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The impacts of nano-SiO_2 and silica fume on cement kiln dust treated soil as a sustainable cement-free stabilizer

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HIGHLIGHTS

- In this study, different types of green cement-free soil stabilizers are proposed.
- CKD outperforms cement based on enhancing kaolinite clay soil strength properties.
- Silica fume and nano-silica are considered stabilization's activators.
- Replacing cement with CKD significantly reduces environmental pollutions.
- Nano-silica should not be applied more than 1% in clayey soil stabilization.

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ABSTRACT

This investigation aims to assess the nano-silica and silica fume effectiveness on engineering clay soils' characteristics stabilized with cement kiln dust. Laboratory tests, including Atterberg limits, standard Proctor compaction, unconfined compressive strength, and California bearing ratio, were performed. The manufactured specimens were tested 7 and 28 days after preparation to analyze the curing time impacts on soil's strength characteristics. Meanwhile, changes in the chemical and microstructures of soil were observed using scanning electron microscope examination and X-ray diffraction analysis. Subsequently, the mixtures were compared based on eight environmental parameters. To this end, a new environmental index was developed to consider all environmental criteria simultaneously. Afterward, three criteria, including 28-day unconfined compressive strength, environmental index, and unit price, were taken into account as sustainability criteria. Moreover, the gray relational analysis was employed to examine the mixtures' sustainability. The results demonstrated that the amount of 1% nano-silica and 15% silica fume by dry soil weight was an optimum addition content of employed activators for enhancing the CKD-treated soil's geotechnical properties, respectively. Furthermore, the sustainability evaluation revealed that CKD-treated soil was the most sustainable mixture. Given the sustainability effects, nano-silica addition less than 2% and silica fume to the CKD-stabilized soil can lead to propose treated soil with considerably more sustainability than cement. It is essential to highlight that the sustainability of CKD-treated soils containing silica fume was considerably more than that of stabilized soils comprising nano-silica.

Abbreviations: CKD, Cement kiln dust; SCM, Supplementary cementitious material; UCS, Unconfined compressive strength; CBR, California bearing ratio; SEM, Scanning electron microscopy; XRD, X-ray diffraction; XRF, X-Ray Fluorescence; LL, Liquid limit; PL, Plastic limit; PI, Plasticity index; MDD, Maximum dry density; OMC, Optimum moisture content; GWP, Global warming potential; EC, Energy consumption; RC, Resource consumption; FW, Net use of freshwater; FR, Abiotic depletion potential for fossil resources; SO, Depletion potential of the stratospheric ozone layer; AP, Acidification potential; NHW, Non-hazardous waste disposed; SF, Silica fume; NS, Nano-silica; C, Cement; GRA, Gray relational analysis; GRG, Gray relational grade; S, Soil (Kaolinite clay); S-10C, Soil + 10% cement; S-15CKD, Soil + 15% cement kiln dust; S-15CKD-0.5NS, Soil + 15% cement kiln dust + 0.5% nano-silica; S-15CKD-1NS, Soil + 15% cement kiln dust + 1% nano-silica; S-15CKD-2NS, Soil + 15% cement kiln dust + 2% nano-silica; S-15CKD-5SF, Soil + 15% cement kiln dust + 5% silica fume; S-15CKD-10SF, Soil + 15% cement kiln dust + 10% silica fume; S-15CKD-15SF, Soil + 15% cement kiln dust + 15% silica fume.

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1. Introduction

Soils with low bearing capacity and high compressibility not possessing sufficient strength due to incumbent loads impose a considerable limitation on designing and constructing infrastructures such as rail and/or road embankments, bridge foundations, canals subgrade, and retaining walls [1,2]. Therefore, proposing reliable soil without excessive settlement and undesirable movements in geotechnical engineering should be of immense concern. To this end, several techniques have been adjusted to enhance the geotechnical features and meet the stability and serviceability of such soils [3]. Amongst different soil improvement techniques, soil modification by stabilization with different additives has been taken into account for several thousand years [4]. Portland cement, fly ash, and lime are mostly-employed stabilization admixtures, which may apply individually or in combinations. Among the mentioned additives, cement has been taken into account the commonly used appropriate stabilizer to enhance soil's mechanical properties in terms of general applicability [5].

Regardless of cement's broad employment as a construction resource in civil infrastructure such as soil stabilization, cement has recently not been preferred owing to cement's cost increment and the environmental concerns relevant to cement production [3]. Scrutinizing the cement environmental impacts has been revealed that producing each ton of cement roughly emits one ton of CO_2 and other greenhouse gases (GHGs) [6], consumes about 60 to 130 kg of fuel oil, 2.8 of ton raw material [7], 5000 MJ of energy, and 120 to 160 kWh of electricity [8]. Regarding this perspective, the cement industry, as the second-largest greenhouse gas producer, accounts for about 7% of embodied CO_2 emissions in the world. Moreover, cement as a nonrenewable source causes vegetation's growth to deteriorate and threaten groundwater's safety when utilizing for soil stabilization. Besides, the cement industry results in human health threats based on the dust generation during Portland cement manufacturing [7]. Ergo, cement-free soil stabilization with waste supplementary cementitious material (SCM) attracted considerable attention from researchers to achieve sustainable solutions [9].

Using waste materials and industrial by-products as raw materials replacement for the construction industry attracted major concern in order to preserve the environment and Sustainable development [8,10–12]. Researchers have been working on strategies to utilize industrial waste capable of improving the soil engineering parameters as a soil stabilizer [2]. Thus, various supplementary cementitious materials (SCMs) have been used as cement replacement enhancing the durability and mechanical properties of weak soils as a fruitful eco-friendly method.

Among different SCMs, cement kiln dust (CKD) as a cement manufacturing by-product causes the environment and plant growth to deteriorate and human health to endanger [13]. CKD contains Na_2O, K_2O, and different ingredients with chloride and/or sulfur, resulting in the impossible reuse of this material in the clinker [14]. Therefore, different research studies aimed to study the possibility of utilizing CKD as a hazardous waste material instead of cement in wastewater treatment, pavement, and soil stabilization [7,13,15]. Moreover, the CKD can be utilized as an activator for other SCMs through the presence of high alkali and sulfate contents in its ingredients [13]. In this regard, it has been demonstrated that CKD can stabilize a wide range of soils [16–18]. The previous studies had been shown that CKD could act as a proper soil stabilizer in the case of clayey soils [16–18]. Furthermore, Miller and Azad [17] observed that CKD addition to the soil could considerably enhance the strength properties, and enhancement was more considerable for soils with inadequate plasticity index (PI) [17].

As another waste material, silica fume can use instead of cement by virtue of very pozzolanic reactivity (based on excessive fineness and extreme amorphous silicon dioxide amount) [19]. Silica fume is "very fine non-crystalline silica produced in electric arc furnaces as a by-product of elemental silicon or alloys containing silicon production" [20]. This pozzolanic material results in concrete characteristics to enhance when utilized as cement replacement [21]. Furthermore, the silica fume is considered a viable soil stabilizer by filling micro-voids and generating denser mixture leading to improve stabilized soil's geotechnical properties [22]. Regarding this issue, Kalkan and Akbulut [23] had investigated the silica fume effects on natural clay liners. They postulated that the compacted clay specimens containing silica fume provide a lower level of swelling pressure, permeability, and considerably more compressive strength compared with virgin clay samples [23]. Besides, Goodarzi et al. [9] studied the impact of replacing cement with silica fume on expansive clay stabilization. In the sample with cement and silica fume, a higher strength (roughly 35%) and a lower compression index (approximately 50%) are achieved compared with the sample without silica fume [9]. Silica fume is an ideal soil stabilizer according to all the concepts mentioned above.

Besides, nano-materials can act as advantageous fillers because of their ultra-high specific surface and ultra-fine particle size leading to fabricating cement-based composites with ultra-high performance and reducing the cement matrix's carbon footprint by cutting down the cement consumption [24]. Furthermore, the previous studies' outcomes showed that the nano-material addition to the fabricated cement mortar with low pozzolanic material as cement replacement could noticeably enhance the mechanical characteristics and durability of the prepared green mortar [25]. Therefore, in addition to using SCMs as cement replacements, nano-materials can reduce the environmental influence caused by the construction activity [26].

Concerning nano-material usage in geotechnical engineering, Bahmani et al. [27] stated that nano-silica addition drastically improved the compactability, hydraulic conductivity, and compressive strength of the examined soil. Moreover, Iranpour and Haddad [28] analyzed nano-materials influences (nano-clay, nano-copper, nano-alumina, and nano-silica) on collapsible soil [28]. They showed that a combination of soil and nano-materials is very sensitive, and nano-materials' type and amount could have both advantages and disadvantages to ideal features. Meanwhile, utilizing a suitable nano-materials percentage would result in soil specifications improvement [28]. Furthermore, Lin et al. [29] used nano-SiO_2 as an additive to the sewage sludge ash/cement-treated soil. They found that treated soil's strength significantly improved after the addition of nano-SiO_2 [29]. In this regard, Ghasabkolaei et al. [30] reported that cement-treated clayey soil's mechanical properties, such as unconfined compressive strength (UCS), elasticity modulus, and California bearing ratio (CBR), were significantly enhanced by using silica nanoparticles [30]. Regarding the nano-SiO_2 impact on cement-treated soil properties, it should be worth mentioning that nano-silica with smaller size accelerated the cemented soil's physical, chemical, and microstructural properties [5].

Given the descriptions above, Portland cement considers a commonly used traditional chemical stabilizer for weak soils. Nonetheless, the cement sector is known as one of the most notorious industries for environmental pollutants. Therefore, proposing green cement-free soil stabilizers should be of immense concern. Based on the concepts mentioned above, through the advanced features of nano-materials and supplementary cementitious materials, consuming SCMs to enhance the cement-free stabilized soil's properties can be considered an environmentally friendly solution.

Ergo, this investigation aims to propose a green soil stabilizer with the beneficial utilization of CKD, silica fume, and nano-SiO_2. To this end, different tests, containing UCS, CBR, compaction, and Atterberg limits, were conducted to elaborate on the proposed soil stabilizers' geotechnical properties. Moreover, the examined treated soils were observed by application of scanning electron microscopy (SEM). Consequently, X-ray diffraction (XRD) is applied to scrutinize the products resulting from the soil and additives' chemical reactions. Ultimately, the sustainability criteria (environmental index and unit price) and sustainability index of studied cement-free treated soil were analyzed.

2. Experimental program

This investigation aims to propose a cement-free stabilizer for kaolinite clay soil based on the concepts mentioned above. The authors' previous studies demonstrated that the UCS of the specimen with 15% CKD is equal to the specimen with 10% cement after 28 days curing [31]. Therefore, 15% CKD by soil's dry weight is employed to stabilize soil in the current study. Afterward, the impacts of different silica fume and nano-silica percentages on the geotechnical characteristics and environmental impacts of treated clayey soil are elaborated. To this end, persuasive tests and analysis methods, including UCS, CBR, Atterberg limits, and compaction tests along with SEM and XRD, were performed. This study's experimental program is presented in two sections. The first section provides details about selected materials' physical and chemical characteristics and sample preparation and conditioning. The next step describes the utilized laboratory test methods along with microstructural and chemical tests.

2.1. Materials

In the current study, the kaolinite clay with low plasticity (CL), based on the Unified Soil Classification System (USCS), as a weak soil is considered for stabilization purposes. The geotechnical features of the selected soil were evaluated according to the ASTM methods depicted in Table 1. Furthermore, the soil's particle size distribution, determined through the sieve and sedimentation testing based on ASTM D 422-63, is presented in Fig. 1. Finally, the examined clay's chemical composition was measured by applying an X-Ray Fluorescence (XRF) analysis, as shown in Fig. 2.

Based on this research's objectives, different supplementary cementitious materials containing CKD with a specific gravity of 2.7 and silica fume with a specific gravity of 2.2 and surface area of 15–30 m^2/g were utilized to propose a cement-free stabilization for weak soil as a green and sustainable solution. Moreover, amorphous nano-silica powder manufactured by Evonik Industries (Essen, Germany) with a solids content of more than 99.8%, an average size of 12 nm, and surface area of 200 ± 25 m^2/g was used in this study as an activator. Ultimately, Portland cement is considered as commonly used soil stabilization to compare with the proposed stabilizers in order to introduce a novel sustainable clayey soil stabilization. The particle size distributions of the CKD and Portland cement are illustrated in Fig. 1. The chemical composition of CKD, silica fume, and Portland cement are also presented in Fig. 3.

5%, 10%, and 15% silica fume and 0.5%, 1%, and 2% nano-silica were added to the soil-15% CKD mixture so as to fabricate the treated soil specimens. Furthermore, stabilized soil with 10% cement was fabricated to compare green stabilizers' performance with that of cement. All proportions were determined as a percentage by dry weight of the soil. CKD, Portland cement, and silica fume were mixed with the kaolinite clay under the dry condition. One of the essential points in using nano-materials is how to add them to the soil. Due to the nanoparticles' small size, their distribution in the soil is not powdery and homogeneous. Therefore, in one part of the soil sample, the nanoparticles' content may be higher, and in the other part, the amounts of nanoparticles may be less. The method used in this study is to add the nano-silica to the quantity of water required to make the sample and then prepare a homogeneous solution of them by an ultrasonic probe device. Subsequently, the mixtures were sprayed on the samples to exchange moisture between the particles, prevent the nanoparticles' agglomeration, and produce a homogeneous blend. The samples were

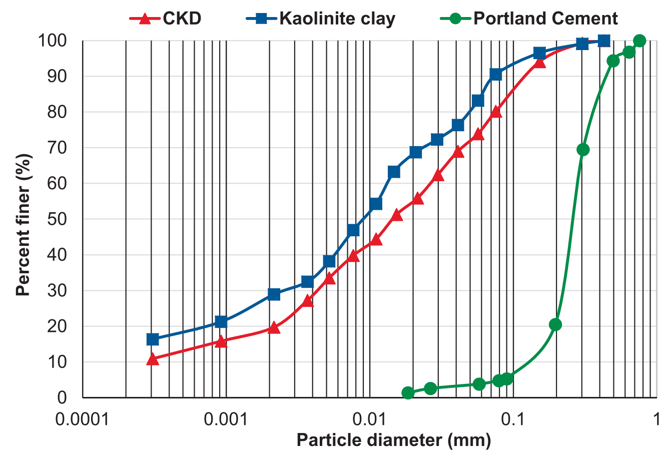

Fig. 1. The Particle size distribution of the kaolinite clay, Portland cement and CKD.

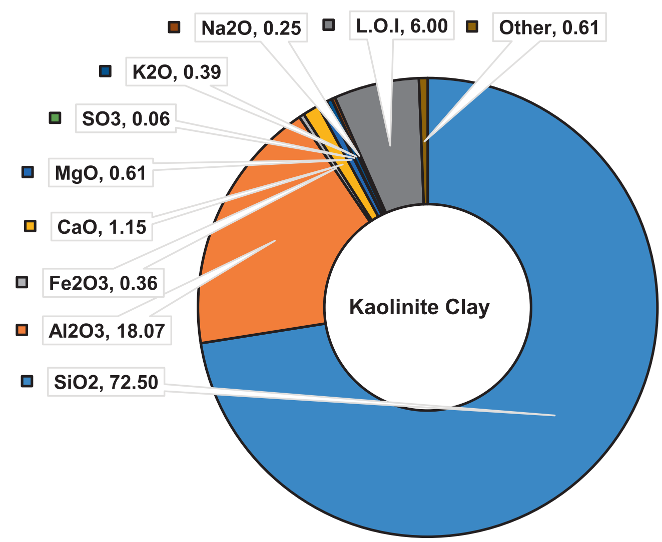

Fig. 2. Chemical composition of the examined untreated soil.

Table 1
Geotechnical properties of untreated soil.

Geotechnical properties	Value	Standard
Liquid limit (LL), %	29.5	ASTM D4318–05
Plastic limit (PL), %	21.5	ASTM D4318–05
Plasticity index (PI), %	8	ASTM D4318–05
Unified soil classification system (USCS)	CL	ASTM D2487–11
Specific gravity	2.65	ASTM D854–02
Maximum dry density (MDD), kN/m^3	17	ASTM D698–00a
Optimum moisture content (%), %	16.2	ASTM D698–00a
Unconfined compressive strength (UCS), kPa	129	ASTM D2166/ D2166M–13

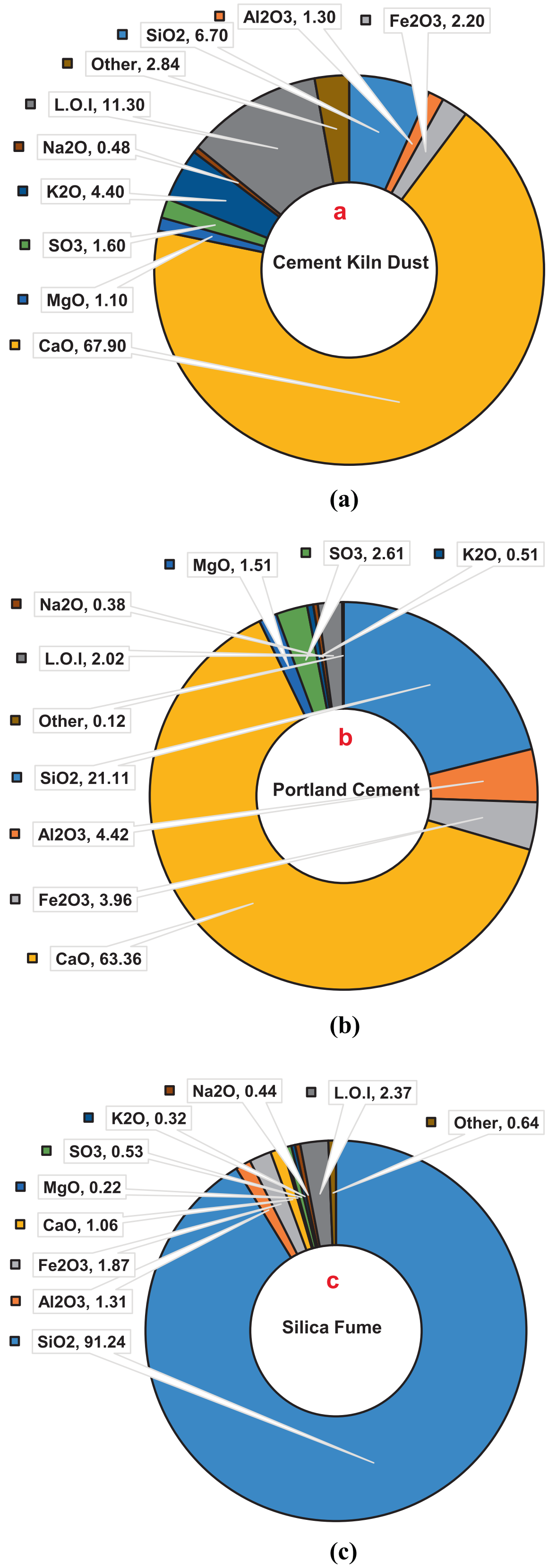

Fig. 3. Chemical composition of (a) CKD, (b) Portland cement, (c) Silica Fume.

tested at 7 and 28 days after preparation to assess the effects of curing time on UCS and CBR.

2.2. Test methods

In this research, the testing program involved conducting a set of Atterberg limits, standard Proctors, UCS, and CBR on untreated and treated soils.

2.2.1. Atterberg limits

The Atterberg limits of original and treated soils were measured according to the procedure described in ASTM D4318 [32] method. The tests are conducted on a soil's portion that passes the 425-µm (No. 40) sieve. After constituting the specimens with moisture for one day, liquid limit (LL) and plastic limit (PL) tests were conducted. Three replication is employed to perform plastic and liquid limit tests. The plasticity index (PI) is determined by the arithmetic mean of the results differences (LL and PL).

2.2.2. Compaction test

The standard Proctor compaction tests were performed according to the procedures presented in ASTM D698 [33] to evaluate the maximum dry density (MDD) and determine the samples' optimum moisture content (OMC). The clayey soil was completely mixed with specific amounts of additives. The compaction process was performed in three different layers. Each of the mentioned layers was compacted with 25 blows.

2.2.3. Unconfined compressive strength tests

UCS tests were conducted based on the details provided by ASTM D2166/D2166M [34] with a loading rate of 1% per minute. The mixtures remained in sealed plastic bags for 24 h. The specimens were compacted into a cylindrical mold (with the diameter and height of 38-mm and 76-mm) to obtain dry unit weight corresponding to 100% maximum dry density (MDD) and on the wet of optimum moisture content (OMC) obtained from the Proctor compaction test. The compacted specimens were cured in plastic for periods of 7 and 28 days at a temperature of 23 ± 2°C The experiments were repeated on at least three same samples to minimize errors that may occur due to changes in the material and testing conditions. The UCS means were then used in the reports.

2.2.4. California bearing ratio tests

Soaked CBR tests were measured based on ASTM D1883 [35]. The mixtures were held in sealed plastic bags for 24 h and then were compacted at an OMC. The specimens were cured in two plastic bags to prevent moisture change. CBR tests were conducted at a strain rate of 1.27 mm/min in the CBR testing machine after 7 and 28 days curing.

2.2.5. Chemical and microstructural tests

In order to evaluate the underlying mechanisms of the additives' effects on the soil, XRD analysis, and SEM examination were performed. Untreated and treated soils' images were magnified 10,000 times using a scanning electron microscope modeled VEGA\\TESCAN. The SEM and XRD tests were done on pieces collected from UCS tests' cylindrical samples. The specimens' central part is taken to perform microstructural tests. They were dried entirely prior to tests. For the XRD analysis, these samples were first ground to produce fine homogeneous powders. Then, the XRD patterns were obtained using Cu-Kα radiation with an input voltage of 40 kV and a current of 30 mA, in the scanning range of 2θ from 5° to 80° with a step size of 0.015° and a scan speed of 2° per minute.

2.3. Sustainability modeling

Sustainability is one of the vital parameters to preserve the environment. Therefore, sustainable development has been a significant concern. In this study, environment effects, materials price, and 28-day UCS are considered sustainability criteria, and different stabilization alternatives are compared based on their sustainability. Global warming potential (GWP), energy consumption (EC), resource consumption (RC), net use of freshwater (FW), abiotic depletion potential for fossil resources (FR), depletion potential of the stratospheric ozone layer (SO), acidification potential (AP), and non-hazardous waste disposed (NHW) are taken into account environmental factors. The different stabilization alternatives applied in this study are compared based on the mentioned environmental criteria in order to detect the most eco-friendly stabilization option. The environmental criteria are modeled from Eqs. (1) to (8).

$$GWP = (U^{C}_{GWP} \times C) + (U^{CKD}_{GWP} \times CKD) + (U^{SF}_{GWP} \times SF) + (U^{NS}_{GWP} \times NS) \tag{1}$$

$$EC = (U^{C}_{EC} \times C) + (U^{CKD}_{EC} \times CKD) + (U^{SF}_{EC} \times SF) + (U^{NS}_{EC} \times NS) \tag{2}$$

$$RC = (U^{C}_{RC} \times C) + (U^{CKD}_{RC} \times CKD) + (U^{SF}_{RC} \times SF) + (U^{NS}_{RC} \times NS) \tag{3}$$

$$FW = (U^{C}_{FW} \times C) + (U^{CKD}_{FW} \times CKD) + (U^{SF}_{FW} \times SF) + (U^{NS}_{FW} \times NS) \tag{4}$$

$$FR = (U^{C}_{FR} \times C) + (U^{CKD}_{FR} \times CKD) + (U^{SF}_{FR} \times SF) + (U^{NS}_{FR} \times NS) \tag{5}$$

$$SO = (U^{C}_{SO} \times C) + (U^{CKD}_{SO} \times CKD) + (U^{SF}_{SO} \times SF) + (U^{NS}_{SO} \times NS) \tag{6}$$

$$AP = (U^{C}_{AP} \times C) + (U^{CKD}_{AP} \times CKD) + (U^{SF}_{AP} \times SF) + (U^{NS}_{AP} \times NS) \tag{7}$$

$$NHW = (U^{C}_{NHW} \times C) + (U^{CKD}_{NHW} \times CKD) + (U^{SF}_{NHW} \times SF) + (U^{NS}_{NHW} \times NS) \tag{8}$$

where C, CKD, SF, and NS are the weights of cement (kg), cement kiln dust (kg), silica fume (kg), and nano-silica (kg) employed to stabilize each ton of soil. Moreover, GWP, EC, RC, FW, FR, SO, AP, and NHW signify the volume of global warming potential (kg CO_2-eq/kg), energy consumption (MJ), resource consumption (kg), net use of freshwater (m^3-eq), abiotic depletion potential for fossil resources (MJ), depletion potential of the stratospheric ozone layer (kg CFC11-eq), acidification potential (kg), and non-hazardous waste disposed (kg) emitted by each ton of soil stabilization. U^{i}_{j} implies the unit amount of environmental pollution j generated by the production of each kg material i. For instance, U^{C}_{GWP} represents the global warming potential emitted by the production of a kg cement. Eight environmental criteria are taken into consideration. It can be complicated to compare different stabilization mixture proportions based on eight environmental parameters. Because a mixture proportion may outperform other mixtures based on some environmental parameters, while the other mixtures may dominate it based on other environmental parameters. There is a dire need to introduce an environmental index that considers all mentioned environmental criteria simultaneously to prevail this deficiency. The environmental criteria have different ranges. They have to be scaled in the same range if they want to be integrated into a unique environmental index. In this regard, Eq. (9) is applied to scale environmental criteria between 0 and 1. In this scale format, 0 implies the ideal level, and 1 signifies the worst case among various alternatives. That is to say, the value 0 is assigned to the mixture proportion with the lowest emission, and value 1 represents the most pollutant mixture proportion.

$$S^{j}_{k} = \frac{x^{j}_{k} - x^{j}_{\min}}{x^{j}_{\max} - x^{j}_{\min}} \quad \forall j \in \{1, 2, ..., J\}, \ \forall k \in \{1, 2, ..., K\} \tag{9}$$

where S^{j}_{k} is the scaled value of environmental criterion j generated by the application of stabilization alternative k. x^{j}_{k} is the rough value of environmental criterion j emitted by applying stabilization alternative k. $x^{j}_{\max}$ and $x^{j}_{\min}$ represent the maximum and minimum value of environmental criterion j among different stabilization alternatives. J and K are the number of environmental criteria and number of stabilization mixture proportions, respectively.

Consequently, the environmental criteria scaled values are integrated into an environmental index indicated in Eq. (10). With the aid of this formula, stabilization alternatives can be compared based on all environmental criteria.

$$ENV_k = (\alpha_1 \times S^{GWP}_{k}) + (\alpha_2 \times S^{EC}_{k}) + (\alpha_3 \times S^{RC}_{k}) + (\alpha_4 \times S^{FW}_{k}) + (\alpha_5 \times S^{FR}_{k}) + (\alpha_6 \times S^{SO}_{k}) + (\alpha_7 \times S^{AP}_{k}) + (\alpha_8 \times S^{NHW}_{k}) \tag{10}$$

In the above equation, ENV_k is the environmental index of stabilization alternative k. α_1, α_2, α_3, α_4, α_5, α_6, α_7, and α_8 are the impact weights of GWP, EC, RC, FW, FR, SO, AP, and NHW in the environmental index in the order given.

Unit cost is another pivotal parameter considered the sustainability criterion. The stabilization unit cost is calculated based on the materials' weight applied to stabilize each ton of soil and the material unit price. Thus, the stabilization unit cost is formulated based on Eq. (11).

$$COST = (U^{C}_{COST} \times C) + (U^{CKD}_{COST} \times CKD) + (U^{SF}_{COST} \times SF) + (U^{NS}_{COST} \times NS) \tag{11}$$

where $COST$ is the materials' cost summation employed to stabilize each ton soil. U^{i}_{COST} signifies the unit cost (each kg) of material i.

28-day UCS is the other sustainability criterion applied to consider performance along with environmental effects and cost. The procedures to evaluate 28-day UCS are explained in the previous parts.

2.3.1. Gray relational analysis

According to the concepts mentioned above, three criteria, including environmental index, cost, and 28-day UCS, are taken into account sustainability criteria. As previously mentioned, alternative ranking can be a complicated task in multi-response parameter comparison. Therefore, gray relational analysis (GRA) is utilized to compare various stabilization alternatives and rank them.

GRG is a robust technique to prioritize different options. In other words, GRA is a multi-objective decision-making parametric modeling that helps the researchers and policy-makers select the optimal option among different alternatives based on various objective functions. GRA can be effective in the circumstances that the different parameters' relationship is not clear. The term "gray" in GRA implies uncertain and poor information. GRA receives the multi-response information about each alternative and converts the multi-response information to a single-response value. The mentioned single-response value is called gray relational grade (GRG). Hence, all alternatives can be compared and ranked according to GRG, a certain value [36].

Initially, the vital parameters (sustainability criteria) should be normalized to decrease the variability and scale the parameters' range to a single unit. The appropriate value for this normalization is the range between 0 and 1. In this normalization, the value of 1 ought to represent the ideal value, and the value of 0 should imply the worst-case alternative [37]. To this end, the minimization objectives (environmental index and cost) should be scaled based on Eq. (12). On the flip side, the maximization objectives (UCS) should be scaled according to Eq. (13). Minimization objectives are the attributes that their ideal value is their minimum value.

Maximization objectives are the features that should be increased to enhance sustainability.

$$G_k^z = \frac{x_{\max}^z - x_k^z}{x_{\max}^z - x_{\min}^z} \ \forall z \in \{1,2,...,Z\},\ \forall k \in \{1,2,...,K\} \quad (12)$$

$$G_k^z = \frac{x_{\max}^z - x_k^z}{x_{\max}^z - x_{\min}^z} \ \forall z \in \{1,2,...,Z\},\ \forall k \in \{1,2,...,K\} \quad (13)$$

where x_k^z signifies the criterion z rough value for the stabilization alternative k. G_k^z is the normalized value of criterion z for the stabilization alternative k. $x_{\max}^z$ and $x_{\min}^z$ imply the maximum and minimum value of sustainability criterion z among different stabilization alternatives.

Afterward, gray relational coefficients are calculated. Eq. (14) is used to evaluate the gray relational coefficients.

$$\xi_k^z = \frac{\Delta_{\min}^z + (\xi \times \Delta_{\max}^z)}{\Delta_k^z + (\xi \times \Delta_{\max}^z)} \quad (14)$$

where ξ_k^z is the gray relational coefficient of criterion z for alternative k. Δ_k^z represents the deviation sequence of the reference sequence. $\Delta_{\max}^z$ and $\Delta_{\min}^z$ are the maximum and minimum values of absolute differences. ξ is the identification coefficient, usually taken between 0 and 1 [36].

Ultimately, the GRG is calculated by the gray relational coefficients. The GRG is calculated based on Eq. (15).

$$GRG_k = \frac{1}{K} \times \sum_{k=1}^{K} \xi_k^z \quad (15)$$

where GRG_k is the alternative k GRG value.

2.3.2. Sustainability essential parameters

The parameters' values required to analyze sustainability are presented in this part. The unit cost of material and their unit environmental pollutant emissions are represented in Table 2. These data are collected from authentic publications [8,11,38–42]. In this table, the CKD and silica fume RC values are 0 because they are by-products and landfill, and they are not considered rough materials in this study. Moreover, there is not any preprocess to prepare CKD in order to apply in stabilization. Accordingly, the unit price and CKD emissions are equal to 0 [7,8,43].

The impact weights of GWP, EC, RC, FW, FR, SO, AP, and NHW are extracted from valid recently-published articles [11,38]. Afterward, these impact weights are normalized by considering the impact weights summation equals 1 $(\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6 + \alpha_7 + \alpha_8 = 1)$. This normalization restricts the environmental index in the range from 0 to 1. The normalized values of α_1, α_2, α_3, α_4, α_5, α_6, α_7, and α_8 are 0.233, 0.175, 0.175, 0.147, 0.039, 0.130, 0.081, and 0.020, respectively.

Eight stabilization alternatives are taken into consideration in this study, the treated soil with 10% cement (S-10C), 15% CKD (S-15CKD), 15% CKD and 0.5% nano-silica (S-15CKD-0.5NS), 15% CKD and 1% nano-silica (S-15CKD-1NS), 15% CKD and 0.5% nano-silica (S-15CKD-2NS), 15% CKD and 5% silica fume (S-15CKD-5SF), 15% CKD and 10% silica fume (S-15CKD-10SF), and 15% CKD and 15% silica fume (S-15CKD-15SF). Hence, $K = 8$. There are eight environmental criteria, including GWP, EC, RC, FW, FR, SO, AP, and NHW, in this study. Ergo, $J = 8$. Meanwhile, three sustainability criteria -- environmental issues, cost, and 28-day UCS – are considered, and accordingly, $Z = 3$.

In GRA, the values of $\Delta_{\max}^z$, $\Delta_{\min}^z$, and ξ are taken into account 1, 0, and 0.5 in the order mentioned based on the details provided by Panda et al. [36].

3. Result and discussion

3.1. Atterberg limits

As a primary soil's characteristics, the Atterberg limits of Raw soil (S) and different treated soil were conducted. The averaged out results for three replicate of each examined soil are shown in Fig. 4. Drawing this figure's findings, adding cement and CKD to the clayey soil increased the liquid limit and the plastic limit due to the increased amount of water needed for the hydration process. The results also showed that the treated soil with 10% cement (S-10C) lowered the plasticity index. Nevertheless, the clayey soil stabilized with 15% CKD (S-15CKD) slightly increased the PI value. The minor increase in soil plasticity with 15% CKD can be attributed to CKD particles' higher specific surface area than clay.

Regarding the influences of nano-silica different percentages on CKD-treated soil's properties, the results demonstrated that the liquid limit values slightly increase with the nano-silica amount increment, which is compatible with the results presented in previous research studies [5,30]. Moreover, increasing the nano-silica

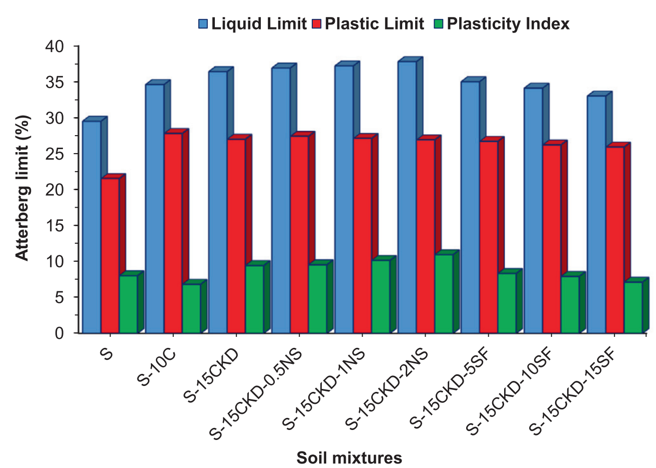

Fig. 4. Variation of Liquid Limit, Plastic Limit and Plasticity Index of the studied soils.

Table 2
The unit price and environmental pollutant emissions of materials.

	Soil	Cement	CKD	Nano-Silica	Silica fume	Water
GWP (kg CO2-eq/kg)	0	0.898	0	4.091	0.00392	0.00057
EC (MJ)	0	4.976	0	71.3625	0.018	0.00574
RC (kg)	0	1	0	1	0	1
FW (m^3 eq)	0	0.0095	0	26.666	0.000427	0.001
FR (MJ)	0	3.44	0	19.833	0.0433	0.00538
SO (kg CFC11 eq)	0	1.21E-10	0	0.0003	9.88E-13	2.35E-14
AP (kg)	0	0.00148	0	0.81	7.26E-06	8.58E-07
NHW (kg)	0	0.0015	0	0.64	7.95E-05	0
COST (USD)	0	0.11	0	7.13	0.69	0.001

content had a marginal effect on the plastic limit. The examined soils' PL value initially increased with the 0.5% nano-silica but then decreased at higher content (2% of NS). The reduction of the plastic limit in high amounts of nano-silica can be attributed to the increased packing density and high surface energy of nano-silica. A thin layer of water surrounds the nanoparticles, so less water is needed to plasticize the matrix [27]. Finally, utilizing the nano-silica along with CKD leading the plasticity index of treated soil to increase. These consequences can be related to a large specific surface area (SSA) of nano-silica due to its tiny size, which interacts with other soil matrix particles resulting in the PI value of CKD-treated soil slightly increase [30].

Fig. 4 also illustrates the effects of silica fume content on the Atterberg limits of the CKD-stabilized soil. As displayed in this figure, there was a steady decrease in the liquid limit, the plastic limit, and the plasticity index of soil as the silica fume dosages increases. This finding is consistent with previous research results, which investigate the impacts of natural pozzolan and lime on the Atterberg limits of clayey soils [3,44]. Concerning the PI values of treated soils by CKD and SF, it can be revealed that reduction of PI may be because of some soil properties such as cation exchange capacity [45,46], the silicate clay minerals' relative value in the samples [47], and adding low-plastic material (silica fume) to the soil [48,49].

3.2. Compaction test

Fig. 5 demonstrates the compaction curves for studied treated soils. OMC increment and MDD reduction occurred in the circumstances that the CKD and cement were added to the soil. The OMC and MDD of soil stabilized with 15% CKD and 10% cement are 21.0% and 1.547 g/cm^3 and 19.2% and 1.6 g/cm^3, respectively, as presented in Fig. 5a. Likewise, OMC increment and MDD reduction have been reported by many researchers [16–18,50]. The OMC increment with adding cement and CKD can be attributed to the hydraulic (water-loving) nature of the calcium oxide in these materials' matrix [4,17]. Particles' aggregation owing to cementitious materials results in larger macro-pores within the soil, and accordingly, MDD appears to be decreased [17,51]. The optimum moisture amount increment will make the compaction easier for the soils, which are wet of optimum [52,53].

Variations in OMC and MDD of specimens with silica fume addition can be seen in Fig. 5b. As can be perceived from this figure, the MDD decreases, and the OMC increases by silica fume content increment. Similar behavior was observed in clays stabilized with lime and silica fume mix [54]. The optimum moisture content increment is because of the composite samples' surface area changing that silica fume increased the mixture's total particle surface [23]. Likewise, the reason for the decrease in the MDD is the replacement of CKD by the silica fume in the mixture, which has a relatively lower specific gravity 2.2 [54]. It may also be caused by coating the soil with the CKD and silica fume, resulting in large particles with larger pores and lower density [54].

Regarding the influences of nano-silica addition to the CKD-stabilized soil through the presented results of Fig. 5c, it can be theorized that nano-silica has no considerable impact on the OMC and the MDD of treated soil. Increasing the nano-silica amount leads to a slight MDD reduction, which can be attributed to nano-scaled powders' agglomeration, thereby increasing the amounts of necks between particles and thus reducing the density of the associated framework [27].

3.3. Unconfined compressive strength tests

The UCS is a crucial indicator to quantify the improvement of soils due to treatment. According to this study objectives, the

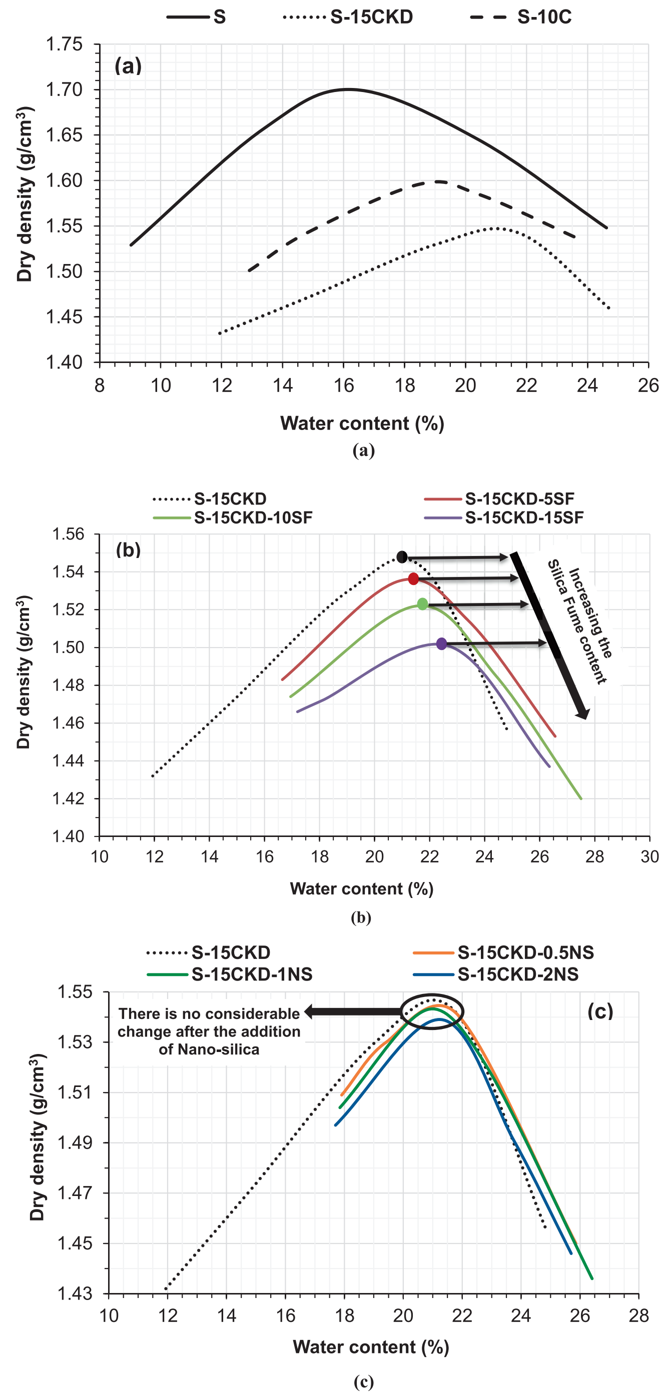

Fig. 5. Compaction curves of examined untreated and treated soils: (a) soil stabilized with cement and CKD (b) CKD-treated soil with silica fume (c) CKD-treated soil with nano-silica.

UCS of 7 and 28 days curing of treated soil with different cement-free stabilization were investigated. The results of USC tests for three replicates were averaged out and depicted in Fig. 6. It can be realized from the results of Fig. 6a that the CKD and cement improved the UCS, which is reported extensively in previous studies [17,55,56]. Upon adding 15% CKD and 10% cement, the 7-day UCS of soil improved to 6.2 and 6.7 times more than USC of untreated soil, respectively. Strength development can be attributed to the free-lime, sulfate, and alkali contents in the soil stabilized with cementitious materials [51]. The crystalline hydration products present in the mixture were assumed to be an essential factor in enhancing the strength of stabilized soils [16,56].

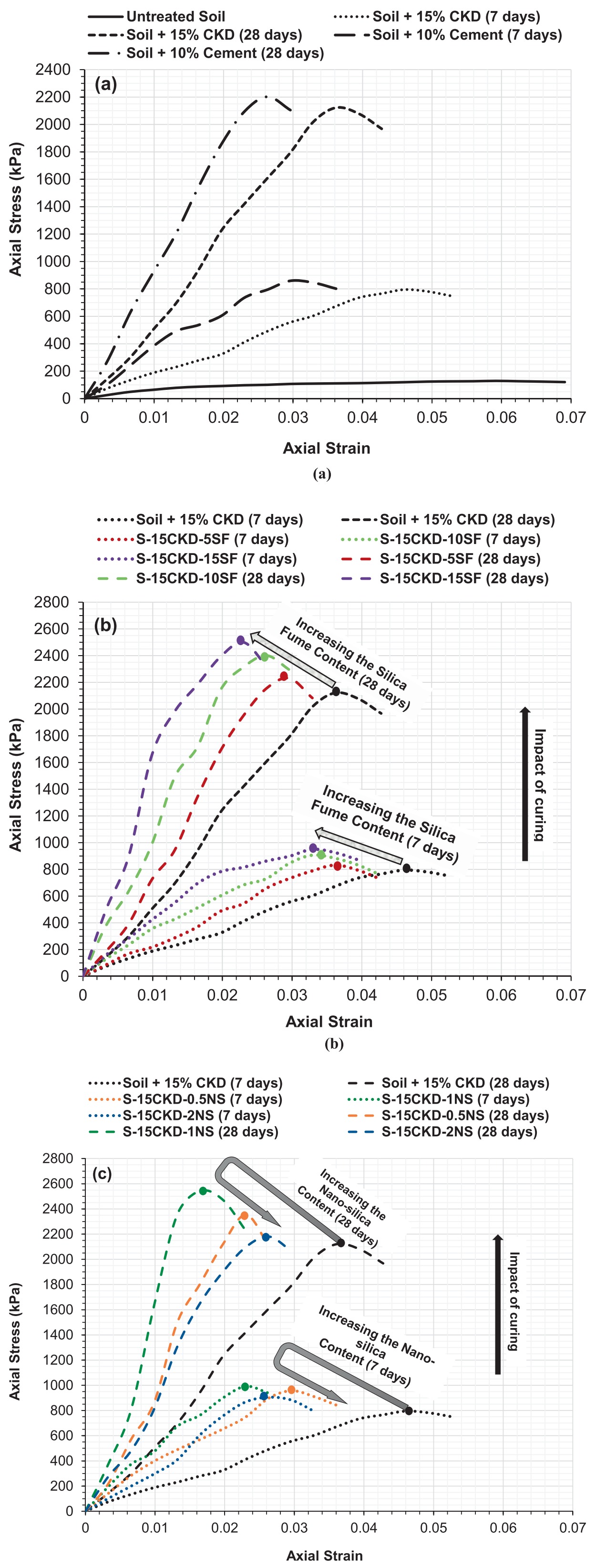

Fig. 6. UCS of the untreated and treated soils after 7 and 28 days curing: (a) soil stabilized with cement and CKD (b) CKD-treated soil with silica fume (c) CKD-treated soil with nano-silica.

Fig. 6b demonstrates the effect of silica fume on UCS of CKD-stabilized soils cured at 7 and 28 days. According to the results of Fig. 6b, silica fume increment has been improved the UCS of CKD-treated soils. The UCS of S-15CKD-15SF soil was 19.5% and 17.8% more than that of S-15CKD soil at the curing ages of 7 and 28 days, respectively. These compressive strength enhancement can be relevant to the impacts of pozzolanic reactions on the USC of soil occurred mostly during the curing process [57]. Furthermore, the rapid consumption of free lime (liberated during hydration) resulted from the high reactivity of SiO_2 in silica fume, producing additional Calcium-silicate-hydrate(C-S-H) gel that increases the stabilized clay's mechanical capacity [9].

Concerning the addition of nano-silica to the CKD-stabilized soil, the consequences of UCS, shown in Fig. 6c, argued that the UCS was improved with the nano-silica increment till 1% of soil weight and curing time. Increasing the nano-silica percentage by more than 1% caused a lower strength. However, the compressive strength of the samples with 2% nano-silica was higher than CKD-treated soil. Like silica fume, the improved compressive strength may be attributed to the chemical reaction between $Ca(OH)_2$ and SiO_2 throughout cement hydration and the formation of additional C–S–H condensed gel [24,27]. Besides, nano-silica could accelerate C–S–H gel formation because of its high specific surface [24,27]. The nano-silica percentage increment to 2% reduced the compressive strength that may be related to dispersion problems caused by the agglomeration of the excessive nano-silica amounts [5,27]. The major problem related to the nano-SiO_2 application is relevant to nanoparticles' agglomeration [58]. Furthermore, it was possible that nano-silica acted as a filler and filled the pore regions. Hydration products can only grow and fill the regions available to them. If the pore region is filled, hydration will cease [57]. This effect probably reduces hydration's degree and causes strength to reduce.

3.4. California bearing ratio tests

The CBR test is considered a commonly utilized method to evaluate soil strength for the pavement thickness design. The three replicates of CBR for each studied soil averaged out and depicted in Fig. 7. The soaked CBR of soil stabilized with cement and CKD at different curing ages was illustrated in Fig. 7a. The CBR Of soil rose from 3% to 72% and 74%, resulting from adding 15% CKD and 10% cement after the 7-day curing time. The increase in CBR by the addition of CKD has been observed by some researchers [4,56,59]. The CBR increment in the soil–CKD may be attributed to cementitious compounds' formation, resulting in bonding between the soil and CKD particles [56]. By adding cement and CKD to the clayey soil, the C–S–H gel formation quantity increases that binds the particles more effectively, leading the CBR value to enhance [60].

Fig. 7b shows the silica fume's effect on the specimens' CBR values containing 15% CKD after 7 and 28 days curing. The CBR values of treated soil, containing CKD and silica fume simultaneously, were enhanced, and this improvement increases as the silica fume content increases. The S-15CKD-15SF mixture boosted the CBR value of S-15CKD from 72% to 160% and 90% to 211% after 7 and 28 days curing in the order given. This observation's possible reason can be explained through the pozzolanic properties of the used silica fume and the gradual formation of cementing compounds between CKD, silica fume, and clay.

The obtained consequences regarding the nano-silica impacts on the CBR value of CKD-treated soil are represented in Fig. 7c. Based on this figure's results, it can be deduced that the addition

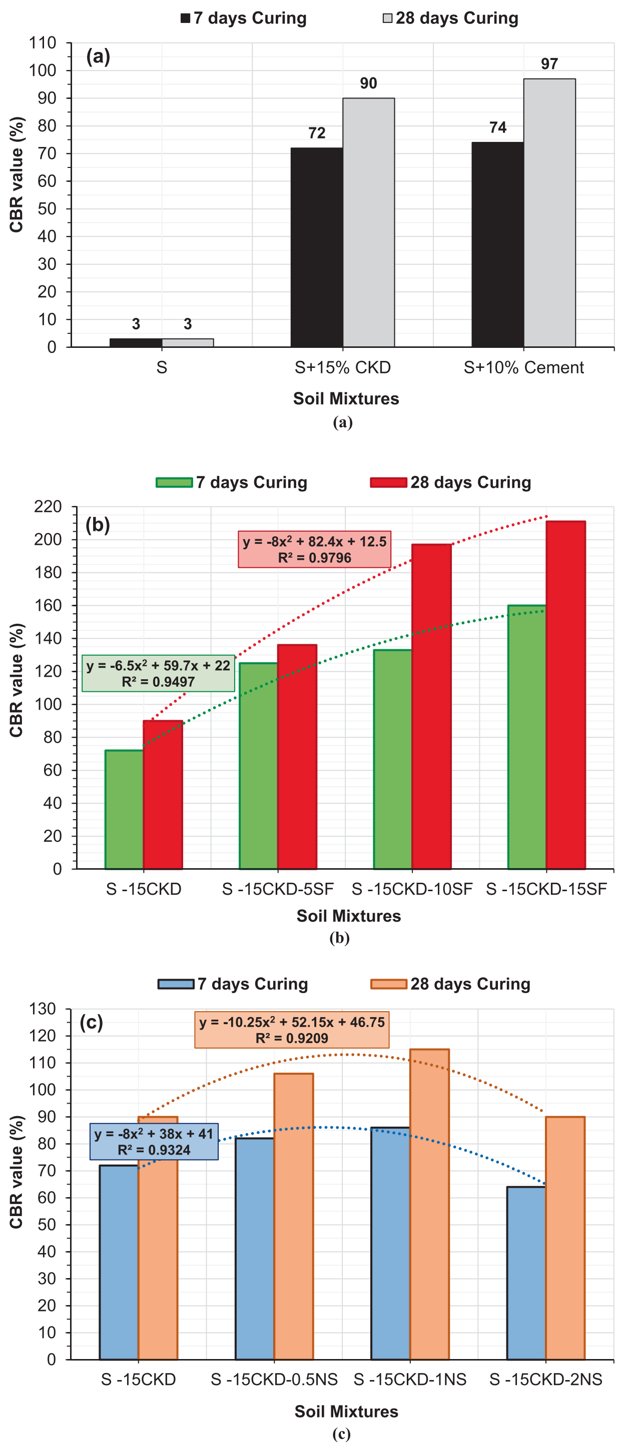

Fig. 7. Variation of CBR of untreated and treated soils after 7 and 28 days curing: (a) soil stabilized with cement and CKD (b) CKD-treated soil with silica fume (c) CKD-treated soil with nano-silica.

of 0.5% and 1% nano-silica lead the CBR of CKD-stabilized soil to improve. The S-15CKD-1NS soil had 14% and 25% CBR values more than that of S-15CKD soil. Nonetheless, further usage of nano-silica (2%NS) causes the CBR value of CKD-treated soil to decrease. The results of the soaked CBR test are consistent with the UCS test results. Possible mechanisms for the increase in CBR concerning the addition of nano-silica may be fine material addition binding the aggregate or cementation. Nano-silica particles can fill the C–S–H gel's porosity and manufacture an adhesive cement paste with more density [30,61].

3.5. Chemical and microstructural tests

Fig. 8(a) illustrates an SEM micrograph of the compacted kaolinite clay, which shows flaky arrangements of clay particles and large voids. Fig. 8(b) indicates the stabilized soil's micrograph with 15% CKD cured for 28 days. It was realized that the hydration reaction product (C–S–H gel) coated and joined the soil and the CKD particles. The cementitious compound occupies and partially fills the pores between particles. So the use of CKD affected the clay strength enhancement. This finding is in line with the outcomes reported by Peethamparan [62].

The micrograph of CKD-treaded soil with the presence of silica fume cured for 28 days can be seen in Fig. 8(c). As can be seen, the flocculated structure occurs because of the addition of CKD and silica fume and shows the formation of patches of cementation products. Compared with Fig. 8(b), it is revealed that higher expansion of the cementitious compounds (higher pozzolanic activity) occurs in the case of using silica fume in CKD-treated soil.

Fig. 8(d) shows the microscopic image of treated soil with CKD and nano-silica after 28 days curing. The specimens with nano-silica are denser than the samples without nano-silica. The formation of secondary C–S–H gel during the chemical reaction between $Ca(OH)_2$ in cementitious compounds produced and SiO_2 nanoparticles can enhance the studied soil's strength properties. During C–H–S gel formation, the pores of loose net structure around the clay particle are filled by nanoparticles, and accordingly, the porosity is decreased [61].

XRD analysis was conducted to assess the untreated soil's minerals and reaction products after mixing with stabilizers and consequently, scanned with a 2θ value ranging from 5° to 80°. The XRD patterns of the specimens compared with untreated soil in Fig. 9. The major minerals in the soil were determined as quartz, kaolinite, and calcite. Twenty-eight days after CKD addition, it can be found that the new reflections of calcium silicate hydrate (C-S-H) and calcium hydroxide phases were observed in treated soil. In addition, the residue part of the unhydrated reactant formed tricalcium silicate (C_3S, Ca_3SiO_5) and dicalcium silicate (C_2S, Ca_2SiO_4) also were found. These reaction products, which can contribute to increased strength in the stabilized soil, indicate that the CKD can be suitably utilized as a cementitious material in soil enhancement. The CKD-treated soil with nano-silica and silica fume XRD pattern presents C-S-H and calcium hydroxide as the primary reaction products, resemblance to those observed in the CKD-treated sample. It can be theorized that the benefits of nano-silica and silica fume as pozzolanic materials have pivotal effects on increasing the reaction products (secondary reaction product).

3.6. Sustainability analysis

As previously mentioned, three sustainability criteria, including environmental pollutions, cost, and 28-day UCS, are considered sustainability criteria. In this section, eight stabilization options are compared based on the sustainability criteria and sustainability index (GRG). The 28-day UCS of stabilization alternatives is comprehensively discussed in Section 3.3.

3.6.1. Environmental effects

In this investigation, vital environmental parameters are analyzed for different stabilization alternatives. Table 3 compares the stabilization alternatives based on GWP, EC, RC, FW, FR, SO, AP, and NHW. As can be seen, the lowest and highest GWP values are related to S-15CKD and S-10C because cement is the greatest contributor to GWP emission among the utilized materials. On the other hand, CKD is a by-product that does not need any preprocess to be employed in soil stabilization. The GWP emitted by trea-

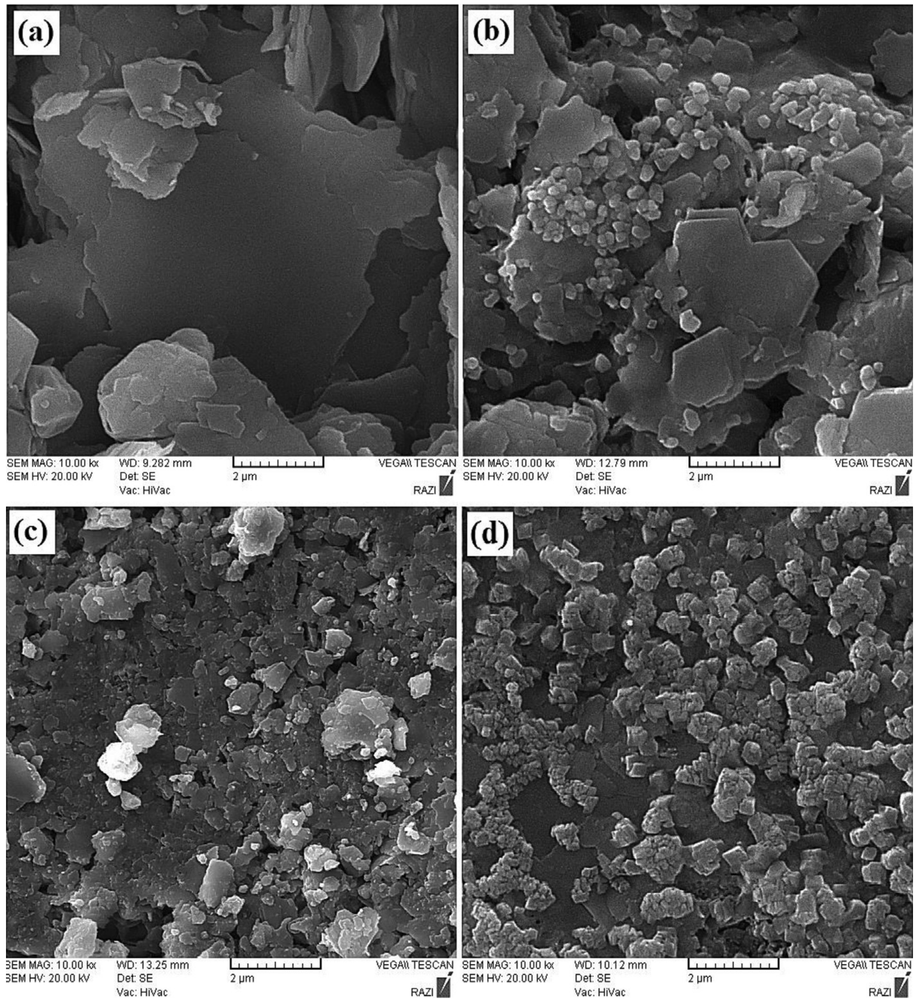

Fig. 8. Scanning electron micrograph of specimens: (a) Untreated soil, (b) Soil + 15% CKD, (c) Soil + 15% CKD + 15% SF, (d) Soil + 15% CKD + 1% NS.

ted soils with CKD and nano-silica is more than that of soils stabilized by CKD and silica fume. S-15CKD, S-15CKD-5SF, S-15CKD-10SF, S-15CKD-15SF, S-15CKD-0.5NS, S-15CKD-1NS, and S-15CKD-2NS can reduce GWP by 99.85%, 99.66%, 99.48%, 99.31%, 78.39%, 57.52%, and 15.78%, respectively, compared with conventional S-10C. Accordingly, CKD significantly outperforms cement, and silica fume dominates nano-silica based on GWP.

Based on the results presented in Table 3, S-15CKD is the eco-friendliest option based on EC, followed by S-15CKD-5SF, S-15CKD-10SF, S-15CKD-15SF, S-15CKD-0.5NS, S-10C, S-15CKD-1NS, and S-15CKD-2NS, with the EC values of 1 MJ, 1.6 MJ, 2.2 MJ, 2.7 MJ, 257.9 MJ, 380.6 MJ, 507.7 MJ, and 1007.2 MJ, in the order given. Thus, it can be deduced that the mixtures containing nano-silica are huge energy consumers, and the application of nano-silica more than 0.5% contradicts saving energy. Nonetheless, CKD mixtures containing silica fume and 0.5% nano-silica outweigh S-10C based on EC, and they can be suitably compared with S-10C.

According to the results presented in Table 3, S-10C utilizes the most content of virgin material compared with other mixtures containing CKD. Because, cement is a rough material extracted from the environment. Nonetheless, CKD is a by-product, and it does not count as virgin material. Ergo, S-15CKD saves the resources the most, and it can save 63.8 kg rough materials to stabilize a ton of soil compared with conventional S-10C. The RC-based performance of other stabilization alternatives containing CKD is approximately the same. In other words, S-15CKD-0.5NS, S-15CKD-1NS, S-15CKD-2NS, S-15CKD-5SF, S-15CKD-10SF, and S-15CKD-15SF can reduce the RC by 25.1%, 23.9%, 20.1%, 26%, 24.9%, and 23.4% in the circumstances that these alternatives are compared with S-10C.

The FW value requires to implement different soil stabilization alternatives is demonstrated in Table 3. A more detailed look at this table reveals that mixtures contained nano-silica need a huge amount of water in the materials production phase. This high water consumption is due to the nano-silica substance that requires a high amount of water to be produced. Accordingly, increasing the nano-silica content significantly increases the FW, and applying nano-silica as an activator is not recommended in countries, which do not have sufficient freshwater. On the flip side, S-15CKD requires the least FW to stabilize the soil. Moreover, silica fume is a valuable and eco-friendly activator-based FW. Compared with S-10C, S-15CKD, S-15CKD-5SF, S-15CKD-10SF, and S-15CKD-15SF are capable of FW reduction by 80.4%, 78.5%, 76.7%, and 74.9% in the order mentioned.

Moreover, Table 3 indicates the FR value consumed by cement and CKD-based stabilization alternatives. As can be perceived from the results shown in this table, the minimum FR value is obtained by S-15CKD implementation, followed by S-15CKD-5SF, S-15CKD-10SF, S-15CKD-15SF, S-15CKD-0.5NS, S-15CKD-1NS, S-10C, and S-15CKD-2NS with the FR values of 0.9 MJ, 2.4 MJ, 3.8 MJ, 8.1 MJ, 72.3 MJ, 141.7 MJ, 263.3 MJ, and 280.6 MJ, respectively. Therefore, it can be theorized that the CKD considerably outperforms cement

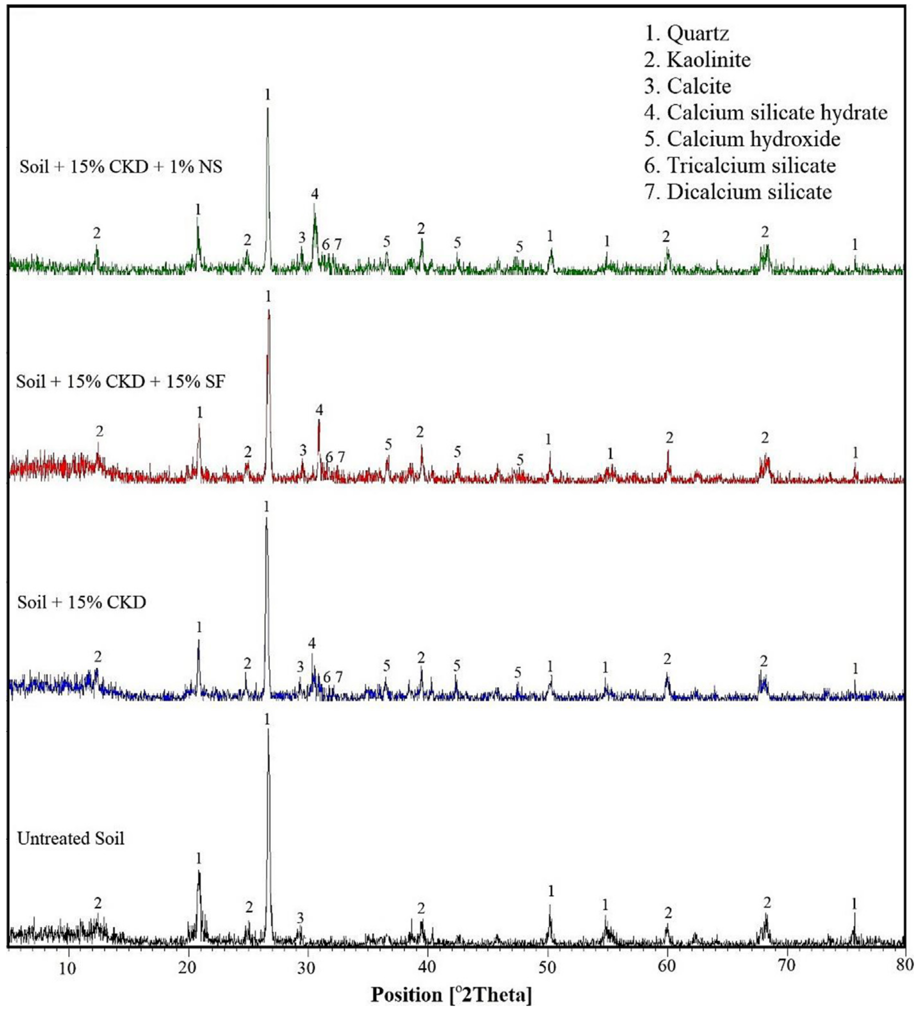

Fig. 9. X-ray diffraction patterns of specimens: Untreated soil, Soil + 15% CKD, Soil + 15% CKD + 15% SF, Soil + 15% CKD + 1% NS.

Table 3
The environmental pollutions generated by different stabilization alternatives.

Stabilization options	GWP (kg CO2-eq/kg)	EC (MJ)	RC (kg)	FW (m^3 eq)	FR (MJ)	SO (kg CFC11 eq)	AP (kg)	NHW (kg)
S-10C	68.61	380.59	237.37	0.89	263.34	9.20E-09	0.1131	0.114
S-15CKD	0.10	1.00	173.55	0.17	0.93	4.07E-12	0.0001	0.000
S-15CKD-0.5NS	14.83	257.91	177.84	96.17	72.34	0.001	2.9161	2.304
S-15CKD-1NS	29.15	507.67	180.65	189.50	141.75	0.002	5.7511	4.544
S-15CKD-2NS	57.78	1007.21	188.34	376.16	280.58	0.004	11.4211	9.024
S-15CKD-5SF	0.23	1.63	175.60	0.19	2.43	3.80E-11	0.0004	0.003
S-15CKD-10SF	0.36	2.21	178.31	0.21	3.81	6.91E-11	0.0006	0.005
S-15CKD-15SF	0.47	2.74	181.67	0.22	5.07	9.75E-11	0.0008	0.008

based on FR. Additionally, the application of nano-silica more than 1% is not suggested owing to the high fossil resources consumed in order to produce nano-silica. On the other hand, silica fume is a precious CKD activator, according to FR. Accordingly, it can be deduced that CKD dominates cement, and silica fume considerably outperforms nano-silica based on FR.

As shown in Table 3, the SO value generated by mixtures comprising nano-silica is by far more than that of other mixtures. That is to say, nano-silica significantly increases the SO value. Hence, applying nano-silica as an activator is detrimental to the stratospheric ozone layer. However, silica fume is an effective activator to decrease SO contents. S-15CKD-5SF, S-15CKD-5SF, and S-15CKD-5SF can reduce SO by 99.6%, 99.3%, and 98.9%, given that they are replaced with S-10C. Furthermore, the S-15CKD SO value is 99.9% lower than that of S-10C. Thus, it can be theorized that nano-silica and cement mixtures deteriorate the environment by generating high content of depletion potential of the stratospheric ozone layer. Nevertheless, CKD and silica fume can preserve the environment by SO reduction.

S-15CKD is the most valuable option in order to minimize AP. In contrast, the AP reaches its highest level in S-15CKD-2NS. Likewise, the AP generation of S-15CKD-0.5NS and S-15CKD-1NS is considerably higher than that of other mixtures. To this end, the application of nano-silica as the CKD activator is not recommended. If S-15CKD, S-15CKD-5SF, S-15CKD-10SF, and S-15CKD-15SF are replaced with S-10C, the stabilization AP value is reduced by

99.9%, 99.6%, 99.4%, and 99.3%. Hence, the AP-based performance of CKD is better than that of cement, and silica fume is significantly better than nano-silica so as to AP reduction.

Based on NHW results, the maximum NHW is relevant to S-15CKD-2NS, followed by S-15CKD-1NS, S-15CKD-0.5NS, S-10C, S-15CKD-15SF, S-15CKD-10SF, and S-15CKD-10SF with the NHW value of 9.02 kg, 4.54 kg, 2.30 kg, 0.114 kg, 0.007 kg, 0.005 kg, 0.003 kg, and 0 kg in the order mentioned. Therefore, it can be theorized that nano-silica application results in NHW increment, deteriorating the environment. Silica fume is by far better than nano-silica, according to NHW, and it is suggested to replace nano-silica with silica fume to reduce NHW. CKD significantly reduces NHW compared with cement, and in the circumstances that nano-silica is not utilized as a CKD activator, CKD can noticeably reduce NHW compared with S-10C.

According to the mentioned environmental pollutions, the environmental index of stabilization alternatives is calculated. In this regard, the environmental pollutions' values are scaled based on the descriptions presented in the sustainability modeling section. Subsequently, the environmental index related to S-10C, S-15CKD-0.5NS, S-15CKD-1NS, S-15CKD-2NS, S-15CKD-5SF, S-15CKD-10SF, and S-15CKD-15SF is calculated and indicated in Fig. 10. Drawing the results shown in Fig. 10, S-15CKD is the most eco-friendly stabilization option considering all vital environmental criteria. In other words, the environmental index of S-15CKD is 0, which implies that S-15CKD provides the lowest emission in all environmental criteria. The S-15CKD-5SF, S-15CKD-10SF, and S-15CKD-15SF are the second, third, and fourth environmental alternatives because their environmental index equals 0.006, 0.015, and 0.024, respectively. The environmental index of S-15CKD-0.5NS, S-15CKD-1NS, and S-15CKD-2NS are 0.213, 0.416, and 0.829. S-10C's environmental index is equal to 0.511. Hence, it can be postulated that S-15CKD-2NS is the most detrimental stabilization type to the environment, and nano-silica should not be used in a percentage of more than 1%. Moreover, all mixtures contain CKD (except S-15CKD-2NS) can be useful to the environment, and their environmental index is lower than that of S-10C. Meanwhile, silica fume as a by-product is a precious activator that is useful for reducing environmental pollutions.

3.6.2. Economic analysis

Fig. 11 exhibits the required cost for implementing each stabilization alternatives for each kg soil. A more detailed look at the results of Fig. 11 reveals that S-15CKD is the cheapest stabilization option. However, S-15CKD has some problems with early-age characteristics. Interestingly, S-10C is the second economical alternative, and it may be the major reason for S-10C selection as a soil stabilizer. Nano-silica and silica fume are expensive materials, and their weight increment in mixture proportion significantly increases the stabilization unit cost. The unit cost of S-15CKD-5SF, S-15CKD-10SF, S-15CKD-15SF, S-15CKD-0.5NS, S-15CKD-1NS, and S-15CKD-2NS is 24.81$, 46.47$, 66.27$, 26.77$, 51.73$, and 101.64$, respectively. Accordingly, activators' weight should be minimized to reduce stabilization costs. Application of nano-silica more than 1% (S-15CKD-2NS) considerably increases the unit cost, and the S-15CKD-2NS application may not be practical in projects with the budget limitation. On the other hand, S-15CKD-5SF and S-15CKD-0.5NS are economic selections compared with other mixtures containing activators.

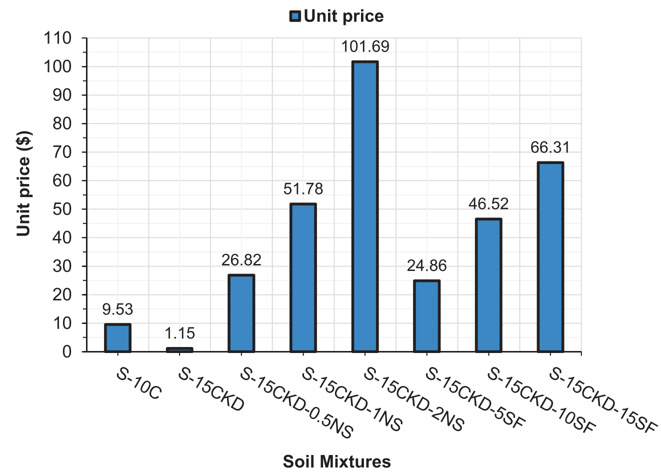

Fig. 11. The unit price of various soil mixtures.

3.6.3. Sustainability comparison

As previously mentioned, three sustainability criteria, including 28-day UCS, environmental index, and stabilization unit price, are taken into account sustainability criteria. Consequently, GRA is employed to consider these criteria simultaneously and compare stabilization alternatives by a single-response index. Ultimately, GRG is applied to rank the stabilization options. Fig. 12 presents the different stabilization alternatives' sustainability index (GRG value). Ac can be perceived, S-15CKD is the most sustainable mixture, and its GRG is 0.777. S-15CKD takes precedence over other alternatives due to providing the cheapest and lowest energy emit-

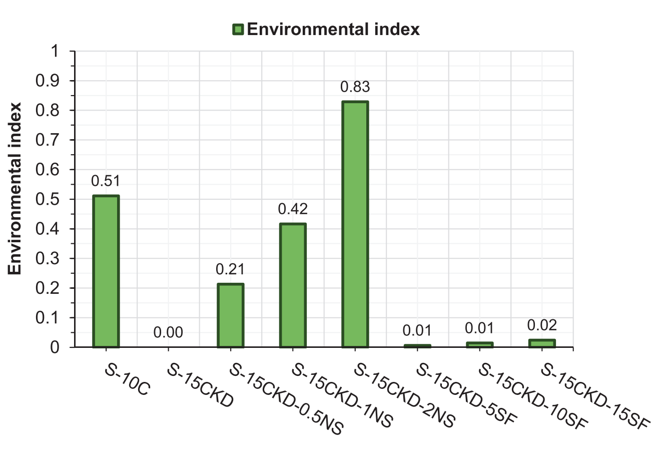

Fig. 10. The environmental index of various stabilization alternatives.

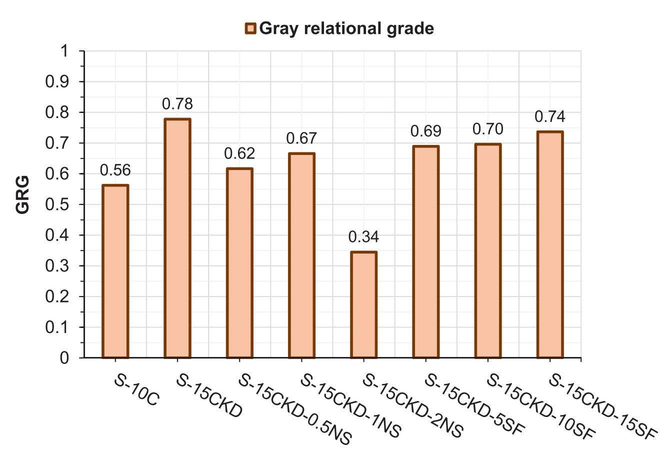

Fig. 12. The soil mixtures GRG value.

ter mixture. The S-15CKD-15SF, S-15CKD-10SF, and S-15CKD-5SF are the second, third, and fourth sustainable options with the GRG value of 0.737, 0.696, and 0.689 in the order given. The mixtures contain silica fume are sustainable due to their low environmental emissions, suitable price, and appropriate 28-day UCS. By analyzing the GRG values, it can be deduced that increasing the silica fume content results in sustainability increment.

The GRG value of S-15CKD-0.5NS, S-15CKD-1NS, and S-15CKD-2NS is 0.616, 0.666, and 0.345, respectively. Therefore, increasing the nano-silica content up to 1% enhances sustainability. Nonetheless, increasing the nano-silica weight more than this level reduces sustainability significantly. Hence, 1% is the optimal value of nano-silica based on sustainability, and it may be because of providing the highest 28-day UCS by S-15CKD-1NS. S-10C is the seventh sustainable mixture among eight alternatives. In other words, the S-10C's sustainability is only better than that of S-15CKD-2NS, and S-10C is dominated by other mixtures based on sustainability. S-15CKD-2NS is the worst mixture based on sustainability, and it may be because of its expensive cost, high emission, and inappropriate 28-day UCS.

4. Conclusions

The primary objective of the current study was to propose a sustainable cement-free stabilizer for kaolinite clay soil. To this end, the CKD was employed as a cement replacement. Furthermore, the impact of silica fume and nano-silica on CKD-treated soil's strength improvement and sustainability was examined. Different geotechnical characteristics (Atterberg limits, standard Proctor, unconfined compressive strength, and California bearing ratio) and also microstructure characteristics (SEM and XRD) of proposed cement-free stabilized soil were investigated to reach the purposes of the research. Moreover, the stabilized mixtures were analyzed based on eight pivotal environmental parameters, including GWP, EC, RC, FW, FR, SO, AP, and NHW. Subsequently, a novel environmental index was introduced in order to compare the mentioned stabilization mixtures. Afterward, three factors, including 28-day UCS, environmental index, and unit stabilization cost, were taken into account sustainability criteria. Ultimately, GRA was performed to determine the most sustainable mixture and rank the mixtures based on their sustainability index (GRG). Consequently, according to the experimental investigation and sustainability analysis, the following conclusions were made:

- The CKD addition to clayey soil increased the plasticity index, optimum water content, while CKD reduced the plasticity index of kaolinite clay soil.
- It was seen that the CKD improved the UCS and the soaked CBR of kaolinite clay soil due to C–H–S gel formation, which partially fills the pores between particles (as indicated in the SEM micrographs in Fig. 8), enhancing clay strength.
- Due to silica fume addition to CKD-treated soil, the maximum dry density decreased, and the optimum water content increases as silica fume content increased. There were not any apparent changes in the OMC and the MDD of the nano-silica treated soil owing to its lightweight.
- Silica fume addition improved the UCS so that the compressive strength of CKD-treated soil containing 15% silica fume was 950 kPa and 2499.6 kPa at 7 and 28 days curing, respectively. The samples' compressive strength stabilized with 15% CKD only was 795 kPa and 2121.9 kPa at 7 and 28 days curing, in the order mentioned. After adding nano-silica, it was observed that UCS was enhanced with nano-silica and curing time increment. In this study, when nano-silica was used 1%, the maximum UCS was observed at all ages. The addition of more than 1% nano-silica led to a lower strength. However, the compressive strength of the specimens with 2% nano-silica was higher than CKD-treated soil.
- The soaked CBR of samples with CKD and silica fume increased significantly relative to soil stabilized with only 15% CKD. The addition of nano-silica increased the CBR of samples, too. The greatest CBR was observed with 1% nano-silica, similar to the results of UCS. More improvement in the CBR was spotted with the curing time increment.
- Based on the SEM micrograph, the flocculated structure occurred because of the addition of CKD and silica fume, and showed the formation of patches of cementation products. It was observed that the specimens with nano-silica were denser than the specimens without nano-silica. The formation of secondary C-S-H gel during the chemical reaction between $Ca(OH)_2$ in cementitious compounds produced and SiO2 nanoparticles could improve the studied soil's strength properties.
- The S-15CKD was the best stabilization alternative based on the environmental index, and S-15CKD provided the lowest emission level for all environmental criteria. The optimal replacement content of silica fume and nano-silica with CKD was 5% and 0.5%, respectively, according to the environmental index. Moreover, silica fume significantly outweighed nano-silica, according to environmental pollution minimization. Nano-silica should not be applied more than 1% in stabilization mixture due to its detrimental effect on the environment.
- S-15CKD was the most economic stabilization alternative. Increasing the content of silica fume and nano-silica increased the stabilization unit price. Accordingly, the silica fume and nano-silica optimal weight was 5% and 0.5%. The average unit cost of mixtures comprising silica fume was lower than that of nano-silica mixtures.
- The highest sustainability index was obtained by S-15CKD. The CKD replacement with cement could significantly enhance sustainability if nano-silica was not in the mixture or used less than 2%. Additionally, all silica fume mixtures were better than all nano-silica mixtures based on sustainability, and accordingly, silica fume was recognized as the most sustainable activator.

CRediT authorship contribution statement

Sadegh Ghavami: Investigation, Validation, Formal analysis, Writing - original draft. **Hamed Naseri:** Investigation, Validation, Formal analysis, Writing - original draft. **Hamid Jahanbakhsh:** Supervision, Conceptualization, Methodology, Writing - review & editing. **F. Moghadas Nejad:** Supervision, Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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