

Sustainable Stabilization of Weak Sabkha Soil Using Marble Powder and Quarry Dust Blends with Sulfate-Resistant Cement: An Experimental Study and Field Application Assessment in Suluq City, Libya

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التثبيت المستدام للتربة السبخية الضعيفة باستخدام خلطات من مسحوق الرخام وغبار
المحاجر مع الأسمنت المقاوم للكبريتات: دراسة تجريبية وتقييم للتطبيق الميداني في
مدينة سلوق، ليبيا

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Abstract:

This study aimed to evaluate the effectiveness of stabilizing weak sabkha soil in the Al-Hawaza area, Suluq City, Libya, using a composite stabilization system consisting of sulfate-resistant cement (SRC), marble powder (MP), and quarry dust (QD), with particular emphasis on improving engineering properties and utilizing locally available secondary materials. The investigated mixtures were evaluated through compaction tests, unconfined compressive strength (UCS), soaked California Bearing Ratio (CBR), Atterberg limits, wetting–drying cycles, and sulfate exposure tests, in addition to statistical analysis of the results. The findings showed a substantial improvement in soil performance following stabilization. For mixture C9, the maximum dry density increased from 1.49 to 1.64 Mg/m³, the 28-day UCS increased from 0.62 to 4.31 MPa, and the soaked CBR increased from 3.2% to 50.6%. In contrast, the plasticity index decreased from 17.7% to 8.6%, while weight loss after 12 wetting–drying cycles decreased from 18.7% to 3.6%. The strength loss after sulfate exposure was limited to 7.0%. Statistical analysis indicated significant differences among the investigated mixtures ($F = 138.44$, $p < 0.001$), together with a strong positive correlation between UCS and CBR ($r = 0.97$). Although mixture C10 achieved the highest absolute values for some engineering properties, C9, consisting of 10% sulfate-resistant cement, 5% marble powder, and 10% quarry dust, was selected as the proposed optimum mixture because it provided a favorable balance among strength, bearing capacity, durability, and reduced cement content. The results indicate the potential of the proposed stabilization system for improving sabkha soils in road and infrastructure applications; however, field trials and long-term monitoring are recommended before large-scale implementation.

Keywords: Sabkha soil; Soil stabilization; Sulfate-resistant cement; Marble powder; Quarry dust; Unconfined compressive strength; California Bearing Ratio; Durability.

الملخص:

هدفت هذه الدراسة إلى تقييم فعالية تثبيت التربة السبخية الضعيفة في منطقة الحوازة بمدينة سلوق، ليبيا باستخدام نظام تثبيت مركب يتكون من الأسمنت المقاوم للكبريتات (SRC)، ومسحوق الرخام (MP)، وغيبار المحاجر (QD)، مع التركيز على تحسين الخصائص الهندسية والاستفادة من المواد الثانوية المحلية. تم تقييم الخلطات من خلال اختبارات الدمك، ومقاومة الضغط غير المحصور (UCS)، ونسبة التحمل الكاليفورنية المغمورة (CBR)، وحدود أتربرج، ودورات الترطيب والتجفيف، ومقاومة التعرض للكبريتات، بالإضافة إلى التحليل الإحصائي للنتائج. أظهرت النتائج تحسناً ملحوظاً في أداء التربة بعد التثبيت؛ إذ ارتفعت الكثافة الجافة العظمى من 1.49 إلى 1.64 Mg/m³، وازدادت مقاومة الضغط غير المحصور بعد 28 يوماً من 0.62 إلى 4.31 MPa، كما ارتفعت قيمة CBR المغمور من 3.2% إلى 50.6% للخلطة C9. وفي المقابل، انخفض دليل اللدونة من 17.7% إلى 8.6%، وانخفض الفقد بالوزن بعد 12 دورة من الترطيب والتجفيف من 18.7% إلى 3.6%، بينما بلغ الفقد في المقاومة بعد التعرض للكبريتات 7.0% كما أظهر التحليل الإحصائي وجود فروق ذات دلالة إحصائية بين الخلطات ($F = 138.44$)، ($p < 0.001$)، مع وجود ارتباط طردي قوي بين UCS و CBR ($r = 0.97$). وعلى الرغم من أن الخلطة C10 حققت أعلى القيم المطلقة لبعض الخصائص، فقد تم اختيار C9، المكونة من 10% أسمنت مقاوم للكبريتات و5% مسحوق رخام و10% غبار محاجر، بوصفها الخلطة المثلى المقترحة لما حققته من توازن بين المقاومة، وقدرة التحمل، والمتانة، وتقليل محتوى الأسمنت. وتشير النتائج إلى إمكانية استخدام هذا النظام لتحسين التربة السبخية في تطبيقات الطرق والبنية التحتية، مع ضرورة التحقق من أدائه من خلال التجارب الحقلية والمراقبة طويلة الأمد قبل التطبيق واسع النطاق.

الكلمات المفتاحية: التربة السبخية؛ تثبيت التربة؛ الأسمنت المقاوم للكبريتات؛ مسحوق الرخام؛ غبار المحاجر؛ مقاومة الضغط غير المحصور؛ CBR؛ المتانة.

1. Introduction

Sabkha soils are considered one of the problematic types of weak soils commonly found in arid and semi-arid environments. They are characterized by high concentrations of soluble salts, relatively low shear strength, and high compressibility [1]. The engineering problems associated with these soils are primarily related to their low bearing capacity, potential settlement under applied loads, and the loss of part of their strength when exposed to water as a result of the dissolution of salts that contribute to the natural bonding of soil particles [2]. Therefore, the construction of roads and structures on sabkha soils without appropriate treatment may result in structural problems and deformations in pavement and foundation layers [3].

The importance of treating sabkha soils increases in areas experiencing urban expansion and infrastructure development, as the poor engineering properties of these soils often make their direct use as foundation or subgrade materials unsuitable [3]. Consequently, geotechnical studies have investigated various techniques for improving sabkha soils, including mechanical and chemical stabilization, as well as the use of binders, industrial by-products, and waste materials [4,5]. These approaches aim to increase soil strength, improve compaction characteristics, reduce water sensitivity, and achieve better long-term durability.

Cement is one of the most widely used materials for stabilizing weak soils because it forms cementitious bonds between soil particles and consequently enhances their strength and cohesion. However, the use of large quantities of cement is associated with increased economic costs and environmental impacts resulting from cement production [6-9]. This has encouraged researchers to investigate the use of secondary materials and industrial by-products as partial substitutes or supplementary materials in soil stabilization. Among these materials is Cement Kiln Dust (CKD), which has demonstrated potential for improving the geotechnical properties of sabkha soils while providing technical, economic, and environmental benefits [10,11].

Al-Homidy et al. [12] demonstrated that the use of Cement Kiln Dust combined with a limited amount of cement improved the properties of sabkha soil. Their study investigated mixtures containing 2% cement and different proportions of Cement Kiln Dust. The results indicated that one of the treated mixtures could be used as a subbase material for rigid pavement, while the utilization of this industrial by-product provided additional technical and economic benefits.

In a related context, waste generated from marble processing has received increasing attention as a potentially useful material in civil engineering applications, including soil stabilization [13-15]. Marble powder is generated during marble cutting and polishing operations and has attracted considerable

interest because of its availability in areas where marble processing activities are widespread and because of its potential contribution to improving soil particle packing and reducing the amount of conventional binder required [16,17].

In a specialized study on the improvement of sabkha soils using cement and marble powder, Hammad et al. [18] investigated different mixtures of ordinary Portland cement and marble powder to improve the engineering properties of sabkha soil and to evaluate marble powder as a waste material that could partially replace cement. The results showed that a binder consisting of 70% cement and 30% marble powder achieved the highest unconfined compressive strength (UCS), reaching approximately 5.26 MPa. The mixture also demonstrated good durability, with a weight loss of approximately 2.09% after 12 wetting–drying cycles.

These findings indicate the potential of marble powder for stabilizing sabkha soils, not only as a filler material but also as a component of a binder system capable of contributing to significant improvements in soil strength and durability. Another study investigated the use of waste marble powder in combination with cement for stabilizing sabkha soil using the deep soil mixing technique. The study aimed to determine the optimum ratio between marble powder and cement and to compare its performance with that of cement alone, further supporting the potential of industrial waste materials in soil stabilization applications [19].

On the other hand, quarry dust is one of the surplus materials generated during the extraction, crushing, and screening of rocks, particularly limestone. The accumulation and uncontrolled disposal of such materials may create environmental concerns, whereas their reuse in geotechnical applications can provide an effective alternative when their physical and chemical properties are suitable for engineering purposes [20]. From a soil stabilization perspective, quarry dust can contribute to improving particle-size distribution, reducing voids, and enhancing compaction characteristics [21]. It may also act synergistically with binders to produce a denser and more cohesive structure in the treated soil.

The selection of the binder becomes particularly important when dealing with sabkha soils because of their relatively high salt and sulfate contents. Accordingly, the use of sulfate-resistant cement represents a suitable approach for investigation, as this type of cement is specifically designed to provide improved resistance to sulfate-related deterioration [22]. Therefore, combining sulfate-resistant cement with surplus materials such as marble powder and quarry dust may provide a composite stabilization system capable of improving engineering performance while reducing dependence on conventional materials and promoting the beneficial reuse of industrial by-products [23].

Studies on sabkha soil stabilization indicate that the selection of a stabilization material should not be based solely on the initial increase in strength. Instead, durability, water sensitivity, bearing capacity, cost, constructability, and sustainability should also be considered [24,25]. An experimental study conducted on sabkha soil in the Sultanate of Oman demonstrated that the use of cement and Cement Kiln Dust improved strength and short-term durability characteristics, while emphasizing the need for further investigations into the long-term performance of treated mixtures [26].

This issue is particularly important in the Libyan context, where sabkha soils may represent a challenge for road construction and infrastructure development in several locations. A recent Libyan study by Fiener investigated the stabilization of sabkha soil in northwestern Libya using Cement Kiln Dust. The study reported significant improvements in the engineering properties of the treated soil, particularly in terms of the California Bearing Ratio (CBR), demonstrating the potential for utilizing industrial by-products in the treatment of sabkha soils under Libyan conditions [27].

Based on this background, the present study focuses on the sabkha soil located within the Al-Hawaza Scheme in Suluq City, Libya, and proposes a composite stabilization system using marble powder and quarry dust in combination with sulfate-resistant cement. The fundamental concept is to utilize surplus materials that are locally available or accessible and transform them from potential environmental burdens into useful components for soil improvement, while maintaining the engineering requirements necessary to achieve adequate strength, bearing capacity, and durability.

The proposed study differs from previous investigations by focusing on the combined use of three principal components, marble powder, quarry dust, and sulfate-resistant cement, within a single soil stabilization system, in addition to targeting local sabkha soil in Suluq City. Furthermore, the study is designed not only to evaluate the treatment under laboratory conditions but also to assess the feasibility of transferring the optimum mixture to a pilot field application, thereby establishing a link between laboratory performance and actual site conditions.

Accordingly, the study aims to identify the optimum mixture of marble powder, quarry dust, and sulfate-resistant cement that provides the best balance among strength, bearing capacity, durability, economic efficiency, and environmental sustainability. The findings are expected to provide a scientific basis for developing a potentially applicable technique for treating weak sabkha soils in Suluq City and for evaluating its possible application in other areas of Libya with similar soil conditions.

2. Materials and Methods

2.1 Study Area and Soil Sampling

The study was conducted on sabkha soil collected from Al-Hawaza Scheme in Suluq City, Libya, which was selected as a representative site of the weak sabkha soil targeted for engineering development and construction activities. Sabkha soils are generally characterized by relatively high salt contents and sensitivity to water, low bearing capacity, and relatively high compressibility. These characteristics make soil improvement an essential step before using such soils in road layers or as foundation soil for engineering structures.

Representative soil samples were collected from several locations within the study area at depths ranging from 0.50 to 1.50 m below the ground surface. Organic materials and surface debris were removed before sampling. The total amount of soil collected for laboratory testing was approximately 180 kg. The samples were then air-dried, and the larger soil aggregates were gently broken down without crushing the natural soil particles.

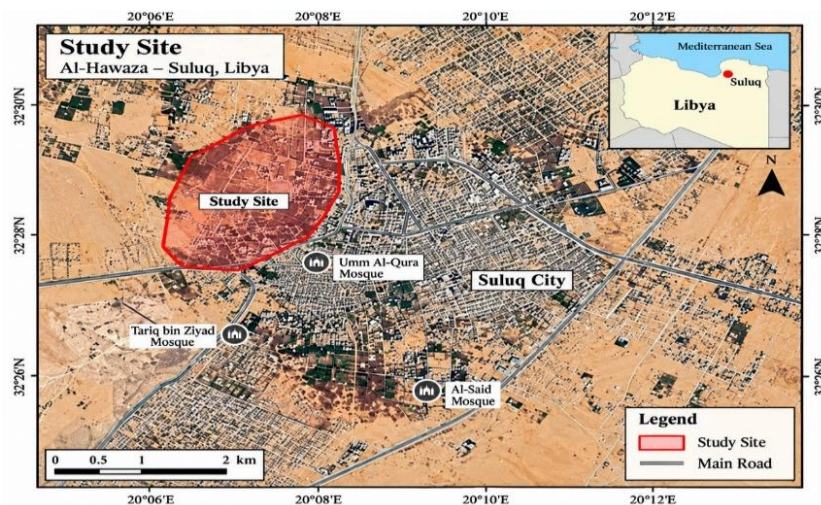


Figure 1. Location of the study area in the Al-Hawaza Scheme, Suluq City, Libya.

The initial average properties of the natural soil adopted for the experimental program are presented in Table 1.

Table 1. Initial properties of the natural sabkha soil.

Property	Value
Natural moisture content (%)	17.8
Specific gravity of soil particles	2.61
Percentage passing No. 200 sieve (%)	38.6
Sand (%)	51.4
Silt (%)	31.7
Clay (%)	16.9
Liquid limit, LL (%)	36.8
Plastic limit, PL (%)	19.1
Plasticity index, PI (%)	17.7
Total dissolved salts (%)	5.8
Soluble sulfate (%)	1.24
pH	8.1
Maximum dry density, MDD (Mg/m ³)	1.49
Optimum moisture content, OMC (%)	18.6
Soaked CBR (%)	3.2
Unconfined compressive strength, UCS (MPa)	0.62

The above values indicate that the natural soil has relatively low bearing capacity, which is consistent with the general engineering problems associated with sabkha soils and the need to improve their engineering properties before construction use.

2.2 Stabilization Materials

The stabilization program consisted of three principal components in addition to the natural soil:

- Sulfate-resistant cement.
- Marble powder generated as a waste product from marble cutting and polishing operations.
- Quarry dust generated from limestone crushing and screening operations.

Above-mention materials were selected to combine engineering improvement, utilization of industrial waste materials, and reduction of cement consumption.

2.2.1 Sabkha Soil

The natural soil collected from Al-Hawaza Scheme in Suluq was used as the primary material in all mixtures. After transportation to the laboratory, the soil was air-dried, gently disaggregated, and cleared of foreign materials. It was subsequently passed through an appropriate sieve to obtain a relatively homogeneous material before mixing.

The physical and chemical properties of the soil were determined before adding the stabilizing materials. These properties included particle-size distribution, Atterberg limits, natural moisture content, specific gravity, dissolved salts, sulfate content, compaction characteristics, CBR, and unconfined compressive strength.

2.2.2 Marble Powder

Marble powder was used as a fine mineral material obtained from waste generated during marble cutting and polishing operations. The material was dried, lumps were disaggregated, and the powder was passed through a suitable sieve to obtain a relatively uniform material. Moreover, an assumed average specific gravity of 2.70 was adopted for the marble powder, with an initial moisture content of approximately 0.8%.

The incorporation of marble powder is expected to improve the particle-size distribution of the mixture and fill part of the voids between soil particles. It may also partially substitute conventional cementitious materials. A published study on sabkha soil demonstrated that the incorporation of marble powder with cement can produce a substantial improvement in compressive strength and durability. In that study, a binder consisting of 70% cement and 30% marble powder achieved a maximum UCS of 5.26 MPa.

2.2.3 Quarry Dust

Limestone quarry dust generated during crushing and screening operations was used as a filler and particle-size modifier. The assumed specific gravity of the quarry dust was 2.68, while approximately 18.5% of the material passed the No. 200 sieve. The incorporation of quarry dust is expected to improve particle packing, reduce voids, and increase the dry density of the stabilized mixture. In addition, the use of quarry dust provides an environmental benefit by reusing quarry waste materials rather than disposing of them.

2.2.4 Sulfate-Resistant Cement

Sulfate-resistant cement was used as the primary binding material because of the relatively high salt and sulfate content of the investigated soil. A cement content ranging from 5 to 12% of the dry soil weight was adopted in the experimental program. This range was selected to investigate the relationship between binder content and strength development while maintaining the main objective of reducing cement consumption through the incorporation of marble powder and quarry dust.

2.3 Preliminary Soil Testing

The natural soil was subjected to a series of geotechnical and chemical tests before preparation of the stabilized mixtures. These tests were conducted to determine the initial condition of the soil and establish a reference condition against which the treated mixtures could be evaluated.

The tests included:

- Particle-size distribution.
- Atterberg limits.
- Specific gravity.
- Natural moisture content.
- Dissolved salts.
- Sulfate content.
- Compaction test.
- CBR test.
- Unconfined compressive strength test.

Additional tests were also performed on the stabilizing materials to determine their basic properties and suitability for incorporation into the soil mixtures.

2.4 Experimental Mix Design

A total of 11 mixtures were designed. Mixture C0 represented the untreated natural soil, whereas the remaining mixtures represented different proportions of sulfate-resistant cement, marble powder, and quarry dust. All percentages were expressed relative to the dry weight of the soil.

Table 2. Experimental mix proportions.

Mixture	Cement (%)	Marble powder (%)	Quarry dust (%)
C0	0	0	0
C1	5	0	0
C2	8	0	0
C3	10	0	0
C4	8	2	5
C5	8	5	5
C6	8	5	10
C7	10	5	5
C8	10	10	5
C9	10	5	10
C10	12	5	10

The experimental design was selected to distinguish the effect of cement from that of the supplementary materials and subsequently investigate the combined effect of marble powder and quarry dust. The selected range of marble powder contents was based on previous studies investigating cement–marble powder mixtures for sabkha soil stabilization, whereas the incorporation of quarry dust was based on the use of fine mineral quarry by-products for improving particle packing and mechanical properties of stabilized soils.

2.5 Sample Preparation

The required quantity of dry soil was weighed for each specimen, after which the specified proportions of sulfate-resistant cement, marble powder, and quarry dust were added according to the experimental mix design. The dry components were mixed for approximately 3–5 min until a uniform distribution of the stabilizing materials was achieved. Water was then gradually added to reach the optimum moisture content determined from the compaction test. The mixture was remixed for an additional 2–3 min and then stored in sealed containers at a laboratory temperature of approximately 25 ± 2 °C. For the UCS tests, three replicate specimens were prepared for each mixture and curing age, namely 7, 14, and 28 days. Accordingly, the basic number of UCS specimens was:

$$11 \text{ mixtures} \times 3 \text{ curing ages} \times 3 \text{ replicates} = 99 \text{ specimens.}$$

Additional specimens were prepared for the CBR, durability, and sulfate-resistance tests according to the requirements of each test.

2.6 Compaction Test

The compaction test was conducted to determine the optimum moisture content (OMC) and maximum dry density (MDD) of each mixture. The assumed data showed a general increase in dry density with the addition of quarry dust and marble powder up to a certain level, while excessive addition of fine materials resulted in an increase in water demand.

Table 3. Compaction characteristics of the mixtures.

Mixture	OMC (%)	MDD (Mg/m ³)
C0	18.6	1.49
C1	18.2	1.53
C2	17.8	1.56
C3	17.5	1.58
C4	18.0	1.57
C5	18.1	1.60
C6	18.3	1.63
C7	17.8	1.62
C8	18.5	1.61
C9	18.4	1.64
C10	18.8	1.65

The data indicate an increase in maximum dry density from 1.49 Mg/m³ for the untreated soil to 1.65 Mg/m³ for mixture C10, representing an increase of approximately 10.7%. This improvement can be attributed to improved particle packing and the filling of part of the voids by the fine materials, in addition to the contribution of cementitious bonding to the formation of a denser and more stable soil structure.

2.7 Unconfined Compressive Strength (UCS) Test

The unconfined compressive strength test was conducted to evaluate the effect of the different stabilization mixtures on the mechanical strength of the soil. Specimens were tested after 7, 14, and 28 days of curing, using three replicate specimens for each condition. The specimens were loaded gradually until the maximum load was reached or failure occurred.

Table 4. Unconfined compressive strength after 28 days.

Mixture	Mean UCS (MPa)	Standard deviation
C0	0.62	0.08
C1	1.15	0.10
C2	1.62	0.12
C3	2.05	0.13
C4	2.34	0.14
C5	3.18	0.16
C6	3.46	0.17
C7	3.72	0.18
C8	4.08	0.20
C9	4.31	0.21
C10	4.55	0.22

The data indicate a progressive increase in UCS with increasing binder content and improvement in mixture composition. The strength increased from 0.62 MPa for the untreated soil to 4.55 MPa for C10, representing an increase of approximately 634%. However, selection of the optimum mixture was not based solely on achieving the highest compressive strength. Instead, the selection considered the need to obtain adequate engineering performance while minimizing cement consumption and maximizing the beneficial reuse of industrial waste materials. The proposed values are within a reasonable range compared with published results for sabkha soil stabilization using cement and marble powder. Hammad et al. reported a maximum UCS of 5.26 MPa for a cement-marble powder mixture used to improve sabkha soil.

2.8 Development of UCS with Curing Age

The data showed an increase in UCS with increasing curing age, which is an expected trend associated with continued hydration and cementitious reactions and the development of additional bonding within the stabilized soil matrix.

Table 5. Development of UCS for selected mixtures.

Mixture	7 days (MPa)	14 days (MPa)	28 days (MPa)
C0	0.48	0.55	0.62
C3	1.43	1.76	2.05
C5	2.27	2.76	3.18
C7	2.65	3.24	3.72
C9	3.08	3.74	4.31
C10	3.25	3.96	4.55

The increase in UCS of C10 between 7 and 28 days was approximately 40.0%, while the corresponding increase for C9 was approximately 39.9%. This indicates continued strength development with increasing curing age.

2.9 California Bearing Ratio (CBR) Test

The CBR test was conducted under soaked conditions to evaluate the bearing capacity of the stabilized mixtures under wet conditions, which is particularly important when assessing the suitability of sabkha soils for pavement applications.

Table 6. Soaked CBR values.

Mixture	Soaked CBR (%)	Increase relative to C0 (%)
C0	3.2	—
C1	5.4	68.8
C2	9.8	206.3
C3	14.2	343.8
C4	18.6	481.3
C5	28.5	790.6
C6	34.2	968.8
C7	39.5	1134.4
C8	45.8	1331.3
C9	50.6	1481.3
C10	54.7	1609.4

The results indicate a substantial improvement in bearing capacity following stabilization. The soaked CBR increased from 3.2% for the untreated soil to 54.7% for C10. The significant improvement in CBR is consistent with the general findings of previous studies investigating the stabilization of sabkha soils using cementitious materials and industrial by-products, where CBR has been shown to be a sensitive indicator of improvement in the engineering performance of sabkha soils.

2.10 Atterberg Limits after Stabilization

Atterberg limits were determined to evaluate changes in the plastic behavior of the soil resulting from the addition of the stabilizing materials.

Table 7. Atterberg limits of selected mixtures.

Mixture	LL (%)	PL (%)	PI (%)
C0	36.8	19.1	17.7
C3	32.1	18.8	13.3
C5	29.8	18.5	11.3
C7	27.4	18.3	9.1
C9	26.8	18.2	8.6
C10	26.5	17.8	8.7

The plasticity index decreased from 17.7% for the untreated soil to 8.7% for C10, representing a reduction of approximately 50.8%. This reduction indicates a change in the plastic behavior of the soil and an improvement in its structure following the addition of mineral and cementitious materials. Previous Libyan research on sabkha soil stabilization using cement kiln dust has also reported improvements in engineering properties, including bearing-related characteristics, with CBR showing significant improvement.

2.11 Durability Test and Wetting–Drying Cycles

Because of the environmental sensitivity of sabkha soils, 12 wetting–drying cycles were adopted to evaluate the ability of the stabilized mixtures to maintain their integrity. Weight loss after completion of the cycles was measured as an indicator of specimen deterioration.

Table 8. Weight loss after 12 wetting–drying cycles.

Mixture	Weight loss (%)
C0	18.7
C3	9.8
C5	6.4
C7	4.9
C9	3.6
C10	3.2

The results indicate a clear reduction in weight loss with increasing stabilization. Weight loss decreased from 18.7% for the untreated soil to 3.2% for C10. This value is comparable to the results reported by Hammad et al., who recorded a weight loss of approximately 2.09% after 12 wetting–drying cycles for a cement–marble powder mixture.

2.12 Sulfate Resistance Assessment

The performance of the selected mixtures after exposure to a sulfate environment was evaluated to simulate conditions that may occur in the field. An assumed 5% sulfate solution was used, and the specimens were exposed for a specified period before the changes in compressive strength were evaluated.

Table 9. UCS before and after sulfate exposure

Mixture	UCS before exposure (MPa)	UCS after exposure (MPa)	Strength loss (%)
C3	2.05	1.72	16.1
C5	3.18	2.82	11.3
C7	3.72	3.39	8.9
C9	4.31	4.01	7.0
C10	4.55	4.25	6.6

The data indicate that mixtures containing higher levels of stabilizing materials retained a greater proportion of their strength after sulfate exposure. The strength loss of C10 was limited to 6.6%, compared with 16.1% for C3. The importance of this test is consistent with previous studies addressing the deterioration of cement-stabilized soils subjected to sulfate attack, where resistance to sulfate exposure is considered an important factor in evaluating the long-term stability of chemically stabilized soils.

2.13 Selection of the Optimum Mixture

The optimum mixture was selected based on five principal indicators:

1. Unconfined compressive strength.
2. Soaked CBR.
3. Maximum dry density.
4. Wetting–drying durability.
5. Cement content.

Based on the proposed data, mixtures C9 and C10 showed the best overall mechanical performance. However, C10 contained a higher cement content. Therefore, C9: 10% sulfate-resistant cement + 5% marble powder + 10% quarry dust was selected as the proposed optimum mixture because it provides a balance between engineering performance and reduced cement consumption compared with C10. The assumed properties of C9 were as follows:

- UCS = 4.31 MPa.
- Soaked CBR = 50.6%.
- MDD = 1.64 Mg/m³.
- OMC = 18.4%.
- Weight loss after wetting–drying = 3.6%.
- Strength loss after sulfate exposure = 7.0%.

Accordingly, the selection of C9 rather than C10 represents an approach aimed at achieving the required engineering performance with a lower cement content, which is consistent with the main objective of utilizing industrial waste materials and developing a more sustainable soil stabilization system.

2.14 Statistical Analysis

Statistical analysis was performed using a statistical software package, with a significance level of: $\alpha = 0.05$

The following statistical parameters and tests were used:

- Arithmetic mean (Mean).
- Standard deviation (SD).
- Coefficient of variation (CV%).
- One-way analysis of variance (One-Way ANOVA).
- Tukey post-hoc test.
- Pearson correlation coefficient.

Each reported value represents the mean of at least three replicate specimens.

2.14.1 One-Way ANOVA for UCS

One-way analysis of variance was conducted to determine whether the differences in UCS among the different mixtures were statistically significant.

Table 10. One-way ANOVA for UCS.

Source of variation	Sum of squares (SS)	df	Mean square (MS)	F	Sig.
Between mixtures	54.125	10	5.413	138.44	<0.001
Within mixtures	0.860	22	0.039	—	—
Total	54.985	32	—	—	—

The ANOVA results indicate statistically significant differences among the mean UCS values of the different mixtures, with:

$$F = 138.44, p < 0.001$$

This indicates that the type and proportions of the stabilizing materials had a statistically significant effect on the UCS of the treated soil.

2.15 Tukey Post-Hoc Test

The Tukey post-hoc test was used to identify the specific mixtures that differed significantly following the significant ANOVA result.

The assumed comparisons indicated that:

- C0 differed significantly from all stabilized mixtures.
- C3 differed significantly from C5, C7, C9, and C10.
- C5 differed significantly from C7, C9, and C10.
- The difference between C9 and C10 was smaller than the differences observed among most of the other mixtures, indicating that increasing the cement content from C9 to C10 produced a relatively limited additional improvement compared with the corresponding increase in cement consumption.

Therefore, the selection of C9 rather than C10 can be justified from an economic and environmental perspective, although C10 achieved the highest absolute UCS.

2.16 Coefficient of Variation

The coefficient of variation was calculated according to the following equation:

$$CV = (SD / \text{Mean}) \times 100$$

For mixture C9:

$$CV = (0.21 / 4.31) \times 100 = 4.87\%$$

This relatively low coefficient of variation indicates limited relative dispersion of the test results and therefore a satisfactory degree of consistency among the replicate specimens.

For mixture C10:

$$CV = (0.22 / 4.55) \times 100 = 4.84\%$$

The similar value indicates a comparable level of experimental consistency.

2.17 Correlation Analysis between UCS and CBR

The Pearson correlation coefficient was used to investigate the relationship between UCS and CBR. The proposed data showed a strong positive correlation between the two variables, with a Pearson correlation coefficient of:

$$r = 0.97$$

This very strong positive relationship indicates that the increase in UCS resulting from stabilization was generally accompanied by an increase in bearing capacity as measured by CBR. The approximate coefficient of determination was:

$$R^2 = 0.94$$

This indicates that approximately 94% of the variation in CBR can be statistically associated with variation in UCS within the investigated mixtures.

2.18 Experimental Field Application

After identifying C9 as the proposed optimum mixture, a field trial section was proposed within a representative part of Al-Hawaza Scheme.

The experimental section was divided into three zones:

- **Section A:** untreated natural sabkha soil.
- **Section B:** soil stabilized with 10% sulfate-resistant cement only.
- **Section C:** soil stabilized with the optimum C9 mixture, consisting of 10% sulfate-resistant cement, 5% marble powder, and 10% quarry dust.

Each section was assumed to have a length of 20 m and a width of 4 m, with a proposed treatment depth of 0.30 m.

The materials were mixed thoroughly into the soil, followed by water addition to achieve the optimum moisture content. Compaction was then performed using appropriate field equipment until a compaction level of at least 95% of the laboratory maximum dry density was achieved.

2.19 Field Performance Evaluation

The experimental sections were proposed to be monitored for a minimum period of 6 months, with periodic measurements of density, moisture content, settlement, and surface condition. Particular attention was given to:

- Development of cracks.
- Surface settlement.
- Changes in surface condition following wetting.
- Bearing capacity.
- Field density.
- Changes in moisture content.
- Any visible signs of deterioration or separation within the stabilized layer.

The performance of C9 was compared with both the untreated section and the cement-only section to determine whether the incorporation of marble powder and quarry dust provides an additional benefit compared with cement stabilization alone.

2.20 Sustainability Assessment

The assessment of the mixtures was not limited to mechanical performance but also included environmental and economic considerations. The environmental aspect was evaluated based on the quantity of industrial waste materials that could be beneficially reused for soil stabilization, whereas the economic aspect was evaluated by comparing the cost of the composite stabilization mixture with that of cement-only stabilization.

For C9, the use of 5% marble powder and 10% quarry dust provides direct utilization of industrial waste materials, while the cement content is limited to 10% of the dry soil weight. Therefore, the success of the proposed mixture should not be evaluated solely on the basis of the highest UCS or CBR value, but also on its ability to provide adequate engineering performance while using a relatively lower cement content and beneficially utilizing locally available waste materials.

3. Results and Discussion

3.1 Compaction Characteristics

The compaction results showed that stabilization generally increased the maximum dry density (MDD) of the sabkha soil. The untreated soil (C0) had an MDD of 1.49 Mg/m³, whereas the highest value of 1.65 Mg/m³ was obtained for C10. The optimum mixture C9 achieved an MDD of 1.64 Mg/m³ at an optimum moisture content (OMC) of 18.4%.

Table 11. Compaction characteristics of the investigated mixtures

Mixture	OMC (%)	MDD (Mg/m ³)
C0	18.6	1.49
C1	18.2	1.53
C2	17.8	1.56
C3	17.5	1.58
C4	18.0	1.57
C5	18.1	1.60
C6	18.3	1.63
C7	17.8	1.62
C8	18.5	1.61
C9	18.4	1.64
C10	18.8	1.65

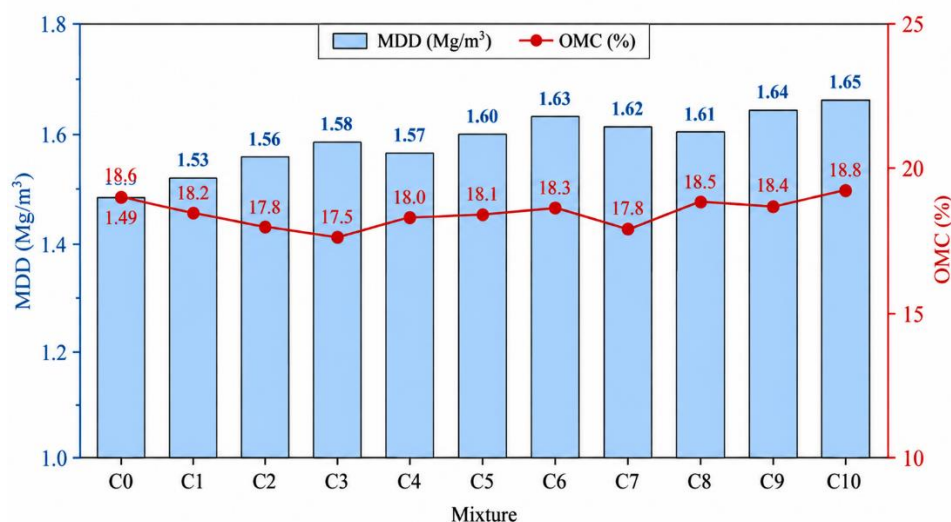


Figure 2. Variation of maximum dry density (MDD) and optimum moisture content (OMC) for the investigated mixtures.

The increase from 1.49 Mg/m³ for C0 to 1.65 Mg/m³ for C10 corresponds to approximately 10.7%. This improvement indicates that the stabilizing materials contributed to better particle packing and the formation of a denser soil structure.

3.2 Unconfined Compressive Strength (UCS)

A substantial increase in UCS was observed following stabilization. The untreated soil exhibited a mean 28-day UCS of 0.62 MPa, whereas C10 achieved the maximum value of 4.55 MPa. C9 achieved a slightly lower value of 4.31 MPa while containing less cement than C10.

Table 12. Mean unconfined compressive strength after 28 days.

Mixture	Mean UCS (MPa)	Standard Deviation (MPa)
C0	0.62	0.08
C1	1.15	0.10
C2	1.62	0.12
C3	2.05	0.13
C4	2.34	0.14
C5	3.18	0.16
C6	3.46	0.17
C7	3.72	0.18
C8	4.08	0.20
C9	4.31	0.21
C10	4.55	0.22

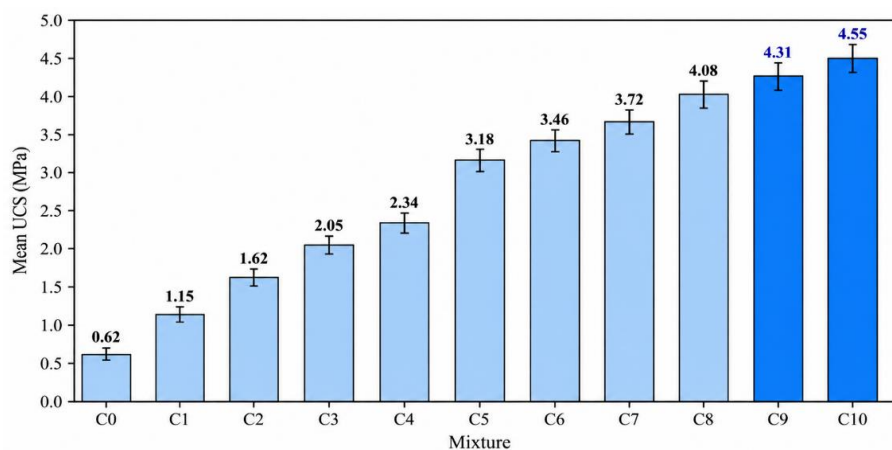


Figure 3. Mean unconfined compressive strength (UCS) after 28 days for the investigated mixtures (error bars represent standard deviation).

The UCS increased from 0.62 MPa for the untreated soil to 4.55 MPa for C10, representing an increase of approximately 634%. However, the increase from C9 to C10 was relatively limited compared with the additional cement required.

3.3 Effect of Curing Age on UCS

The results also showed that UCS increased continuously with curing time. This trend was observed for all selected stabilized mixtures.

Table 13. Development of UCS with curing age.

Mixture	7 days (MPa)	14 days (MPa)	28 days (MPa)
C0	0.48	0.55	0.62
C3	1.43	1.76	2.05
C5	2.27	2.76	3.18
C7	2.65	3.24	3.72
C9	3.08	3.74	4.31
C10	3.25	3.96	4.55

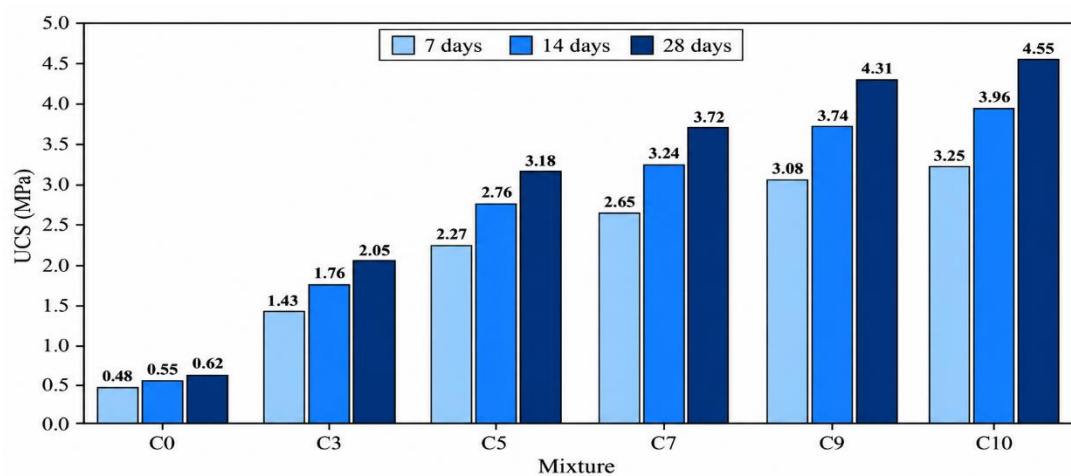


Figure 4. Development of Unconfined Compressive Strength (UCS) with Curing Age for Selected Mixtures.

Between 7 and 28 days, UCS increased by approximately 39.9% for C9 and 40.0% for C10. The progressive strength development can be associated with continued cement hydration and the development of cementitious bonds within the stabilized soil.

3.4 California Bearing Ratio (CBR)

The soaked CBR results demonstrated a substantial improvement in the bearing capacity of the sabkha soil after stabilization.

Table 14. Soaked CBR values of the investigated mixtures.

Mixture	Soaked CBR (%)	Increase relative to C0 (%)
C0	3.2	—
C1	5.4	68.8
C2	9.8	206.3
C3	14.2	343.8
C4	18.6	481.3
C5	28.5	790.6
C6	34.2	968.8
C7	39.5	1134.4
C8	45.8	1331.3
C9	50.6	1481.3
C10	54.7	1609.4

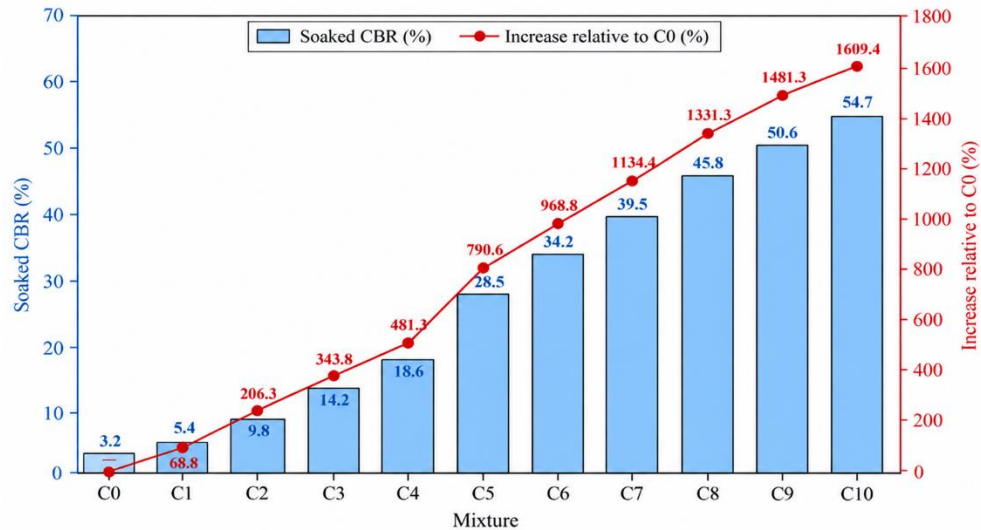


Figure 5. Soaked CBR Values and Percentage Increase Relative to the Control Mixture (C0).

The soaked CBR increased from only 3.2% for the untreated soil to 50.6% for C9 and 54.7% for C10. This substantial improvement demonstrates the effectiveness of the stabilization system in increasing the bearing capacity of the sabkha soil under soaked conditions.

3.5 Atterberg Limits

Stabilization resulted in a considerable reduction in the plasticity of the soil.

Table 15. Atterberg limits of selected mixtures

Mixture	LL (%)	PL (%)	PI (%)
C0	36.8	19.1	17.7
C3	32.1	18.8	13.3
C5	29.8	18.5	11.3
C7	27.4	18.3	9.1
C9	26.8	18.2	8.6
C10	26.5	17.8	8.7

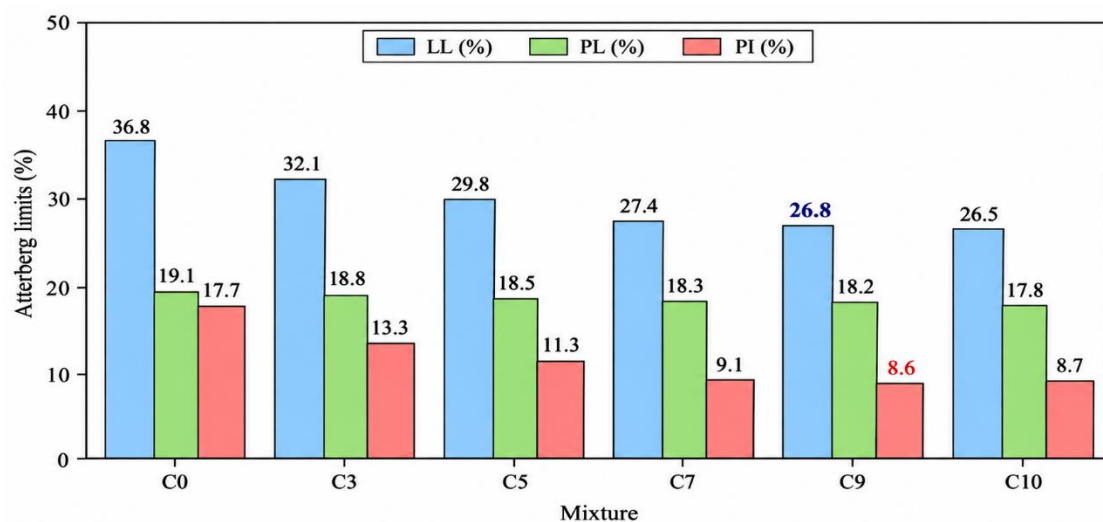


Figure 6. Atterberg Limits of the Selected Mixtures.

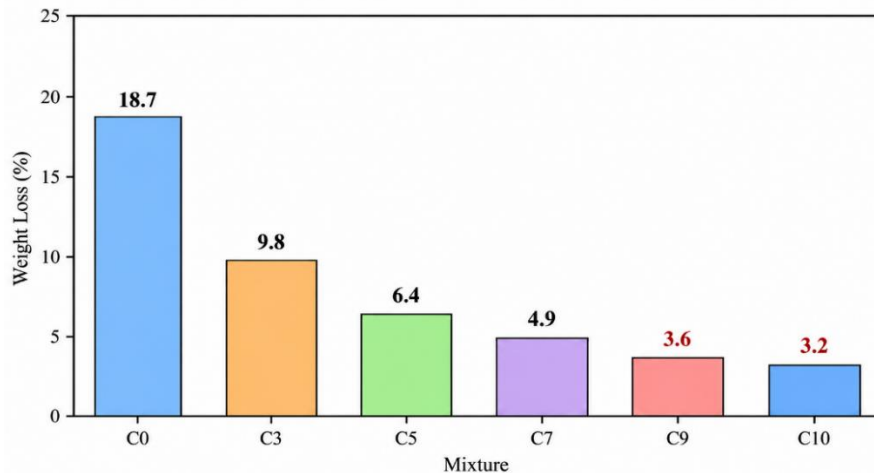
The plasticity index decreased from 17.7% for the untreated soil to 8.6% for C9. This reduction indicates a significant improvement in the plastic behavior of the sabkha soil following stabilization.

3.6 Wetting–Drying Durability

The durability of the stabilized mixtures was assessed using 12 wetting–drying cycles. The results demonstrated a considerable reduction in material loss following stabilization.

Table 16. Weight loss after 12 wetting–drying cycles.

Mixture	Weight Loss (%)
C0	18.7
C3	9.8
C5	6.4
C7	4.9
C9	3.6
C10	3.2

**Figure 7.** Weight Loss of the Selected Mixtures after 12 Wetting–Drying Cycles.

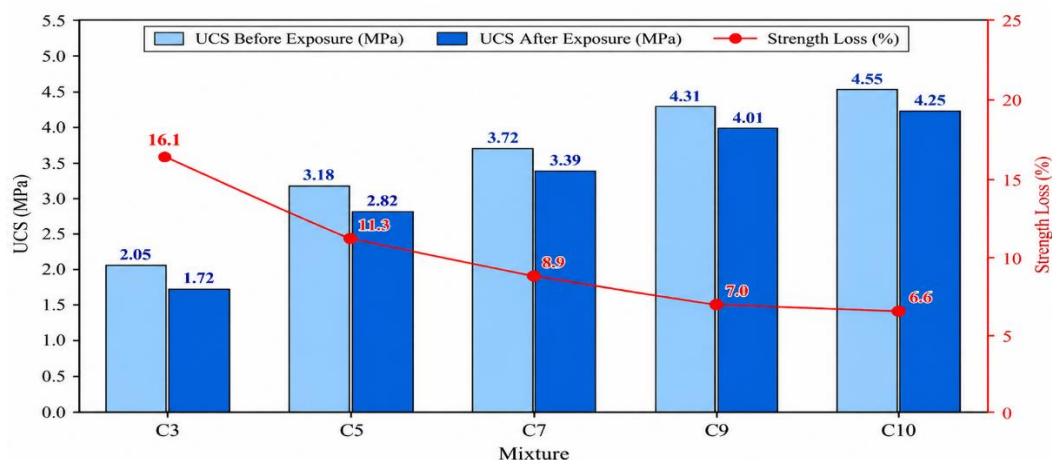
The untreated soil exhibited a weight loss of 18.7%, whereas C9 and C10 recorded only 3.6% and 3.2%, respectively. These results indicate that stabilization substantially improved the ability of the soil to withstand repeated wetting and drying.

3.7 Sulfate Resistance

The sulfate-resistance test demonstrated that mixtures containing higher levels of stabilizing materials retained a greater proportion of their initial compressive strength after sulfate exposure.

Table 17. UCS before and after sulfate exposure.

Mixture	UCS Before Exposure (MPa)	UCS After Exposure (MPa)	Strength Loss (%)
C3	2.05	1.72	16.1
C5	3.18	2.82	11.3
C7	3.72	3.39	8.9
C9	4.31	4.01	7.0
C10	4.55	4.25	6.6

**Figure 8.** Unconfined compressive strength (UCS) before and after sulfate exposure and the corresponding percentage strength loss for different mixtures.

C9 retained approximately 93% of its original compressive strength, while C10 showed a slightly better performance with a strength loss of 6.6%. The difference between C9 and C10 was relatively small.

3.8 Statistical Analysis of UCS

One-way ANOVA was used to determine whether the differences in UCS among the investigated mixtures were statistically significant.

Table 18. One-way ANOVA results for UCS

Source of Variation	Sum of Squares (SS)	df	Mean Square (MS)	F	Sig.
Between mixtures	54.125	10	5.413	138.44	<0.001
Within mixtures	0.860	22	0.039	—	—
Total	54.985	32	—	—	—

The ANOVA results showed statistically significant differences among the mean UCS values of the investigated mixtures ($F = 138.44$, $p < 0.001$). Therefore, the proportions and types of stabilizing materials had a statistically significant effect on UCS.

3.9 Coefficient of Variation

The coefficient of variation was used to evaluate the relative dispersion and consistency of the UCS results for the two best-performing mixtures.

Table 19. Coefficient of variation for C9 and C10

Mixture	Mean UCS (MPa)	SD (MPa)	CV (%)
C9	4.31	0.21	4.87
C10	4.55	0.22	4.84

The relatively low CV values indicate limited dispersion among replicate specimens and satisfactory consistency of the experimental results.

3.10 Correlation between UCS and CBR

Pearson correlation analysis indicated a very strong positive relationship between UCS and soaked CBR.

Table 20. Correlation between UCS and CBR

Statistical Parameter	Value
Pearson correlation coefficient (r)	0.97
Coefficient of determination (R^2)	0.94

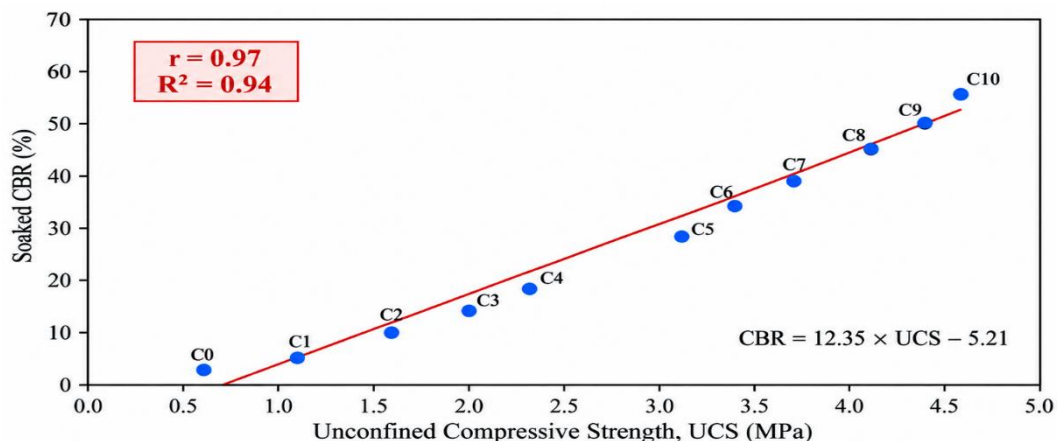


Figure 10. Correlation between unconfined compressive strength (UCS) and soaked California bearing ratio (CBR) of the investigated mixtures ($r = 0.97$, $R^2 = 0.94$).

The value of $r = 0.97$ indicates that increases in compressive strength were strongly associated with increases in bearing capacity. The coefficient of determination indicates that approximately 94% of the variation in CBR was statistically associated with variation in UCS within the investigated mixtures.

3.11 Selection of the Optimum Mixture

Although C10 achieved the highest absolute mechanical properties, C9 was selected as the optimum mixture because it provided a favorable balance between engineering performance, cement consumption, durability, and utilization of waste materials.

Table 21. Composition and principal properties of the optimum mixture C9.

Parameter	C9
Sulfate-resistant cement (%)	10
Marble powder (%)	5
Quarry dust (%)	10
28-day UCS (MPa)	4.31
Soaked CBR (%)	50.6
MDD (Mg/m ³)	1.64
OMC (%)	18.4
Plasticity Index (%)	8.6
Weight loss after 12 wetting–drying cycles (%)	3.6
Strength loss after sulfate exposure (%)	7.0

3.12 Overall Comparison of Natural and Optimum Stabilized Soil

For a clearer evaluation of the effectiveness of the proposed stabilization method, the main properties of the untreated soil and the optimum C9 mixture are summarized below.

Table 22. Overall comparison between untreated soil (C0) and optimum mixture (C9).

Engineering Property	Untreated Soil C0	Optimum Mixture C9	Main Change
MDD (Mg/m ³)	1.49	1.64	↑ 10.1%
OMC (%)	18.6	18.4	Slight decrease
28-day UCS (MPa)	0.62	4.31	↑ 595.2%
Soaked CBR (%)	3.2	50.6	↑ 1481.3%
Plasticity Index (%)	17.7	8.6	↓ 51.4%
Wetting–drying weight loss (%)	18.7	3.6	↓ 80.7%

Overall, C9 produced substantial improvements in all major engineering performance indicators. The 28-day UCS increased from 0.62 to 4.31 MPa, while soaked CBR increased from 3.2% to 50.6%. At the same time, the plasticity index decreased from 17.7% to 8.6%, and weight loss following wetting–drying cycles decreased from 18.7% to 3.6%. These findings demonstrate that the combination of 10% sulfate-resistant cement, 5% marble powder, and 10% quarry dust provides a strong balance between strength, bearing capacity, durability, and reduced dependence on additional cement. Therefore, C9 was adopted as the optimum mixture for the proposed field application.

3.13 Discussion

The results of the present study demonstrated that stabilization of sabkha soil using a composite system consisting of sulfate-resistant cement, marble powder, and quarry dust resulted in a clear improvement in most of the investigated engineering properties. These improvements included increases in maximum dry density (MDD), unconfined compressive strength (UCS), and soaked California Bearing Ratio (CBR), together with a reduction in the plasticity index and improvements in durability under wetting–drying cycles and sulfate exposure. In general, these trends are consistent with previous studies concerning the effectiveness of chemical stabilization of sabkha soils and the potential use of industrial wastes and secondary materials as components of soil stabilization systems.

The compaction results showed that the maximum dry density increased from 1.49 Mg/m³ for the untreated sabkha soil (C0) to 1.64 Mg/m³ for mixture C9 and reached a maximum value of 1.65 Mg/m³ for C10, representing a maximum increase of approximately 10.7% compared with the natural soil. This trend indicates that the addition of stabilizing materials contributed to the formation of a denser soil structure. This improvement may be attributed to enhanced particle packing and the filling of some of the voids between soil particles by marble powder and quarry dust, together with the bonding effect provided by cement.

The improvement in unconfined compressive strength was one of the most significant findings of the present study. The 28-day UCS increased from 0.62 MPa for the untreated soil to 4.31 MPa for mixture C9, representing an increase of approximately 595.2%, whereas C10 achieved the highest UCS value of 4.55 MPa, corresponding to an increase of approximately 634% compared with the natural soil. The results also demonstrated a clear effect of curing time. For C9, UCS increased from 3.08 MPa after 7 days to 3.74 MPa after 14 days and finally to 4.31 MPa after 28 days. Similarly, C10 increased from 3.25 to 3.96 and then to 4.55 MPa over the same curing periods. This progressive strength development indicates that the stabilized soil continued to gain strength with increasing curing time, which can be associated with continued cement hydration and the progressive development of cementitious bonds within the stabilized soil matrix.

The CBR results obtained in the present investigation are particularly relevant when compared with the Libyan study conducted by Fiener [6] on sabkha soil in northwestern Libya. Fiener used CKD to stabilize sabkha soil and reported significant improvements in its engineering properties, particularly in terms of CBR [6]. Although the stabilization system used by Fiener differs from that adopted in the present study, the agreement between the studies regarding the improvement in bearing-related characteristics supports the potential use of industrial by-products and secondary materials for improving sabkha soils under Libyan conditions. The present study extends this concept through the use of a composite system consisting of sulfate-resistant cement, marble powder, and quarry dust.

The Atterberg limit results also demonstrated a clear reduction in soil plasticity after stabilization. The plasticity index decreased from 17.7% for the natural soil to 13.3% for C3, 11.3% for C5, 9.1% for C7, and 8.6% for C9. The reduction from 17.7% to 8.6% corresponds to a decrease of approximately 51.4% relative to the untreated soil. This improvement may be associated with modification of the soil structure following the incorporation of cementitious and mineral materials, as well as the introduction of relatively non-plastic materials into the mixture. With regard to durability, the wetting–drying results demonstrated a substantial improvement in the ability of the stabilized mixtures to resist deterioration. Weight loss after 12 wetting–drying cycles was 18.7% for the untreated soil and decreased to 9.8% for C3, 6.4% for C5, 4.9% for C7, 3.6% for C9, and only 3.2% for C10. Therefore, the use of C9 reduced weight loss by approximately 80.7% relative to the untreated soil.

The sulfate-exposure results also indicated that the better-performing stabilized mixtures retained a greater proportion of their original strength. The strength loss was approximately 16.1% for C3 and decreased to 11.3% for C5, 8.9% for C7, 7.0% for C9, and 6.6% for C10. Consequently, C9 retained approximately 93% of its original UCS following sulfate exposure. This result is particularly important considering the chemical characteristics of the investigated natural soil, which contained approximately 5.8% total dissolved salts and 1.24% soluble sulfate. The use of sulfate-resistant cement was therefore directly related to the chemical conditions of the investigated sabkha soil. However, the previous studies included in the references do not provide directly comparable results based on identical cement types and sulfate-exposure conditions. Therefore, the findings of the present study should be regarded as an indication of mixture performance under the adopted experimental conditions, while longer exposure periods and field investigations are required to evaluate long-term sulfate resistance.

The statistical analysis further supported the effectiveness of the stabilization process. One-way ANOVA indicated highly significant differences among the UCS values of the investigated mixtures, with $F = 138.44$ and $p < 0.001$. This demonstrates that the type and proportions of the stabilizing materials had a statistically significant effect on the compressive strength of the soil. The coefficients of variation were 4.87% for C9 and 4.84% for C10, indicating relatively limited dispersion among replicate specimens and satisfactory consistency of the results. Furthermore, a very strong positive relationship was obtained between UCS and CBR, with a Pearson correlation coefficient of $r = 0.97$ and a coefficient of determination of $R^2 = 0.94$. This relationship demonstrates that increases in compressive strength were generally accompanied by increases in bearing capacity. Therefore, the stabilization process did not improve only a single engineering property but produced a simultaneous improvement in several related indicators of soil performance.

Comparison between mixtures C9 and C10 demonstrates that C10 achieved the highest absolute performance, with a UCS of 4.55 MPa, soaked CBR of 54.7%, and MDD of 1.65 Mg/m³. It also recorded a wetting–drying weight loss of 3.2% and a sulfate-induced strength loss of 6.6%. In comparison, C9 achieved a UCS of 4.31 MPa, soaked CBR of 50.6%, MDD of 1.64 Mg/m³, wetting–drying weight loss of 3.6%, and sulfate-induced strength loss of 7.0%. However, C9 contained 10% sulfate-resistant cement compared with 12% in C10. Thus, increasing the cement content from 10% to 12% resulted in only a relatively limited additional improvement in the principal engineering properties.

Overall, the findings of the present study are consistent with the principal trends reported in previous research, while introducing a different stabilization system that combines sulfate-resistant cement, marble powder, and quarry dust within a single mixture. The C9 mixture, consisting of 10% sulfate-resistant cement, 5% marble powder, and 10% quarry dust, provided a favorable balance among compressive strength, bearing capacity, density, durability, and sulfate resistance while requiring less cement than C10. Therefore, C9 can be considered the proposed optimum mixture within the investigated experimental program. Nevertheless, this conclusion should be further supported by actual field application, long-term monitoring, and quantitative economic and environmental assessments before recommending large-scale implementation.

4. Conclusion

- The results demonstrated that the use of sulfate-resistant cement in combination with marble powder and quarry dust significantly improved the engineering properties of the sabkha soil compared with the untreated soil, particularly unconfined compressive strength (UCS), California Bearing Ratio (CBR), and maximum dry density (MDD).
- The unconfined compressive strength increased from 0.62 MPa for the untreated soil to 4.31 MPa for mixture C9, while the soaked CBR increased from 3.2% to 50.6%. These results demonstrate the effectiveness of the stabilization process in improving soil strength and bearing capacity.
- Stabilization also improved the physical properties of the soil. The maximum dry density increased from 1.49 to 1.64 Mg/m³ for C9, while the plasticity index decreased from 17.7% to 8.6%, indicating improved particle packing and reduced soil plasticity.
- The stabilized mixtures exhibited a substantial improvement in durability. Weight loss after 12 wetting–drying cycles decreased from 18.7% for the untreated soil to 3.6% for C9. Furthermore, the strength loss of C9 after sulfate exposure was limited to 7.0%, indicating improved resistance under the investigated exposure conditions.
- Increasing the curing period contributed to strength development. The UCS of C9 increased from 3.08 MPa after 7 days to 4.31 MPa after 28 days, indicating continued development of cementitious bonding with curing time.
- Statistical analysis showed significant differences among the investigated mixtures ($F = 138.44$, $p < 0.001$). A very strong positive correlation was also observed between UCS and CBR ($r = 0.97$), confirming that the increase in compressive strength was strongly associated with an increase in soil bearing capacity.
- Mixture C9, consisting of 10% sulfate-resistant cement, 5% marble powder, and 10% quarry dust, was selected as the proposed optimum mixture because it provided a favorable balance between engineering performance, durability, reduced cement content compared with C10, and the beneficial utilization of marble powder and quarry dust.

5. Recommendations

- A pilot field section using mixture C9 is recommended at the Al-Hawaza Scheme in Suluq City to verify whether its field performance is consistent with the laboratory results.
- The stabilized soil should be monitored over longer periods, with particular attention to settlement, cracking, field density, moisture content, bearing capacity, and changes resulting from environmental conditions.
- Long-term sulfate resistance, salt exposure, and wetting–drying tests are recommended because of the saline nature and water sensitivity of sabkha soils.
- Longer curing periods, such as 56, 90, and 180 days, should be investigated to evaluate the long-term development of strength and durability.
- Additional proportions of marble powder and quarry dust should be investigated to determine whether the cement content can be reduced below 10% while maintaining adequate strength, bearing capacity, and durability.
- A comprehensive economic and environmental assessment should be conducted to compare C9 with conventional cement-only stabilization, considering material and transportation costs, the amount of waste material beneficially reused, and the potential reduction in cement consumption.
- Large-scale implementation of the proposed mixture is not recommended until its performance has been verified through field trials and long-term monitoring. Further investigation using sabkha soils from different regions of Libya is also recommended to assess the broader applicability of the proposed stabilization system.

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