

Effect of sodium compounds additives on the strength of cement-stabilized soils

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Abstract

Chemical stabilisation using cement is a common method of improving the weak properties of soft soils. This study presents the results of experimental tests on the effects of three sodium additive solutions, sodium hydroxide (NaOH), sodium carbonate (Na₂CO₃) and sodium chloride (NaCl), on the strength of clayey (CS) and non-plastic/low plasticity property (NPS) soil-cement mixtures. Both soils condition, CS and NPS, represent the predominant soils in Mosul city, Iraq. The physical properties of these natural soils were obtained. X-ray diffractometry (XRD), X-ray fluorescence spectrometry (XRFS), and mercury intrusion porosimetry (MIP) tests were performed to further examine the microstructural characteristics of the soil samples. Furthermore, various concentrations of sodium additive solutions (0.5, 1, 1.5, 2, 2.5 and 3% by dry soil weight) were added to the soils to study the effect of these solutions on the unconfined compressive strength (UCS), California bearing ratio (CBR), and swelling potential characteristics of the soils. Variables such as cement content, curing period and concentration of chemical additives were considered. The results show an increase in the UCS of soil-cement mixtures corresponding to the incremental increases in the cement content and curing period of the samples. Also, the addition of NaOH and Na₂CO₃ increased the strength of soil-cement mixtures, with a limited effect in the case of NaCl addition. The results indicate that 1% and 1.5% of sodium additives were optimal additive contents for maximal UCS and CBR values, respectively. The results also confirm the decreased swelling potential of CS-cement mixtures with the addition of sodium additives and demonstrates the superiority of NaOH over Na₂CO₃ as an additive for soil stabilization.

Keywords: Soil-cement mixtures, Sodium additives, Chemical stabilization, Microstructural characteristics of soil

1. Introduction

Soft soils are stabilized to improve their engineering properties. Stabilisation can be achieved through various physical, mechanical and chemical methods [1-3]. Portland cement is the most common chemical stabilizers used to stabilize large expanses of soil for highway and airfield construction [4-6]. Soil-cement mixtures are mostly characterized by their compressive strength, which indicates the degree of reaction of soil-cement-water mixtures, setting time, rate of hardening and the durability of the products. The compressive strength of a soil-cement mixture usually increases with the cement content, density and curing period [7-10].

When cement is added to clayey soils (CS), primary and secondary processes are activated. Hydrolysis and hydration of cement have been regarded as the primary processes in which the hydration products are basic calcium silicate hydrates, calcium aluminate hydrates and hydrated lime [11-12]. Clay contains a small but important fraction of silica and alumina. The solubility of the soil silica is greatly

increased by alkali materials while alumina may dissolve in high pH environments [13-15]. In a secondary process, the Ca²⁺ produced by cement hydration replaces the exchangeable cations on the surface of the clay particles and tends to intensify flocculation initiated by the increase in total electrolyte content. Then, the dissolved silica and alumina in the pore water become mixed with calcium ions, and additional cementation material is formed [10, 16-17]. In the case of non-plastic soils (NPS) such as sandy, silty and granular soils, these are preferred in cement stabilization [18-19].

Chemical additives are usually incorporated into soil-cement mixtures to enhance the effectiveness of Portland cement as soil stabilizer by reducing the required quantity of cement. Also, it reduces shrinkage cracking and volumetric changes of stabilized soils, as well as increasing the durability and resistance of stabilized soils to adverse chemical compounds [20-22]. Some chemical additives can strongly modify the engineering properties of soils. These additives are categorised into two sub-groups, inorganic and organic additives. Inorganic additives are the most

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commonly available and include acid, neutral and alkaline types. Acid and alkaline inorganic additives owe their effects primarily to an actual attack on the soil components (i.e., clay minerals) with subsequent precipitation of new and insoluble minerals that bind the soil materials together [23].

NaCl is a common salt additive and it affects all soil types with lesser effects in already salt-rich soils (i.e., saline soils and soils with high organic matter content). NaCl is very easy to apply either as a solid or spray solution. It acts as a compaction aid by promoting higher densities [24]. It is reported that the addition of NaOH or Na₂CO₃ to soil-cement mixtures modifies the ability of Portland cement as a stabilizer by decreasing the required quantity of cement, and by reducing the shrinkage behaviour and volumetric changes. With the addition of about 1% sodium hydroxide or sodium carbonate to silty-clay soils, about 5% cement can be saved [25-26]. NaOH and Na₂CO₃ have been found to be very effective in lateritic soils. Both are easily applied in combination with water and act as powerful compaction aids, yielding higher densities [27-28].

To the best of our knowledge, CS and NPS soils from Mosul city, Iraq have not been previously studied. This study aims to quantify the effect of three sodium additives, NaOH, Na₂CO₃ and NaCl, on the properties of CS and NPS-cement mixtures. Characterization of CS and NPS was done using several complementary techniques, MIP, XRD, UCS (unconfined compressive strength) and CBR (California bearing ratio). Factors such as curing period, cement content and the amount of various additives were varied to examine their influence on the soil samples.

2. Materials and methodology

2.1 Soils

The soils used herein are CS and NPS. These soil types represent the predominant soils in Mosul city, Iraq. The index properties, porosity, mineralogical composition and chemical properties of these soils were characterized.

2.1.1 Index properties by laboratory techniques

The specific gravity, Atterberg limits and grain size distribution of both CS and NPS soils were determined according to ASTM D 854-02, ASTM D 4318-00 and ASTM D422-63, respectively [29-31]. The maximum dry density (MDD)/optimum moisture content (OMC) and California bearing ratio, CBR values were obtained according to ASTM D1883 – 16 [32].

2.1.2 Porosity and pore size distribution

The pore size distribution of the soils was determined using a mercury intrusion method. Soil samples were dried using liquid nitrogen at -198 °C. The samples were immersed in nitrogen until all materials in the samples were frozen. This was followed by freeze drying the frozen samples using vacuum to promote sublimation. An ALPHA 1-2 LD plus freeze drier was used. This process ensured that the original pore size of soil samples was effectively maintained.

Porosity was determined via mercury intrusion porosimetry, MIP, using a Poresizer 9320 porosimeter apparatus. Suitable pressure (up to 210 MPa) was applied

while real-time monitoring of the intruded mercury volume within the pores of the test samples was done.

2.1.3 Mineralogical characterization and chemical analysis of the used soils

X-ray diffraction patterns were obtained on soil powders using a Philips apparatus with the K_α line of copper ($\lambda_{Cu} = 1.5406 \text{ \AA}$) with 2θ from 1.5 to 60 degrees. The main quartz reflection was used to scale the X-ray pattern intensities for pattern comparisons.

The pH value and the cation exchange capacity of the soils were determined according to ASTM D4972-01 [33]. Furthermore, total soluble salts were measured according to ASTM D4542-07 [34], while the organic matter content was obtained following the ASTM D2974-07 method [35]. The amounts of other chemical compounds in soils were determined using X-ray fluorescence analysis on a Philips PW 2400 XRF spectrometer at wavelengths of 10^{-5} \AA to 100 \AA .

2.2 Cement

Ordinary Portland cement with a specific gravity of 3.15, obtained from Badoosh Manufacturing (Northwest of Mosul city, Iraq) was added to both soil samples at varying concentrations of 3, 6, 9 and 12% dry weight of the soils.

2.3 Water

Distilled water was used for specimen preparation and to observe chemical additive effects, while ordinary tap water was used for soaking the samples.

2.4 Chemical additives

Solutions of three chemical compounds were used as additives, NaOH, Na₂CO₃ and NaCl. These solutions were prepared at varying concentrations of 0.5, 1, 1.5, 2, 2.5 and 3% by dry weight of soil.

2.5 Specimen preparation and tests

Both soils samples were air dried, pulverized and passed through a No. 4 sieve (4.75 mm, British standard). The required amounts of cement, 3, 6, 9 and 12% dry weight, were thoroughly mixed with the soil samples that passed a 4.75 mm (No. 4) sieve to a uniform consistency using Blakeslee Mixer (Blakeslee DD-80 QT Mixer, USA). Then, the appropriate amount of water, equal to the OMC obtained from CBR test, and an additive solution required were added to the soil-cement mixture and mixed again using the same mixer. Cubic molds with dimensions of 152 mm x 152 mm x 152 mm were used to compact the soil-cement mixture under MDD and OMC conditions.

The treated soil was placed in five equal layers, each having a square face of 44 mm x 44 mm. Each layer was compacted by 93 blows from 4.5 kg hammer falling from a height of 457 mm. This hammer was designed to apply the modified compaction effort of AASHTO T180-18 [36]. The compacted specimen in its mold was covered with a metal plate to prevent the loss of moisture and left for 24 hours for curing.

Table 1a Properties of CS and NPS

Description	Units	CS	NPS
Specific Gravity (G_s)		2.72	2.65
Liquid limit	%	52	24
Plastic limit	%	24	*NP
Plasticity index	%	28	NP
California bearing ratio test			
CBR value	%	4.97	11
Max. dry density (MDD)	gm/cm ³	1.73	1.86
Optimum moisture content (OMC)	%	17	7
Max. UCS at MDD and OMC	kN/m ²	200	600
Grain Size Distribution			
Sand	%	12	45
Silt	%	45	46
Clay	%	43	9
Unified soil classification system (USCS)		CH	ML
Soil description		Reddish Clay	Brown Silty Soil

*NP: Non-plastic, plasticity index $\leq 6\%$

Table 1b Mineralogy of CS and NPS

CS	Clay Minerals: montmorillonite, illite, kaolinite, low plagioclase Non Clay Minerals: high peak of Calcite and Quartz
NPS	Clay Minerals: small amount of kaolinite, and illite, low plagioclase Non Clay Minerals: high peak of calcite, quartz and feldspars

Table 1c Properties of soils (CS and NPS)

Description	Units	CS	NPS
Bulk Density	gm/cm ³	1.68	1.58
Skeletal density (ρ_s)	gm/cm ³	2.68	2.61
Specific gravity ($G_s = \rho_s / \rho_w$)	gm/cm ³	2.68	2.61
Porosity	%	28.2	38.4

The specimens were removed from their molds and wrapped several times using wax paper and followed by a six-day curing period in a laboratory incubator at 25 °C [17, 37-39].

2.6 Characterization methods

A multi-scale characterization was conducted on the tested samples (CS/NPS and CS/NPS-cement mixtures chemical additives solutions) to identify the chemical solution effects on the properties of the soil-cement mixtures.

2.6.1 Water retention curves (WRC)

Remoulded samples with a 63.5 mm diameter and 19.05 mm height, were used for both the CS and NPS soil samples. They were prepared under MDD and OMC compaction conditions at a static compaction rate of 1.27 mm/sec. The remoulded soil samples were oven dried at 105 °C for 24 hours before testing. Other remoulded samples were mixed with different percentages of cement, i.e., 3, 6, 9 and 12% dry weight of the soil, to identify the cement addition effects on the soil-cement mixtures.

2.6.2 UCS test

The UCS was done on 152 mm x 152 mm x 152 mm cubic mold samples of CS/NPS and CS/NPS-cement mixtures under constant strain using a universal tester with a 20000 N limit at a loading rate of 0.02 mm/sec. In this study, unconfined strength was defined as the average stress obtained from four test specimens. The specimens were

immersed in water for 24 hours prior to testing [40]. This was done to allow moisture equilibrium.

2.6.3 CBR test

A CBR test was carried out at MDD and OMC conditions on CS/NPS and CS/NPS-cement mixtures according to ASTM D1883 – 16 [32]. The specimens were moulded in standard CBR moulds. For all samples, 56 blows were applied to each of the five layers utilising a modified proctor hammer. After the required curing period, the specimens were soaked in water for four days and the free swelling potential was documented for the CS and CS-cement mixtures.

3. Results, analysis and discussion

Table 1a shows the index properties of both soils (CS and NPS) from laboratory tests. CS can be described as a clayey soil with moderate to high plasticity. This is affirmed by the high clay fraction in the grain size distribution analysis and the soil mineralogical analysis. Table 1b reveals that the dominant clay mineral of CS is montmorillonite followed by illite, kaolinite and plagioclase, with calcite and quartz as non-clay minerals. The presence of montmorillonite in CS gives the soil a high specific surface area and in turn influences the soil plasticity. In contrast, NPS was characterized as a very low to non-plastic soil ($P.I < 7\%$) with a small clay fraction of about 9%, a low specific surface area due to the presence kaolinite as the predominantly clayey mineral along with illite and plagioclase, as well as calcite, quartz and feldspar as non-clay minerals [41].

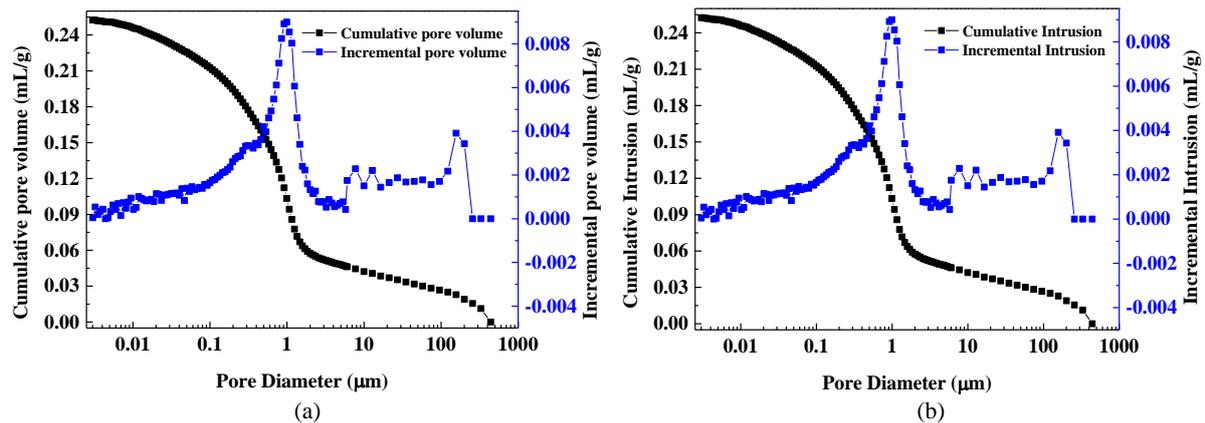


Figure 1 Pore size distribution of a) CS and b) NPS

Table 2 Chemical composition and properties of CS and NPS

Description	Units	CS	NPS
pH-value at saturation condition	7.1	7.55
Organic matter	%	0.6	1.2
Cation exchange capacity	Meg/100gm	26.4	8.1
Total soluble salts (TSS)	%	0.95	2.93
SiO ₂	%	42.3	42.81
R ₂ O ₃	%	19.36	16.82
CaO	%	14.46	15.7
MgO	%	5.44	5.34
SO ₃	%	0.48	1.57
Fe ₂ O ₃	%	4.95	5.24
Al ₂ O ₃	%	14.41	11.59
Na ₂ O	%	0.13	0.5

Figures 1a and b show the pore size distribution of CS and NPS soils in term of cumulative and incremental pore volume determined using a mercury intrusion porosimetry test. Also, Table 1c shows the densities, specific gravity and porosity of both CS and NPS determined from the mercury intrusion technique.

Figure 1a shows the pore size distribution of CS. The proportion of the pores between 1 μm to 100 μm are the predominant pore diameters in the soil structure with a lesser amount of pores with diameters of 250 μm. Therefore, the pore distribution of CS can be described as meso- to micro-porous with a small degree of macro-porosity. In the case of NPS (Figure 1b), the pore structure predominantly presented pore diameters of 1 μm with a smaller amount of 6 to 250 μm diameter pores. The NPS structure is also described as a meso- to micro-porous with a small degree of macro-porosity. In spite of the similarity in the descriptions of soils, the nature of the pore structure of NPS seems to be more open, i.e., NPS has more pores with diameters in the range of 1 μm to 3 μm, and in turn a higher porosity was obtained for NPS than for the CS (Table 1c).

Based on the chemical composition shown in Table 2, the major components are oxidized forms, SiO₂, Al₂O₃, R₂O₃, CaO, Fe₂O₃, and MgO. CS and NPS were characterized by their alkaline nature (pH>7), which in turn facilitated their function and reactions in cement (cement stabilization) [42]. CS may produce a higher degree of reaction with cement than NPS because of its greater cation exchange capacity [43]. Figures 2a-d show the relationships between dry density, moisture content and unconfined compressive strength of CS and NPS, treated with cement addition. An increased in dry density and unconfined compressive strength was noticed to accompany incremental

increases in the amount of the absorbed moisture. Figure 2e shows the relationship between the unconfined compressive strength of the CS/NPS soils and cement under a curing period condition of 7 days. An approximately linear-continuous rate for both soils was evident, but with different magnitudes due to the variation in the plasticity and the nearly well graded pore size distribution, which is reflected in the grain size distribution for CS and NPS [18, 44].

Figures (3a and b) show the ability of CS and NPS – cement mixtures, respectively, to retain water within their structure. This ability has been presented in terms of the degree of saturation and suction pressure (matrix suction). It is clearly noted that CS soil has a higher amount of retained water inside in its structure compared to NPS soil. This was because of the distinct plasticity and mineralogical composition of CS. Consequently, the addition of cement to CS and NPS leads to formation of a cementitious gel with a closed pore structure of CS and NPS. This, in turn, reduces CS-NPS-cement mixtures ability to retain water. From the curve, both soils have distinct values for air-entry, residual conditions and degree of saturation.

The sample with 12% cement produced a soil-cement mixture with a compressive strength of 2100 kN/m² for CS and 3400 kN/m² for NPS. Figure 4 shows the effect of curing periods, i.e., 3, 7 and 28 days, on the soils stabilized with 12% of cement under a curing temperature of 25 °C, in terms of their unconfined compressive strength. Linear correlations between the unconfined compressive strength and the curing periods were observed for both CS and NPS. This could be attributed to the low curing temperature, which produces continuity in the pozzolanic reaction. Similar observation were made by Li et al. [45].

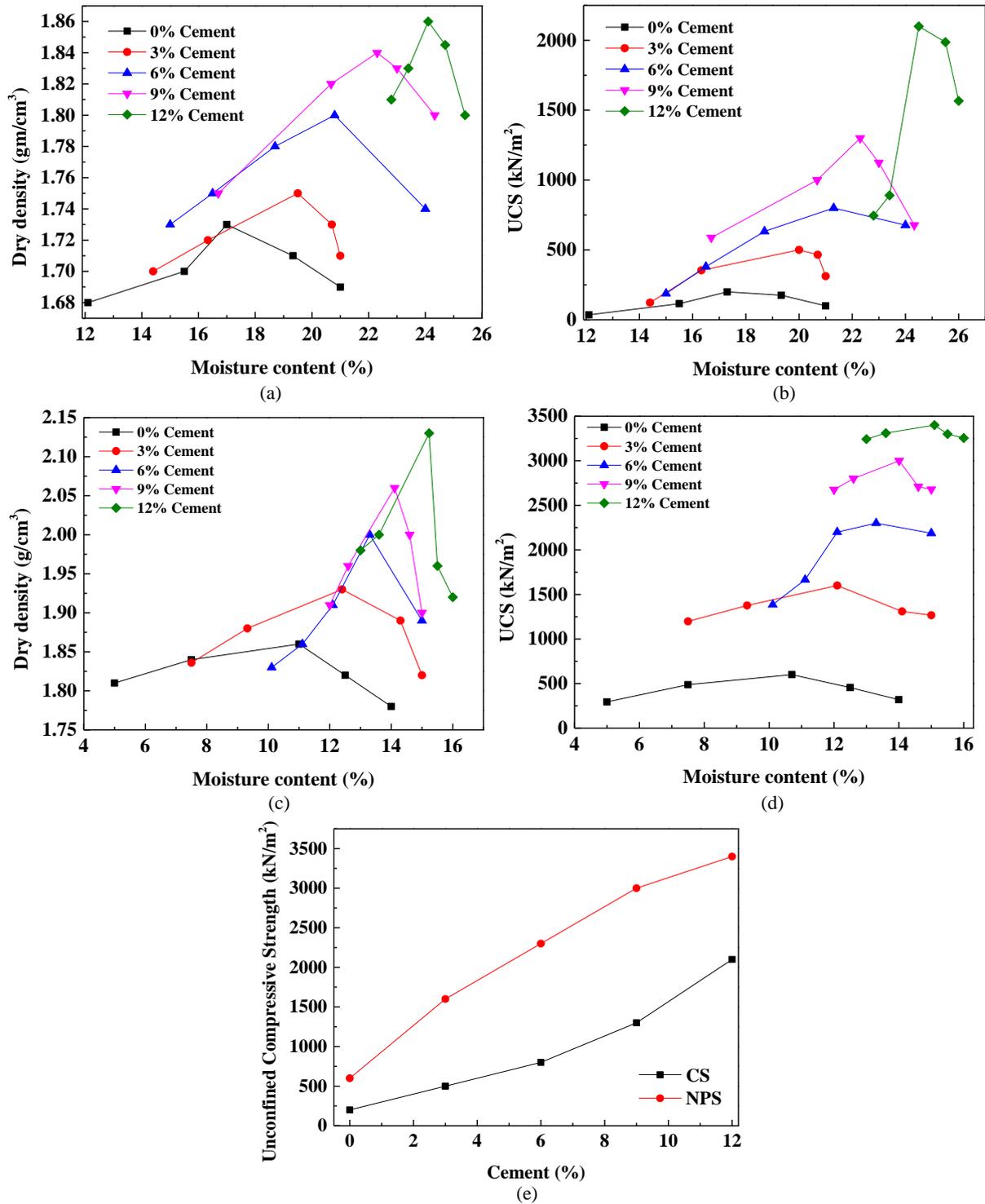


Figure 2 Effect of cement content on compaction properties and unconfined compressive strength for: a) density and b) UCS of CS soil, c) density and d) UCS of NPS soils, and e) maximum UCS of investigated soils cured for seven days

Figure 5 shows the effect of sodium additives at various concentrations on the unconfined compressive strength of the CS and NPS stabilized with 12% cement with a seven-day curing period. Differences in strength between CS and NPS samples were noted due to soil plasticity [44]. For CS (Figure 5a), increased strength was seen with NaOH and Na₂CO₃ additives to a 1% level, then decreased unconfined compressive strength was observed. This increased strength could have been related to the formation of more

cementitious gels than those of CS-cement mixtures alone [22, 46]. However, the effect of NaCl was limited due to a reduction in CS-cement mixture strength. The NaOH and Na₂CO₃ additive optimal concentration was 1% to attain higher strength for CS-cement mixtures. In contrast, the strength of CS-cement mixtures treated with the optimum concentration of NaOH additive produced 6.6% higher strength compared with the CS-cement mixtures treated with Na₂CO₃. Beyond the optimal additive level, the strength of

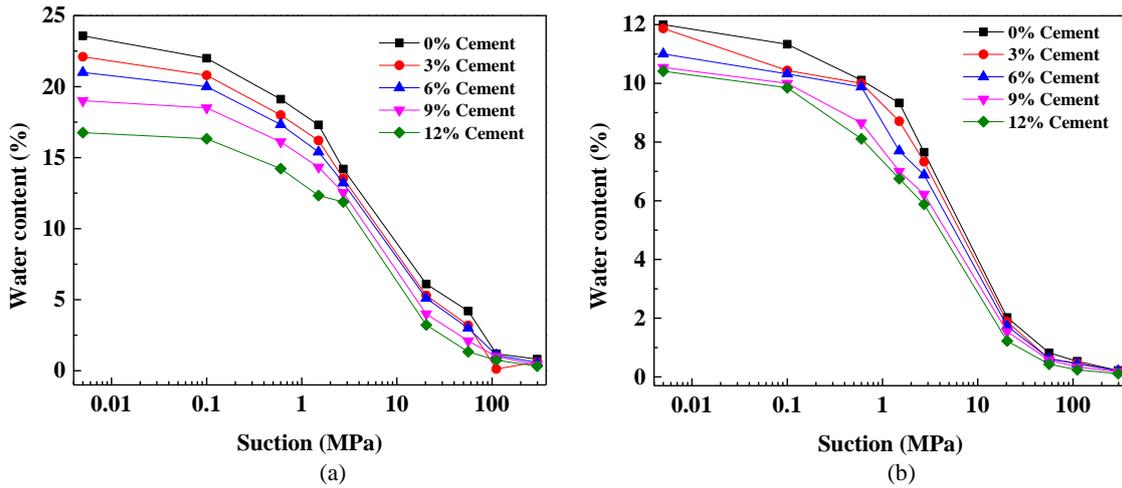


Figure 3 Water retention curve of: (a) CS-cement mixture, (b) NPS-cement mixture

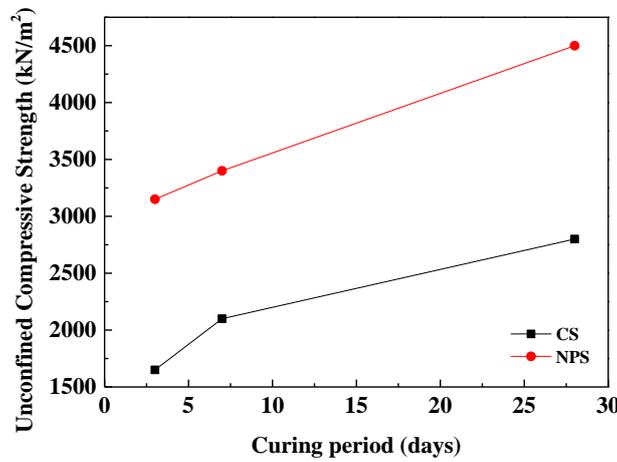


Figure 4 Effect of curing period on the strength of soils stabilized with 12% cement

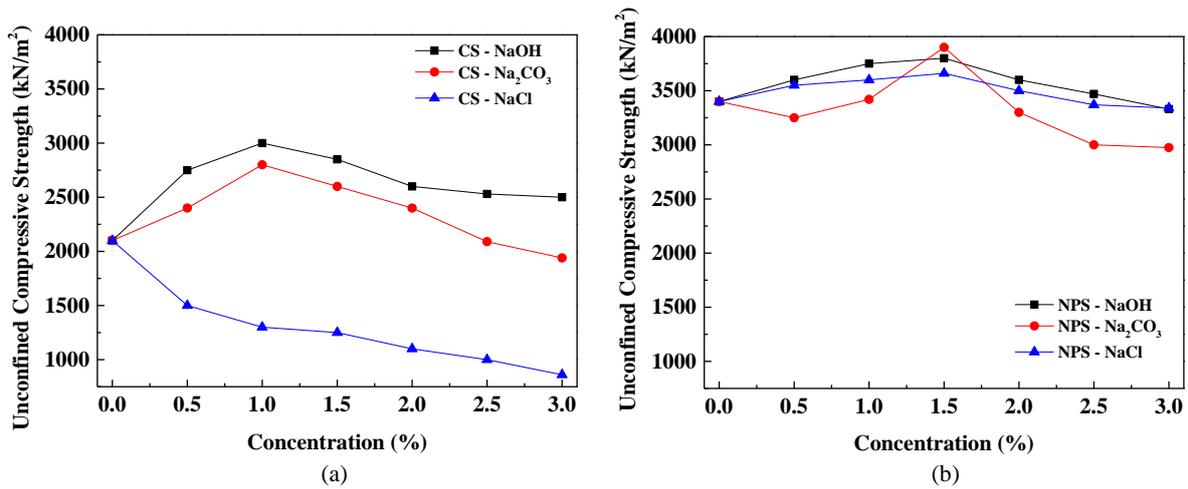


Figure 5 Effect of additives on the strength of soils stabilized with 12% cement at 7 days curing a) CS b)NPS

CS-cement mixtures treated with NaOH and Na₂CO₃ additives tended to decline due an excessive concentration of cations in the soil [47].

Furthermore, the UCS of NPS–cement mixtures treated with NaOH, Na₂CO₃ and NaCl additives exhibited little improvement in strength, 12.3% for Na₂CO₃, 10.5% for

NaOH and 7.1% for NaCl, compared with the untreated NPS-cement mixture (Figure 5). This strength improvement was achieved at additive concentrations of about 1.5%, i.e., the optimum concentration (Figure 5b). Beyond this optimal percentage, a reduction in soil strength was evident.

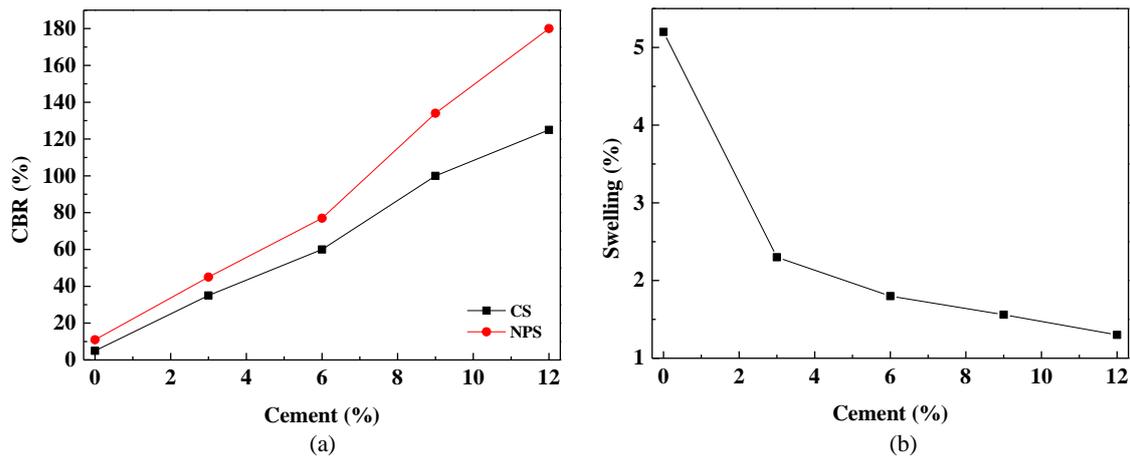


Figure 6 Effect of cement content on: a) CBR values for CS and NPS, and b) free swelling of CS in the CBR test

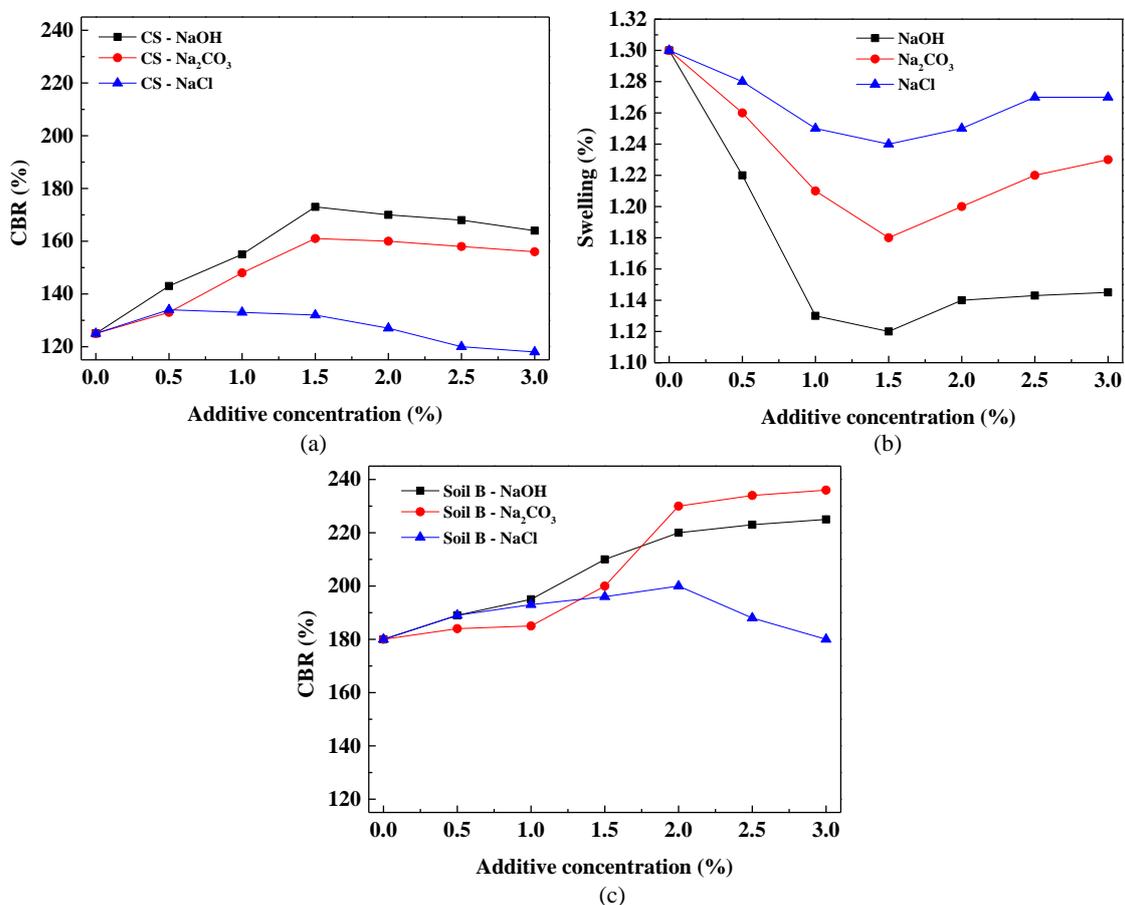


Figure 7 Effect of type and concentration of chemical additives on a) CBR, b) free swelling values respectively of CS, and c) CBR values of NPS

It is important to refer to the limited effect of sodium additives in NPS-cement mixtures through the overlapping of unconfined strength curves. Similar behavior was documented by previous researchers [25-26, 48].

The difference in the optimum concentration values of sodium additives in both CS/NPS-cement mixtures reflects the important role of plasticity in the formation of high strength cementitious gels within CS-cement mixtures. The CS-cement mixture utilized a lower amount of sodium

additives compared with the NPS-cement mixtures. This was exploited to produce high strength soils [48].

Figure 6a shows the effect of cement content on CBR values for both CS and NPS soil samples compacted at MDD and OMC conditions. Figure 6b shows the swelling potentials of CS under soaking in the CBR test. An improvement in CBR values was observed for CS and NPS, from 4.97% and 11% to 125% and 180% for the soils treated with 12% cement, respectively. This improvement was due

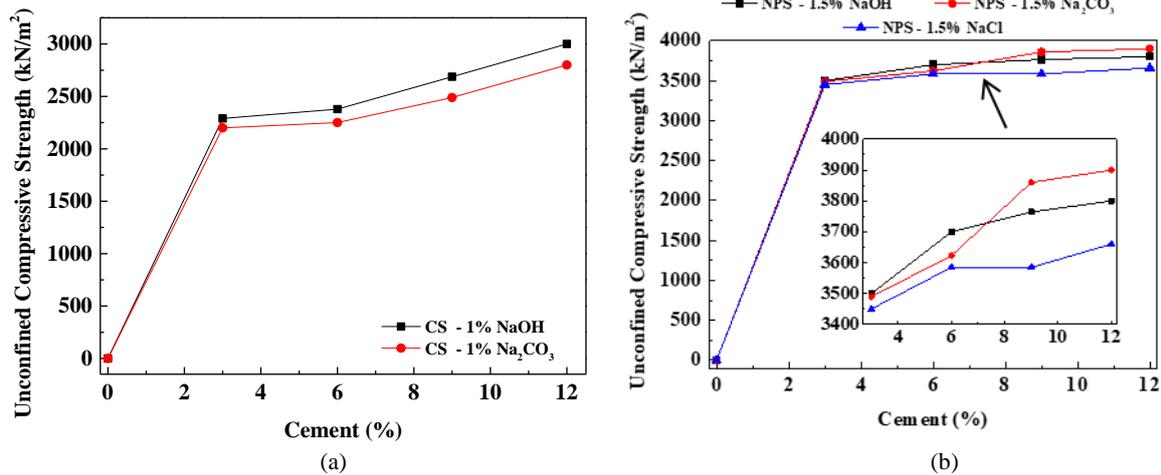


Figure 8 Effect of cement level on the strength of CS and NPS stabilized and the optimum percentage of chemical additives for a) CS and b) NPS

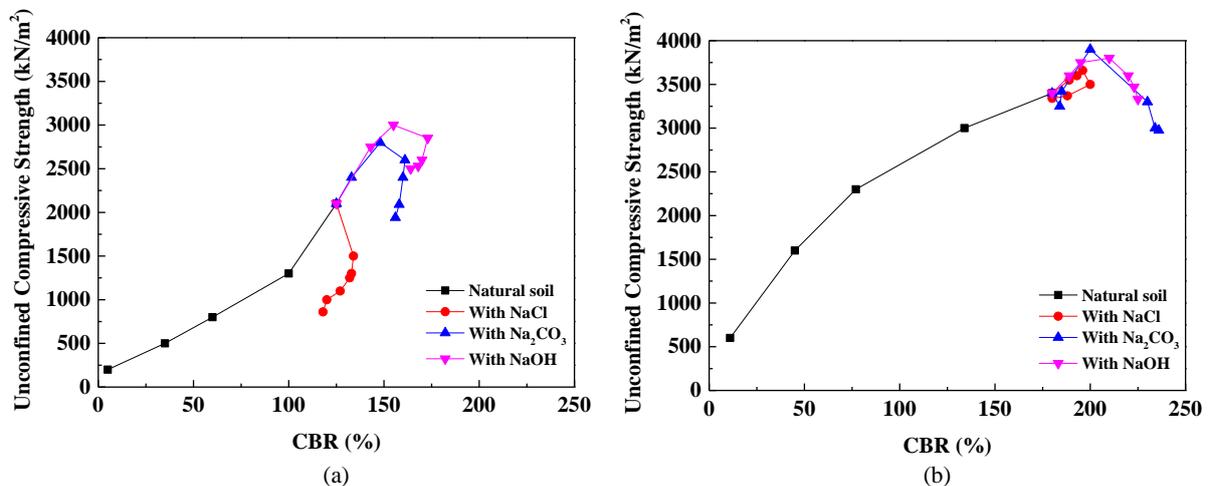


Figure 9 UCS and CBR values of CS and NPS cement-mixtures with and without sodium addition for a) CS and b) NPS

to cement addition. It enabled the cementation of soil components, and in turn increased strength [49-50]. There was the reduction in swelling potential of CS, by about 75%, i.e., from 5.2% for natural soil to 1.3% for soil treated with 12% cement addition [51].

Figures 7 (a-c) show the effect of sodium additives on CBR values and swelling potential of CS/NPS-cement mixtures compacted at MDD and OMC. Figure 7a shows that CBR values of CS-cement mixture increased by 26% for NaOH and 22% for Na₂CO₃, when compare with the untreated CS-cement mixture. The CBR value increase slightly in the case of NaCl addition. However, the increase in CBR values for soils with NaOH and Na₂CO₃ additives was about 1.5%, which could be considered the optimum NaOH and Na₂CO₃ additive concentration. Variation in the optimum additive concentrations of CS-cement mixture, from 1% in unconfined compressive strength to 1.5% in CBR test, could be attributed to soaking in water prior to the CBR test, which increased cement hydration of the soil-cement mixture [38].

However, Figure 7b reveals a reduction in the swelling potential of the CS-cement mixture treated with sodium additives until the optimal 1.5%, followed by increased swelling values. This was probably due to an excessive concentration of cations from the sodium additives [38-39].

Figure 7c illustrates the CBR curves of NPS-cement mixtures treated with sodium additives. All the CBR additive curves show an overlap in their values up to an additive concentration of 2% (i.e., the optimal concentration), followed by a reduction in CBR values. These overlaps indicate the limited effect of sodium additives on NPS-cement mixtures. Here, due to the soaking process of the samples before the CBR test, a modification in the optimum concentration of additives from 1.5% in unconfined strength to 2% in the CBR test was recorded [38].

Figures 8a-b show the effects of cement percentages on the UCS of CS and NPS soil samples treated with optimal concentrations of sodium additives. An increase in the UCS with increased cement levels was noticed for both soils. For CS, NaOH addition is more effective than Na₂CO₃ (Figure 8a), while the addition of various cement levels had limited effect on the strength of NPS. This is clearly seen from the overlap of the curves in Figure 8b [26].

Figures 9a-b show the relationship between the obtained UCS and CBR values of CS/NPS-cement mixtures treated with various amounts of sodium additives. Figure 9a shows a clear improvement in the UCS-CBR curve of a CS-cement mixture treated with sodium additives. NaOH was unique in that it was more effective in modification of CS-cement mixture strength. The effect of NaCl addition was limited.

Figure 9b shows a very limited modified in the UCS-CBR curve of NPS-cement mixtures treated with sodium additions, with a slightly better effect of NaOH in the modification of NPS-cement mixture strength. The clear improvement in CS-cement mixture could be related to the plasticity factor. Sodium additives (especially NaOH) allow for generation of more cementitious gels, which gives CS-cement mixtures additional strength [46].

4. Conclusions

Both the CS and NPS soils from Mosul City, Iraq, are soft soils that require stabilisation to improve their properties before they can be suitable for construction purposes. This research studied the effects of adding NaOH, Na₂CO₃ and NaCl as a means of chemical stabilisation to enhance their properties.

The UCS of CS/NPS-cement mixtures with or without sodium addition improved with increases in the cement content and curing period. Both NaOH and Na₂CO₃ additives increased the strength of CS/NPS-cement mixtures. However, NaCl addition had marginal impacts on soil-cement mixtures. The optimum concentrations of sodium additives that produce maximal strength (i.e., UCS and CBR) varied for CS and NPS based on their distinct physical properties. NaOH was found to be more effective as an additive for soil stabilization than Na₂CO₃, while NaCl was found to have the least effect. The swelling potential of CS-cement mixture was reduced proportionally with increasing addition of sodium additives. This study provides a platform to exhibit the distinct features of the tested soils and the impacts of the sodium additives on soil properties. Our main finding is that NaOH is the most suitable sodium compound for chemical stabilisation of both CS and NCS soils from Mosul city, Iraq.

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