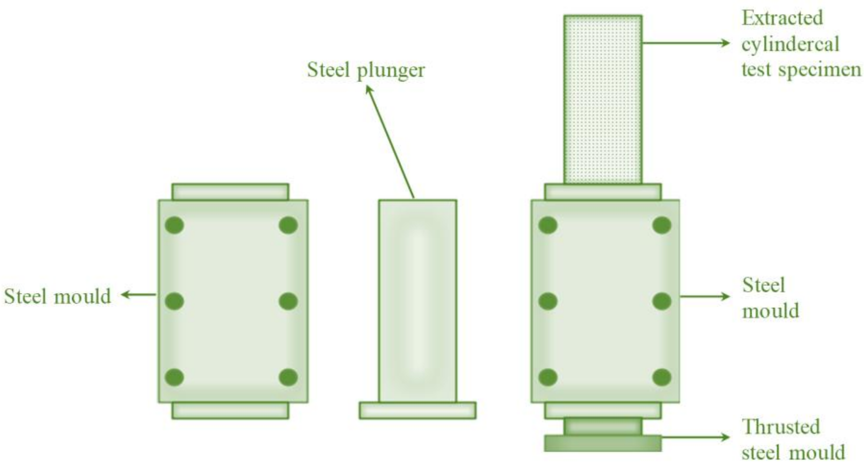

Figure 3: Fabricated steel mould.

Testing method

Unconfined compressive strength (UCS)

The UCS investigations were applied to triplicate samples per mix combination at different ages (7, 28, and 90 days). The test was performed according to [37] by using a Hounsfield machine, where three samples were utilized as the representative UCS.

Linear expansion

The linear expansion test was applied according to the relevant standard [38], through a longer soaking duration of 200 days, as commonly followed with soil stabilization-based research [36,39–42]. Three samples for each mix combination were used for the analysis. Directly, on the completion of 7 days curing, the 10 mm of both sides of each sample were removed and installed onto a porous disc inside a Perspex cell, as illustrated in Figure 4. Thereafter, the dial gauge was calibrated to zero, and water was added to the cell through the upper inlet until the unwrapped bottom part of the samples was soaked in water to allow the samples to swell. Eventually, the dial gauge reading was reported throughout the period of immersing in water (200 days, and the average of the three readings was reported as the representative of expansion.

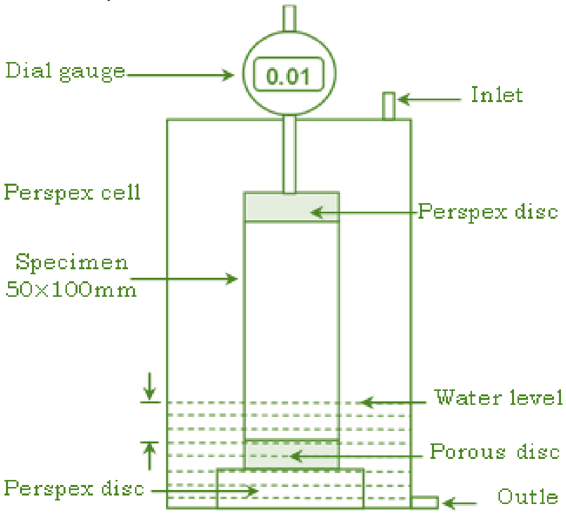

Figure 4: Schematic diagram of a linear expansion cell.

Result observation and discussions

UCS investigation

The impact of differences in water amount and mix blending approach on the UCS of soil samples rich in gypsum and stabilized by 7C-3S and 5C-5S is shown in Figure 5.

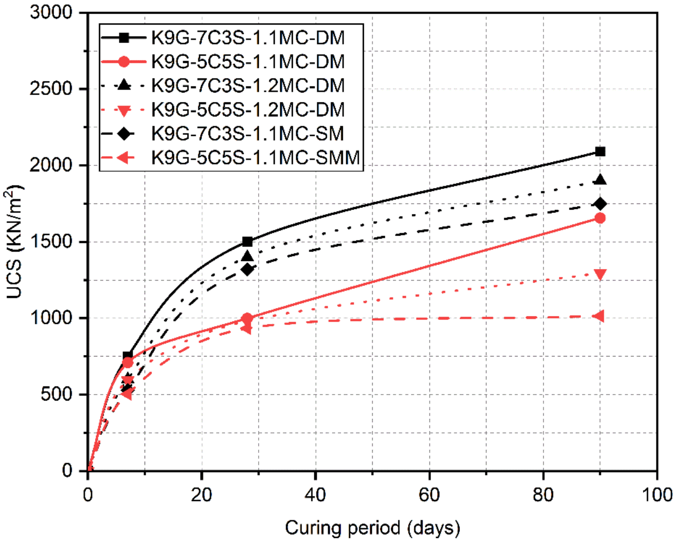

Figure 5: The UCS of K9G-7C-3S and K9G-5C-5S samples mixed at different blending approaches and moisture content.

The outcomes revealed that the UCS values increased with a prolonged curing period, and this development in strength can be attributed to two reasons. These included 1) short-term reaction and 2) long-term reaction. The short-term reaction involved cation exchanges and flocculation of soil particles, and the long-term reaction included the pozzolanic reaction between binder and soil particles, which ultimately led to the growth of hydrates, such as CSH and CAH [43]. Such crystalline hydrates combine with soil particles and fill the voids, resulting in a hardened matrix, accompanied by the enhancement of strength values [44,45]. Moreover, the rise in water amount above 31% for treated gypseous soil (7C-3S-1.1MC-DM and 5C-5S-1.2MC-DM) presented a decline in UCS values. This decline in UCS values increased with the variation in blending approach from DM (7C-3S-1.1MC-DM) to SM (7C-3S-1.2MC-SM) and DM (5C-5S-1.1MC-DM) to SM (5C-5S-1.2MC-SM). Therefore, such a decline indicates that increaseng the water amount and utilizing SM method are unsuitable for a better performance of soil stabilization. The decline in UCS values with increasing water amount could be attributed to the lower friction force, poorer interlocking and increasing voids between particles of soil. These voids harm the hardened matrix of soil by raising the porosity [46,47]. Moreover, the creation of ettringite in high quantities contributes to a decline in the UCS values as the moisture amount rises [48,49]. As for the decrease in UCS values related to changing the mixing method from DM to SM, probably because the cementitious compounds (C and S) clumped during the mixing process, and the hydrated compounds (CSH and CAH), was inhomogeneously distributed, thus a lower hardened matrix was produced.

Volume change behaviour

The impact of varying water amount and blending approaches on the swelling of gypseous soil treated with 7C-3C and 5C-5S is presented in Figure 6. The outcomes revealed that the increased moisture content (from 1.1 to 1.2) induced a decline in swelling values, where the swelling value of KG9-7C-3C was decreased from 2.8% to 2.38%, and the swelling of K9G-5C-5S was reduced from 1.42% to 0.83%, as the water content rose from 31% to 33%, respectively. Contrarywisely, the change in the mixing method from DM to SM has a reversal effect on expansion magnitude, where the swelling values of K9G-7C-3C and K9G-5C-5S were (2.8% and 1.42%) for DM and (4% and 3%) for SM, respectively. According to the results, it could be concluded that utilizing a higher water amount is suitable for reducing the swelling magnitude, whereas utilizing SM is not advicable. The probable reason for the decline in swelling values with increasing moisture content relates to the rise in the inter-particle void pores [46]. At an increase in moisture content (from 31% to 33%), the treated samples would not be densified enough, inducing a high volume of voids, creating more spaces available for the accommodation of ettringite, thereby reducing swelling values [49,50]. As for the increase in expansion magnitude, which was related to the use of SM, it could be attributed to the poor interlocking, due to the clumped cementitious compounds, and poorer distribution of hydrates in the stabilization system.

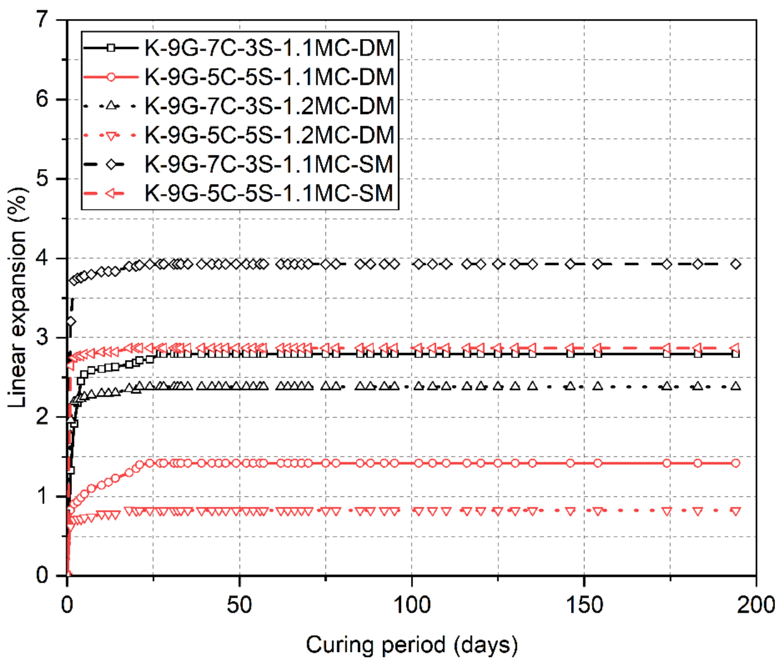

Figure 6: Typical plots of expansion of K9G-7C-3S and K9G-5C-5S samples mixed using different mixing approaches and two different water contents.

Conclusions

The current research evaluated the effect of binders 7C-3 and 5C-5S on prepared gypseous soil samples at a variety of moisture contents and different mixing methods by using the UCS and expansion test. Accordingly, it could be concluded that:

1- Utilizing a higher moisture amount (1.2%) prompts a decline in the UCS and a decline in the expansion magnitude, as compared to the use of (1.1%). This can be related to the lower friction force between the particles of the soil matrix and the expansion of voids; both together reduce the hardness of the soil and ease the ettringite growth.

2- The slurry blending approach, where the blend was first blended with water before the soil was introduced, showed a deterioration in UCS and swelling values. This is due to the cementitious compounds being clumped and the hydrated products inhomogeneously distributed within the soil matrix; thereby, the slurry mixing method is not recommended.

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