

The effect of lime, GGBS, and Metakaolin on sulfate soil stabilization

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تأثير الجير، وخبت الافران الحبيبي، والميتاكولين على تثبيت التربة الغنية بالكبريتات

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Abstract

Treatment of sulfate-bearing soil with lime has a negative effect due to the formation of an expansive mineral (ettringite), posing a challenge for geotechnical engineers due to the considerable damage and unpredictable deformation associated with heaving. This challenge includes multi-hazard environmental and economic effects on various civil engineering structures. This, therefore, led to this study, which focuses on the short and long-term curing (7, 28, and 90 days) of sulfate-bearing soil treated with lime (L), Ground Granulated Blast-Furnace Slag (GGBS) and Metakaolin (MK). Various laboratory tests were performed, including unconfined compression strength (UCS), and linear expansion, to investigate the effect of different blended proportions of L, GGBS and MK. The results showed that soil samples treated with 5L-5MK exhibit lower swelling percentage (0.04%) than those treated with 10% of lime, 5L-5GGBS, and 5L-2.5MK-2.5GGBS after 7 days of curing. Meanwhile, soil samples stabilized with 10% of (L-GGBS) exhibited higher strength performance after 90 days of curing (3315.67 kN/mm²) compared to those stabilized with 10% of lime. Overall, the test results proved the potential of L-MK, L-GGBS, and L-MK-GGBS as effective stabilizers for sulfate-bearing soil.

Keywords: swelling, strength, sulfate-bearing soil, expansion mineral, gypsum.

الملخص

لمعالجة التربة الحاملة للكبريتات بالجير تأثير سلبي نتيجة لتكوين معدن تمددي (الإترنجيت)، مما يشكل تحدياً لمهندسي الجيوتقنية نظراً للأضرار الجسيمة والتشوهات غير المتوقعة المرتبطة بالرفع. ويشمل هذا التحدي آثاراً بيئية واقتصادية متعددة المخاطر على مختلف منشآت الهندسة المدنية. ولذلك، أدى ذلك إلى هذه الدراسة، التي تركز على المعالجة قصيرة وطويلة الأجل (7 و 28 و 90 يوماً) للتربة الحاملة للكبريتات المعالجة بالجير وخبت الافران الحبيبي المطحون والميتاكولين. أجريت اختبارات معملية متنوعة، بما في ذلك قوة الضغط غير المحصورة والتمدد الخطي، لدراسة تأثير نسب مختلفة من خليط L و GGBS و MK. أظهرت النتائج أن عينات التربة المعالجة بـ 5L-5MK أظهرت نسبة انتفاخ أقل (0.04%) مقارنة بتلك المعالجة بـ 10% من الجير، و 5L-5GGBS و 5L-2.5MK-2.5GGBS بعد 7 أيام من المعالجة. في المقابل، أظهرت عينات التربة المثبتة بـ 10% من (L-GGBS) أداءً أعلى في مقاومة الضغط بعد 90 يوماً من المعالجة.

(3315.67 كيلو نيوتن/مم²) مقارنةً بتلك المثبتة بـ 10% من الجير. وبشكل عام، أثبتت نتائج الاختبار فعالية L-MK و L-GBS و GGBS كمثبتات فعالة للتربة الحاملة للكبريتات.

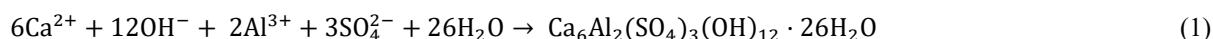
الكلمات الدالة: الانتفاخ، القوة، التربة الحاملة للكبريتات، معدن التمدد، الجبس.

Introduction

In their natural form, expansive soils have low bearing strength and a high sensitivity to swelling and shrinkage, particularly those that are mostly made of clay minerals [1]. As a result, it may be risky to build engineering structures on soil that has these properties since it may result in differential settlement, fractures, and unexpected structure collapse [2]. In the USA and the UK, for instance, the annual cost of the detrimental effects caused by these expanding soils is roughly \$1000 million and £150 million, respectively, according to [3,4]. Weak soils with low strength and high compressibility are thought to be the root cause of the majority of geotechnical issues in this setting; therefore, these soils need to be treated with appropriate stabilisers or solidifiers to increase their load-bearing capability [5,6]. In the sulfate-bearing soil, this decline in strength is evident. Certain minerals, such as sodium sulphate (Na₂SO₄), gypsum (CaSO₄·2H₂O), magnesium sulphate (MgSO₄), anhydrite (CaSO₄), and barite (BaSO₄), dissolve to create sulphate, a soil anion. The primary source of sulphate in soil is still gypsum, but sulphate ions can also come from the oxidation of some soil minerals, like pyrite (FeS₂) [7,8]. Therefore, gypsum in soil caused major issues in construction (cavities, leaks, and cracks that resulted in a decrease in strength and an abrupt increase in compressibility and collapse of structures), making it difficult for geotechnical engineers to build pavement and highways on such soil [2,9,10].

By chemically changing the soil's characteristics, stabilisation of expansive soils can be done inexpensively and technically while also improving the stabilised or treated soil's geotechnical and engineering qualities. The most widely used treatment method for soil stabilisation is chemical stabilisation using Portland cement and lime (calcium-based stabilisers) [5,7,11–13]. However, even though it has been shown that cement and lime work well as stabilisers for clayey soils, this stabilisation method might have negative consequences and could cause the treated soil to be destroyed [14,15]. The presence of sulphate (SO_4^{2-}) in the stabilised soil is one of the most frequent causes of this kind of failure. With a gypsum content ranging from extremely low (<5%) to very high (≥50%), sulphate is a common salty component found in many types of natural soils, primarily in the form of gypsum. Sulfate-bearing soils are widespread and make up around 20% of the world's land area [13]. These soils are frequently found in the subgrades and layers of road pavement during civil engineering construction.

There have been reports of volume expansion when sulfate-rich soil is treated with cement or lime [2,7,16–19]. When water is available, the calcium-based stabilisers' Ca²⁺ ions combine with the sulphate and aluminium from the clay minerals to generate ettringite (Ca₆Al₂(SO₄)₃(OH)₁₂·26H₂O) (see Equation 1), a highly hydrated and expansive mineral. High pH, reactive aluminium availability, reactive calcium availability, sulphate present, and water availability are all necessary for the formation of ettringite [20]. High temperatures (over 60 to 70 °C) expedite the development of ettringite [21–23], and under the right circumstances, ettringite can form even as the ingredients are being mixed. The development of this mineral was demonstrated by Ouhadi and Yong [24,25] over a period of one month in one experiment and between the soil mixture with lime and 48 hours in another. The soil becomes volumetrically unstable after ettringite forms, and it has been noted that this mineral improves the soil's bearing capacity in dry conditions by influencing the dewatering and interlocking of the soil profile [20,21,26].



Recently, civil engineers have concentrated on creating building materials with minimal cement content in an effort to lessen the industry's carbon footprint, greenhouse gas emissions, and climate change. Environmental pollution is largely caused by the methods used to produce cement and lime. For instance, producing one tonne of cement uses around 5000 MJ of energy and emits nearly 0.95 tonnes of CO₂ [6,27–29]; producing one tonne of lime uses approximately 3200 MJ of energy and produces approximately 0.79 tonnes of CO₂ [30]. This necessitates taking into account waste materials as a full or partial substitute for traditional binders, as suggested by a number of studies. A waste product of the iron industry, GGBS has been thought to be an appropriate substance for stabilising soil. Regarding energy consumption and CO₂ emissions, 1 tonne of GGBS is produced using just 1300 MJ of energy and emitting only 0.07 tonnes of CO₂ [31].

In sulfate-rich soils, new techniques ought to be able to suppress heaving and ettringite development. Pozzolanic materials, including GGBS and MK, are thought to be good sulphate soil stabilisers because they

typically consume lime, which decreases its availability for the development of expansive products while increasing the soil's strength. Metakaolin is a reactive, highly pozzolanic, supplemental cementitious material that complies with AASHTO M295 [33] and ASTM C 618 [32]. For use in cementing, metakaolin is made from natural minerals. It is made from kaolin clay that has been calcined at high temperatures (600–800 °C) to produce an amorphous aluminosilicate that reacts in concrete [34–36]. The cement paste-aggregate link is weakened by sulphate ions' penetration into concrete, which results in serious damage such expansion and widespread cracking. When used with cement that has intermediate and high C3A content, it has been shown that an increase in MK content (5–20%) reduces mortar expansion [36].

To stop or lessen the development of ettringite in stabilised sulphate soils, GGBS can be used in place of some or all of the cement or lime. Ettringite production can be decreased or avoided by the rapid reaction of GGBS's alumina and silica contents with the calcium content of the soil to create a cementitious gel [14,37]. By creating a denser cementitious matrix, GGBS can also decrease water availability and permeability, increasing resistance to internal and external sulphate assaults [38–41].

The primary goal of this study is to develop a novel technique for stabilising soils that are attacked by internal sulphate by adding gypsum (CaSO_4) using a mixture of lime, MK, and GGBS. Several stabilised specimens were subjected to various tests, including linear expansion (LE) and unconfined compressive strength (UCS) tests, for this reason. To accomplish the goals of this study, two actions have been conducted. Compaction characteristics are run for each mixture in step 1, and UCS and LE tests are conducted after 7, 28, and 90 days of curing and seven days of curing, respectively.

Materials and Methods

Materials

Kaolin clay (K), hydrated lime (L), calcium sulphate (gypsum) (G), MK, and GGBS were the components used in this study. Under the brand name MK40, KAOLIN (Malaysia) SDN BHD provided kaolin clay as a white, odourless powder that was finely milled. Because of its (i) high alumina content, which allows it to release more alumina at high pH levels and contribute to the formation of ettringite, which increases susceptibility to sulphate attack [17,31], (ii) uniform and consistent mineralogy, (iii) low cation exchange capacity, and (iv) higher alumina content than most other expensive minerals, kaolin clay was used. These factors make kaolin clay an appropriate control soil for the process of stabilising soil. The main characteristics of kaolin clay are presented in Table 1. In accordance with BS EN ISO 17892-4:2016 [44], a clay hydrometer test was performed using the grading curve displayed in Figure 1.

Table 1. Characteristics of the kaolin clay used in this study.

Properties	Value
'Liquid lim' (%)	057.78
'Plastic lim' (%)	038.13
'Shrinking lim' (%)	04.4
Plasticity index	019.65
Sand (%)	-
Silt (%)	088.35
Clay (%)	011.65
Electric conductivity ($\mu\text{S}/\text{cm}$)	0320
pH	05
"Specific gravity" (G_s)	02.46
"Water content" (%)	01.01
"Optimum moisture content" (%)	029
"Maximum dry density" (Mg/m^3)	01.326

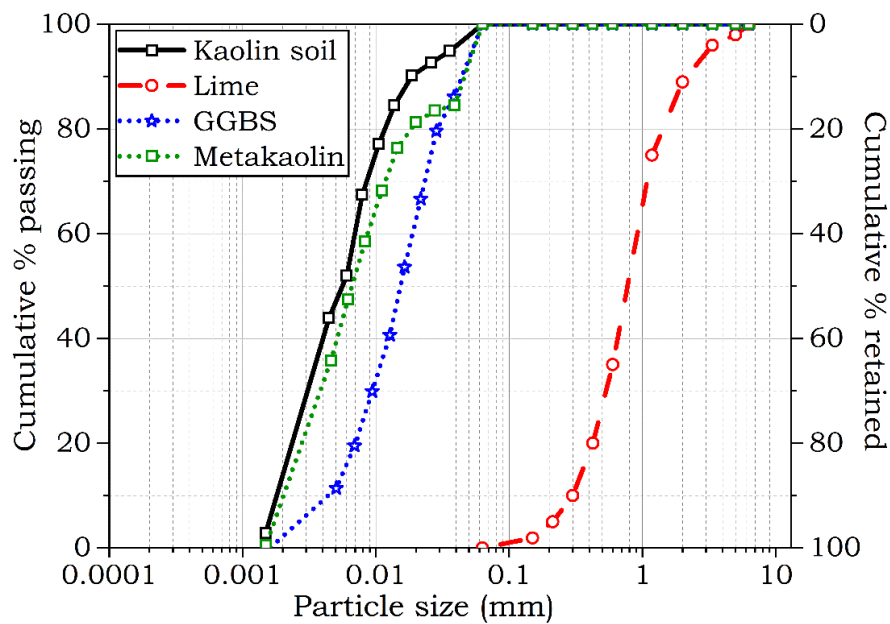


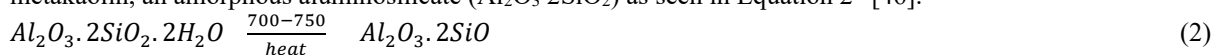
Figure 1. Particle size distribution (PSD) of the kaolin clay , MK, L and GGBS used in this study.

L, G, and MK were collected from Sungai Jawi, 14200, Penang, Malaysia. However , G ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) was selected in this research due to its much lower solubility compared to other sulfate types (potassium sulfate, magnesium sulfate, and sodium sulfate) . Moreover, it is one of the sulfates that contain calcium, and it is logical that it would form ettringite if a non-calcium-based stabilizer had been used, as presented in Table 2.

Table 2. Chemical compositions of kaolin clay , L, G, GGBS, and MK.

Oxides	Characteristic (%)				
	"Kaolin clay"	L	G	GGBS	MK
CaO	-	-		37	0.2
CaOH ₂	-	92		-	-
SiO ₂	58	2.5		32.7	52
Al ₂ O ₃	38	0.9		15.3	36
Ca ₂ SO ₄	-	0.1	99	-	-
SO ₃	-	-		4.7	-
MgO	-	3.5		8.1	0.1
Cl	-	-	0.005	-	-
Fe	-	0.06	0.005	-	8
H ₂ O	-	0.7		-	-
Loss on ignition	11-14	0.24	0.99	2.2	3.7
pH	5	11.85	7.5	10.23	6.71
Specific gravity	2.46	2.23	2.34	2.96	2.33

Metakaolin is produced from kaolin, a natural material. It is a pozzolanic material that produced from the heating of kaolin at 700–750 °C its classification as a pozzolanic material follows the ASTM C 618 standard MK exhibits a high surface area and amorphous structure which contributes to its high pozzolanic reactivity [36,45]. The water content of kaolin is reduced during the heating process, thereby altering its structure and forming metakaolin, an amorphous aluminosilicate ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) as seen in Equation 2 [46].



Molten iron slag is rapidly cooled to preserve its amorphous structure, and then it is ground to increase its specific surface area to create GGBS, a waste product from the pig-iron manufacturing process . The MDC Sungai Pentani Company in Malaysia provided the GGBS used in this investigation. By providing additional Al and Si, which react with Ca^{2+} to generate complex cementing gels, it was decided to slow down the pace of ettringite production [17,38,39]. Superior sulphate resistance should be a result of GGBS's denser structure and lower calcium ion

content [31,37,47]. Figure 1 displays the MK and GGBS grading curve that was acquired using a hydrometer test. As indicated in Table 2, the "X-ray fluorescence test (XRF)" was used to ascertain the materials' chemical composition.

Samples preparation

Sulfate-bearing soil or sulfate-bearing soil was prepared artificially by mixing kaolin clay with 10% gypsum (by dry weight of soil) . The concentration of sulfate was determined as the worst case according to AASHTO [23,48–50] . The risk of different sulfate levels is summarized in Table 3.

Table 3. Severity of sulfate levels .

"Risk Level"	"Sulfate Concentration"	
	"Parts per Million"	"Percentage of Dry Weight"
Low risk	> 3000.0 ppm	> 03 %
Moderate risk	3000.0–5000.0 ppm	03 % – 05%
Moderate to high risk	5000.0–8000.0 ppm	05 % – 08%
High to unacceptable risk	>8000.0 ppm	> 08 %
Unacceptable risk	> 10,000 ppm	> 10 %

In accordance with [10,51,52], cylinder samples of 50 x 100 mm (diameter x height) were made for tests of unconfined compressive strength (UCS) and linear expansion (LP). As indicated in Table 4, each mixed system was compacted using the BS EN 13286–2:2010 standard [53] at maximum dry density (MMD) and optimum moisture content (OMC). Each sample was coated with cling film after compression to prevent moisture loss.

Table 4. Results of compaction test.

"Stabilizer"		MDD (Mg/m ³)	OMC (%)
Type	"Binder ratio" (%) 10%	"Dosage" (%) 10%	"Dosage" (%) 10%
K	0	1.326	29
Unary			
L	100	1.28	29.4
Binary			
L-MK	5:5	1.25	29.4
L-GGBS	5:5	1.29	28.6
Ternary			
L-MK-GGBS	5:2.5:2.5	1.29	29

The total binder content was fixed at 10% based on the weight of the soil (see Table 5) for each system (unary, binary, and ternary) . This was achieved using activator (L) calcium-based stabilizer at dosage of 10%, with (G) calcium sulfate dosed at 10% (as a worst case) into kaolin clay . The ratios of L stabilizer with (MK and GGBS) were set as (1:1) for Binder ratio 10% in a binary system, and (1:0.5:0.5) for Binder ratio 10% in a ternary system .

In total, 90 cylindrical samples were prepared : 54 for testing UCS, and 36 for LP.

Table 5. Mixture designs of stabilizer agents .

"Mix code"	"Binder composition"	"Binder ratio (%) 10%"
Unary		
K	K	-
K-L	L	100
K-G-L	L	100
Binary		
K-G-L-MK	M:MK	1:1
K-G-L-GGBS	M:GGBS	1:1
Ternary		
K-G-L-MK-GGBS	M:MK:GGBS	1:0.5:0.5

(K) Kaolin, (G) Gypsum, (L) lime, (MK) Metakaolin, (GGBS) Ground granulated blast-furnace slag. Experiments.

Linear Expansion Test (Swelling) (LP) Test

To determine the vertical swelling ratio (%), two cylindrical samples were made for each mix percentage and cured for seven days. After partial soaking in water, swelling readings were taken every 24 hours until no discernible swelling ratio was seen. In accordance with the BS EN 13286-49:2004 standard, the LP test was carried out [54].

Unconfined Compressive Strength (UCS) Test

For every mix proportion, the UCS test was carried out in accordance with BS EN ISO 17892-7:2018 [55]; the compressive strength of three cylindrical samples was assessed at curing ages (7, 28, and 90 days). Until failure, the samples were compressed and strained at a steady rate of 1 mm per minute.

Results and Discussion

Unconfined Compressive Strength (UCS) Test

Figure 2 depicts the effect of the L stabilizer on the UCS values after 7, 28, and 90 days of curing for the sulfate-bearing soil samples. The UCS values for L-treated samples increased to 570, 997, and 1766.33 kPa as compared to kaolin samples (without stabilizer), at curing periods (7, 28, and 90 days), respectively, due to an increase in the hydration process. This hydration process leads to the release of more calcium and produces extra cementitious materials, calcium-silicate hydrates (C-S-H) and calcium-aluminate hydrates (C-A-H). However, samples treated with L (10%) "showed a decrease in UCS values in the presence of sulfate (Figure 2)". The UCS values deteriorated from 570, 997, and 1766.33 to 523.67, 802.33, and 1643.33 kPa, at curing ages (7, 28, and 90 days), respectively. The observed deterioration in the UCS results can be attributed to ettringite production, the growth of which between the particles of the sample soil would lead to the destruction of the soil structure.

The effect of the MK showed an enhancement in the USC values for the L-treated samples during all curing periods (7, 28, and 90 days) in the presence of sulfate, relative to the K10G-10L samples. However, the treated samples with MK at long-term curing (90 days) exhibited lesser strength than soil samples treated lime alone (K-10L, without sulfate). This improvement could be due to the neoformation of pozzolanic product (C-S-H), which would have improved the USC value for the samples with L-MK. However, a possible reason for the loss in strength of the L-MK stabilized soil as compared to samples treated with 10%L (without sulfate) is the increased surface area caused by the availability of extensive amount of metakaolin or excess lime content, thereby making the mixture require more water and lime (calcium hydroxide) for hydration process with excess metakaolin content or making the binder to require more metakaolin (alumina and silica) with extra lime content [56]. Similar findings were reported by many researchers who conducted their studies on sulfate soil stabilization using lime and metakaolin-based geopolymers [57].

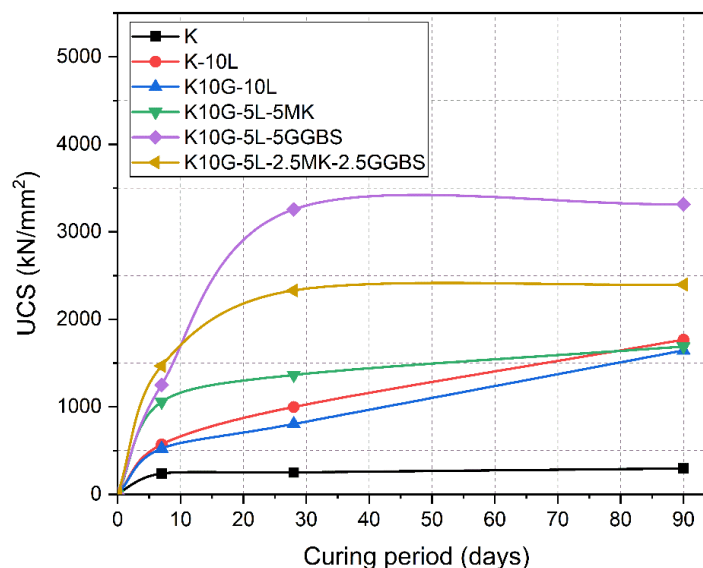


Figure 2. UCS of soils stabilized with 10% of L, and L-MK in the presence of sulfate at curing ages (7, 28, 90 days).

As for the L-GGBS stabilizer, such specimens showed the highest values of UCS at all the curing periods (7, 28, and 90 days), which were 1251.67, 3256, and 3315.67 kPa after curing for 7, 28, and 90 days, respectively. The improved strength of the treated soil is due to the strong bonding of soil particles due to the availability of more calcium, alumina, and silica contents, the availability of which promotes the faster development of bonds within the matrix of the treated soil. The GGBS utilized is characterized by 37% and 32.7% of calcium oxide and silicate content, respectively. This led to the relatively high availability of C-S-H, which improves the strength of stabilized clays [58]. The increase in UCS induced by lime and GGBS treatment was expected and agrees with other studies [59,60].

In comparison to samples treated with 10% L, the application of ternary binder compositions (5L-2.5MK-2.5GGBS) produced an enhanced UCS performance. Nevertheless, after 7, 28, and 90 days of curing, the enhancement was lower than that of samples treated with 5L-5GGBS samples, which were 1468.33, 2330.33, 2396.33, and 2697 kPa, respectively. The hydration procedure after the curing time was extended from 7 to 90 days, which should guarantee adequate hydration, enhanced strength, and resistance against sulphate attacks, may have contributed to this improvement in the UCS values [37]. Additionally, ettringite formation was inhibited by the generation of more cementitious gels, such as calcium silicate hydrates (C-S-H), calcium aluminate hydrates (C-A-H), and calcium aluminosilicate hydrates (C-S-A-H), which helped to consume the available calcium [61].

Linear Expansion Test (Swelling) (LP) Test

Following seven days of moist curing, Figure 3 shows the typical swelling plots for K clay, K-L, K-L-G, K-L-M, and K-L-M-G clay systems dosed with 10% wt of gypsum and 10% wt of L. After soaking the cylinder samples in water, swelling was seen right away, and it persisted during monitoring until it stopped. This investigation showed a comparatively higher rate of swelling than the expansion of sulfate-bearing soils stabilised by lime, as reported by [14,19].

Figure 3 shows the higher degree of swelling obtained for a calcium-based stabilizer (10% wt), which was 25.22% in the case of 10% lime. It can be inferred that there was an increase in swelling with an increase in lime content due to the availability of extra calcium, leading to the formation of more ettringite, which significantly contributes to raising the expansion magnitude [62].

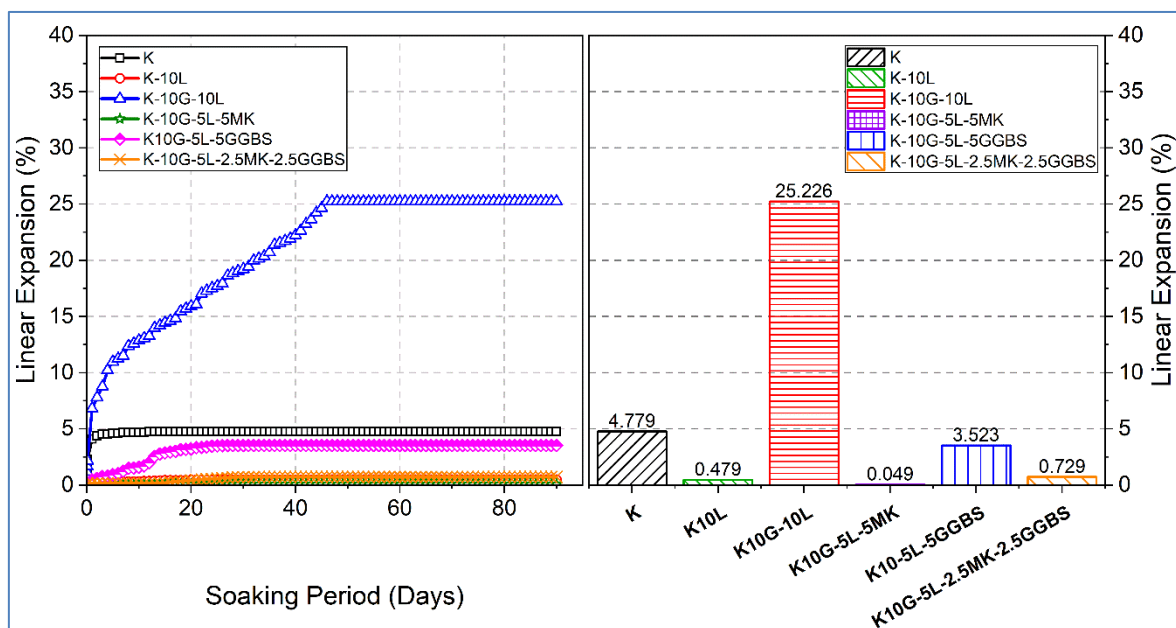


Figure 3. Vertical swelling strain of soil specimens stabilized with 10% of L, 5L-5MK, 5L-5GGBS, and L-MK-GGBS after 7 days of curing.

All sulfate-bearing soil sample showed a limitation in volume change (swelling) when the L-MK stabiliser was used. 5L-5MK had the lowest swelling value (0.04%), while 10% lime had the highest value (25.22%). The inhibition of ettringite formation and the increased synthesis of C-S-H compounds in the absence of calcium are responsible for this decrease in swelling. The observed results were significantly lower than those reported by

[18], who used MK-based geopolymer in the presence of 5% sulphate and reported a reduction in the expansion magnitude to 1.5%.

Sulfate-bearing soil treated with L-GGBS stabiliser showed less swelling in terms of vertical volume change (swelling), whereas soil samples stabilised with 5L-5GGBS showed a swelling of 3.52%. The adoption of GGBS, which demonstrated higher sulphate resistance in addition to its denser structure and reduced Ca^{2+} concentration, was responsible for the decrease in swelling values [59]. The use of the L-GGBS-MK stabiliser considerably lessens the amount of swelling in the sulfate-bearing soil and further alters the behaviour of the volumetric change. The swelling magnitudes for 5L-2.5MK-2.5GGBS were 0.72% after 7 days of observation, and the swelling values were suppressed to almost 97%.

The linear expansion test results showed that the high-sulfate soil treated with the L-MK and L-MK-GGBS stabilisers had limited swelling behaviour. The treated high-sulfate soils showed improved swelling characteristics, as evidenced by the fact that their volume changes were smaller than those of the K-L-G. There are two explanations for this phenomenon: (1) More calcium in the lime-stabilized soil leads to the synthesis of ettringite when sulphate is present, and (2) sulphate consumes calcium, which reduces the formation of cementitious material such C-S-H, C-A-H, and C-S-A-H. According to Ehwailat et al. [11], oedema varies in intensity. The K-10L-10G mixing in this investigation had the highest expansion of 25.226%. The soil samples (K-10L-10G) can produce excessive swelling when they come into contact with water since their maximum expansion is greater than 2%, according to the level of swelling displayed in Table 6.

Table 6. Levels of swelling for clay soil .

"Swelling (%)"	"Swelling level"
0.00	"No swell"
0.00–0.10	"Negligible"
0.10–0.50	"Light"
0.50–1.00	"Medium"
1.00–2.00	"Strong"

Conclusion

Because of their considerable swelling and strength loss, sulfate-bearing soils pose serious problems for pavement and other civil engineering projects. The study's findings demonstrated the effectiveness of using MK and GGBS in place of some of the conventional stabilisers (L) when treating high-sulfate soils. The study's findings led to the following deductions being made.:

Stabilization of sulfate-bearing soil with lime induced a massive expansion behaviour due to the ettringite nucleation.

The binary blend of L-GGBS yielded the best strength performance, the binary blend of L-Mk induced the lowest expansion behaviour, while ternary blend of L-GGBS-MK experienced a balanced performance in between.

Because of the effects of the hydration process, the curing period has had a major impact on the sample's resistance against sulphate assault. Increased strength and proper hydration in the presence of sulphate (gypsum) were the results of extending the curing period from 7 to 90 days.

Because cementing gels like C-S-H and C-A-H filled in the spaces and strengthened the link between the soil particles, they increased the UCS values of the stabilised samples. Consequently, the UCS values of the treated soils increased.

The L-MK- and L-MK-GGBS binders were demonstrated as suitable and effective agents for stabilizing sulfate-bearing soil.

References

1. Chemed, Y.C.; Deneele, D.; Ouvrard, G. Short-term lime solution-kaolinite interfacial chemistry and its effect on long-term pozzolanic activity. *Applied Clay Science* **2018**, *161*, 419–426, doi:10.1016/j.clay.2018.05.005.
2. Aldaood, A.; Bouasker, M. Mechanical Behavior of Gypseous Soil Treated with Lime. *Geotechnical and Geological Engineering* **2020**, doi:10.1007/s10706-020-01517-w.
3. Phanikumar, B.R.; Singla, R. Swell-consolidation characteristics of fibre-reinforced expansive soils. *Soils and Foundations* **2016**, *56*, 138–143, doi:10.1016/j.sandf.2016.01.011.

4. Phanikumar, B.R.; Nagaraju, T. V. Effect of Fly Ash and Rice Husk Ash on Index and Engineering Properties of Expansive Clays. *Geotechnical and Geological Engineering* **2018**, *36*, 3425–3436, doi:10.1007/s10706-018-0544-5.
5. Hozathloglu, D.T.; Yilmaz, I. Shallow mixing and column performances of lime , fly ash and gypsum on the stabilization of swelling soils. *Engineering Geology* **2021**, *280*, doi:10.1016/j.enggeo.2020.105931.
6. Cai, G.; Liu, S.; Du, G.; Chen, Z.; Zheng, X.; Li, J. Mechanical performances and microstructural characteristics of reactive MgO-carbonated silt subjected to freezing-thawing cycles. *Journal of Rock Mechanics and Geotechnical Engineering* **2021**, *13*, 875–884, doi:10.1016/j.jrmge.2021.03.005.
7. Sindhu, A.R.; Minukrishna, P.; Abraham, B.M. Experimental Study on the Impact of Type of Sulphate in Lime Stabilised Clays. In Proceedings of the International Web Conference in Civil Engineering for a Sustainable Planet; AIJR Publisher: India in, 2021.
8. Caselles, L.D. Stabilisation des sulfates et du molybdène par des liants alternatifs, University of Toulouse, 2020.
9. Khaled Ehwaitat; Mansour Ebailila; Alissawi Asbeiai; Muftah Aljoat; Saleh Ben Lamma The Effect of Variation in Water Compaction and Blending Approach on the Performance of Gypsum-Based Soil Stabilized with Cement and Silica Fume . *المجلة الأفروآسيوية للبحث العلمي (AAJSR)* **2025**, *3*, 429–437.
10. Li, W.; Yi, Y.; Puppala, A.J. Suppressing Ettringite-Induced Swelling of Gypseous Soil by Using Magnesia-Activated Ground Granulated Blast-Furnace Slag. *Journal of Geotechnical and Geoenvironmental Engineering* **2020**, *146*, 1–6, doi:10.1061/(ASCE)GT.1943-5606.0002292.
11. Ehwaitat, K.I.A.; Ismail, M.A.M.; Ezreig, A.M.A. Novel Approach to the Treatment of Gypseous Soil-Induced Ettringite Using Blends of Non-Calcium-Based Stabilizer, Ground Granulated Blast-Furnace Slag, and Metakaolin. *Materials* **2021**, *14*, 25–27, doi:10.3390/ma14185198.
12. Raja, P.S.; Thyagaraj, T. Significance of compaction time delay on compaction and strength characteristics of sulfate resistant cement-treated expansive soil. *Journal of Rock Mechanics and Geotechnical Engineering* **2021**, doi:10.1016/j.jrmge.2021.03.003.
13. Ebailila, M.; Kinuthia, J.; Oti, J. Role of Gypsum Content on the Long-Term Performance of Lime-Stabilised Soil. *Materials* **2022**, 1–14, doi:https://doi.org/10.3390/ma15155099.
14. Seco, A.; Miqueleiz, L.; Prieto, E.; Marcelino, S.; García, B.; Urmeneta, P. Sulfate soils stabilization with magnesium-based binders. *Applied Clay Science* **2017**, *135*, 457–464, doi:10.1016/j.clay.2016.10.033.
15. N Alsharaa, N Saleh, M Ebailila, A.M. *The role of moisture content, mixing method and sample size on the swelling of sulfate soil stabilised with lime-silica fume blend*; 2023; Vol. 16; ISBN 0123456789.
16. Ebailila, M.; Kinuthia, J.; Oti, J.; Muhmed, A. A comparative study on the long-term microstructure of soil stabilisation with calcium and magnesium-based binders. *Journal of Bani Waleed University for humanities and Applied Science* **2023**, doi:10.58916/jhas.v8i3.169.
17. Eyo, E.U.; Abbey, S.J.; Ngambi, S.; Ganjian, E.; Coakley, E. Incorporation of a nanotechnology-based product in cementitious binders for sustainable mitigation of sulphate-induced heaving of stabilised soils. *Engineering Science and Technology, an International Journal* **2020**, doi:10.1016/j.jestch.2020.09.002.
18. Khadka, S.D.; Jayawickrama, P.W.; Senadheera, S.; Segvic, B. Stabilization of highly expansive soils containing sulfate using metakaolin and fly ash based geopolymer modified with lime and gypsum. *Transportation Geotechnics* **2020**, *23*, 100327, doi:10.1016/j.trgeo.2020.100327.
19. Bazyar, M.H.; Ebrahimi, M.; Lenjani, M.Z.; Makarchian, M. The Effect of Rice Husk Ash on Mechanical Properties of Clayey Soils Stabilized with Lime in the Presence of Sulphate. *Journal of Engineering Geology* **2017**, *11*, 23–52.
20. Perlot, C.; Marcelino-s, S.; Prieto, E. Experimental Study of the Valorization of Sulfate Soils for Use as Construction Material. *Sustainability* **2022**, *14*, 1–11.
21. Rajasekaran, G. Sulphate attack and ettringite formation in the lime and cement stabilized marine clays. **2005**, *32*, 1133–1159, doi:10.1016/j.oceaneng.2004.08.012.
22. Pavoiné, A.; Brunetaud, X.; Divet, L. The impact of cement parameters on Delayed Ettringite Formation. *Cement and Concrete Composites* **2012**, *34*, 521–528, doi:10.1016/j.cemconcomp.2011.11.012.
23. Ehwaitat, K.I.A.; Ismail, M.A.M.; Ezreig, A.M.A. Ettringite Formation and Stabilization Methods of Sulfate-Bearing Soil: A State-of-the-Art Review. *Indian Geotechnical Journal* **2022**, *52*, 927–941, doi:10.1007/s40098-022-00619-x.
24. Ouhadi, V.R.; Yong, R.N. The role of clay fractions of marly soils on their post stabilization failure. *Engineering geology* **2003**, *70*, 365–375.

25. Ouhadi, V.R.; Yong, R.N. Ettringite formation and behaviour in clayey soils. *Applied Clay Science* **2008**, *42*, 258–265.
26. Min, Y.; Jueshi, Q.; Ying, P. Activation of fly ash–lime systems using calcined phosphogypsum. *Construction and building materials* **2008**, *22*, 1004–1008.
27. Jin, F.; Al-Tabbaa, A. Evaluation of novel reactive MgO activated slag binder for the immobilisation of lead and zinc. *Chemosphere* **2014**, *117*, 285–294, doi:10.1016/j.chemosphere.2014.07.027.
28. Cai, G.H.; Liu, S.Y.; Zheng, X. Influence of drying-wetting cycles on engineering properties of carbonated silt admixed with reactive MgO. *Construction and Building Materials* **2019**, *204*, 84–93, doi:10.1016/j.conbuildmat.2019.01.125.
29. Yi, Y.; Liska, M.; Al-Tabbaa, A. Initial investigation into the use of GGBS-MgO in soil stabilisation. *Grouting and Deep Mixing* **2012**, 444–453.
30. Yi, Y.; Liska, M.; Jin, F.; Al-tabbaa, A. Mechanism of reactive magnesia – ground granulated blastfurnace slag (GGBS) soil stabilization. *Canadian Geotechnical Journal* **2016**, *55*, 773–782, doi:10.1139/cgj-2015-0183.
31. Ehwailat, K.I.A.; Ismail, M.A.M.; Ezreig, A.M.A. Novel Approach for Suppression of Ettringite Formation in Sulfate-Bearing Soil Using Blends of Nano-Magnesium Oxide, Ground Granulated Blast-Furnace Slag and Rice Husk Ash. *applied sciences Article* **2021**, *11*, 23–26, doi:10.3390/app11146618.
32. ASTM C618-05., (AASHTOM295) *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for use in Concrete*; ASTM International, West Conshohocken, 2005;
33. *AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing*; American Association for State Highway and Transportation Officials, 14th Ed. Washington, D.C, 1996;
34. Bayang, F.; Academy, N.D.; Garba, H.; Academy, N.D.; Sani, J.E.; Academy, N.D. Laboratory Assessment of Metakaolin Effect on the Volumetric Shrinkage of Black Cotton Soil for Flexible Pavement Construction. *Civil and Environmental Research* **2017**, *9*, 16–29.
35. Billong, N.; Kinuthia, J.; Oti, J.; Melo, U.C. Performance of sodium silicate free geopolymers from metakaolin (MK) and Rice Husk Ash (RHA): Effect on tensile strength and microstructure. *Construction and Building Materials* **2018**, *189*, 307–313, doi:10.1016/j.conbuildmat.2018.09.001.
36. Thankam, G.L.; Thurvas Renganathan, N. Ideal supplementary cementing material – Metakaolin: A review. *International Review of Applied Sciences and Engineering* **2020**, *11*, 58–65, doi:10.1556/1848.2020.00008.
37. Seco, A.; del Castillo, J.M.; Espuelas, S.; Marcelino, S.; García, B. Sulphate soil stabilisation with magnesium binders for road subgrade construction. *International Journal of Pavement Engineering* **2020**, 1–11, doi:10.1080/10298436.2020.1825711.
38. Pai, R.R.; Patel, S.; Bakare, M.D. Applicability of Utilizing Stabilized Native Soil as a Subbase Course in Flexible Pavement. *Indian Geotechnical Journal* **2020**, *50*, 289–299, doi:10.1007/s40098-020-00432-4.
39. Truong, S.B.; Thi, N.N.; Thanh, D.N. An Experimental Study on Unconfined Compressive Strength of Soft Soil-Cement Mixtures with or without GGBFS in the Coastal Area of Vietnam. *Advances in Civil Engineering* **2020**, *2020*, 20–25.
40. Pal, S.C.; Mukherjee, A.; Pathak, S.R. Investigation of hydraulic activity of ground granulated blast furnace slag in concrete. *Cement and Concrete Research* **2003**, *33*, 1481–1486, doi:10.1016/S0008-8846(03)00062-0.
41. VÁCLAVÍK, V.; DIRNER, V.; DVORSKÝ, T.; Daxner, J. The use of blast furnace slag. *Metalurgija* **2012**, *51*, 461–464.
42. Yu, B.W.; Du, Y.J.; Jin, F.; Liu, C.Y. Multiscale study of sodium sulfate soaking durability of low plastic clay stabilized by reactive magnesia-activated ground granulated blast-furnace slag. *Journal of Materials in Civil Engineering* **2016**, *28*, 1–10, doi:10.1061/(ASCE)MT.1943-5533.0001517.
43. Ehwailat, K.; Ebailila, M.; Ezreig, A.; Aljoat, M. Optimization of Cement-Silica Fume Blends for The Suppression of Sulphate Soil Swelling. *The North African Journal of Scientific Publishing (NAJSP)* **2025**, *3*, 227–235.
44. British Standards Institution *BS EN ISO 17892-4:2016: GGeotechnical investigation and testing. Laboratory testing of soil Part 4: Determination of particle size distribution*; BSI Standards Ltd: London, UK, 2014;
45. Wu, Z.; Deng, Y.; Liu, S.; Liu, Q.; Chen, Y.; Zha, F. Strength and micro-structure evolution of compacted soils modified by admixtures of cement and metakaolin. *Applied Clay Science* **2016**, *127–128*, 44–51, doi:10.1016/j.clay.2016.03.040.
46. Sazali, N.; Harun, Z.; Tijani Abdullahi; Azhar, F.H.; Sazali, N. Revolution of Malaysia's Kaolin to Metakaolin towards various application: A Mini Review. *JOURNAL OF MODERN MANUFACTURING SYSTEMS AND TECHNOLOGY* **2019**, *4*, 722–728, doi:10.1016/j.eng.2018.07.020.

47. He, J.; Li, Z.X.; Wang, X.Q.; Shi, X.K. Durability of Soft Soil Treated with Soda Residue and Ground Granulated Blast Furnace Slag in a Soaking Environment. *Journal of Materials in Civil Engineering* **2020**, *32*, 1–10, doi:10.1061/(ASCE)MT.1943-5533.0003033.
48. National Academies of Sciences, E.A.M. *Recommended Practice for Stabilization of Sulfate-Rich Subgrade Soils*; The National Academies Press: Washington, 2009; ISBN 9780309429825.
49. Puppala, A.J.; Talluri, N.; Chittoori, B.C.S. Calcium-based stabiliser treatment of sulfate-bearing soils. *Proceedings of the Institution of Civil Engineers - Ground Improvement* **2014**, *167*, 162–172, doi:10.1680/grim.13.00008.
50. Talluri, N.; Puppala, A.J.; Congress, S.S.C.; Banerjee, A. Experimental Studies and Modeling of High Sulfate Soil Stabilization. *Journal of Geotechnical & Geoenvironmental Engineering* **2020**, *146*, 1–16 (in-press), doi:10.1061/(ASCE)GT.1943-5606.0002240.
51. Chegenizadeh, A.; Keramatikerman, M.; Miceli, S.; Nikraz, H. Investigation on Recycled Sawdust in Controlling Sulphate Attack in Cemented Clay. *Applied Sciences* **2020**, *10*, 20–21, doi:10.3390/app10041441.
52. Ebailila, M.; Kinuthia, J.; Oti, J. Suppression of Sulfate-Induced Expansion with Lime–Silica Fume Blends. *Materials* **2022**, *8*, 2–17, doi:10.3390/ma15082821 Academic.
53. British Standards Institution *BS EN 13286-2:2010: Unbound and hydraulically bound mixtures Part 2 : Test methods for laboratory reference density and water content — Proctor compaction*; BSI Standards Ltd: London, UK, 2012;
54. British Standards Institution *BS EN 13286-49:2004: Unbound and hydraulically bound mixtures Accelerated swelling test for soil treated by lime and/or hydraulic binder*; BSI Standards Ltd: London, UK, 2004;
55. British Standards Institution *BS EN ISO 17892-7:2018: Geotechnical investigation and testing. Laboratory testing of soil Part 7 :Unconfined compression test strength*; BSI Standards Ltd: London, UK, 2018;
56. Muhammad, A.; Polytechnic, K.S.; Yusuf, A. Assessment of Lateritic Soil stabilized using Metakaolin. *Journal of Geotechnical Studies* **2021**, doi:10.5281/zenodo.3676443.
57. Jang, J.; Puppala, A.J.; Biswas, N.; Chakraborty, S.; Radovic, M. Utilization of Metakaolin-Based Geopolymers for Stabilization of Sulfate-Rich Expansive Soils. In *Proceedings of the Geo-Congress 2022 GSP 331*; 2022; pp. 222–231.
58. Darsi, B.P.; Molugaram, K.; Madiraju, V.S.H. Subgrade Black Cotton Soil Stabilization Using Ground Granulated Blast-Furnace Slag (GGBS) and Lime, an Inorganic Mineral. *Environmental Sciences Proceedings* **2021**, 1–15, doi:10.3390/iecms2021-09390 Academic.
59. Abbey, S.J.; Eyo, E.U.; Jeremiah, J.J. Experimental Study on Early Age Characteristics of Lime-GGBS-Treated Gypseous Clays under Wet – Dry Cycles. *Geotechnics* **2021**, 402–415, doi:10.3390/geotechnics1020019 Academic.
60. Al-dakheeli, H.; Asce, S.M.; Bulut, R.; Asce, M.; Garland, G.S.; Clarke, C.R. Utilization of Blast-Furnace Slag as a Standalone Stabilizer for High Sulfate-Bearing Soils. *Journal of Materials in Civil Engineering* **2021**, *33*, 1–10, doi:10.1061/(ASCE)MT.1943-5533.0003880.
61. Devi, A.; Bishnoi, M. Strength Parameter of Rigid Pavement by Replacing Cement with Metakaolin, GGBS and Silica Fumes Article. *Journal of Xidian University* **2020**, *14*, doi:10.37896/jxu14.9/140.
62. Mansour Ebailila; Khaled Ehwalat; Saleh Ben Lamma; Muftah Aljoat Engineering properties of concrete made with GGBS and pulverised fuel ash . *African Journal of Advanced Pure and Applied Sciences (AJAPAS)* **2025**, *4*, 234–244.