Iraqi National Journal of Earth Science

www.earth.mosuljournals.com

Effect of the Addition of Industrial Materials on the Properties of Expansive Soil in the Al-Azraq Area, Jordan

Mohammad Al-Masri [1], **Islam Al-Dabsheh** [2], **Faten Al-Slaty** [3]

[1,2] *Department of Applied Geology and Environmental Sciences, Institute of Earth and Environmental Sciences, Al al-Bayt University, Mafraq, Jordan.*

[3] *Department of Earth and Environmental Sciences, Prince El Hassan bin Talal Faculty of Natural Resources and Environment, The Hashemite University, Zarqa, Jordan.*

Article information

Received: 01- Mar -2023

Revised: 31- Mar -2023

Accepted: 07- May -2023

Available online: 30- June- 2023

Keywords:
Expansive soil
Clayey soil
Stabilization
Lime
Sandstone
Phosphatic clay
Cement kiln dust

Correspondence:

Name: Faten Al-Slaty
Email: fatenm@hu.edu.jo

ABSTRACT

This study aims to investigate the stabilization of representative samples of expansive soil in the Al-Azraq area. This is achieved by mixing soil with different proportions of four types of stabilizers: lime, phosphatic clay, cement kiln dust (CKD), and sandstone. The index properties of the base soil have been investigated through various tests. The chemical and mineralogical compositions of materials have been examined. Compaction, California bearing ratio, and unconfined compression tests are used to assess the engineering properties of the stabilized soil. The results reveal that with 5% lime, 10% phosphatic clay, 7.5% CKD, and 10% sandstone, the plasticity index has been reduced from 60% to 17.2%, 18.47%, 17.52%, and 22.70%, respectively. The maximum dry density has increased by adding 5% lime from 1.19 mg/cm3 to 1.58 mg/cm3. The optimum moisture content decreased from 40.1% to 25.1% with the addition of 5% lime. The California bearing ratio has increased from 9% to 17.5% with the addition of 7.5% CKD. The unconfined compression strength improved significantly with the addition of all stabilizers due to chemical reactions that resulted in the production of binding compounds. The maximum compressive strengths were gained after 21 days of adding 5% lime and 7.5% CKD (1800 and 1720 Mpa, respectively). According to the results, the addition of 5% lime and 7.5% CKD is responsible for forming new product-binding materials that improve the mechanical strength via the pozzolanic reaction. Reusing by-product materials such as CKD and phosphatic clay as non-traditional soil stabilizers could reduce the amount of these materials destined as waste.

DOI: 10.33899/earth.2023.138680.1051, ©Authors, 2023, College of Science, University of Mosul.

تأثير إضافة المواد الصناعية على خصائص التربة الانتفاخية

محمد عبد اللطيف المصري [1]، اسلام محمود الدبشه [2]، فاتن مصطفى السليتي [3]

[1، 2] قسم علوم الأرض والبيئة التطبيقية، كلية علوم الأرض والبيئة، جامعة آل البيت، المفرق، الأردن.

[3] قسم علوم الأرض والبيئة ، كلية الأمير الحسن بن طلال للموارد الطبيعية والبيئة، الجامعة الهاشمية، الزرقاء، الأردن.

معلومات الارشفة

تاريخ الاستلام: 01- مارس -2023

تاريخ المراجعة: 31- مارس -2023

تاريخ القبول: 07- مايو-2023

تاريخ النشر الالكتروني: 30- يونيو-2023

الكلمات المفتاحية:
التربة الانتفاخية
التربة الطينية
تثبيت التربة
الجير
الحجر الرملي
الطين الفوسفاتي
غبار حرق الاسمنت

المراسلة:
الاسم: فاتن مصطفى السليتي
Email: fatenm@hu.edu.jo

الملخص

تهدف هذه الدراسة لعمل تثبيت للتربة الانتفاخية وتقليل تمددها في منطقة الأزرق. وقد تحقق هذا الهدف من خلال خلط التربة مع نسب مختلفة من اربعة مواد صناعية مثبتة هي: الجير، الطين الفوسفاتي، غبار الاسمنت بعد الحرق، و الحجر الرملي. تم دراسة الخواص الدالة للتربة الأصلية من خلال عدة فحوصات. وتم دراسة التراكيب الكيمائية والمكونات المعدنية للمواد المستخدمة في البحث. أجري فحص رص التربة واختبارنسبة تحميل كاليفورنيا و تحديد مقاومة الضغط الغير محصور لتقييم الخواص الهندسية للتربة الانتفاخية بعد اضافة المواد المثبتة لها. أشارت نتائج الفحوصات الى تناقص مؤشر اللدونة من 60% في التربة الأنتفاخية الى 17.2% بعد اضافة 5% من الجير، وإلى 18.47% بعد إضافة 10% من الطين الفوسفاتي، وإلى 17.52% عند إضافة 7.5% من غبار الاسمنت، وأصبحت 22.7% عند إضافة 10% من الحجر الرملي. بالمقابل تزايدت القيم القصوى للكثافة الجافة من 1.19 غ/سم^3 إلى 1.58 غ/سم^3 عند اضافة 5% من الجير، بينما تناقصت القيم المثلى للمحتوى الرطوبي من 40.1% إلي 25.1% . بالنسبة لنسبة تحميل كاليفورنيا فقد تزايدت من 9% إلى 17.5% بعد اضافة 7.5% من غبار الاسمنت. ولوحظ تحسن في قيم مقاومة الضغط الغير محصور عند اضافة جميع المواد المثبتة نتيجة للترابط القوي بين التربة والمواد المضافة. وكانت أعلى قيمة لمقاومة الضغط الغير محصور بعد 21 يوم من إضافة 5% من الجير 1800 ميغا باسكال، و 1720 ميغا باسكال بعد اضافة 7.5% من غبار الاسمنت. اثبتت النتائج ان اضافة 5% من الجير و 7.5% من غبار الاسمنت أدى إلى انتاج خليط مترابط مع التربة أظهر تحسن ملحوظ في الخواص الميكانيكية وأثبت فعاليته في تثبت التربة وتقليل نسبة الانتفاخ لها أكثر من المواد الأخرى.

DOI: 10.33899/earth.2023.138680.1051,

Introduction

In many countries, expansive soil is regarded as one of the primary sources of building and construction damage. The damage includes severe structural losses, cracked sidewalks, road and highway structures heaving pipelines, and sewer line disruption. One type of expansive soil unsuitable for the construction project is bentonite-rich clay soil. The major problems associated with these soils are swelling, excessive settlements, low strength, high plasticity, erodibility, high compressibility, and sensitivity to environmental conditions (Amu et al., 2005; Hurt, 1994; Ouhadi et al., 2014; Ahmed, 2015).

Soil stabilization uses stabilizers in expansive soil to enhance unfavorable geotechnical criteria such as strength, permeability, compressibility, and durability. It aims to avoid potential failures resulting in human life loss or significant financial loss (Lee and Karunaratne, 2007; Turkoz, 2011). Stabilization reduces soil plasticity and permeability, making the soil more workable, decreasing swelling and shrinkage, and enhancing compressive strength and load-bearing properties (Hasan et al., 2016; Sagnak, 2018). Various soil stabilizers have recently been used for stabilization approaches; some of these stabilizers are naturally occurring alumino-silicate materials, such as kaolinite, while others are artificially produced, such as lime, or produced from industrial wastes that are dumped randomly in open areas, such as phosphatic clay and CKD. Choobbasti et al. (2010), Dash and Hussain (2012), Jawad et al. (2014), Hasan et al. (2016), López et al. (2017), and Harshita (2018) have used lime for stabilizing clayey soil. They concluded that lime improved the performance and properties of expansive soil. The effect of CKD on soil stabilization was studied by Peethamparan and Oleo (2008), Moses and Saminu (2012), Keerthi et al. (2013), Sudheer Kumar and Janewoo (2016), and Naseem et al. (2019). Their conclusions indicated an improvement in soil strength, swelling index, maximum dry density, and optimum moisture content of expansive soil. Kollaros, Athanasopoulou (2016), Bahia and Ramadane (2012), Ramesh (2014), and Schanz and Elsawy (2017) have demonstrated a significant increase in strength with the addition of sandstone to base soil, as well as they noticed a significant change in the moisture-density relationship and a reduction in swelling action.

Many structures in Jordan have been damaged by the gradual movement of the expansive surface clay because, in the design foundation, the expanded properties of the soil have not been taken into consideration (Abduljauwad et al., 1998; Akawwi and Al-Kharabsheh, 2000). The behavior of these soils' swelling and shrinkage potential owing to the surrounding environment and mineralogical constituents causes severe problems for various types of construction (Ismail and El-Shamy, 2009). The main goal of the present study is to characterize and improve the expansive behavior of soil by adding different industrial materials (lime, CKD, phosphatic clay, and sandstone). Furthermore, a few systematic studies on the stabilization processes of expanded soil have been conducted to provide a new finding on using geo-materials for stabilization purposes.

Materials and Methods

Several samples of the base soil (BS) were collected from different sites in the Al-Azraq area near Al-Azraq castle road in NE Jordan (Fig. 1). The samples were mixed to homogenize their components and then air-dried after being pulverized in a crusher to break up the lumps and sieved through IS sieve No. 40 (475micrometers). Four stabilizing materials were examined: lime (L), phosphatic clay (PhC), cement kiln dust (CKD), and sandstone (Ss) to improve the expansive soil behavior in the Al-Azraq area. Lime is a calcium oxide material formed by the calcination of limestone that combines with water to produce heat. Cement kiln dust is a fine powder material that contains some calcium oxide. It varies depending on where the dust collection system is located, the type of operating condition, the facility for dust collection, and the fuel type (Berry and Malhotra, 1986; Balogh, 1995). Lime and CKD were obtained from Cementra Company for cement production in Al-Mafraq City. Phosphatic clay is a by-product of the phosphate mining process, and it is obtained from the Jordanian Phosphate Company Mine in the Eshydiah area in south Jordan. Sandstone with high SiO_2 content was obtained from the Ras Al-Naqab area in southwest Jordan.

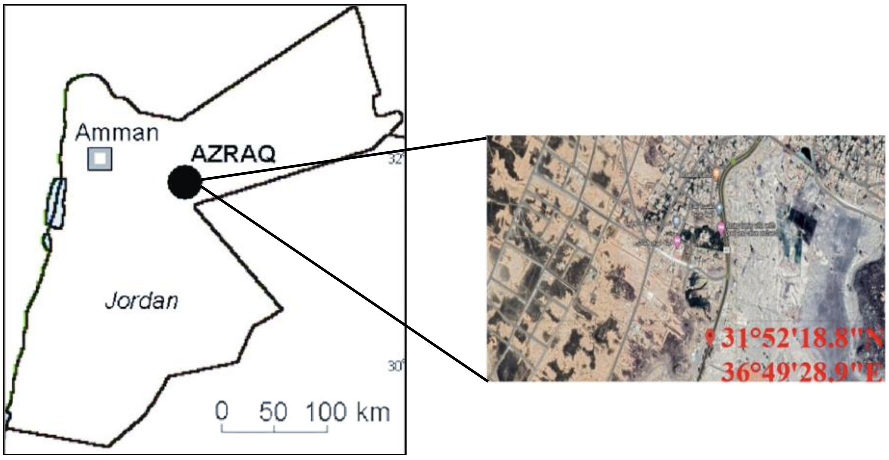

Fig. 1. Location map of the base soil area (modified after Stêpniewska, 2011)

Several tests were conducted to characterize the physical properties of the base soil: moisture content (ASTM D2216-10), specific gravity (ASTM D854-14), bulk density (ASTM D698-12e2), Atterberg's limits (ASTM D427-04), shrinkage limit (ASTM D4943-08), and particle size distribution (ASTM D421-85 and ASTM D422). X-ray fluorescence spectroscopy (XRF) was done using an automatic fusion technique by the Rigaku ZSX Primus instrument to determine the major components of the materials used. The mineralogical features were investigated using X-ray diffraction (XRD) with Cu-K radiation (1.5418 A) on a Shimadzu lab instrument. The mineral peaks at various 2θ angles are detected according to the American Mineralogist Database (AMD). SEM/EDX determines the structural details. The coated samples with platinum were scanned using a high-energy beam of primary electrons in a raster scan pattern using the model FEI Quanta 600 FEG. The stabilization tests were performed on the base soil sample mixed with varying percentages of stabilizing materials (5%, 7.5%, and 10%). For stabilized soil, the tests include:

1. Atterberg limits testing,
2. Standard compaction test (ASTM D698-12e2),
3. California Bearing Ratio-CBR (ASTM D1883–16), and
4. Unconfined compressive strength-UCS (ASTM D2166/D2166M-16).

Results and Discussion

Materials characterization

The physical properties of BS are shown in Table (1). The color is grey to greenish-grey. The moisture content is approximately 21.5%, the specific gravity is estimated at 2.43 g/cm3, and the bulk density is about 1.41 g/cm3. The Atterberg limits were evaluated for particles smaller than 45 μm. The liquid limit (LL), plastic limit (PL), and plastic index (PI) are respectively 105%, 45%, and 60%. According to Schanz and Elsawy (2017), the studied soil is classified as clayey soil (CH) with a high degree of plasticity and cohesiveness. The shrinkage limit is nearly 14.7%. According to the results of the grain size distribution analysis, approximately 73% of the BS particles have a size of less than 0.002 mm and are classified as clay soil according to the Unified Soil Classification System–USCS. Based on the PI and the percentage of clay particles, the studied soil has normal activity (82%).

Table 1. Base soil characteristics

Color	Grey to greenish-grey	Activity%	82% Normal
Specific gravity (Gs)	2.43 g/cm^3	Bulk density	1.41 g/cc
Moisture content	21.5%	Particle size distribution	0.43% Fine sandstone (0.425- 0.075 mm) 26.57% silt (0.075-0.002 mm), 73% clay (0.002 mm)
Atterberg's limits	105% LL 45% PL 60% PI	Texture	Clay soil
Shrinkage limit	14.7%	Soil Class	CH
Plasticity	High		

The chemical compositions of BS, L, PhC, CKD, and Ss are shown in Table (2). The major oxides of the base soil are silica (SiO_2) and alumina (Al_2O_3), about 53.92% and 16.96%, respectively. The sample BS contains 7.49% iron oxide (Fe_2O_3) and a small amount of calcium oxide (CaO). Calcium oxide is lime's most abundant component in sample L (74.06%). According to the analyses, phosphatic clay is primarily composed of CaO (42.08%), P_2O_5 (20.13%), and SiO_2 (14.78%). CaO (65.66%) is the main component of CKD. Meanwhile, SiO_2 is the most abundant element in sandstone (83.42%).

Table 2. Chemical composition of the base soil and stabilizing materials

Oxide/ Material	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
BS	53.92	1.98	16.96	7.49	0.044	2.45	0.58	2.23	2.70	0.02	11.63	88.37
L	1.97	0.10	5.24	0.76	0.04	0.53	74.06	0.39	0.10	0.02	16.25	83.75
PhC	14.78	0.15	5.74	1.28	0.06	0.52	42.08	0.70	0.08	20.13	14.48	85.52
CKD	7.88	0.30	6.27	2.26	0.05	0.84	65.66	0.37	0.32	0.05	15.99	84.01
Ss	83.42	0.06	4.89	0.54	0.27	0.00	0.51	0.11	0.02	0.16	10.02	89.98

LOI: loss of ignition

The XRD patterns of BS, L, PhC, CKD, and Ss are shown in Fig. (2). It is primarily composed of kaolinite (Al2(Si2O5) (OH)4), montmorillonite ((Na, Ca) 0.33 (Al, Mg)$_2$ (Si_2O_{10}) $(OH)_2 \cdot nH_2O$), and quartz (SiO_2), with traces of illite ($K_5Al_2(Al_{0.65}Si_{3.35}O_{10})$ $(OH)_2$) and hematite (Fe_2O_3). The three main components of lime are calcite ($CaCO_3$), portlandite (Ca (OH)), and lime (CaO). PhC is made of apatite ($Ca_5(PO_4)_5$(F,Cl,OH)), calcite and quartz, with a trace of montmorillonite. CKD mainly consists of calcite, halite (NaCl), and quartz. Ss grains are mostly quartz with a trace of kaolinite.

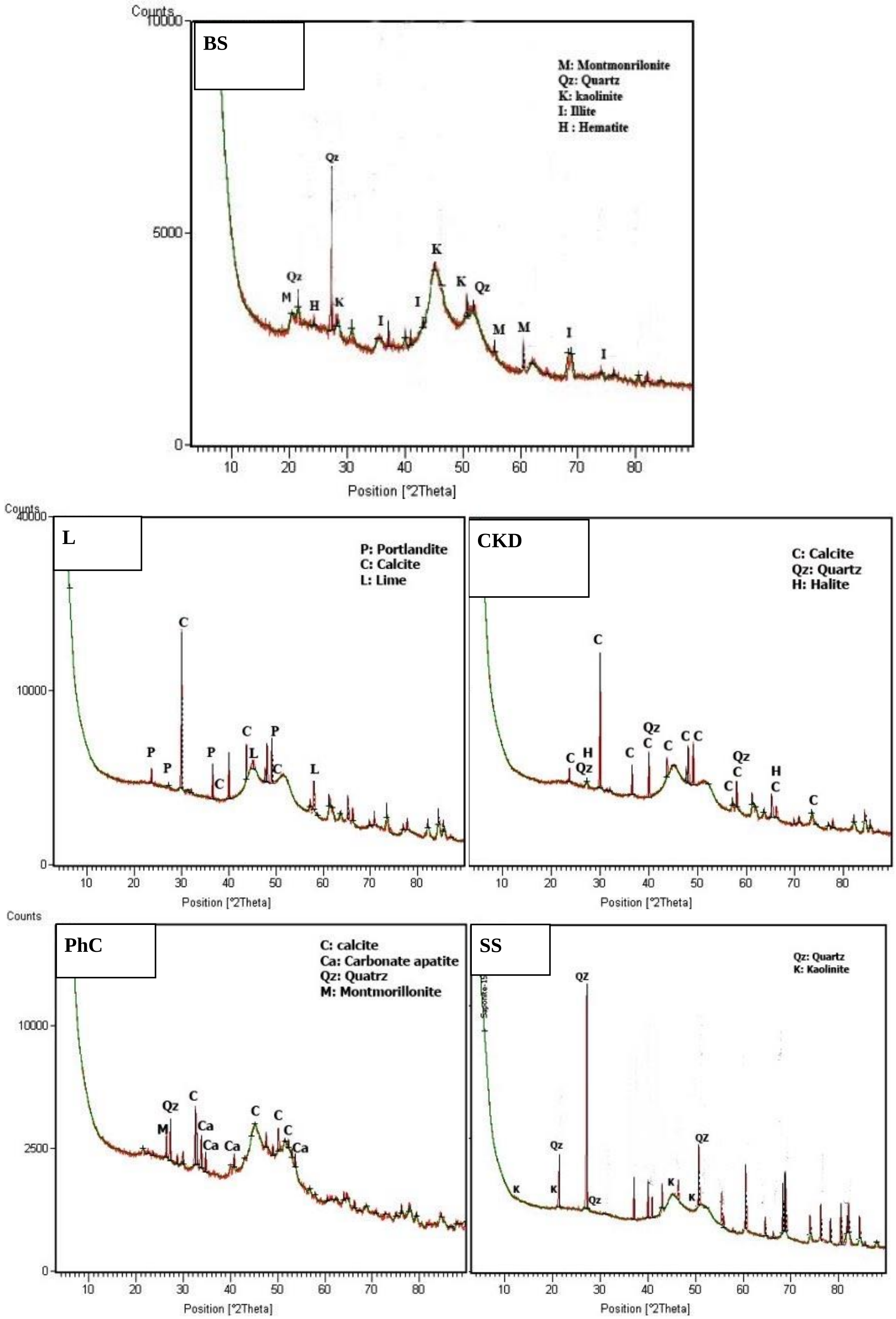

Fig. 2. XRD spectra of the base soil and stabilizing materials. a: BS, b: L, c: PhC, d: CKD, and e: Ss

Stabilizing Tests

1. Atterberg limits

The base soil was mixed with different ratios of stabilizers (5%, 7.5%, and 10%) to determine the effect of stabilizers addition on the Atterberg limits. Fig. (3) shows a significantly reduced liquid limit. Furthermore, a decrease in the plastic limit is noted, except when 5% lime and 7.5% CKD were added. As a result, the plasticity index declined substantially in these ratios.

The overall influence of stabilizer treatment on plasticity properties is a decrease in the percentage of plasticity index (PI) for soil mixtures. According to Dash and Hussain (2012), Okoro et al. (2012), and Cherian and Arnepalli (2015), when active ions are released by the stabilizer and exchange with ions within the clay structure, a cation exchange occurs, which can cause an immediate change in the material's workability. This cation exchange can raise the plastic limit (PL) and lower the PI. This decrease in plasticity contributes to the stabilized soil's more friable texture, making it easier to move and manipulate with field equipment. According to Raman (1967), untreated soil has a high potential for expansion. Based on the plasticity index values for stabilized base soil with variable lime contents, the degree of expansion potential changed from very high for base soil to medium after adding 5% lime as a best lime addition ratio. The best addition ratios for PhC, CKD, and Ss were 10%, 7.5%, and 10%, respectively. The results indicate that small amounts of L, PhC, CKD, and Ss could significantly improve the workability of high plastic base soil.

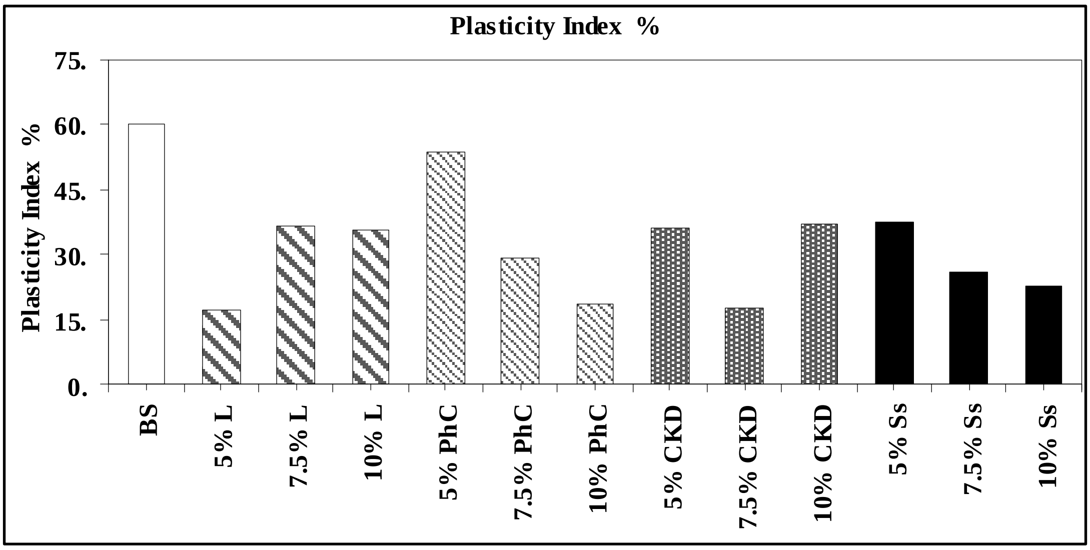

Fig. 3. Plasticity Index% of the base soil mixtures with different ratios of stabilizing materials

2. Compaction Test

The compaction test determines the relationship between compacted soil dry unit weights and soil moisture content. For this test, approximately 5 kg of air-dried base soil is mixed with (5%, 7.5%, and 10%) ratios of each stabilizer. The mixtures were compacted and mixed with varying amounts of distilled water to achieve the desired moisture content. Figs. (4 and 5) show the compaction curve, which is the relationship between the maximum dry density (gm/cm3) and the optimum moisture content of the mixtures. The results show that adding 5% lime reduced the moisture content (25.1%) and raised the dry density (1.58

mg/cm3) compared with the base soil's moisture content (40.2%) and dry density (1.19%). Furthermore, adding more lime reduces the dry density while increasing the moisture content. These results match the results of the Atterberg limit regarding the best-adding ratios of the used stabilizers.

Generally, the stabilized soil's maximum dry density exceeds the base soil's density. However, the optimum moisture content in treated soil is lower than in untreated soil. The change in maximum dry density is most likely due to the reaction between stabilizers and base soil, which results in filling the soil pores with stabilizers, then resulting in a decrease in the mixture's void ratio and an increase in the dry density of the stabilized soil (Ramesh, 2014). These findings are consistent with Kolay and Ramesh (2016) and Kumar and Lingo (2020).

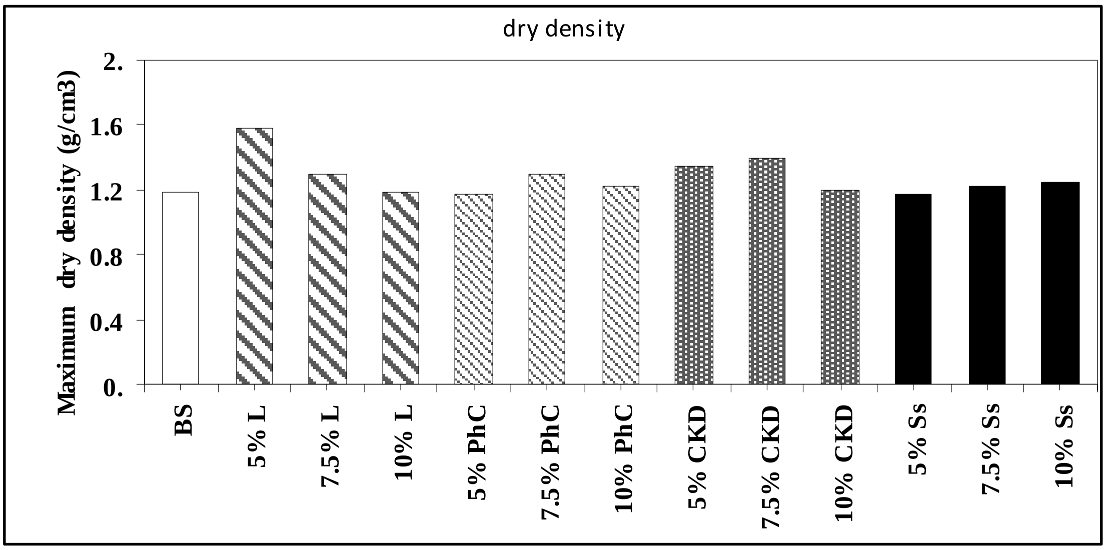

Fig. 4 . Maximum dry density for the base soil mixed with different ratios of stabilizing materials

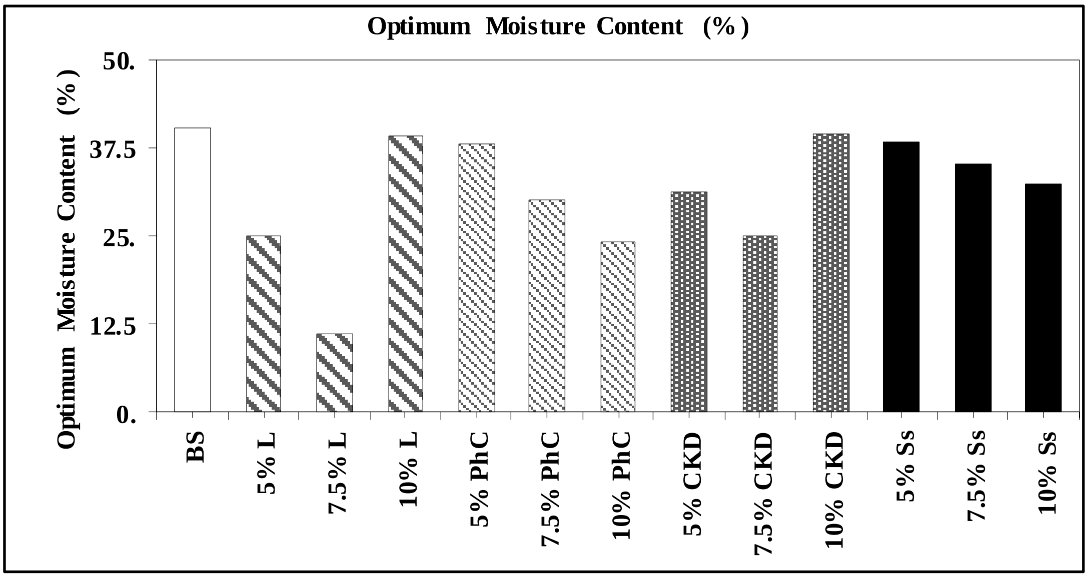

Fig. 5. Optimum moisture content of the base soil mixed with different ratios of the stabilizing materials

3. California Bearing Ratio (CBR)

The CBR test results are shown in Fig. (6). It is proposed that adding 5% lime increases the bearing ratio of the base soil from 9% to 17.17%. On the other hand, the best CBR values are obtained by combining 10% PhC, 7.5% CKD, and 10% Ss, which increased the CBR values to 14.5%, 17.5%, and 15.3%, respectively. This increase in the bearing ratio is due to the stabilizers being taken up by the base soil, which changes the behavior of the soil and causes an improvement in the bearing ratio of the mixtures.

The CBR values of the 5% lime and 7.5% CKD mixtures are higher than the other mixtures due to the formation of cementitious compounds, particularly calcium-silicate-hydrates (C-S-H) and calcium-aluminate-hydrates (C-A-H), which results in a gradual increase in the strength (Consoli et al., 2014; Du et al., 2012). This result is similar to the results of Du et al. (2012), Zhao et al. (2014), and Gandhi (2018).

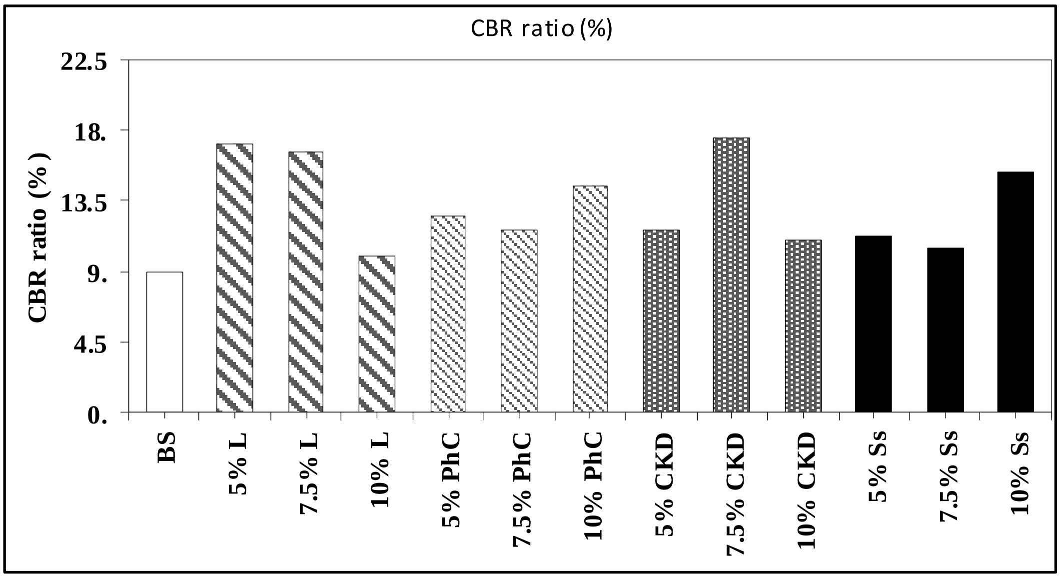

Fig. 6. CBR % for the stabilized soil with the stabilizing materials

4. Unconfined Compressive Strength (UCS)

Fig. (7) illustrates the stabilization process's impact on the unconfined compressive strength of the base soil. The optimal ratios for studying UCS behavior by varying the curing time to 3, 7, 14, and 21 days are a mixture of 5% L-BS, 10% Ph-BSC, 7.5% CKD-BS, and 10% Ss-BS. The results show a significant increase in UCS due to the stabilization process. The findings are consistent with previous research of Raoul et al. (2010); Amid and Eberemu (2013). The cation exchange between the stabilizers and the negatively charged clay particles and the flocculation-agglomeration mechanism may be responsible for the increased UCS of the stabilized soil. Due to the pozzolanic reaction, lime, and CKD are more effective in stabilizing soil than phosphatic clay and sandstone. This reaction occurs between calcium ions and the clay minerals' silica and alumina. As a result, calcium-silicate-hydrates (C-S-H), calcium-aluminate-hydrates (C-A-H), and calcium-aluminum-silicate-hydrates (C-A-S-H) form Amadi and Eberemu (2013).

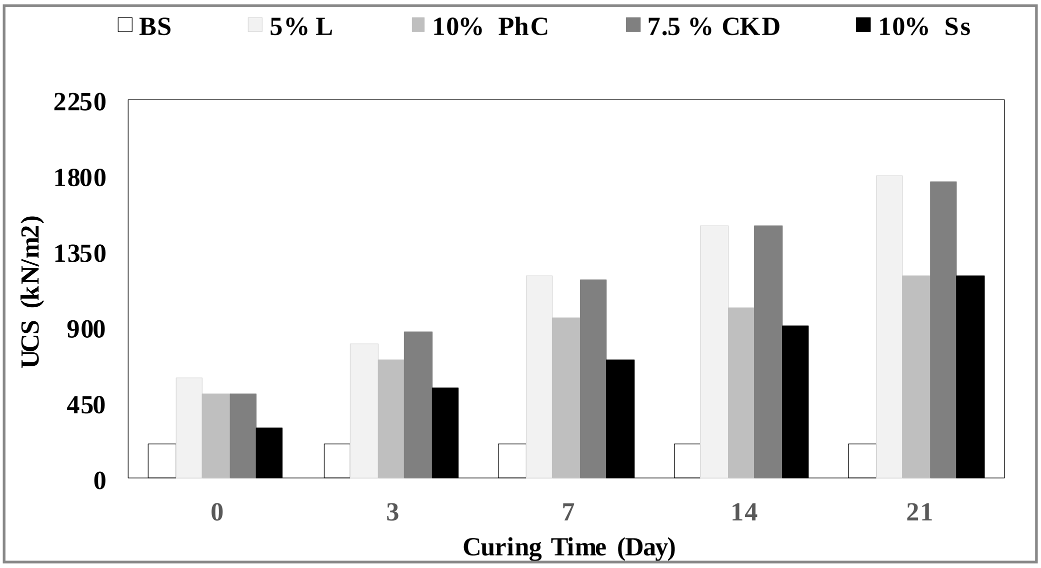

Fig. 7. The effect of curing time on USC of the base soil and stabilizing materials at different mixing ratios

The crystalline reaction products formed when 5% lime is added to the base soil are described using X-ray diffraction. Fig. (8) demonstrates the spectrum of 5% lime-stabilized soil after 21 days of curing. The intensity of the reflection of clay minerals decreases due to the interaction of the stabilizer with the soil matrix, which destructs clay particles, resulting in the formation of new CSH phases (Yoobanpot et al., 2017).

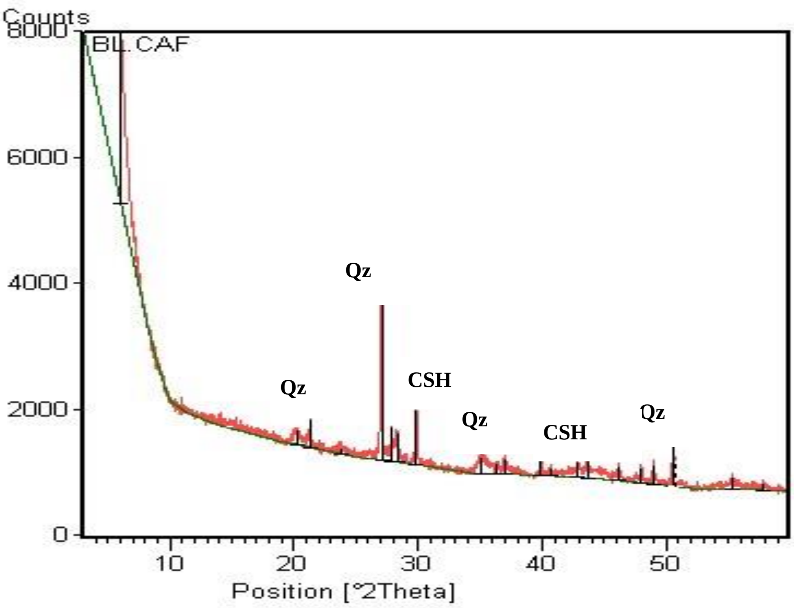

Fig. 8. XRD spectrum of the stabilized soil with 5% lime

Fig. (9) represents the lime-stabilized soil micrograph and EDX spectrometry. The EDX spectra show that calcium ions from lime are newly formed during curing. During the 21-day curing period, chemical stabilization changes the clay particles. The crystal edges dissolved, and the voids filled up, forming a cloudy formation with the soil particles.

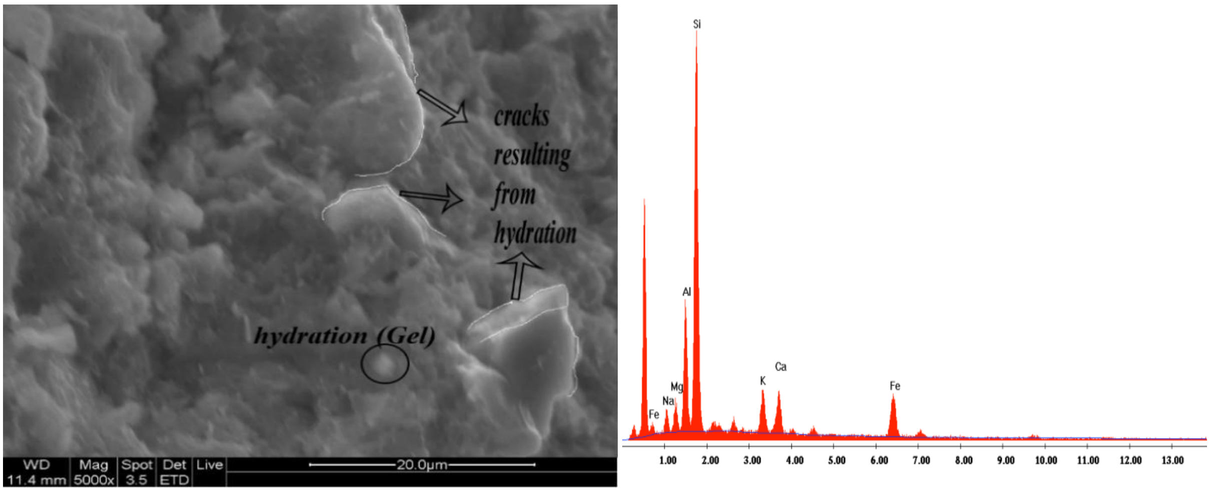

Fig. 9. SEM micrograph of the stabilized soil by 5% lime and EDX chart

Conclusions

The effects of stabilization on the main characteristics of the base soil are investigated in an experimental study using different ratios of lime, phosphatic clay, CKD, and sandstone as stabilizers. The optimal mix designs with the used stabilizers are 5% lime, 10% phosphatic clay, 7.5% CKD, and 10% sandstone based on the decrease in the Atterberg limits and degree of expansion, as well as the increase in maximum dry density. After stabilization, the CBR and USC values are raised. The reaction between the base soil and the stabilizers used resulted in cation exchange, which occurs when active ions that are released by the stabilizer exchange with metal ions within the soil structure. Lime and CKD are found to be more effective in improving soil than phosphatic clay and sandstone stabilization; this could be attributed to the pozzolanic reaction between the calcium ions in lime and CKD and the clay minerals' silica and alumina.

Acknowledgment

The authors are grateful to all members of the Faculty of Earth and Environmental Sciences and the Water, Environment, and Arid Regions Research Center at Al Al-Bayt University for ‘[their continuous support.

Declarations

Ethics Statement: This article does not contain any studies with human participants or animals performed by any authors.

Conflicts of interest: The authors have no conflicts of interest to declare.

Data availability: Any data supporting this study's findings is included within the article.

Code availability: "Not applicable"

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