Turkish Journal of Civil Engineering, 2027, xxxx-xxxx, Paper xxx, ***Research Article***

Stabilization Of Sulfate-Rich Soils Mixed With Siliceous Sand At Varying Ratios Using Portland Cement, Sulfate-Resistant Cement, Fly Ash, And Lime

Ayşe Gül HORUZ[1]
Erol ŞADOĞLU[2*]

ABSTRACT

Stabilization of Sulfate-Rich Soils Mixed with Siliceous Sand at Varying Ratios Using Portland Cement, Sulfate-Resistant Cement, Fly Ash, and Lime

Sulfate-rich soils (SRS) are commonly located in various regions of the world, including in USA. In current studies, it has been detected that stabilization of the soils, containing excessive amounts of sulfates or organic matter, using calcium-containing binders can result in undesirable phenomena, including heaving, swelling, cracking, and fracturing. In light of these challenges, this study initially involved blending SRS with siliceous sand (SS) at varying ratios to produce soil mixtures of different sulfate content. These mixtures were then stabilized using different binders, namely ordinary Portland cement (CEM I 42.5), sulfate-resistant cement (CEM I 42.5-R-SR5), Class F fly ash (FFA), and lime. The prepared samples underwent curing for 7 and 28 days, after which unconfined compressive strength (UCS) tests were performed. Following the 28-day curing period, durability tests were also conducted to assess the long-term performance of the stabilized specimens. The results from both strength and durability evaluations are presented in tabular and graphical formats. Among the various combinations tested, the best performance in terms of both strength and durability was achieved with a mixture containing 25% sulfate soil and 75% siliceous sand, stabilized with 20% CEM I 42.5-R-SR5. Conversely, the poorest performance was observed in the specimen comprising a 50:50 sulfate soil–siliceous sand mixture stabilized with 10% CEM I 42.5-R-SR5.

Key Words: Sulfate-rich soil, siliceous sand, soil stabilization, cement, fly ash, lime.

Note:
- This paper was received on April 3, 2026 and accepted for publication by the Editorial Board on September 29, 2026.
- Discussions on this paper will be accepted by xxxxxxx xx, xxxx.
- https://doi.org/

1 Karadeniz Technical University, Department of Civil Engineering, Trabzon, Türkiye
aysegulxcelik@gmail.com - https://orcid.org/0000-0002-9293-9060
2 Karadeniz Technical University, Department of Civil Engineering, Trabzon, Türkiye
esadoglu@ktu.edu.tr - https://orcid.org/0000-0003-3757-5126
* Corresponding author

PREPRINT

INTRODUCTION

Soils must possess the capacity to reliably sustain both the structural loads and the structure itself. Accordingly, the subgrade intended for construction must demonstrate adequate geotechnical properties. In instances where soil conditions are deemed inadequate in terms of bearing capacity or are susceptible to excessive settlement, it is essential to implement appropriate ground improvement techniques prior to the commencement of construction activities. The primary objectives of such stabilization interventions are to enhance the soil's load-bearing capacity, limit potential deformations and settlements, and reduce its permeability, in alignment with the specific functional and structural demands of the proposed development. Over time, numerous ground improvement methods have been developed, which are generally classified into two main groups: mechanical and chemical methods.

Mechanical stabilization techniques encompass procedures such as compaction, pre-wetting, soil strengthening, and electrokinetic cure. In contrast, chemical stabilization involves incorporating additives like cement, lime, fly ash (FA), or various salts into soil, followed by thorough mixing [1]. The selection of an appropriate additive in chemical stabilization is effected by various factors, soil type, intended engineering function, and characteristics of the surrounding environment [2].

In civil engineering practice, calcium-containing binders are widely utilized to recover the mechanical features of weak soils. Nevertheless, research has demonstrated that stabilizing sulfate-bearing soils with lime may adversely influence the strength and long-term durability of the improved soils due to formation of expansive chemical reactions, particularly the occurrence of ettringite [3]. Specifically, when calcium-based stabilizers are introduced into SRS, deleterious reactions can cause to the occurrence of ettringite, a mineral known for inducing swelling and structural instability. The reaction mechanism involved in the occurrence of ettringite has been outlined by Hunter (1989) [4]. Figure 1 presents the stages involved in the occurrence mechanism of ettringite.

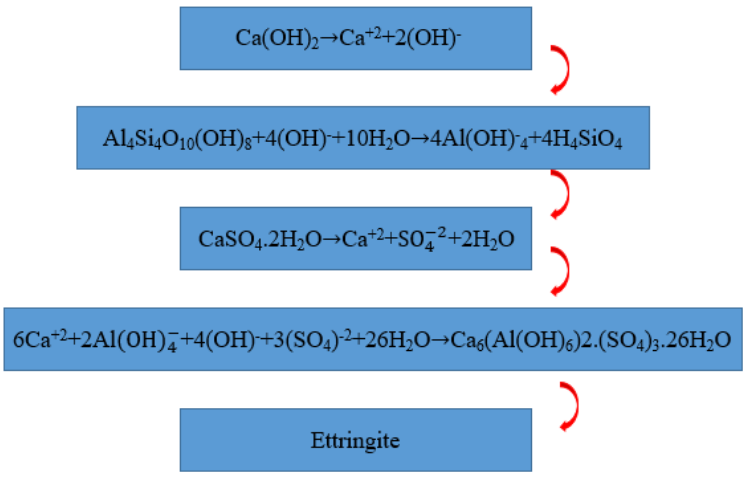

Fig 1 - Reaction mechanism involved in the occurrence of ettringite.

During the aforementioned reaction process, addition of lime creates a highly alkaline environment, elevating soil pH to approximately 12.3. This high pH facilitates release of substantial amount of calcium ions (Ca^{2+}) into soil matrix. Concurrently, when soil pH exceeds 10.5, clay minerals undergo chemical transformations, resulting in formation of aluminum hydroxide and silicic acid. Additionally, dissolution of gypsum contributes to release of sulfate ions (SO_4^{2-}) into the system. In the presence of moisture, these calcium and sulfate ions react with available aluminates to form ettringite, a hydrous calcium aluminum sulfate mineral known for causing volumetric expansion in stabilized soils [5].

The existing literature cautions against use of lime-cement treatment in natural soils with high sulfate content, recommending that such methods be applied with great care—or avoided altogether—due to the risk of deleterious chemical reactions. In response to these challenges, alternative stabilizers and innovative techniques have been developed specifically for the improvement of SRS [6]. Puppala et al. [7] managed a study on the stabilization of SRS using sulfate-resistant cements. In a separate study, Zhang et al. [8] explored the potential of geopolymers with no calcium as stabilizing binders for SRS. Their results indicated that calcium-free geopolymers effectively stabilized such soils without inducing excessive expansion. Talluri et al. [9] researched the impact of pre-compaction on the stabilization performance of SRS and observed that pre-compaction effectively prevented shrinkage in the treated soils. Puppala et al. [10] have achieved significant increases in small stress shear moduli by stabilizing natural and artificial clays of low sulfate content (1000 ppm) using cement and lime.

Additionally, Adeleke et al. [11] employed a binder comprised of granulated blast furnace slag (GGBS) and waste-derived magnesium oxide (MgO) to stabilize SRS, reporting promising outcomes. In another study, Alsafi et al. [12] evaluated impacts of intrinsic sulfate concentration on settlement potential of gypsiferous soils stabilized with a FA-based geopolymer binder. Using potassium hydroxide (KOH, 12 M) to activate the FA, they assessed both the settlement behavior and permeability characteristics of the stabilized soil. Consoli et al. [13] investigated effect of mixing lime, fly ash, and lime amount on the stabilization performance of sulfate-rich, dispersive, swelling clayey soil. Caselles et al. [3] examined stabilization of SRS through incorporation of hydraulic binders. Their findings indicated that favorable results could be achieved when ground GGBS was employed as the primary stabilizing agent for sulfate-bearing soils. Similarly, Celik et al. [14] studied the use of GGBS during stabilization of sulfate-containing clayey soils and highlighted its effectiveness in enhancing soil performance. Shooshpasha and Shirvani [15] aimed to stabilize sandy soils using cement. They observed that stabilizing sandy soils with cement resulted in an increase in strength parameters and a decrease in displacement at failure. Talluri et al. [16] conducted an experimental study to evaluate the effectiveness of lime stabilization with pre-softening on six different sulfate-rich soils. Adams et al. [17] aimed to determine the sulfate threshold level at which adverse reactions occur as a result of lime stabilization in soils located in Oklahoma. Loskutova et al. [18] investigated the effects of using calcium sulfoaluminate cement in combination with phosphogypsum (PG) to increase the compressive strength of sand.

Doğruyol [19] researched influence of SRS on unconfined compressive strength (UCS) of concrete, particularly in Siirt and Batman cities of Türkiye. In another study, Ebailila et al. [20] showed that the joined use of silica fume-GGBS as lime precursors constitutes an

effective strategy for improving the behavior of SRS. Khadka et al. [5] explored the stabilization performance of two types of geopolymers—FA and metakaolin-based—synthesized from aluminosilicate sources. Their results revealed these geopolymers' capacity to control shrink-swell behavior in the expansive SRS. Consoli et al. [21] aimed to improve mechanical properties of sulfate-rich dispersive soils using a binder consisting of carbide lime and ground glass, and fiberglass. Jumassultan et al. [22] investigated the effect of cyclic freeze-thaw action on both the strength and durability properties of sand stabilized with calcium sulfoaluminate cement. Canakci et al. [23] attempted to stabilize expansive soils using lignin, rice husk powder, and rice husk ash.

McCarthy et al. [24] assessed mechanical properties of soils treated with a blend of treated lime and low-lime FA, focusing on mitigating sulfate-induced expansion during ground improvement activities. Parhizkar et al. [25] investigated synergistic influences of combining GGBS, lime, and FA to enhance the geotechnical features of SRS. Additionally, Rahmat and Kinuthia [26] conducted research on swelling behavior of stabilized sulfate containing clayey soil. Saygılı et al. [27] also carried out experimental studies on the stabilization of SRS, contributing further insights into appropriate treatment approaches for such problematic soils. Seco et al. [28] assessed stabilization potential of five different SRS using an alternative magnesium-based additive—PC-8—an industrial by-product, as a substitute for conventional calcium-based binders.

In a related investigation, Wild et al. [29] assessed the influence of combining ground GGBS with lime on strength characteristics of gypsum-containing clayey soils. Their findings exposed that the synergistic use of lime and GGBS during the stabilization of gypsum-containing clays led to substantial enhancements in strength development, making it a promising approach for the treatment of such problematic soils. In the study, the deep soil mixing (DSM) technique was also employed as part of the soil stabilization process. DSM involves in-situ blending of soil with binder materials through specialized machinery, typically equipped with counter-rotating augers [30]. In Sweden, for instance, lime columns have been successfully utilized to stabilize soft clay soils [31].

DSM has gained widespread application in the United States, particularly for addressing infrastructure-related challenges, mitigating seismic risks, and supporting regional ground rehabilitation efforts [32 - 33]. Chen et al. [34] through centrifuge modeling, investigated the mechanisms of soil–structure interaction in excavation scenarios. Their results indicated that DSM columns installed in soft soils significantly enhanced the stability of anchored sheet pile walls retrofitted with cementitious materials.

Esmaeili et al. [35] conducted research to address the challenges associated with saline and loose soils by applying the DSM method enhanced with micro silica additives. Their findings revealed that increased soil salinity adversely affected the mechanical performance of the treated soils, resulting in reduced Young’s modulus and UCS after 28 days of curing. In a related experimental study, Fidan [36] investigated the factors influencing the performance of DSM columns formed using amorphous silica in stratified soils. The results demonstrated that amorphous silica significantly improved the permeability characteristics of the treated grounds. Similarly, Paulo et al. [37] reported that the implementation of DSM columns contributed to a reduction in both total and differential settlements beneath an embankment, indicating enhanced ground stability and performance. In a complementary study, Shen and Han [38] researched the influence of DSM columns on the geotechnical features of

surrounding grounds during and after installation. Celik and Sadoglu [39] investigated the stabilization of sulfate-rich soils with high sulfate concentrations using geopolymer binders. Their findings revealed that GGBS and fly ash (FA)—which are used as binding materials in geopolymer production—are more effective in promoting early-stage strength development, while metakaolin (MK) makes a more significant contribution to long-term strength gain.

Previous studies on sulfate-rich soils were thoroughly examined and the review indicated that no studies were available on soils with high sulfate content. The soil mixtures with different sulfate concentrations were prepared by blending the sulfate-rich soil with siliceous sand at various proportions. The objective of preparing mixtures consisting of sulfate-rich soil and siliceous sand was to obtain soils with different sulfate concentrations. Thus, the study aimed to evaluate the stabilization of soils with varying sulfate concentrations using different types of cement and stabilizing additives. The incorporation of binders are carried out using procedures developed for traditional deep soil mixing applications.

1. MATERIALS AND TESTING PROGRAM

1.1. Sulfate-Rich Soil

The SRS was sourced from a site located in Çorum, Turkey. The sulfate-rich soil used in this study was oven-dried, ground, and sieved prior to testing to improve its homogeneity and workability. However, during the laboratory tests performed to determine the physical properties of the soil, problems such as rapid stiffening, flash setting, and premature hardening were encountered due to its extremely high sulfate content. These issues prevented the reliable determination of the particle size distribution of the sulfate-rich soil. Therefore, within the scope of this study, the characterization of the soil was primarily focused on determining its sulfate concentration. The sulfate content was determined using both quantitative X-ray diffraction (XRD)/Rietveld analysis and gravimetric testing.

XRD was performed to characterize the mineralogical composition of the SRS. The resulting diffraction patterns are shown in Figure 2. Based on the Rietveld refinement of the XRD data, the major mineral phases and their estimated weight percentages were identified as follows: calcite ($CaCO_3$) – 11.8%, albite ($NaAlSi_3O_8$) – 18%, and gypsum ($CaSO_4 \cdot 2H_2O$) – 35%. The total sulfate concentration of the soil, as determined from the XRD results, was approximately 195 300 ppm (mg/kg).

In addition to the mineralogical analysis, the sulfate concentration of the SRS was also calculated through experimental methods. Gravimetric analysis was conducted to quantify the sulfate content. According to the results of this procedure, the sulfate content of the SRS was approximately 252 300 ppm (mg/kg). Figure 3 illustrates the stages of the experimental procedure conducted to determine the sulfate content in the SRS.

The sulfate concentration of the soil was assessed using both experimental methods and theoretical estimations. A comparison of the results obtained from these two approaches

PREPRINT

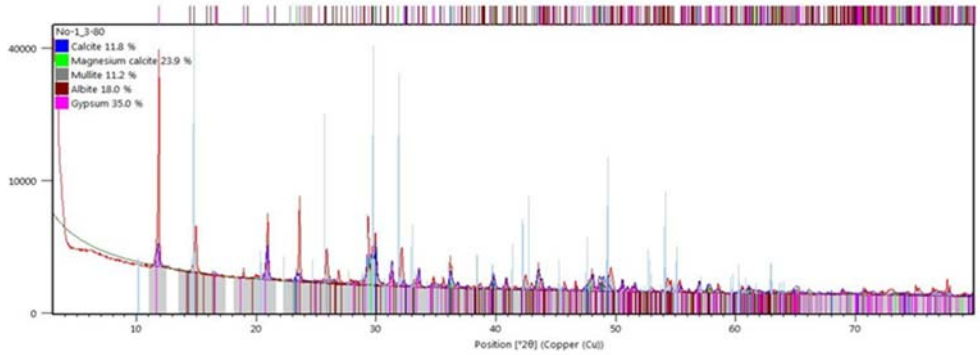

Fig 2 - XRD pattern of the SRS sample.

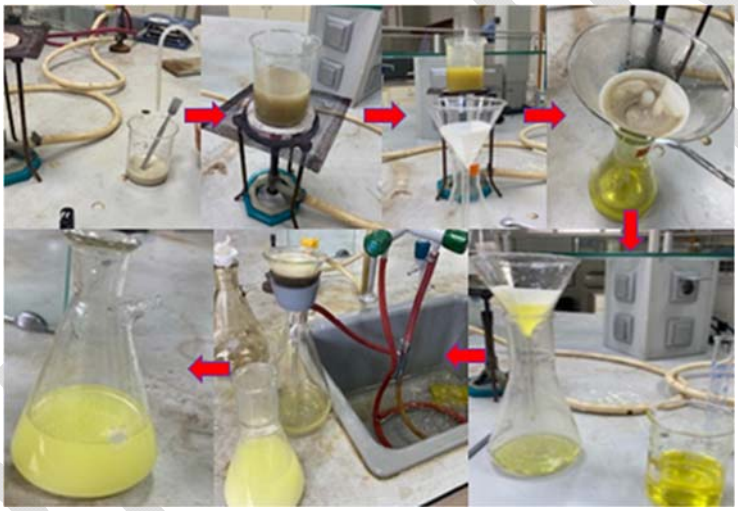

Fig 3 - Determination of sulfate concentration in soil samples through laboratory-based gravimetric analysis.

revealed a strong level of agreement, within the acceptable range of experimental uncertainty. Both methods consistently confirmed that the sulfate concentration in the tested soil was significantly high (average approximately 223,800 ppm) .

1.2. Siliceous Sand

The SS characterized through sieve analysis conducted in accordance with ASTM D422 (2007) [40]. Based on the resulting grain size distribution curve, the specific particle diameters were determined as D_{10} = 0.15 mm, D_{30} = 0.21 mm, and D_{60} = 0.333 mm. Using these values, the uniformity coefficient (C_u) and the coefficient of curvature (C_c) were

calculated as 2.22 and 0.883, respectively. Soil classification was carried out according to the Unified Soil Classification System (USCS) as per ASTM D2487 (2017) [41]. Since $C_u < 6$ and $C_c < 1$, the sand was classified as poorly graded sand (SP). ASTM D854 (2014) [42] was taken into consideration in determining the specific gravity of SS. Additionally, the internal friction angle was obtained from direct shear testing conducted according to ASTM D3080 (2020) [43], at a relative density of $D_r = 0.5$. The geotechnical features of the SS used in this study are summarized in Table 1.

Table 1 – Geotechnical properties of the SS employed in the experimental program

Property	Symbol	Unit	Value
Color			Yellowish
Specific gravity	G_s	-	2.65
Maksimum dry density	$\mathbf{r}_{kmax}$	Mg/m^3	1.675
Minimum dry density	$\mathbf{r}_{kmin}$	Mg/m^3	1.403
Effective diameter	D_{10}	mm	0.150
Uniformity coefficient	C_u	-	2.22
Coefficient of curvature	C_c	-	0.883
Soil classification (USCS)			SP
Internal friction angle	f	(º)	36.69

2.3. Additive Materials for Soil Stabilization

A review of the relevant literature indicates that a wide variety of additives have been utilized in soil stabilization applications. The chemical compositions of the cements used in the experimental program are detailed in Table 2.

Table 2 – Chemical Content of Portland Cement and Sulfate Resistant Cement

Chemical Analysis	Portland cement (%)	Sulfate resistant cement (%)
SiO_2	18.35	18.09
Al_2O_3	4.52	4.41
Fe_2O_3	3.24	4.18
CaO	61.83	61.91
MgO	2.07	1.89
SO_3	2.93	2.88
Na_2O	0.29	0.26
K_2O	0.84	0.83
Cl^-	0.0112	0.0097
Superheat Loss	4.83	4.67

The FA used in the experiments possesses pozzolanic properties. Since its CaO content is below 10%, it is classified as low-calcareous FA, in accordance with the classification by

PRE-PRINT

Bilici et al. [44] . The chemical content of the FFA used in the experimental program is presented in Table 3, and its physical features are given in Table 4.

2.4. Specimen Preparation and Laboratory Testing Procedures

According to the literature, for soils containing sulfate concentrations greater than 8,000 ppm, the use of alternative ground improvement techniques is recommended, or the sulfate-rich soil should be blended with non-plastic soils to reduce the sulfate concentration [45]. In the present study, sulfate-rich soil with a very high sulfate content was mixed with siliceous sand at different proportions to obtain soil mixtures with varying sulfate concentrations. This approach was adopted to improve the workability of the mixtures and to evaluate the stabilization performance of soils containing high sulfate concentrations.

Table 3 – Chemical Content of Class FFA Used in the Experimental Program

Chemical Content of FFA Used in the Experiments	
SiO_2 (%)	58.75
CaO (%)	1.46
Al_2O_3 (%)	25.24
Fe_2O_3 (%)	5.76
MgO (%)	2.22
SO_3 (%)	0.08
K_2O (%)	4.05

Table 4 – Physical Features of FFA Used in the Experimental Program

Physical Features of FFA Used in the Experimental Program	
Specific Gravity (G_s)	2.00
Specific Surface	2165
Grain Size Analysis (%)	6 (0.075-4.75 mm) /79(0.002-0.0075 mm) / 15 (<0.002 mm)
LL (%)	45
PL (%)	21
PI	24

The sulfate concentrations in the soil mixtures were 11,190 ppm for a mixture containing 5% sulfate-rich soil and 95% siliceous sand, 55,950 ppm for a mixture containing 25% sulfate-rich soil and 75% silica sand, and 111,900 ppm for a mixture containing 50% sulfate-rich soil and 50% silica sand. By varying the proportion of sulfate-rich soil in the mixtures, soils with different sulfate concentrations—all exceeding the critical threshold of 8,000 ppm—were obtained. Consequently, the stabilization behavior of soils containing high sulfate concentrations at various levels was systematically investigated throughout the study.

The proportions of the soil and stabilizing materials used in the experimental program are presented in Table 5 as percentages. It was observed that the workability of the mixtures decreased as the proportion of sulfated soil increased. Consequently, soil mixtures containing

PREPRINT

75% sulfated soil – 25% siliceous sand and 100% sulfated soil were excluded from further testing due to inadequate workability. The decline in workability with increasing sulfate content is presented in Figure 4.tabl

The specimens were prepared in accordance with the procedures specified in JGS 0821 (2000) [46] and Euro Soil Stab (2001) [47]. Cement was incorporated at contents of 10%, 15%, and 20% by dry weight of soil, maintaining a constant water-to-cement (w/c) ratio of 1 throughout the experimental program. According to Some et. al. [48], a water-to-cement ratio of 1.0 is generally recommended and widely used in deep soil mixing (DSM) applications. This ratio ensures sufficient fluidity of the slurry, allowing the cement-based binder to be distributed homogeneously throughout sulfate-rich soil. It also supports the efficient occurrence of hydration reactions, which are critical for strength development and the overall performance of the stabilized soil. To obtain a homogeneous mixture, the dry constituents were first pre-mixed to ensure their uniform distribution. Subsequently, a predetermined amount of water was gradually added to the dry blend, and the resulting mixture was mechanically mixed using a laboratory mixer for approximately 5 minutes until a homogeneous slurry with adequate workability was achieved. A mixing period of 5 minutes was considered adequate to achieve a homogeneous mixture during the experimental program. Extending the mixing duration promoted uncontrolled hydration reactions in the soil with a high sulfate concentration, causing adverse effects such as rapid setting, flash set, and premature hardening of the stabilization slurry, which negatively affected the workability of the mixture. The resulting mixtures were compacted into cylinder-shaped molds in three layers. The diameter of the sample molds is 50 mm and the height is 100 mm. To facilitate demolding, the inner surfaces of the molds were lubricated prior to casting. Gentle vibration was applied during compaction to eliminate entrapped air bubbles. Following demolding, the specimens were subjected to curing. The specimens were removed from the molds and subsequently cured in a desiccator under controlled laboratory conditions at a temperature of 20 ± 3 °C until the specified curing periods were reached. UCS tests were conducted after 7 and 28 days of curing to evaluate the effect of curing time on strength development. All UCS tests were performed according to ASTM D2166 (2013) [49]. A constant axial displacement rate of 1 mm/min was applied during testing to ensure specimen failure occurred within the recommended time range specified by the standard. The sequence of the experimental procedure is illustrated in the flowchart provided in Figure 5.

CEM I 42,5 is a hydraulic binder that has the property to react with water to transform into a hard and water resistant material. CEM I 42.5-R-SR5 enhances the durability of concrete by increasing its resistance to sulfate attack when exposed to sulfate-bearing environments such as groundwater, seawater, or industrial sources. This type of cement is manufactured by grinding clinker with calcium sulfate, with the clinker specifically produced to contain a maximum of 5% tricalcium aluminate (C_3A). The low C_3A content minimizes the risk of expansive chemical reactions, making it particularly suitable for use in aggressive sulfate conditions. The testing program was designed to contain the specimens prepared with these types of cement (Table 5).

PREPRINT

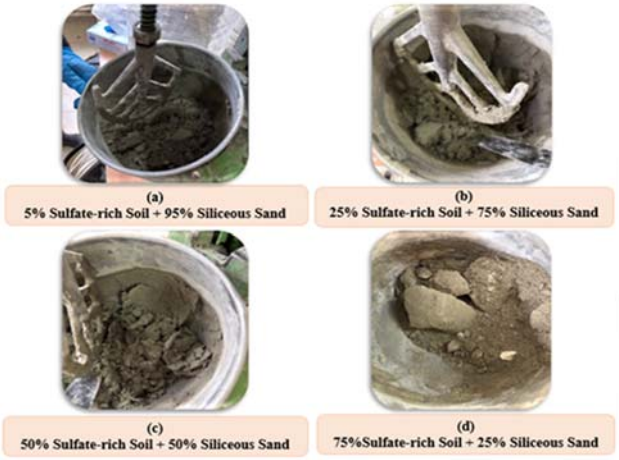

Fig 4 - Variation in workability with increasing proportion of SRS in soil mixtures.

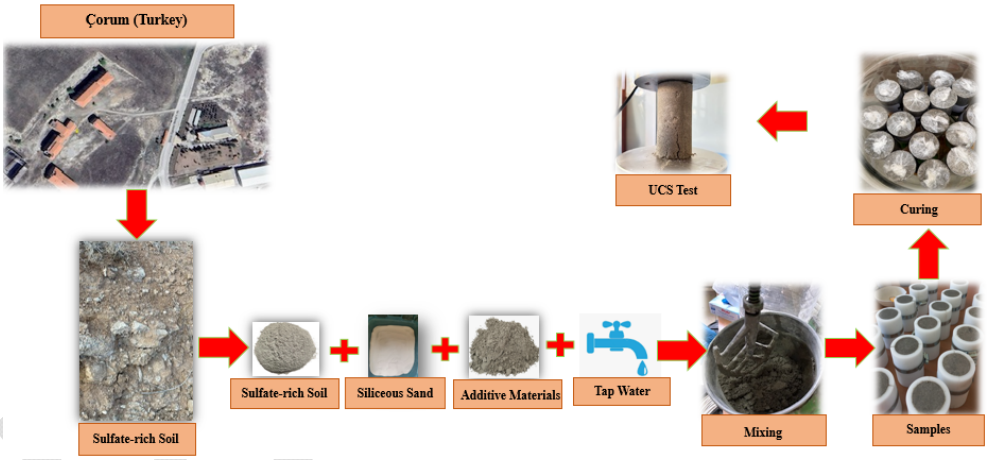

Fig 5 - Schematic representation of the experimental procedure

Previous studies have demonstrated the widespread pozzolanic materails in the stabilization of various soil types [50-51]. For instance, Noaman et al. [52] examined the influence of high-volume FFA (ranging from 5% to 50%) on the geotechnical and microstructural properties of clayey soils. Similarly, Chen et al. [53] utilized FA in combination with sea sand to stabilize saline soil and reported a significant improvement in UCS. Abdelbaset et al. [54] investigated the stabilization of low-plasticity kaolin soil using FA. In the present study, building upon insights from previous research, mixtures of sulfate-bearing soil and siliceous sand were stabilized using FA in combination with cement and lime. As an initial step, specimens were prepared by incorporating 15% FFA and 5% lime into the soil mixtures. Also, some specimens were prepared by incorporating 10% CEM I 42.5-R-SR5 and 10%

Table 5 – Experimental Program for Specimens Prepared with CEM I 42.5 and CEM I 42.5-R-SR5 Cements

Sample	SRS (%)	Siliceous Sand (%)	Portland Cement (%)	Sample	SRS (%)	Siliceous Sand (%)	Sulfate-Resistant Cement (%)
S5C10	5	95	10	S5CR10	5	95	10
S25C10	25	75	10	S25CR10	25	75	10
S50C10	50	50	10	S50CR10	50	50	10
S5C15	5	95	15	S5CR15	5	95	15
S25C15	25	75	15	S25CR15	25	75	15
S50C15	50	50	15	S50CR15	50	50	15
S5C20	5	95	20	S5CR20	5	95	20
S25C20	25	75	20	S25CR20	25	75	20
S50C20	50	50	20	S50CR20	50	50	20

*S5C10: 5% Sulfate- rich soil+10% Portland cement; S25C10: 25% Sulfate- rich soil+10% Portland cement; S5CR10: 5% Sulfate- rich soil+10% Portland resistant-cement; S25CR10:25% Sulfate- rich soil+10% Portland resistant-cement; S50CR10: 50% Sulfate-rich soil+10% Sulfate resistant-cement

FFA into mixtures of sulfate-bearing soil and siliceous sand. These samples were then subjected to UCS testing. UCS values were recorded after 7 and 28 days of curing to assess the strength development over time. The experimental program related to the FA, lime and cement stabilization is summarized in Table 6.

Table 6 – Test Program for Stabilization Using FFA, Lime and Sulfate-Resistant Cement

Sample	SRS (%)	Siliceous Sand (%)	FFA (%)	Lime (%)	Cement(CEM I 42,5-R-SR5) (%)
S5F15L5	5	95	15	5	---
S25F15L5	25	75	15	5	---
S50F15L5	50	50	15	5	---
S5F10CR10	5	95	10	---	10
S5F10CR10	25	75	10	---	10
S5F10CR10	50	50	10	---	10

*S5F15L5: 5% Sulfate-rich soil+15% FFA+5% Lime; S5F10CR10: 5% Sulfate-rich soil+15% FFA+10% Sulfate resistant-cement

PREPRINT

2.5. Durability Tests of Sulfate-rich Soils

There are few testing procedures used by researchers for durability of SRS. In the study by Helson et al. [55], an initial curing period of 180 days was implemented to minimize the influence of ongoing hydration on strength gain and to prevent the masking of sulfate-induced swelling due to endogenous shrinkage. To accelerate deterioration mechanisms, Na_2SO_4 solution with a concentration of 25 g/L was employed. During the exposure phase, a subset of specimens was immersed in the Na_2SO_4 solution, while another subset was placed in tap water to serve as a control group. In both cases, the immersion media were pre-saturated with lime to prevent the leaching of calcium-containing compounds from the samples. UCS tests were carried out after 6, 12, and 22 months to evaluate the long-term durability performance of the specimens. Jiang et al. [56] immersed each cured specimen in 1.5 liters of Na_2SO_4 solution with a concentration of 0.176 mol/L for a period of 28 days. The soaking durations were set at 3, 7, 14, 28, 60, 90, and 120 days, respectively. At the end of each immersion interval, the specimens were evaluated for percentage mass change and UCS to monitor degradation and mechanical performance over time.

The review of the literature revealed that it is common practice to evaluate both the strength and durability performance of stabilized soil specimens after they have completed a standard curing period of 28 days and are subsequently exposed to sulfate solutions [57-59]. The durability tests of the study was carried out in accordance with the procedure outlined by Rashidian-Dezfouli and Rangaraju [60] following a 28-day initial curing period, the specimens were completely submerged in a 5% Na_2SO_4 solution and maintained under these conditions for an additional 28 days. The specimens that have completed the immersion period, were carefully retrieved from the solution and carefully dried with a diaper to remove any surface moisture. Subsequently, UCS tests were conducted to assess the durability performance. The experimental steps involved in the durability testing process are illustrated in Figure 6.

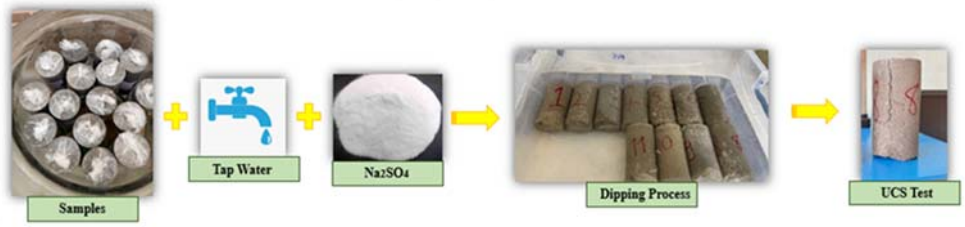

Fig 6 - Stages of the Durability Testing Procedure

3. RESULTS AND DISCUSSIONS

The effect of various additives on the UCS of samples composed of sulfate-bearing soil and siliceous sand is discussed below. Lime is a widely used additive in soil stabilization practices, particularly for improving the plasticity and strength characteristics of cohesive soils. Lime stabilization leads to an increase in soil strength [61-62]. Within the scope of the study, soil mixtures composed of sulfate-rich soil and siliceous sand were subjected to stabilization using 15% FFA and 5% lime. However, the experimental results indicated that the incorporation of 15% FFA in combination with 5% lime did not lead to a significant

improvement in UCS. In a separate investigation, McCarthy et al. [24] stabilized sulfate-bearing soils using lime and observed an improvement in UCS. This enhancement was further pronounced with the addition of FA and GGBS to the stabilization mix. Ebailila et al. [20] investigated the effects of incorporating lime–silica fume and lime–GGBS separately into pure kaolin and sulfate-amended kaolin soils. The study concluded that the lime–GGBS blend exhibited superior performance in UCS tests.

The 7- and 28-day UCS test results are given in Figure 7. These tests were performed on soil mixtures containing different ratios of SRS and siliceous sand, each stabilized with 20% of various cement types. In the mixtures composed of SRS and SS, an increase in UCS was observed when the SRS content was raised from 5% to 25%. However, further increase in the SRS content from 25% to 50% resulted in a notable decline in strength. This decrease can be attributed that increasing the proportion of SRS led to a reduction in workability. The highest UCS values at both curing intervals were recorded in mixtures containing 25% sulfate-rich soil and 75% siliceous sand, when stabilized with 20% sulfate-resistant cement. Conversely, for the mixture with equal parts of sulfate-rich soil and siliceous sand (50%–50%), the highest strength was achieved using 20% ordinary Portland cement. When 20%

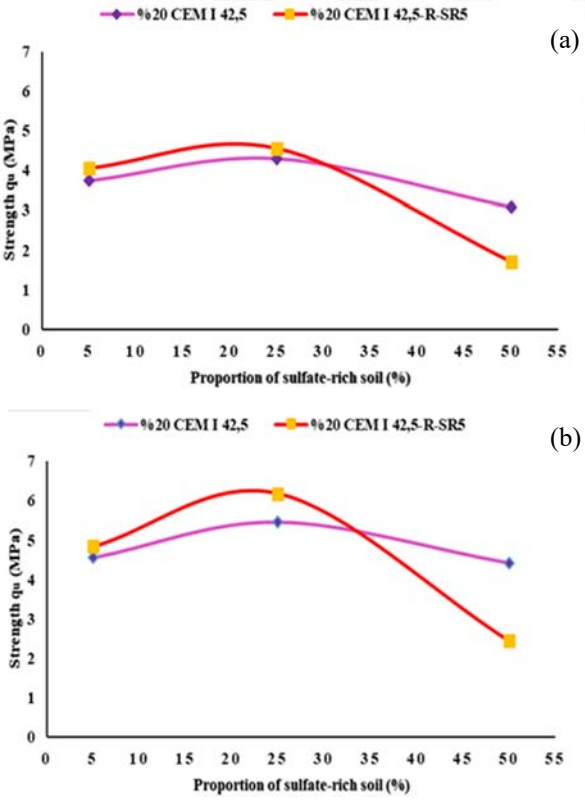

Fig 7 - UCS of soil mixtures stabilized with 20% cement. (a) 7-day UCS (b) 28-day UCS

cement was incorporated into a soil mixture comprising 5% sulfate soil and 95% siliceous sand, the CEM I 42.5-R-SR5 exhibited approximately 6% higher strength than the CEM I 42.5. In the mixture containing 25% sulfate soil and 75% siliceous sand, the use of CEM I 42.5-R-SR5 resulted in an approximate 13% increase in strength compared to CEM I 42.5. However, in the case of a soil mixture consisting of equal persentages of sulfate soil and siliceous sand (50% each), the strength obtained with CEM I 42.5-R-SR5 was found to be approximately 45% lower than that achieved with CEM I 42.5. Seco et al. [28] employed PC-8, an alternative magnesium-based additive, in place of traditional calcium-based additives for the stabilization of SRS. They achieved strength values of approximately 1-3 MPa for soils stabilized with 4% PC-8 dosage, and strength values ranging from 2-5 MPa at an 8% dosage. In their study, they observed that the strength increased to 11-13 MPa when PC-8 was combined with GGBS. Additionally, a mixture of lime and GGBS yielded strength values up to 6-7 MPa. The highest strength value observed in this study was 6.181 MPa, achieved by incorporating 20% CEM I 42.5-R-SR-5 into a soil mixture composed of 25% sulfate soil and 75% siliceous sand.

Figure 8 presents the results of the experiments conducted with a reduced cement content of 15%. The highest UCS values at both 7 and 28 days were obtained using CEM I 42.5-R-SR5 cement in the soil mixture containing 5% sulfate-rich soil and 95% siliceous sand. However, when 15% CEM I 42.5 was used, higher UCS values were observed compared to CEM I 42.5-R-SR5 in mixtures containing 25% sulfate-rich soil – 75% siliceous sand and 50% sulfate-rich soil – 50% siliceous sand.

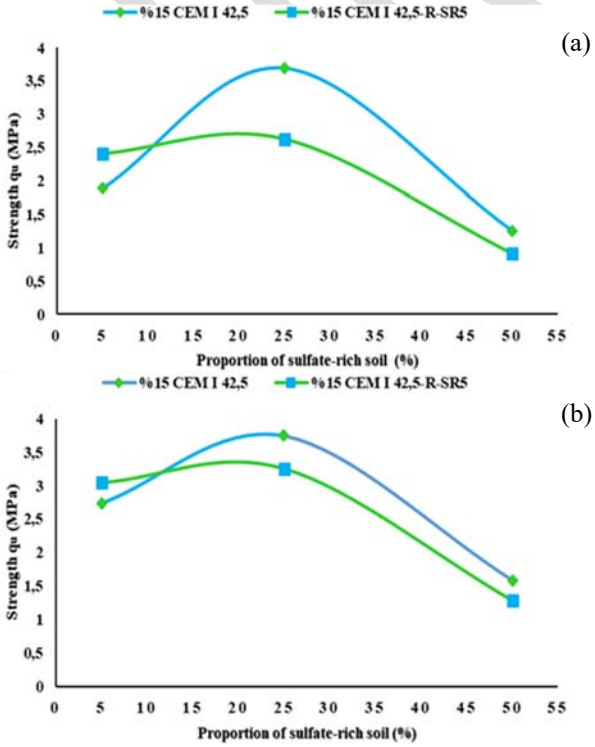

Fig 8 - UCS of soil mixtures stabilized with 15% cement. (a) 7-day UCS (b) 28-day UCS

Figure 9 presents the UCS of the mixtures on 7th and 28th day after the addition of 10% cement. The graphs also highlight the UCS values obtained from samples stabilized with 10% CEM I 42.5-R-SR5 and 10% FFA. The experimental results demonstrate that the most favorable UCS values at both 7 and 28 days were attained in the mixture comprising 5% sulfate-rich soil and 95% siliceous sand when stabilized with a combination of 10% CEM I 42.5-R-SR5 and 10% FFA. For the mixture containing 25% sulfate-rich soil and 75% siliceous sand, the highest UCS performance was observed with the addition of 10% CEM I 42.5, outperforming other stabilizers at both curing intervals. In the case of the 50% sulfate-rich soil – 50% siliceous sand mixture, although the UCS values obtained with different additives were relatively close, the combination of 10% CEM I 42.5-R-SR5 and 10% FFA yielded the best mechanical performance. An increase in the proportion of SRS in the mixture resulted in a noticeable reduction in UCS values. The highest UCS was recorded in the sample containing 5% sulfate-rich soil and 95% siliceous sand, indicating that lower sulfate content may has positively influenced the mechanical performance of the stabilized mixtures.

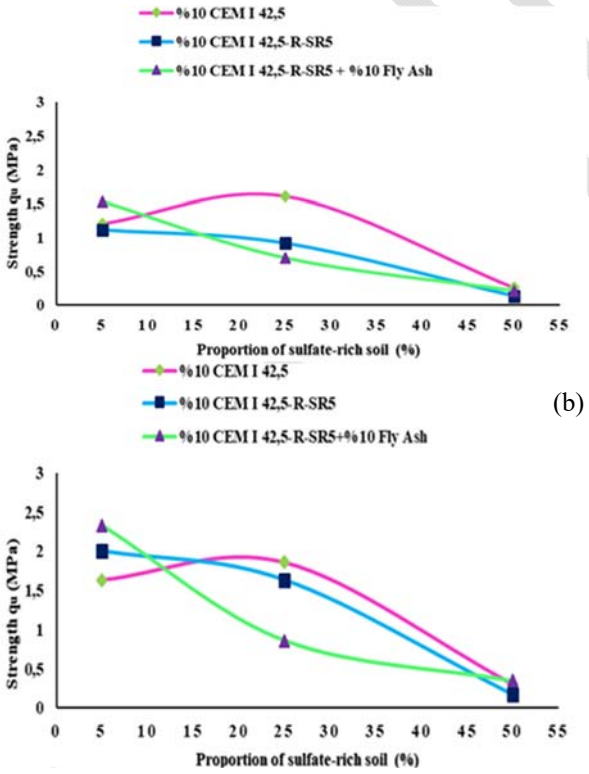

Fig 9 - UCS of soil mixtures stabilized with 10% cement. (a) 7-day UCS (b) 28-day UCS

In the stabilization study utilizing CEM I 42.5 and CEM I 42.5-R-SR5 cements, the lowest 28-day UCS values were recorded when a 10% cement content was applied to the soil mixture containing 50% sulfate soil and 50% siliceous sand. The 28-day UCS for the soil

treated with CEM I 42.5 cement was calculated as 0.298 MPa, whereas the corresponding value for the soil stabilized with CEM I 42.5-R-SR5 cement was 0.168 MPa. Celik and Sadoglu (2026) [39] employed geopolymer binders for the stabilization of sulfate-rich soils and reported that the use of GGBS as the sole binder resulted in an approximately 22% reduction in strength as the curing period increased. Adeleke et al. (2022) [11] investigated the stabilization of SRS using a binder system consisting of ground granulated blast furnace slag (GGBS) and activated MgO waste (MG1). The results showed that, following a standard 28-day moist curing period, the UCS values of soils stabilized with GGBS and activated MgO waste were 1.5–3 times higher than those of the control samples.

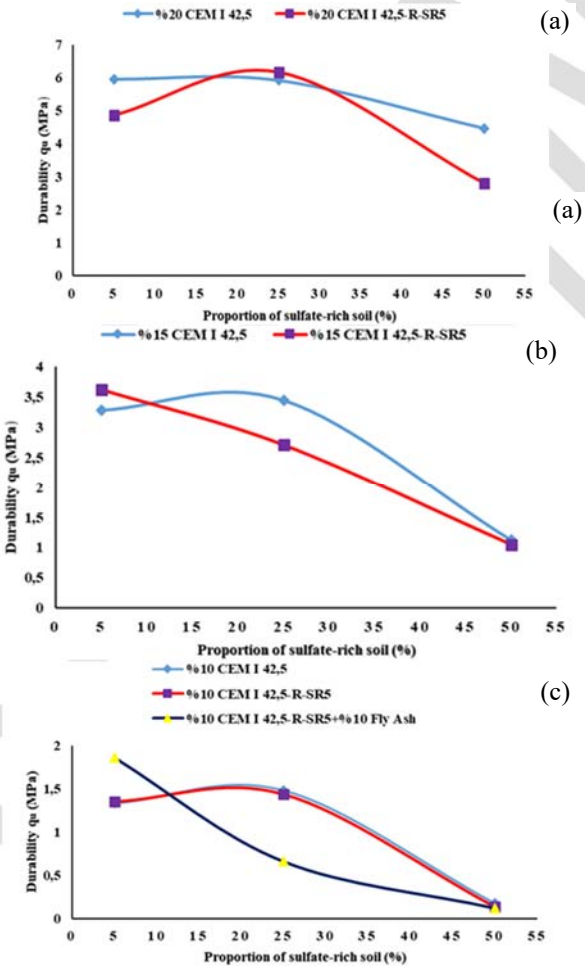

Fig 10 - Durability Test Results of Soil Mixtures Stabilized with CEM I 42.5, CEM I 42.5-R-SR5 Cements, and FFA. (a) 20% Cement (b) 15% Cement (c) 10% Cement

Durability tests were carried out to assess the long-term performance of soil mixtures stabilized with CEM I 42.5 and CEM I 42.5-R-SR5. The results are illustrated in the graphical representations provided in Figure 10. A slight increase in UCS was observed following the durability testing procedures. Overall, both CEM I 42.5 and CEM I 42.5-R-SR5 demonstrated similar performance in terms of durability. Nevertheless, a marked difference was noted in the soil mixture comprising 50% sulfate-rich soil and 50% siliceous sand, stabilized with 20% cement. In this particular case, specimens stabilized with CEM I 42.5 exhibited higher UCS values compared to those treated with CEM I 42.5-R-SR5, indicating a better long-term performance under sulfate exposure conditions.

The combined use of 10% CEM I 42.5-R-SR5 and 10% FFA in a soil composed of 5% sulfate soil and 95% siliceous sand resulted in an approximate 16% increase in strength compared to the use of 10% CEM I 42.5-R-SR5 alone. In contrast, when the same combination (10% cement + 10% FFA) was applied to a soil mixture containing 25% sulfate soil and 75% siliceous sand, a reduction in strength of approximately 72% was observed relative to the use of only 10% CEM I 42.5-R-SR5 cement. Furthermore, in the soil composed of equal proportions of sulfate soil and siliceous sand (50% each), the use of 10% CEM I 42.5-R-SR5 cement with 10% FFA led to a significant decrease in strength, approximately 93%, compared to the case where only 10% CEM I 42.5-R-SR5 cement was used.

4. CONCLUSIONS

In this article, an extensive investigation was carried out on the stabilization of SRS. Given the poor engineering properties of SRS, the native material was blended with siliceous sand in varying proportions to enhance workability and mechanical behavior. The stabilization of the resulting soil mixtures was achieved through the incorporation of different additives. The effect of these stabilization approaches on the strength and durability characteristics of the treated samples was systematically evaluated. The following data were obtained as a result of the experimental studies.

- Increasing the proportion of the SRS in the mixtures led to a reduction in workability. This situatation caused reduction in strength of the mixtures.
- In soil mixtures composed of SRS and siliceous sand, an increase in UCS was observed when the SRS quantity was raised from 5% to 25%. However, further increasing the SRS content from 25% to 50% resulted in a notable decline in strength.
- As the cement quantity increased, improvements in the strength of the SRS–siliceous sand mixtures were observed. When evaluating the effects of CEM I 42.5 and CEM I 42.5-R-SR5 cements on strength development, both cement types yielded comparable results. Nevertheless, CEM I 42.5-R-SR5 demonstrated a slightly superior performance, indicating a more favorable contribution to the strength of the stabilized soils.
- The highest strength values were obtained by incorporating a 20% cement into the soil mixture composed of 25% sulfate soil and 75% siliceous sand. The 28-day UCS of the soil stabilized with CEM I 42.5 was measured as 5.454 MPa, whereas the corresponding strength achieved with CEM I 42.5-R-SR5 cement was 6.181 MPa.

PRE-PRINT

- In the stabilization study involving 10% CEM I 42.5-R-SR5 and 10% FFA, a progressive reduction in both 7-day and 28-day UCS values was observed with increasing proportions of sulfate-rich soil. The highest UCS values were obtained in the mixture containing 5% sulfate-rich soil and 95% siliceous sand. Moreover, when the performance of the blend containing both CEM I 42.5-R-SR5 and FFA was compared to that of the mixture stabilized with 10% CEM I 42.5-R-SR5 alone, the addition of FA was found to enhance strength characteristics, thereby contributing positively to the overall mechanical behavior of the stabilized soil.
- Within the scope of the study, soil mixtures composed of sulfate-rich soil and siliceous sand were subjected to stabilization using 15% FFA and 5% lime. However, the experimental results indicated that the incorporation of 15% FFA ash in combination with 5% lime did not lead to a significant improvement in UCS.
- A slight increase in the strength of soils stabilized with CEM I 42.5 and CEM I 42.5-R-SR5 cements was observed during the durability tests, a reduction in strength was recorded in specimens stabilized with a combination of CEM I 42.5-R-SR5 and FFA following the durability testing procedures.

Acknowledgments

This study was supported by the Scientific Research Projects Coordination Unit of Karadeniz Technical University, Türkiye (Project No: FDK-2024-16089).

I would like to express deepest gratitude to TÜBİTAK-BİDEB for accepting into the TÜBİTAK 2211 Domestic Postgraduate Scholarship Program in 2022 and supporting me as a doctoral scholarship recipient.

References

[1] Barman, D., & Dash, S. K., Stabilization of expansive soils using chemical additives: A review. Journal of Rock Mechanics and Geotechnical Engineering, 14, 1319–1342, 2022. https://doi.org/10.1016/j.jrmge.2022.02.011

[2] Firoozi, A. A., Olgun, C. G., Firoozi, A. A., & Baghini, M. S., Fundamentals of soil stabilization, Geo-Engineering, 8(26), 1–27, 2017.

[3] Casalles, L. D., Hot, J., Roosz, C., & Cyr, M., Stabilization of soils containing sulfates by using alternative hydraulic binders. Applied Geochemistry, 113, 104494, 2020. https://doi.org/10.1016/j.apgeochem.2019.104494

[4] Hunter, D. (1989). The geochemistry of lime-induced heave in sulfate bearing clay soils. http://hdl.handle.net/11714/1385

[5] 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, 23, 100327, 2020. https://doi.org/10.1016/j.trgeo.2020.100327

PRE-PRINT

[6] Kota, P. B. V. S., Hazlett, D., & Perrin, L., Sulfate-bearing soils: Problems with calcium-based stabilizers, Transportation Research Record, 1546, 62–69, 1996.

[7] Puppala, A. J., Wattanasanticharoen, E., & Punthuzaecha, K., Experimental evaluations of stabilisation methods for sulphate-rich expansive soils, Ground Improvement, 7(1), 25–35, 2003.

[8] Zhang, M., Zhao, M., Zhang, G., Nowak, P., Coen, A., & Tao, M., Calcium-free geopolymer as a stabilizer for sulfate-rich soils, Applied Clay Science, 108, 199–207, 2015. https://doi.org/10.1016/j.clay.2015.02.029

[9] Talluri, N., Puppala, A. J., Chittoori, B. C. S., Gaily, A. H., & Harris, P., Stabilization of high-sulfate soils by extended mellowing, Transportation Research Record: Journal of the Transportation Research Board, 2363(1), 96–104, 2013.

[10] Puppala, A.J., Kadam, R., Madhyannapu, R.S. & Hoyos, L.R., Small-strain shear moduli of chemically stabilized sulfate-bearing cohesive soils, Journal of Geotechnical and Geoenvironmental Engineering, 132(3), 322-336, 2006.

[11] Adeleke, B. O., Kinuthia, J. M., & Oti, J. E., Impacts of MgO waste: GGBS formulations on the performance of a stabilised natural high sulphate bearing soil, Construction and Building Materials, 315, 125745, 2022. https://doi.org/10.1016/j.conbuildmat.2021.125745

[12] Alsafi, S., Farzadnia, N., Asadi, A., & Huat, B. K., Collapsibility potential of gypseous soil stabilized with fly ash geopolymer: Characterization and assessment. Construction and Building Materials, 137, 390–409, 2017. https://doi.org/10.1016/j.conbuildmat.2017.01.079

[13] Consoli, N.C., Marin, E.J.B., Samaniego, R.A.Q., Filho, H.C.S., Miranda, T. & Cristelo, N., Effect of mellowing and coal fly ash addition on behavior of sulfate-rich dispersive clay after lime stabilization, Journal of Materials in Civil Engineering, 31(6), 04019071, 2019. DOI: 10.1061/(ASCE)MT.1943-5533.0002699.

[14] Celik, E., & Nalbantoglu, Z., Effects of ground granulated blastfurnace slag (GGBS) on the swelling properties of lime-stabilized sulfate-bearing soils. Engineering Geology, 163, 20–25, 2013. https://doi.org/10.1016/j.enggeo.2013.05.016

[15] Shooshpasha, I. & Shirvani, R.A., Effect of cement stabilization on geotechnical properties of sandy soils, Geomechanics and Engineering, 8 (1), 17-31, 2015.

[16] Talluri, N., Puppala, A.J., Congress, S.S.C. & Banerjee, A., Experimental studies and modeling of high-sulfate soil stabilization, Journal of Geotechnical and Geoenvironmental Engineering, 146(5), 04020019, 2020. DOI: 10.1061/(ASCE)GT.1943-5606.0002240

[17] Adams, A.G., Dukes, O.M., Tabet, W., Cerato, A.B.& Miller, G.A., Sulfate induced heave in Oklahoma soils due to lime stabilization. GeoCongress 2008: Characterization, Monitoring and Modeling of Geosystems. ASCE, 2008.

[18] Loskutova, A., Kim, J., Satyanaga, A.&Moon, S.W., Sustainable soil stabilization using calcium sulfoaluminate cement and phosphogypsum, Geomechanics and Engineering, 41(1), 1-10, 2025. https://doi.org/10.12989/gae.2025.41.1.001

PREPRINT

[19] Doğruyol, M. (2011). "Siirt ve Batman yöresine ait sülfatlı zeminlerin beton davranışına etkisi" Dicle Üni., Fen Bilimleri Ens., Yüksek Lisans Tezi, Diyarbakır.

[20] Ebailila, M., Kinuthia, J., Oti, J., & Al-Waked, Q., Sulfate soil stabilisation with binary blends of lime–silica fume and lime–ground granulated blast furnace slag, Transportation Geotechnics, 37, 100888, 2022. https://doi.org/10.1016/j.trgeo.2022.100888

[21] Consoli, N.C., Festugato, L., Miguel, G.D., Moreira, E.B. & Filho, H.C.S., Fatigue life of green stabilized fiber-reinforced sulfate-rich dispersive soil, Journal of Materials in Civil Engineering, 33(9), 04021249, 2021. DOI: 10.1061/(ASCE)MT.1943-5533.0003842.

[22] Jumassultan, A., Sagidullina, N., Kim, J., Ku, T.& Moon, S.W., Performance of cement-stabilized sand subjected to freeze-thaw cycles, Geomechanics and Engineering, 25,(1), 41-48, 2021.

[23] Canakci, H., Aziz, A.& Celik, F., Soil stabilization of clay with lignin, rice husk powder and ash. Geomechanics and Engineering, 8(1),67-79, 2015.

[24] McCarthy, M. J., Csetenyi, L. J., Sachdeva, A., & Dhir, R. K., Engineering and durability properties of fly ash treated lime-stabilised sulphate-bearing soils, Engineering Geology, 174, 139-148, 2014. https://doi.org/10.1016/j.enggeo.2014.03.001

[25] Parhizkar, A., Nazarpour, A., & Khayat, N., Investigation of geotechnical and microstructure characteristics of gypsum soil using ground granulated blast-furnace slag (GGBS), fly ash, and lime, Construction and Building Materials, 418, 135358, 2024. https://doi.org/10.1016/j.conbuildmat.2024.135358

[26] Rahmat, M. N., & Kinuthia, J. M., Effects of mellowing sulfate-bearing clay soil stabilized with wastepaper sludge as for road construction, Engineering Geology, 117, 170–179, 2011. https://doi.org/10.1016/j.enggeo.2010.10.015

[27] Saygılı, G., Yıldırım, Y., & Şahin, H., Stabilization of high sulfate soils with nontraditional additives. In PanAm Unsaturated Soils 2017: Proceedings of the 2nd Pan-American Conference on Unsaturated Soils, 236–245, 2017, ASCE.

[28] Seco, A., Miqueleiz, L., Prieto, E., Marcelino, S., Garcia, B., & Urmeneta, P., Sulfate soils stabilization with magnesium-based binders, Applied Clay Science, 135, 457–464, 2017. https://doi.org/10.1016/j.clay.2016.10.033

[29] Wild, S., Kinuthia, J. M., Jones, G. I., & Higgins, D. D., Effect of partial substitution of lime with ground granulated blast furnace slag (GGBS) on the strength properties of lime-stabilised sulphate-bearing clay soils, Engineering Geology, 51(1), 35–53, 1998.

[30] Taki, O., & Yang, D. S., Soil-cement mixed wall technique. In L. F. Johnsen, D. A. Bruce, & M. J. Byle (Eds.), Proceedings of the Geotechnical Engineering Congress (pp. 298–309), 1991, American Society of Civil Engineers.

[31] Arasan, S., Bagherinia, M., Akbulut, R. K., & Zaimoglu, A. S., Utilization of polymers to improve soft clayey soils using the deep mixing method. Environmental & Engineering Geoscience, 23(1), 1–12, 2017.

PREPRINT

[32] Bruce, D. A., Bruce, M. E. C., & DiMillio, A., Deep mixing method: A global perspective. In Geo-Congress 1998: Soil improvement for big digs (ASCE, Geotechnical Special Publication No. 81, pp. 1–15, 1998.

[33] Bruce, D., & Bruce, M., The practitioner's guide to deep mixing, Grouting and ground treatment: Proceedings of the Third International Conference on Grouting and Ground Treatment (Geotechnical Special Publication No. 120, 474–488, 2003, American Society of Civil Engineers (ASCE).

[34] Chen, Q., Rong, H., Tao, G., Nimbalkar, S., & Xie, K., Fatigue characteristics of nano-SiO_2 cemented soil under coupled effects of dry-wet cycle and seawater corrosion, Construction and Building Materials, 401,132579, 2023. https://doi.org/10.1016/j.conbuildmat.2023.132579

[35] Esmaeili, M., Astaraki, F., Yaghouti, H., & Rad, M. M., Laboratory investigation on the effect of microsilica additive on the mechanical behavior of deep soil mixing columns in saline dry sand. Periodica Polytechnica Civil Engineering, 65(4), 1080–1091, 2021.

[36] Fidan, B. (2023)."Tabakalı zemin ortamında oluşturulan amorf silika katkılı derin karıştırma kolon davranışlarının model deneylerle araştırılması". Konya Teknik Üniversitesi, Lisansüstü Eğitim Enstitüsü, Doktora Tezi, Konya.

[37] Paulo, J. V. O., Joao, L. P., & Antonio, A. S., Numerical analysis of an embankment built on soft soil reinforced with deep mixing columns: Parametric study, Computers and Geotechnics, 38, 566–576, 2021. https://doi.org/10.1016/j.compgeo.2011.03.005

[38] Shen, S. L., & Han, J., Laboratory studies on property changes in surrounding clays due to installation of deep mixing columns, Marine Georesources & Geotechnology, 21(1), 13–35, 2003.

[39] Celik, A.G. & Sadoglu, E., Application of Geopolymers with Different Binding Materials for the Stabilization of Sulfate-Rich Soils. Soils and Foundations, 66(4), 101824, 2026.

[40] ASTM. (2007). ASTM D422-63(2007): Standard test method for particle-size analysis of soils. ASTM International.

[41] ASTM. (2017). ASTM D2487-17: Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). ASTM International.

[42] ASTM. (2014). ASTM D854-14: Standard test methods for specific gravity of soil solids by water pycnometer. ASTM International.

[43] ASTM. (2020). ASTM D3080/D3080M-20: Standard test method for direct shear test of soils under consolidated drained conditions. ASTM International.

[44] Bilici, H., Türköz, M., & Savaş, H., Üç farklı termik santralden alınan uçucu külün ince taneli zeminin kompaksiyon ve dayanım özellikleri üzerindeki performansı. ESOGÜ Mühendislik Mimarlık Fakültesi Dergisi, 30(3), 379–388, 2022.

PRE-PRINT

[45] Texas Department of Transportation (2005). Guidelines for Treatment of Sulfate-Rich Soils and Bases in Pavement Structures. Construction Division Materials & Pavements Section Geotechnical, Soils & Aggregates, Brach. TxDOT 09/2005.

[46] Japanese Geotechnical Society. (2000). JGS 0821-00: Practice for making and curing stabilized soil specimens without compaction (Translated version). In Geotechnical test procedure and commentary. Japanese Geotechnical Society.

[47] EURO SOIL STAB. (2001). Development of design and construction methods to stabilize soft organic soils: Design guide soft soil stabilization (EC Project BE 96-3177). European Commission.

[48] Some, D.D., Yameogo, O.G. & Than, M.N., Influence of Water-Cement Ratio on the Strength Distribution inside a Soil-Cement Material, American Journal of Civil Engineering and Architecture, 12(2), 24-29, 2024.

[49] ASTM. (2013). ASTM D2166 / D2166M-13: Standard test method for unconfined compressive strength of cohesive soil. ASTM International.

[50] Sadoglu, E. & Calık, U., Permeability of high plasticity clayey soil stabilized with lime and perlite, Journal Of The Faculty Of Engineering and Architecture of Gazi University, 35(2), 551-561, 2020. https://doi.org/10.17341/gazimmfd.488720

[51] Calık, U. & Sadoglu, E., Engineering properties of expansive clayey soil stabilized with lime and perlite, Geomechanics and Engineering , 6(4), 403-418, 2014. https://doi.org/10.12989/gae.2014.6.4.403

[52] Noaman, M. F., Haq, M., Khan, M. A., Ali, K., & Kamyab, H., Geotechnical and microstructural analysis of high-volume fly ash stabilized clayey soil and machine learning application, Case Studies in Construction Materials, 21, e03628, 2024. https://doi.org/10.1016/j.cscm.2024.e03628

[53] Chen, Y., Maimait, A., Cheng, J., Duan, Y., Yin, D., Dong, H., & Li, Y., Properties of saline soil stabilized with fly ash and modified aeolian sand, Case Studies in Construction Materials, 21, e03503, 2024. https://doi.org/10.1016/j.cscm.2024.e03503

[54] Abdelbaset, A. M., Katunský, D., Zeleňáková, M., & El-Feky, M. H., Mechanical properties stabilization of low plasticity kaolin soil using fly ash and hydrated lime, Case Studies in Construction Materials, 21, e03662, 2024. https://doi.org/10.1016/j.cscm.2024.e03662

[55] Helson, O., Eslami, J., Beaucour, A.-L., Noumowe, A., & Gotteland, P., Durability of soil mix material subjected to wetting/drying cycles and external sulfate attacks, Construction and Building Materials, 192, 416–428, 2018. https://doi.org/10.1016/j.conbuildmat.2018.10.095

[56] Jiang, N.-J., Du, Y.-J., & Liu, K., Durability of lightweight alkali-activated ground granulated blast furnace slag (GGBS) stabilized clayey soils subjected to sulfate attack, Applied Clay Science, 161, 70–75, 2018. https://doi.org/10.1016/j.clay.2018.04.014

PREPRINT

[57] Rashidian-Dezfouli, H., & Rangaraju, P. R., A comparative study on the durability of geopolymers produced with ground glass fiber, fly ash, and glass powder in sodium sulfate solution, Construction and Building Materials, 153, 996–1009, 2017. https://doi.org/10.1016/j.conbuildmat.2017.07.139

[58] Luo, Z., Zhang, B., Zou, J.& Luo, B., Sulfate erosion resistance of slag-fly ash based geopolymer stabilized soft soil under semi-immersion condition, Case Studies in Construction Materials, 17, e01506, 2022.

[59] Wang, G., Chen, S., Xia, M., Zhang, W., Han, X., Luo, B., Sabri, M.M.S. & Huang, J., Experimental Study on Durability Degradation of Geopolymer-Stabilized Soil under Sulfate Erosion, Materials, 15, 5114, 2022. https://doi.org/10.3390/ma15155114

[60] Yi, X., Wang, G., Zhang, B., Zhang, G., Liu, Y. & Luo, Z., Durability Deterioration of Geopolymer Stabilized Soft Soil under Sodium Sulfate and Magnesium Sulfate Attack: A Comparative Study, Buildings, *13*(4), 1075, 2023.

[61] Harichane, K., Ghrici, M., Kenai, S., & Grine, K., Use of natural pozzolana and lime for stabilization of cohesive soils, Geotechnical and Geological Engineering, 29(5), 759–769, 2011.

[62] Kavak, A., & Akyarlı, A., A field application for lime stabilization, Environmental Geology, 51(6), 987–997, 2007.

PRE-PRINT