

Influence of Compaction Energy on Cement Stabilized Soil for Road Construction

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Received 08 November 2021; Revised 12 February 2022; Accepted 16 February 2022; Published 01 March 2022

Abstract

Compactness is an important feature to ensure subgrade stability where temperature and water infiltration exist in semi-arid areas. Chemical soil stabilization can improve soil properties. This research studies the impact of compaction energy on stabilized subgrade soil and how to improve its geotechnical characteristics in the experimental tests on both unstabilized and stabilized soil samples by adding ordinary Portland cement and sulfate-resistant cement, in percentages by the soil's weight, in order of identification and classification, to the strength properties tests: compaction at multiple energies, CBR, and UCS. A test protocol was followed to assess the relationship between cement soil treatment, mechanical characteristics, and compaction parameters at different energy levels. Findings show that the higher UCS values were recorded with an increase in compaction energy. The MDD of cement stabilized soil increases as compaction energy increases, whereas the OMC decreases, the UCS improves, and the CBR increases. These improvements have a positive influence on the performance of soil used as a subgrade. The combination of cement stabilization and a high compaction level for subgrades using weak soil can improve strength parameters throughout any phase of earthwork construction design that leads to strengthening subgrades, reducing the thickness, and, as a result, low construction cost.

Keywords: Compaction Energy; Subgrade; Soil Stabilization; Cement; Geotechnics; Soil Strength.

1. Introduction

Soil compaction is an essential aspect of civil engineering work. Many engineering structures, such as highway embankments and earth dams, require soil compaction to improve mechanical properties. Also, compaction is necessary when wanting to reduce permeability. Soil compaction improves its strength properties, therefore improving the foundation's bearing capacity. Three principal parameters: water content, type of soil, and compaction energy, affect the compaction. Subbase is not an integral section of the pavement, but rather its supporting soil. As a principal layer, it is for the short term to ensure trafficability and the long term to guarantee bearing capacity. This layer constitutes the roadway foundation. Compaction of the subbase is one of the most difficult operations to carry out during road construction. It mainly links stability and durability to material characteristics and compaction methods adapted to the soil type. However, nature does not always provide the engineer with materials with the right water content, particularly in arid and semiarid areas where getting the optimum Proctor water content requires the supply of considerable quantities of water. Results of previous research show that the optimum water content decreases with the energy of compaction while the dry density increases. The purpose of the treatment is to get a subbase material of the superior mechanical

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<http://dx.doi.org/10.28991/CEJ-2022-08-03-012>



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class. Cement treatment does not constitute a sufficient increase in bearing capacity to be used alone for subbase; however, cement use is suitable to stabilize the embankments. Its major action is to lower the water content of clay soils or soils that are wet, but it can provide sufficient improvement in the mechanical performance of the subbase.

For both treated and untreated soil compaction, compaction energy is a critical element. High compaction energy applied to the soil produces more densification, and thus a higher maximum dry density [1]. Many scientists have investigated compaction energy's impact on the engineering characteristics of both unstabilized and stabilized soils. Low subgrade soil conditions will cause insufficient pavement support, reducing pavement life. Drew (2005) [2] analyzed the impact of compaction energy level on soil engineering characteristics such as OMC, MDD, and UCS. It was discovered that variations in compaction energy generate considerable changes in soil behavior. Vinod et al. (2015) [3] investigated the role of compaction energy. He reported an increase in max density and a decrease in optimal moisture content when the compaction energy increased. When the energy of compaction increased, the CBR value also increased. Attom (1997) [4] studied the impact of increasing compaction energy on compacted coherent soil parameters, such as swelling pressure, shear strength, and permeability. They observed that increasing compaction energy increases shear strength parameters when the soil has dry optimal water content but has little or no effect on UCS when the soil has higher water content. In soil, when compaction energy on the dry optimum, reduces permeability and elevates swelling pressure. The performance of fine-grained soils was studied by Sridharan and Gurtug (2004) [5] after compaction.

Researchers found that variations in compaction energy had a major effect on both swell potential and swelling pressure. Soil swell potential is proportional to the plasticity index. They found that increasing compaction energy improves certain soil engineering properties while simultaneously increasing the soil's swell potential, which is undesirable. Here, civil engineering structures on these soils face high swelling. Basack et al. (2021) [6] researched the impact of various compaction energies on compaction parameters, UCS, CBR, and soil swell%. When compaction energy went up, MDD increased, OMC reduced, UCS increased, and CBR increased, according to the author, which shows a high gain in these parameters. As a result, increasing compaction energy can be an effective method for stabilizing tested soil up to a certain level. However, when we compact soil above the limit, the permeability decreases, causing the swell potential in the soil to change. Sabat and Moharana (2015) [7] studied compaction energy's effect on local expansive soil. MDD raised 3.2 KN/m³, OMC reduced 2.77%, UCS increased 532 KN/m², and soaking CBR increased 4.38% when the energy of compaction increased by 2108 KJ/m³. Based on the above findings, they confirmed that raising compaction energy improves most soil engineering qualities. It increases soil swell potential, and it is undesirable.

Yusoff et al. (2017) investigated the effects of compaction energies on different geotechnical characteristics of laterite soil and kaolin to better understand the effects of compaction energies on the soil. By compacting specimens with two different levels of impact energy, one can estimate the dry unit weight over a wide range of moisture content as well as the Unconfined Compression Strength parameter. Based on research and different geotechnical tests done on laterite and kaolin, they discovered that the MDD values improve as compaction energy increases. The variations in MDD and OMC for both soils, however, are moderate. In addition, the dimensions of the small particles have a significant impact on compaction factors. And the ratio of clay has a significant impact on the result. Soil with a higher percentage of fine elements has more void space and is less dense than sandy soil. The same tendency with compaction was seen when it came to UCS. Higher UCS values were shown to be linked to increased compaction energy.

The physical soil characteristics have a significant influence on upgrading the engineering parameters of the soil. Ene & Okagbue (2009) [9] concluded that no strong relation exists between CBR value and consistency limits. These experimental findings on subgrade in highway design (CBR and UCS tests) used soil samples (20<LL<70) collected from many locations to measure subgrade strength. There is a direct relationship between the consistency limits and the CBR. MDD and OMC have strong empirical relationships when it comes to predicting CBR value. Ene & Okagbue (2009) used linear regression in both simple and multiple analyses. In addition, a predictive equation to estimate CBR from experimental index values was developed to look at the linear relationships between index properties, CBR, and UCS. As density affects the consolidation ratio of soil, the creep parameter as well. For clay soils, Alhaji et al. (2020) observed that when applying five compaction energy levels on air-dried soil specimens and passing consolidation tests, the creep parameters increased when loading increased to 387 kN/m², and decreased after. They found the resulting curves to increase as the compaction energy level increased and to tend towards the straight line at modified Proctor compaction energy. The maximum amount of creep over a three-year period went from 455.5 mm to half of that [10].

Another study discussed the variation of hydraulic conductivity under different energy levels. The results illustrate that, by applying high compaction energy, it can reach a low hydraulic conductivity (about $k < 1 \times 10^{-9}$ m/s). As a result, the lower hydraulic conductivity associated with an additional compaction energy level could make them suitable for use as compacted soil in geotechnical work [11]. Srihandayani et al. (2020) [12] describe how to project laboratory compaction results in the field (a Vibro-roller grinding machine) based on finding the number of compaction trajectories. Lindh (2004) [13], concluded that compaction of stabilized soil is necessary to ensure high quality and the required

service life of the stabilized material, citing different studies by researchers. Stabilization affects the compaction parameters of the material, requiring extra compaction energy to get the same dry density as untreated soil. Rauch (2002) [14] performed compaction and triaxial tests on commercial additive-treated soils. They allowed compacted samples to cure for seven days, using a modified Proctor compaction method. The results show individual cases of marked improvement, according to the authors. According to Vorobieff (2006) [15], some practitioners' assumption that changed sample compaction will cause a high-performing bound stabilized pavement should be replaced with a requirement that all research testing be at standard compaction. Anjaneyappa (2013) [16] attempted to increase the mechanical performance of loamy soil by compaction and chemical stabilization. The author studied the treatment of soil samples compacted by various compaction efforts in the laboratory. According to the findings, increased compaction effort leads to increased soil density. An increase in the density of chemically treated soil is inconsiderable. Both the strength and performance parameters of the soil treated with a chemical stabilizer improve.

Santoni et al. (2002) [17] performed UCS experiments on silty sand treated with six polymers. For various curing periods, they cured samples at 22 degrees C and 40% relative humidity. According to the authors, few polymers improved unconfined compressive strength significantly. Nwaiwu et al. (2012) [18] explored the role of compaction efforts in the quality of waste product soil mixtures using a graphical technique. Adding quarry dust to the soil increased mechanical parameters. At high compaction efforts, the soil attained a higher value of the swell potential and swelling pressure parameters. Variations of MDD, OMC, CBR SP, and PS resulting from the compactive efforts raising and quarry dust percentage are statistically significant at a 5% level. Bera (2014) [1] presented the compaction parameter variations of grained soil (fine) treated by rice husk ash. Based on the findings, he created linear regression analyses to estimate the density and moisture content of the soil-RHA mixture and drew the following conclusions: (1) the density of soil reduces when the addition proportion increases. (2) Independently of compaction energy, increased RHA proportion in fine-grained soil reduces MDD and increases OMC. Independently of the soil type.

The Stabilizing of pavement subgrade soils and foundation materials is based on the traditional use of treatment with cement. Soil properties can be improved by chemical or cement additions, such as Portland cement. Pongsivasathit et al. (2019) [19] studied the behaviour of cement stabilized subgrade soil samples. To assess the impact of cement addition on the resistance of stabilized soil samples, they used the UCS, S-CBR, third-point loading test, and PLT. As a result, the modulus of rupture and the subgrade reaction modulus of the three stabilized subgrade soils all increased as the cement content increased [19]. It will be important to get remark, when the excess in cement addition amount, the stabilized layer may crack because of thermal and shrinkage cracks. Also, water can infiltrate the pavement through cracks that reflect light through the surfacing. Another problem is that the stabilizing reaction is reversible if CO₂ has access to the material, and the layer's strength can be reduced [20]. When we add 8% cement to soil, cohesion increases by 37% while the UCS increases by 76% [21, 22]. According to Yilmaz & Ozaydin (2013) [23], increased cement concentration during the UCS test changed the soil specimen's failure pattern from ductile to brittle. Croft (1967) [24] claims that soil compositions can help achieve excellent stabilization, and stabilizers such as cement can affect the physical properties of stabilized soil..

Croft (1968), studied texture effect in cement-soil mixture, chemical compositions, and mineralogical components of soil in another research. Particles of cement occupy the pore space, and compaction changes the soil into a dense state by forming soil particles over each other and creating groups together [25, 26]. Soil stabilization by cement is the hydration of cement particles, which causes them to develop into crystals that can interlock with one another, resulting in high compressive strength. Cement particles need to coat the majority of the material particles to create a good bond. To provide excellent interaction (soil particles and cement), and therefore effective soil cement stabilization, the cement, and soil must mix with a certain particle size distribution [27, 28]. Cement stabilization offers the same strength improvement in soils as lime stabilization. And its composition contains calcium needed for pozzolanic reactions; however, the origin of the silica required for pozzolanic reactions varies. Because silica is present in cement, no need to break down the clay mineral. As a result, cement stabilization is independent of soil characteristics; therefore, the stability has nothing to do with soil nature; the requirement is that the soil contains some water to start the hydration process. Mousavi and Wong (2015) [29] focused on cement and kaolin use for soft clay stabilization, like soil stabilized as a highway embankment material. Findings show that using a binder mixing of Portland cement (ordinary) 8%, kaolin 2%, and silica sand 5%, the direct shear tests, CBR value, and UCS of the treated soil increased. They have shown that stabilized soils with binder compositions of cement 8%, Kaolin 2%, and silica sand 5% have superior engineering properties than samples stabilized with lower kaolin amounts (i.e., < than 2%). The cement and kaolin-stabilized soil may be considered in highway buildings. The study's findings provide an optimally stabilized clay mix design that may improve soft clay.

It may partially substitute ordinary Portland cement with 2% kaolin, according to findings. In situ treatment of damaged road pavements using cementitious binders offered as a viable option to repair and overlay in a modern study by Kodikara and Yeo (2005) [30]. Comparing both the traditional binder, General Portland cement, the analysis showed that pavement stabilized using slag mixes can be successful. Literature suggests that understanding the strength and performance behavior of soil treated with any new stabilizer compacted to various energy levels is necessary.

This present work represents in a part an overview of the particularities of cement soil treatment effect. In the second part, the compaction energy level influences. The analysis objectives are to highlight the impact of high compacting subbase soil, as well as to see how compaction energy affects subbase materials engineering parameters (untreated/treated), and economic gains in construction projects. Environmentally, minimize the irrational use of water, particularly in areas where the climate is arid, and where it is preferable to preserve water resources for the resident's benefit.

2. Methods and Materials

2.1. Description of Materials

The selected soil was sampled at a 2 m depth of five excavated trial pits from the Kenadsa street area in the southwest exit of the city of Béchar, southwestern Algeria. Based on the UCS method, the soil was silty to clayey sand (Figure 1).

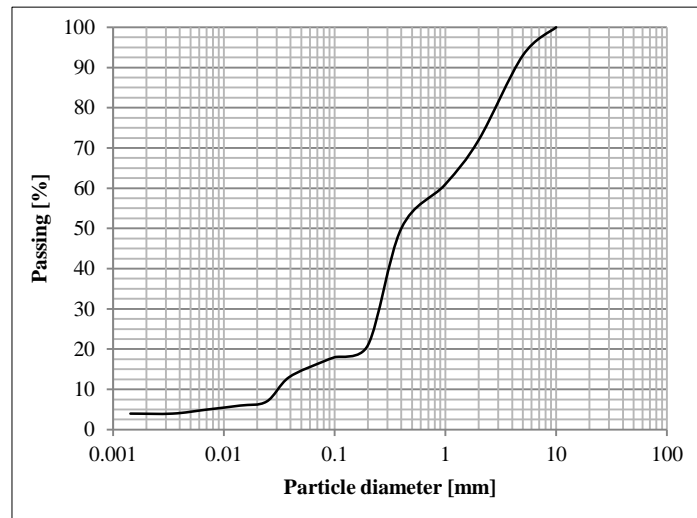


Figure 1. Grain Size Distribution Curve

Atterberg limit, sieve analysis, specific gravity, standard/ modified proctor test, CBR, and UCS tests, all were done. Standard (SP) and modified (MP) proctor tests were done using 10 cm diameter compaction mould (volume = 933 cm³) following AFNOR standard [31].

Table 1. Property the studied Soil

Parameter	Natural Soil	Parameter	Natural Soil
W (%)	2.73	CaCO ₃ (%)	12
Gravel (%)	13	SO ₄ (%)	0.287
Sand (%)	59	Chloride (%)	0.006/0.568
Clay (%)	7	Insoluble (%)	87.14
Silt (%)	21	VBS	1.05
Cu	30	LL (%)	46
Cc	1.96	LP (%)	22
Specific gravity	1.76	IP (%)	24
USCS class.	SC	GTR-92 class.	A2th

2.2. Procedures

To investigate the compaction energy and its effect on stabilized soil, two stages were added to the experimental program. The first step, stabilize the soil (adding cement), an increment of 2 to 9% by substitution of selected soil. In this study, cement was used to amend the soil (Figure 2).



Figure 2. Selected materials

On soil stabilized with various percentages of cement, standard geotechnical tests such as standard Proctor compaction, UCS, and CBR tests were performed. Samples for the UCS tests were compacted with the relevant MDD and OMC (Figure 3). The optimum percentage of cement for this study was found to be OPC and Sulphate resistant cement (SRC) from the GICA Company for stabilization of soil.



Figure 3. Experimental procedures

In the second step, eight compaction energy levels have been applied. The experiments have been done on four standard proctor energy levels using a mold with a compaction test specification and the same as a modified Proctor mold [31] with a change in several blows, the number of layers, and the weight of the hammer. Table 2 shows different levels of compaction energy that have been used in the experiment.

Table 2. Procedures of Laboratory Compaction

Compaction energy level	Proctor type	Weight of Hammer (kg)	No. of blows	No. of layer	Height of Drop (m)	Energy of compaction (kJ/m ³)
E1	modified	45.35	25	3	0.457	564
E2	standard	24.9	25	3	0.305	611
E3	modified	45.35	25	5	0.457	940
E4	standard	24.9	25	5	0.305	1018
E5	modified	45.35	56	3	0.457	1263
E6	standard	24.9	56	3	0.305	1368
E7	modified	45.35	56	5	0.457	2105
E8	standard	24.9	56	5	0.305	2279

The UCS and CBR tests were executed and evaluated, for both treated and untreated soil samples respecting the NF P94-078 [32], and NF P94-077 [33] standards for the compacted samples under eight 08 different combinations at the correspondent optimum moisture content. A flowchart in Figure 4 shows the research method.

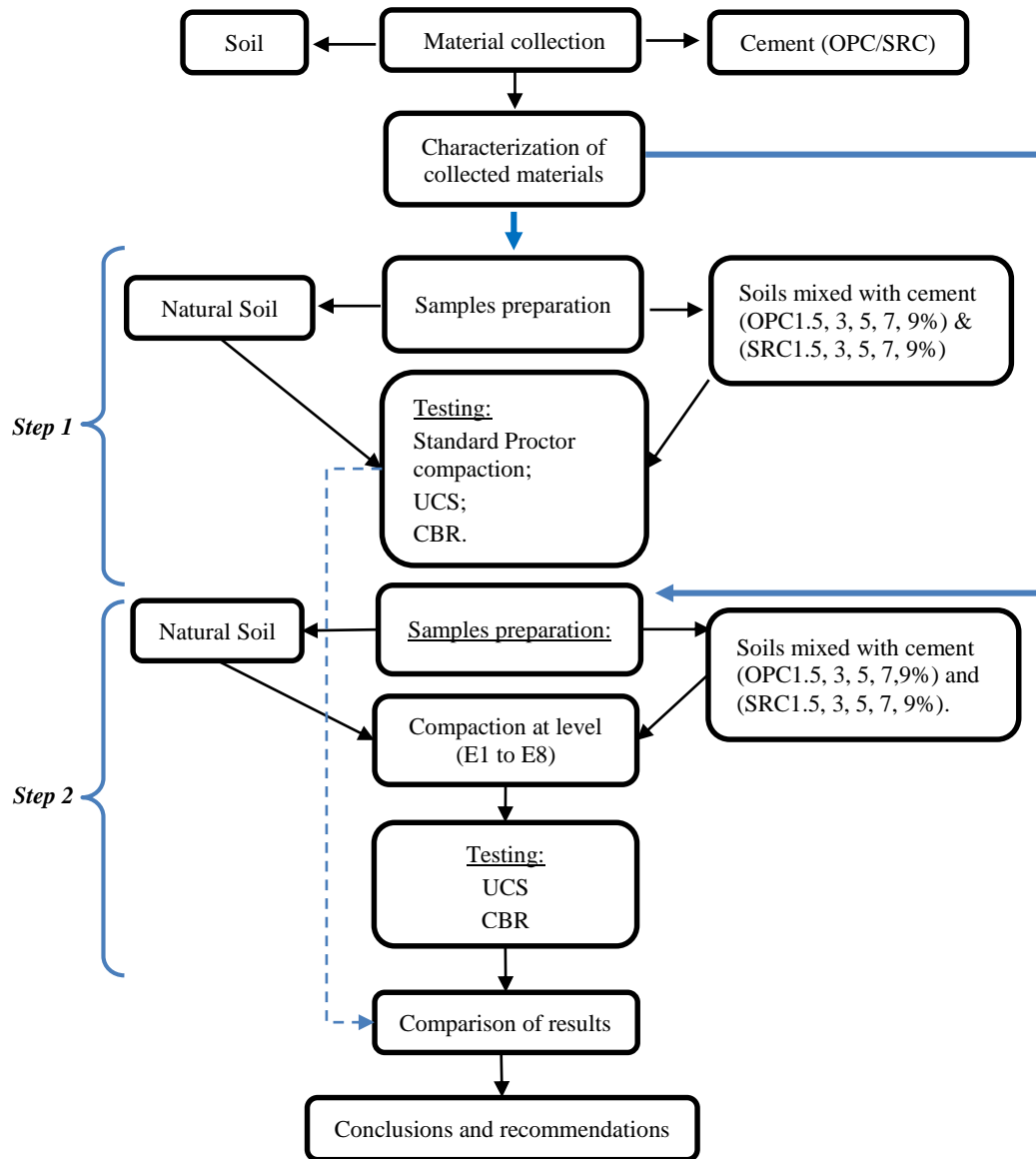


Figure 4. Flow chart of the experimental program

3. Results and Discussion

3.1. Cement Soil Stabilization

In this study, the addition of cement (CRS and OPC) at different percentages of dry mass (1.5 to 9%) to the soil samples was investigated. The mixing process is performed so that the samples are properly homogenized. To evaluate changes in compaction parameters, the Proctor test was performed in accordance with the relevant standard on soil (treated and untreated). Figure 5 illustrates the maximum dry density and optimum water content changes of cement-stabilized soil. We observed the cement (CRS and OPC) effects on MDD and OMC. Figure 6 shows a proportional variation of the maximum density with the amount of cement dosage. A decrease in the water content and a continuous increase of the MDD by increasing the cement content means the cement absorbs the amount of water and therefore more density. This behaviour offers a saving of water. In the case of SRC, it was observed that the gain in water is strongly related to the cement compared to the OPC. This is because cement particles are added to the mix, which changes the granulometry (decreases void space) and, therefore, increases the density [34].

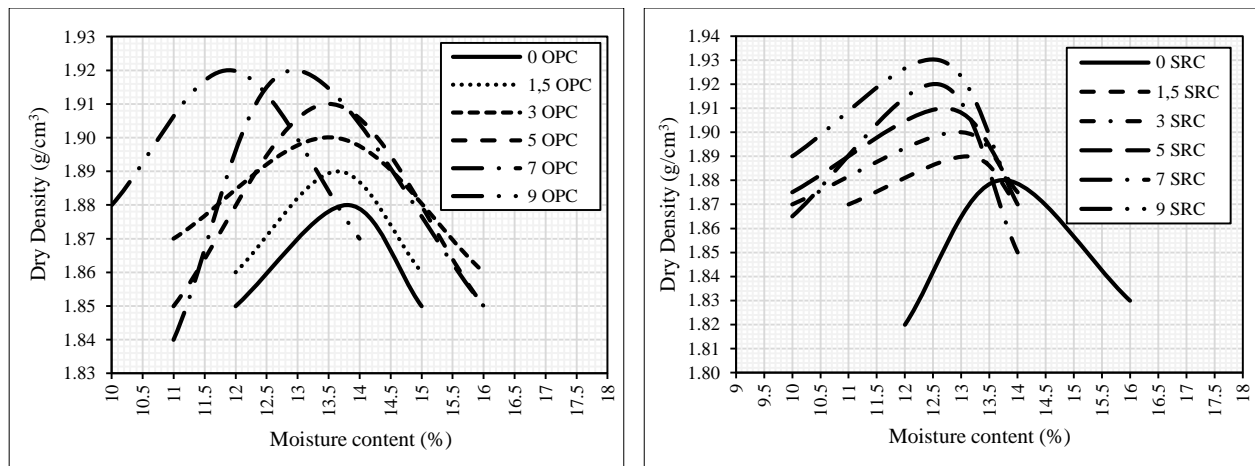


Figure 5. Effect of cement stabilization on compaction curves

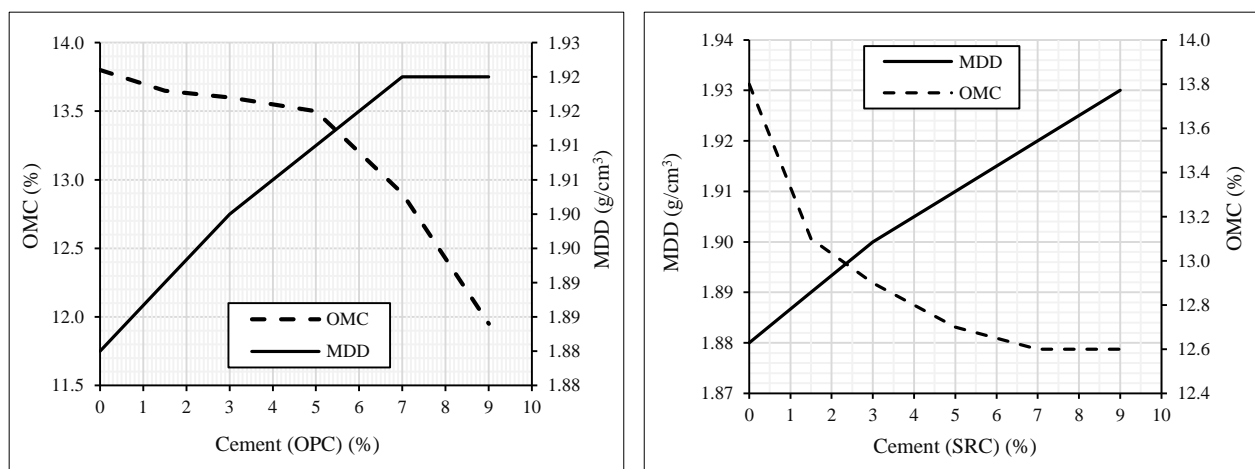


Figure 6. Effect of cement content on maximum dry unit weight and moisture content

According to Figure 5, the curve flattens out by increasing the amount of cement (OPC and emersion in CRS). As a result, the soil is less affected by water content (ideal for backfill). For more than 7% cement, the max density remains almost constant, which is consistent with Pongsivasathit (2019) [19] results. For more than 8%, cement can destroy the soil structure. As a result, a higher cement-specific gravity than sand, changes in the particle-size curve, and a decrease in moisture content all have an influence on compaction parameters. At lower percentages of cement content, changes in compaction characteristics are meaningful. However, the improvement in soil compaction characteristics stabilized with the addition of cement with higher percentages is minimal.

In this study, the UCS analysis was performed to evaluate the compressive strength of the subgrade material. The purpose of the CBR test is to measure the soil punching resistance with the water content corresponding to the Proctor optimum. These tests will characterise the soil bearing capacity (before and after treatment). As for compressive strength, the results show a better overall performance for the approximate water content of 13.6%. Indeed, the highest value is 363 kPa for a cement content of 1.5% (OPC) (Figure 7). This value shows the influence of cement, which improves the strength almost twice as much as untreated soil. Figure 7 shows that after 3% of cement, the OPC treated soil loses significantly more strength than the SRC treated soil. (SRC) cement addition keeps an almost constant strength, unlike the values obtained by the cement (OPC). We can observe the tendency of the mixtures above 3% to reach low strength (275 kPa as SRC) and (325 kPa as OPC). However, it is possible to notice a significant decrease of 24% of the resistance for the sample treated with OPC, whereas the soil treated with SRC loses 9%. In this sense, hydration occurs because of the cementing process. However, the strength gain of the compacted soil is not largely affected by its saturation. Chemical reactions and the help of the moisture in the grain can explain that behaviour [35]. Cement stabilization comprises three phases: hydration, cation exchange reactions, and pozzolanic reactions to carbonation [36].

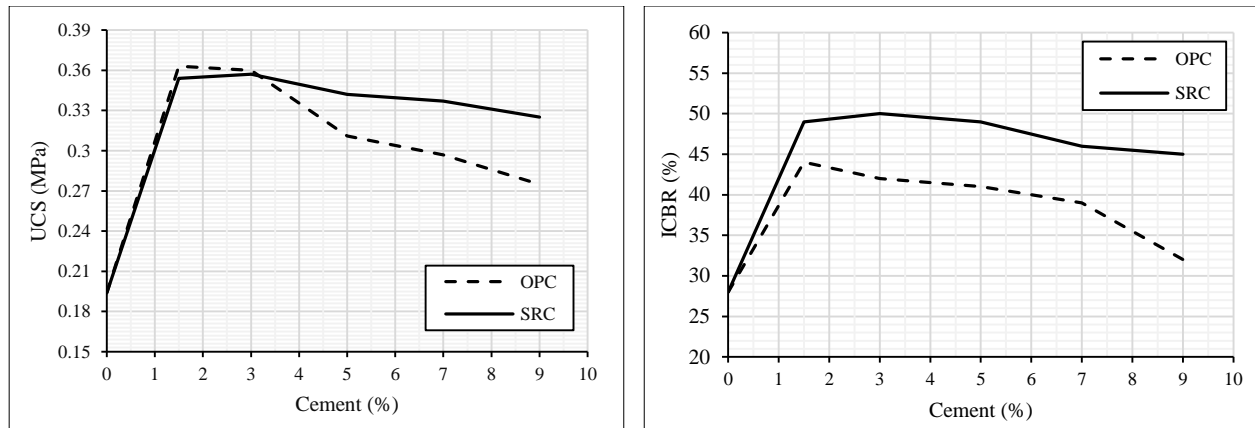


Figure 7. Effect of cement contents on maximum UCS

Graphical analysis of evolution curves (Figure 7), (CBR index), shows the rapid increase according to the cement treatment, which allows confirming that the cement dosage has a significant impact on the CBR. It's worth noting that the content of SRC is significantly more influential on the punching resistance than that of OPC. The punching resistance is the highest for this (13.6% water at 3% SRC cement), with a value of 43%. The decrease in void volume can justify the improvement (CBR increase) because of the good distribution of the soil particles with the fine cement particles. The CBR index increases by 43% with the addition of cement (SRC) and then slowly decreases until it reaches 45 at 9% cement (Figure 7). The phenomenon of cement hydration, which allows a gain in rigidity, can explain these results. When cement is put in contact with a material containing silicates and aluminates, it forms aluminates and hydrated calcium silicates, which, by crystallizing, cause a real "setting" of the materials in contact [26]. The treatment with the cement of the soil under study gives excellent results, but we can note that the CBR values are not significantly improved. A good bearing capacity level of stabilized material subgrade must have a minimum CBR of 50%, corresponding to an EV2 modulus of at least 200 MPa [37, 38]. As a result, for any site condition with a majority of sand or sand-silt, we can suggest 1.5%-3% cement to use as a stabilizer and get double the compressive strength of natural soil in the case of standard compaction.

3.2. Compaction Energy Effect on Soil

Figure 8 presents evolution versus compaction energy levels. The relationship is proportional to MDD and inversely proportional to OMC, so 10% compactness gain, and 8% water content when increasing the compaction energy level (611–2279 KJ/m³) because of grain rearrangement (saving the soil grain size distribution). It reduces the pores available for water accumulation when the soil particles are compacted closer together. Figure 8 shows the evolution of compaction parameters. It shows the soil's workability over a range of water content and compaction efforts. An increase in compaction energy lowers the OMC, requiring a small water amount and higher compaction energy to get a high MDD.

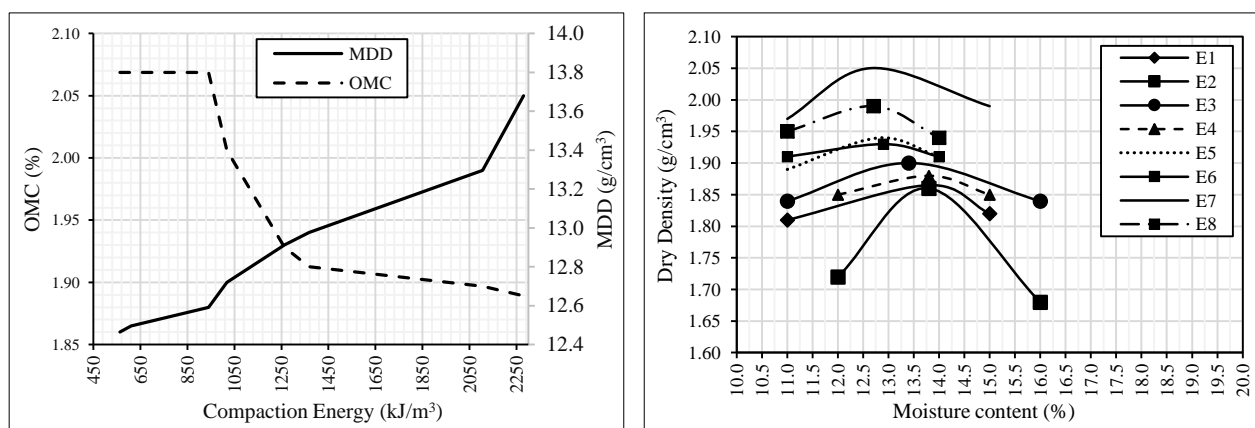


Figure 8. Variations of proctor properties of untreated soil samples under different compaction effort

Figure 9 shows the compaction energy impact on the UCS of untreated soil. UCS continues to rise as compaction energy increases. UCS increased by two times. Grain tightening leads to a decrease in the void volume and thus solidarity between the grains, which will generate a high compression strength. [3-5]. A logarithmic regression model was used to characterize the change of UCS with compaction energy [39]:

$$\begin{cases} UCS = 0.1202 \ln(Energy) - 0.6145 \\ R^2 = 0.982 \end{cases} \quad (1)$$

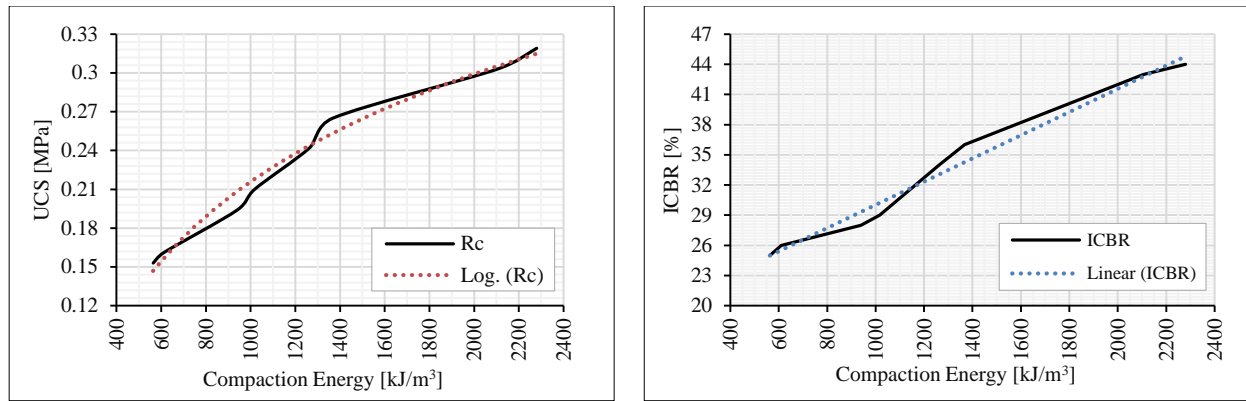


Figure 9. Influence of compaction efforts on UCS of the unstabilized soil

Another soil parameter that is affected by soil structure and inter-particle pressures is CBR. Figure 9 illustrates the variation in CBR [%] with increasing compaction effort. With an increase in compaction energy, the CBR keeps on increasing (44%). As MDD increases when compaction energy increases, the CBR also increases. CBR is increasing because soil UCS is also increasing. Increasing the compaction energy decreases the water content, which decreases the permeability and increases the punching shear resistance. A linear regression model has been used to explain CBR evolution under the compaction level effect:

$$CBR = 0.0115(Energy) - 18.495$$

$$R^2 = 0.971$$
(2)

3.3. Compaction Energy Effect on Stabilized Soil

To focus on the energy-treatment relationship and limiting parameters, we presented the results of only modified proctor mould energies. Figures 10 to 13 show the variation of compaction parameters for different energies under OPC/SRC cement stabilization. Figure 10 shows that at any level of compaction energy, OMC decreases when cement increases. At low energy, and with 9% of cement, we will have 2% of water quantity gain, so that OMC reaches 11.95%. Under higher energy (2279 kN/m³), the grains are tighter than before and the soil has a greater cement content, the water content is absorbed more, and reduced to 11%. It is necessary to mention that Yilmaz and Ozaydin [23] concluded a similar conclusion.

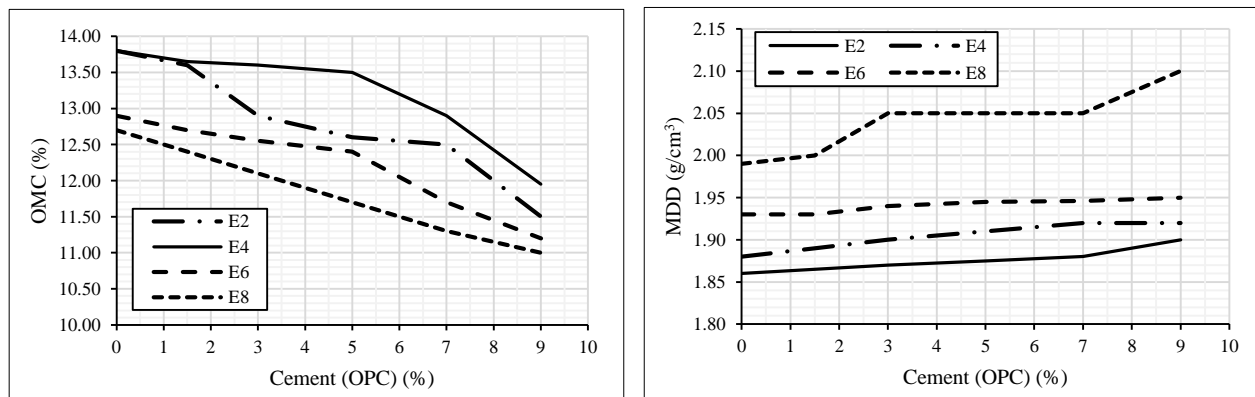


Figure 10. Comparison of OMC and MDD versus OPC content at different compaction efforts

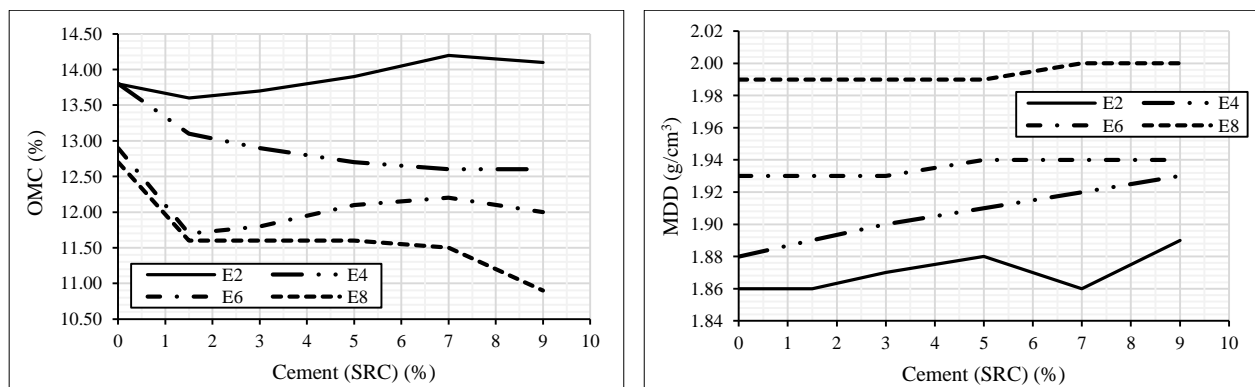


Figure 11. Comparison of OMC and MDD versus SRC content at different compaction efforts

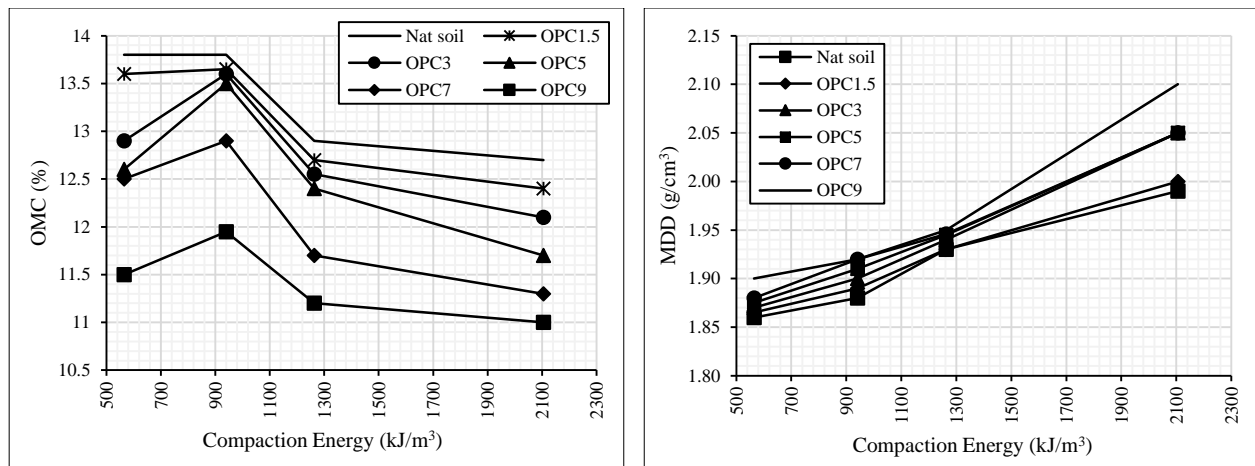


Figure 12. Comparison of OMC and MDD versus compaction effort at different OPC percentages

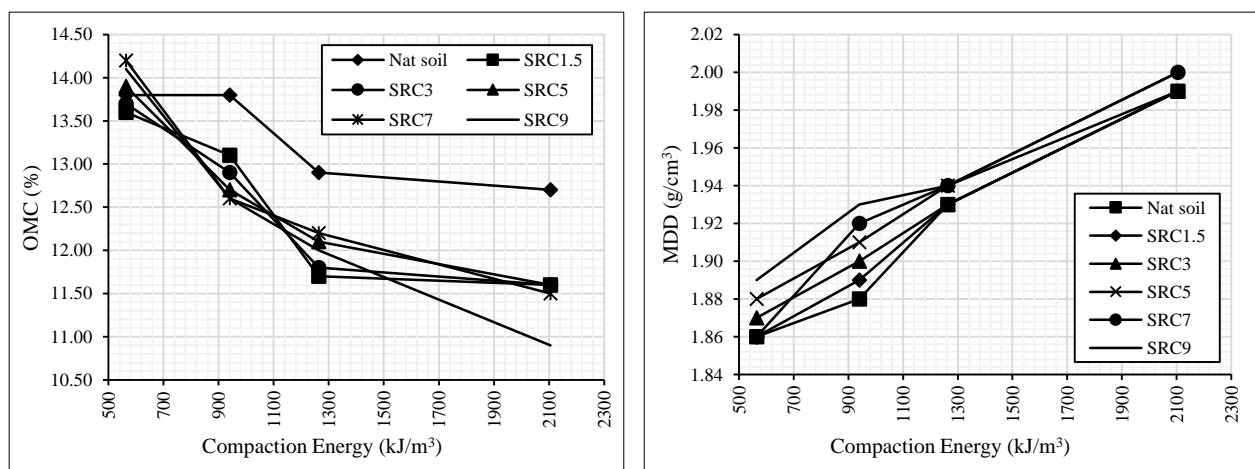


Figure 13. Comparison of OMC and MDD versus compaction effort at different SRC percentages

On the other part, we achieved an important gain as compactness, because of the voids reduction, and solidarity of the grains and therefore MDD increase. The cement content (SRC) under low energy relative to the compaction standard (Figure 11), does not have a considerable effect on the water content of the treated soil and therefore its compactness, however, an excess in cement content ($>3\%$) may require more water (water loss) and therefore a loss of benefit. Demand for water due to the hydration reaction [36]. At compaction energy of 2279 kN/m^3 , the compactness and the gain of the content come back to resume their values and reach a minimum OMC value (10.5%), with an MDD of (2 g/cm^3).

Figures 12 and 13 represent the variation of the OMC and MDD appearing on the ordinates, as a function of the parameter compaction energy appearing on the abscissa for mixed samples. It can be observed, the MDD value increases linearly, and vice versa the OMC value decrease (-5% for OPC3, -14% for OPC9, and SRC3) at a compaction energy level of 2279 kN/m^3 .

Figure 13 also shows the MDD variation with energy level increase, because of a tightening between grains, decrease in porosity, and increase of compactness, but it can also be noticed that beyond 1100 kN/m^3 , the density of different cement dosages approaches, so the soil it reaches the maximum compactness, this is the conclusion found by Sabat A. et al. [39]. The hydration of C3A generates hydrated calcium aluminate (C-A-H) which immediately causes the cement paste to set and the formation of C3A ettringite due to its reaction with calcium sulfate. Portland cement contains an average of 7% of C3A, while SRC has 4.5% . This justifies the better value, in terms of density and compressive strength of (OPC) treated soil (Figures 12, 13, and 14). The C3A dosage in cement explains the gain in OMC shown in figure 12, before the application of higher energy. The influence of combination (cement dosage - compaction energy) has a double role, decreasing the starting value of OMC and gaining the maximum amount of water. For economic purposes and to reduce the cement dosage by increasing the Energy level, the formula $(\text{CE}8 + \text{SRC}\%1.5)$ offers us a minimum requirement for treated soil compaction parameters, used as a subgrade according to CCTP [37] criteria. Under different Energy levels, and for each cement content (OPC and SRC), we performed a bearing capacity study. The punching resistance is the highest at 9% SRC cement, with an Energy level (E8) and recorded 89% .

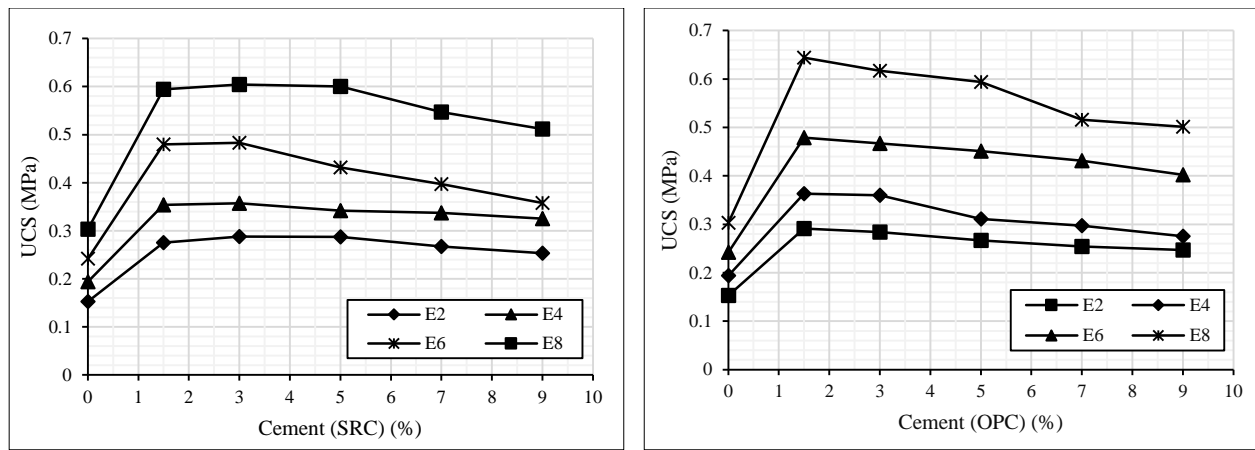


Figure 14. Comparison of UCS versus cement content at different compaction efforts

Figures 15 and 16 show a remarkable increase in CBR values at 1.5% SRC cement (82%) and continue increasing (slight slope) up to 89% (SRC 9%). For the OPC soil treatment, the bearing capacity marked a maximum of 73% at 3% cement and decreased with the cement excess

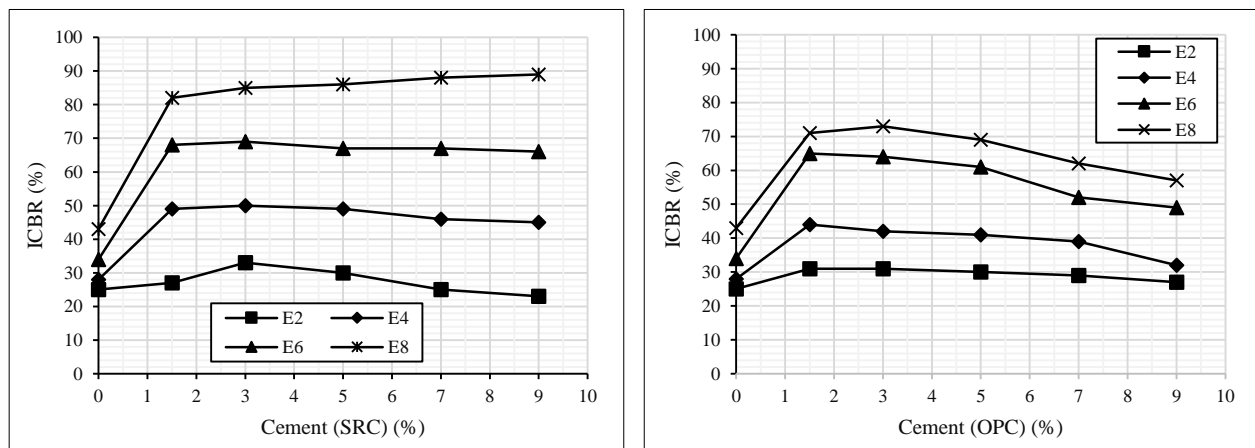


Figure 15. Comparison of CBR% versus cement content at different compaction effort

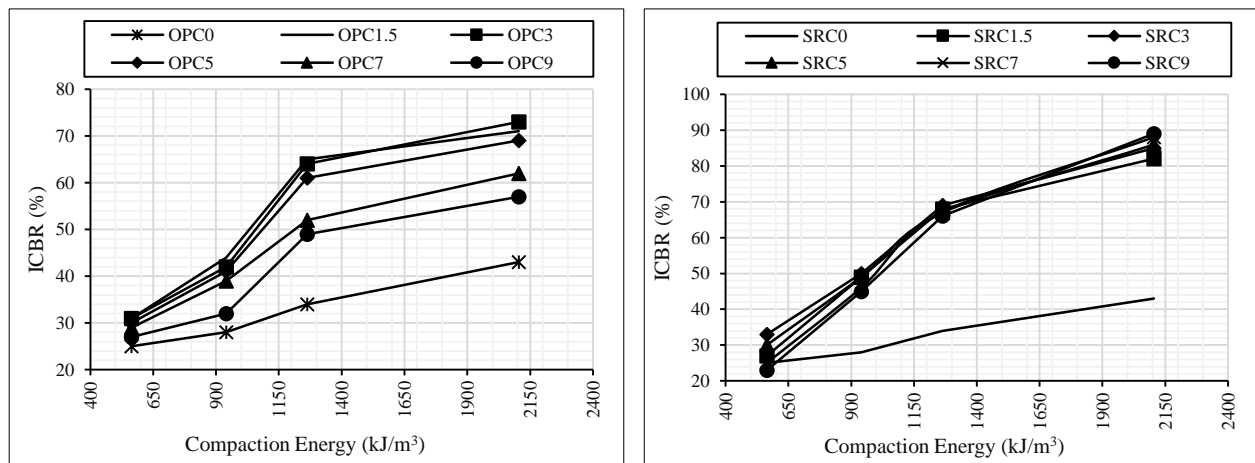


Figure 16. Comparison of CBR% versus compaction effort at different cement content

In terms of UCS, several tests were done on the compacted mixtures and the strength was measured at different energy. Figure 14 and 17 express the soil strength [MPa] as varying with compaction energy [KJ/m3]. The results give a better performance for a cement content (OPC) of 1.5%. At failure, the highest value is 644 kPa at 2279 kN/m³ (Figure 14). More than SRC3% and for each level of energy (Figure 14), the strength of the mixes is observed to reach low strength. The same with (OPC), the peak strength is reached at 1.5% and gives the maximum strength at (2279 kK/m³), and then it decreases with a slight slope by increasing cement content.

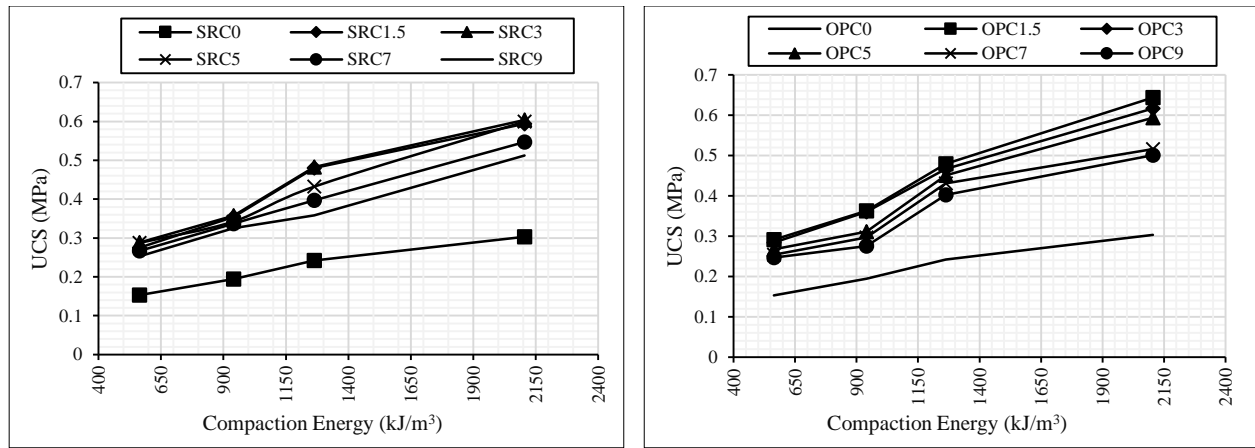


Figure 17. Comparison of UCS versus compaction effort at different cement content

The role of cement here is to make the pore volume decrease and increase the compactness [44]. Mousavi (2017) studied that the cement crystals occupy the empty spaces of the soil (hydration) to provide hardening in the stabilized soil. During hydration, the fine particles of cement do not hydrated agglomerate and create pores of large volume, so the strength decreases. At high energies, grain reaches the maximum tightening, so there is a strong coherence between the grains, then the cement will not have a significant impact on the strength. It is possible to deduce that a proportion of cement with considerable energy compaction improves the compressive strength (Figure 17). Also, at high energy levels, a small amount of cement can be sufficient for better strength, but the excess makes the treated soil lose its compactness.

4. Conclusions

Cement treatment improves the performance of arid areas' soils, allowing them to be used in their place without having to replace them. In some types of soils, stabilization (only) does not achieve the required criteria, and the soil may lose its resistance at high dosages. An increase in energy level presents its effect in this case with better results at a lower cement content. This work was to investigate the impact of the combination (cement/energy) on soil behavior for pavement construction in arid areas. Based on experimental studies, the following results are presented:

- Improvement of CBR has a direct relation to compressive strength improvement, and both are increased with cement addition.
- Cementation decreases the plastic behaviour of soil. The results show that 1.5 to 3% is the optimum percentage of cement (OPC and SRC) for stabilization of the clayey sand soil.
- Experimental results present that when the compaction energy increases, we gain in water quantity, the density improves, permeability decreases, and the punching shear resistance increases.
- Soil unit weight, soil strength characteristics, and soil energy compaction are all affected by energy and OMC. The same trend with compaction for UCS has been observed. Experimental results show that higher UCS values are associated with an increase in compaction energy.

The experimental results allowed us to deduce the combinations of cement dosage and energy level that provided the best soil performance. At high energy levels, a small amount of cement can greatly strengthen the soil, but the excess makes the treated soil lose its compactness. It is possible to note that these combinations are an effective way to improve the soils used for the subgrade while avoiding an additional budget.

The following suggestions are for improving the current study and future research:

- Variations in compaction energy affect other engineering properties like shear strength, permeability, and compressibility, which should be studied.
- A cost estimate must be made to evaluate the cost-effectiveness of improving the site by replacing on-site material with high-quality borrowed material and increasing compaction energy.
- It is recommended to investigate the impact of the curing time on the cement-soil mixture at different compaction energy levels.

5. Declarations

5.1. Author Contributions

Conceptualization, S.Y.; methodology, S.Y.; formal analysis, S.Y.; investigation, S.Y.; resources, R.T.; data curation, A.T. and D.A.; writing—original draft preparation, S.Y.; writing—review and editing, S.Y.; visualization, R.T.; funding acquisition, S.Y. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

This work was supported by LTPO Béchar and the Geotechnical Laboratory, University of Tahri Mohamed, Béchar, Algeria.

5.4. Acknowledgements

The authors thankfully acknowledge the support of the staff of the Geotechnics Laboratory, Department of Civil Engineering, University Tahri Mohamed and LTPO Béchar.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

- [1] Bera, A. K. (2014). Compaction characteristics of fine grained soil and rice husk ash mixture. *International Journal of Geotechnical Engineering*, 8(2), 121–129. doi:10.1179/1939787913Y.0000000007.
- [2] Drew, I. R. (2005). Influence of compaction energy on soil engineering properties. Master Thesis. Iowa State University, Iowa USA. Available online: <https://dr.lib.iastate.edu/server/api/core/bitstreams/a5366889-bcc1-4db8-b9a5-c1ce0a760a28/content> (accessed on January 2022).
- [3] Vinod, P. P., Sridharan, A., & Soumya, R. J. (2015). Effect of compaction energy on CBR and compaction behaviour. *Proceedings of the Institution of Civil Engineers: Ground Improvement*, 168(2), 116–121. doi:10.1680/grim.13.00059.
- [4] Attom, M. F. (1997). The effect of compactive energy level on some soil properties. *Applied Clay Science*, 12(1–2), 61–72. doi:10.1016/S0169-1317(96)00037-3.
- [5] Sridharan, A., & Gurtug, Y. (2004). Swelling behaviour of compacted fine-grained soils. *Engineering Geology*, 72(1–2), 9–18. doi:10.1016/S0013-7952(03)00161-3.
- [6] Basack, S., Goswami, G., Khabbaz, H., Karakouzian, M., Baruah, P., & Kalita, N. (2021). A Comparative Study on Soil Stabilization Relevant to Transport Infrastructure using Bagasse Ash and Stone Dust and Cost Effectiveness. *Civil Engineering Journal*, 7(11), 1947–1963. doi:10.28991/cej-2021-03091771.
- [7] Sabat, A. K., & Moharana, R. K. (2015). Effect of compaction energy on engineering properties of fly ash -granite dust stabilized expansive soil. *International Journal of Engineering and Technology*, 7(5), 1617–1624.
- [8] Yusoff, S. A. N. M., Bakar, I., Wijeyesekera, D. C., Zainorabidin, A., Azmi, M., & Ramli, H. (2017). The effects of different compaction energy on geotechnical properties of kaolin and laterite. *AIP Conference Proceedings*, 1875(1). doi:10.1063/1.4998380.
- [9] Ene, E., & Okagbue, C. (2009). Some basic geotechnical properties of expansive soil modified using pyroclastic dust. *Engineering Geology*, 107(1-2), 61–65. doi:10.1016/j.enggeo.2009.03.007.
- [10] Alhaji, M. M., Alhassan, M., Adejumo, T. W., & Jibrin, R. (2020). Effect of Density on Consolidation and Creep Parameters of Clay. *Indonesian Journal of Science and Technology*, 5(1), 31–44. doi:10.17509/ijost.v5i1.16819.
- [11] Khalid, N., Mukri, M., Kamarudin, F., & Abdul Ghani, A. H. (2020). Effect of compaction characteristics on hydraulic conductivity performance for sedimentary residual soil mixed bentonite as compacted liners. *IOP Conference Series: Earth and Environmental Science*, 498(1), 12003. doi:10.1088/1755-1315/498/1/012003.
- [12] Srihandayani, S., Soehardi, F., & Putri, L. D. (2020). CBR Laboratory Analysis for Determining the Number of Compaction Tracks to Achieve Field CBR. *IOP Conference Series: Earth and Environmental Science*, 469(1), 12012. doi:10.1088/1755-1315/469/1/012012.
- [13] Lindh, P. (2004). Compaction- and strength properties of stabilised and unstabilized fine-grained tills. PhD Thesis, Soil Mechanics and Foundation Engineering. Lund University, Lund Sweden.

- [14] Rauch, A. F., Harmon, J. S., Katz, L. E., & Liljestrand, H. M. (2002). Measured effects of liquid soil stabilizers on engineering properties of clay. *Transportation Research Record*, 1787, 33–41. doi:10.3141/1787-04.
- [15] Vorobieff, G. (2006). A new approach to laboratory testing of stabilised materials. ARRB Conference, 22nd, 2006, Canberra, Australia (29 October-2 November 2006).
- [16] Anjaneyappa, A. M. (2013). Influence of Compaction Energy on Soil Stabilized with Chemical Stabilizer. *International Journal of Research in Engineering and Technology*, 2(13), 211. doi:10.15623/ijret.2013.0213037.
- [17] Santoni, R. L., Tingle, J. S., & Webster, S. L. (2002). Stabilization of silty sand with nontraditional additives. *Transportation Research Record*, 1787(1787), 61–72. doi:10.3141/1787-07.
- [18] Nwaiwu, C. M. O., Mshelia, S. H., & Durkwa, J. K. (2012). Compactive effort influence on properties of quarry dust-black cotton soil mixtures. *International Journal of Geotechnical Engineering*, 6(1), 91–101. doi:10.3328/IJGE.2012.06.01.91-101.
- [19] Pongsivasathit, S., Horpibulsuk, S., & Piyaphipat, S. (2019). Assessment of mechanical properties of cement stabilized soils. *Case Studies in Construction Materials*, 11, 301. doi:10.1016/j.cscm.2019.e00301.
- [20] Solihu, H. (2020). Cement Soil Stabilization as an Improvement Technique for Rail Track Subgrade, and Highway Subbase and Base Courses: A Review. *Journal of Civil and Environmental Engineering*, 10(3). doi:10.37421/jcde.2020.10.344.
- [21] Khan, K. A., Nasir, H., Alam, M., Khan, S. W., & Ahmad, I. (2020). Performance of Subgrade Soil Blended with Cement and Ethylene Vinyl Acetate. *Advances in Civil Engineering*, 2020. doi:10.1155/2020/9831615.
- [22] Consoli, N. C., Rotta, G. V., & Prietto, P. D. M. (2000). Influence of curing under stress on the triaxial response of cemented soils. *Geotechnique*, 50(1), 99–105. doi:10.1680/geot.2000.50.1.99.
- [23] Yilmaz, Y., & Ozaydin, V. (2013). Compaction and shear strength characteristics of colemanite ore waste modified active belite cement stabilized high plasticity soils. *Engineering Geology*, 155, 45–53. doi:10.1016/j.enggeo.2013.01.003.
- [24] Croft, J. B. (1967). The influence of soil mineralogical composition on cement stabilization. *Geotechnique*, 17(2), 119–135. doi:10.1680/geot.1967.17.2.119.
- [25] Croft, J. B. (1968). The problem in predicting the suitability of soils for cementitious stabilization. *Engineering Geology*, 2(6), 397–424. doi:10.1016/0013-7952(68)90018-5.
- [26] Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., Raksachon, Y., & Suddeepong, A. (2010). Analysis of strength development in cement-stabilized silty clay from microstructural considerations. *Construction and Building Materials*, 24(10), 2011–2021. doi:10.1016/j.conbuildmat.2010.03.011.
- [27] Afrin, H. (2017). A Review on Different Types Soil Stabilization Techniques. *International Journal of Transportation Engineering and Technology*, 3(2), 19. doi:10.11648/j.ijtet.20170302.12.
- [28] Patel, M. A., & Patel, H. S. (2012). A Review on Effects of Stabilizing Agents for Stabilization of Weak Soil. *Civil and Environmental Research* 2(6), 1–7.
- [29] Mousavi, S., & Wong, L. S. (2015). Mechanical behavior of compacted and stabilized clay with kaolin and cement. *Jordan Journal of Civil Engineering*, 9(4), 477–486. doi:10.14525/jjce.9.4.3120.
- [30] Kodikara, J., & Yeo, R. (2005). Chapter 15 Performance evaluation of road pavements stabilized in situ. *Elsevier Geo-Engineering Book Series*, 3(C), 409–443. doi:10.1016/S1571-9960(05)80018-7.
- [31] NF P 94-093 (1999). Sols: Reconnaissance et essais: Détermination des références de compactage d'un matériau. In *Essai Proctor Normal-Essai Proctor Modifié* [Soils: Investigation and testing. Determination of the compaction characteristics of a soil. Standard Proctor test. Modified Proctor test]. Association Française de Normalisation, Paris, France.
- [32] NF P94-078 (1997). Sols: reconnaissance et essais-Indice CBR après immersion. Indice CBR immédiat. Indice Portant Immédiat-Mesure sur échantillon compacté dans le moule CBR. Association Française de Normalisation, Paris, France.
- [33] NF P94-077 (1997). Norme française." Sols : reconnaissance et essais—Essai de compression uni axiale. Association Française de Normalisation, Paris, France.
- [34] Al-Aghbari, M. Y., Mohamedzein, Y. E. A., & Taha, R. (2009). Stabilisation of desert sands using cement and cement dust. *Proceedings of the Institution of Civil Engineers: Ground Improvement*, 162(3), 145–151. doi:10.1680/grim.2009.162.3.145.
- [35] Adeyemi, G. O., & Abolurin, S. B. (2000). Strength characteristics of a chemically stabilized lateritic soil from kilometer 4, Ile-Ife/Sekona road, Southwestern Nigeria. *Journal of Mining and Geology*, 36(1), 113–119.
- [36] Jaritngam, S., Somchainuek, O., & Taneerananon, P. (2014). Feasibility of laterite-cement mixture as pavement base course aggregate. *Iranian Journal of Science and Technology - Transactions of Civil Engineering*, 38(C1+), 275–284.
- [37] CTPP Algérie. (2001). Catalogue de des Chaussées Neuves Fascicule 1, NOTICE D'UTILISATION. Organisme National de Contrôle Technique des Travaux Publics, Kouba. Algérie.

- [38] Bowles, J. E. (1992). Engineering properties of soils and their measurement. Second edition. In Engineering properties of soils and their measurement (4th Edi.). McGraw-Hill Inc., New York City, United States.
- [39] Sabat, A. K., & Moharana, R. K. (2015). Effect of compaction energy on engineering properties of fly ash -granite dust stabilized expansive soil. *International Journal of Engineering and Technology*, 7(5), 1617–1624.
- [40] Amadi, A. A., & Eberemu, A. O. (2012). Delineation of compaction criteria for acceptable hydraulic conductivity of lateritic soil-bentonite mixtures designed as landfill liners. *Environmental Earth Sciences*, 67(4), 999–1006. doi:10.1007/s12665-012-1544-z.
- [41] Das, B. M. (2021). *Principles of Geotechnical Engineering*. Cengage Learning, Massachusetts, United States.
- [42] CEBTP. (1984). *Guide pratique de dimensionnement des chaussées pour les pays tropicaux*. ISBN2110848111. Available online: https://www.francescomiceli.com/blog/Guide_pratique_dimensionnement.pdf (accessed on January 2022).
- [43] Akmal Abd, N., Safuan A., A., Md Noor, N., & Yaacob, H. (2014). Effect of Cement Stabilized Kaolin Subgrade on Strength Properties. *Journal of Applied Sciences*, 14(8), 842–845. doi:10.3923/jas.2014.842.845.
- [44] Mousavi, S. E. (2017). Stabilization of compacted clay with cement and/or lime containing peat ash. *Road Materials and Pavement Design*, 18(6), 1304–1321. doi:10.1080/14680629.2016.1212729.