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Sabkha Soil Improvement by the Use of Chemical Additions

Mohammad Fadhil Abbas

Dep. of Civil Engineering, College of Engineering, Al- Muthanna University
mohammadfashil@mu.edu.iq

Abstract

Iraq is located within the arid and semi-arid region which include large areas of Sabkha soil particularly in the southern regions. Stabilization of properties of Sabkha soils in terms of strength, durability, and cost is required from engineering point of view. In this study the synthesis of a new chelating Schiff's base of Furfural with Metal ions (SFM) was used for stabilization Sabkha soil. The present study investigates the possibility of using the SFM to enhance Sabkha soil properties in the southern regions in Iraq. In this study, experimental approach was employed to investigate the properties of treated and untreated Sabkha soil. In laboratory tests, Sabkha soil samples have been mixed with 2%, 4%, and 6% of SFM for mineralogical tests whereas other samples tested in order to identify the physical and mechanical properties of the treated samples. The stabilization mechanisms of treated sabkha soil have been investigated using modern approaches, such as Scanning Electron Microscope (SEM), Energy Dispersive X-ray analysis (EDX) and X-Ray Diffraction analysis (XRD). Sabkha soil, when mixed with 4% and 6% SFM, has been observed to transform into a solid material potentially suitable for use in the sub-base layer of rigid pavements. The study revealed that the compressive strength of the treated Sabkha samples was increased from 51 kPa to 402 kPa. Compared to untreated Sabkha soil the improvement ratio of treated sabkha soil increased from 119% to 443%. However, results of triaxial test showed that the cohesion increased by133.6 kPa without affecting the angle of internal friction. While the results of direct shear test showed that the angle of internal friction increased from 35 to 41 degrees. The soaked CBR values showed an increase with the addition of SFM at concentrations of 0%, 2%, 4%, and 6%, rising from 11% to 21%, 32%, and 58%, respectively. Added SFM values were increases this showed Sabkha soil is suitable material for to be a pavement foundation course. Based on the wetting and drying testing results, stabilized Sabkha soil with 6% SFM lost roughly 8.4% of its weight over time. In contrast, soil stabilized with 4% SFM and 2% SFM lost approximately 10.5%, and 15.4% of its weight respectively.

Keywords: *advanced techniques, chemical additives, Furfural, improvement, Sabkha*

1. Introduction

In hot and arid regions, the rate of evaporation substantially exceeds that of precipitation. Consequently, such climatic conditions are conducive to the formation of saline or evaporitic soils, characterized by the accumulation of mineral salts through the evaporation of water [1]. The Arabic word for "salt flat" is Sabkha, which is a phonetic translation. The coastal sedimentation known as Sabkha is made up of evaporates, tidal-flood deposits, and eolian deposits. It is characterized by dry or almost dry conditions above the water's edge. Comparatively greater fines concentration, chloride content higher sulfate, higher compressibility, and lower shear strength are some of the ways in which Sabkha soil stands apart from other surficial sandy soils in the nation from a geotechnical engineering perspective [2]Sabkha can be categorized as either muddy or sandy soil types (Juillie and Sherwood 1983) [3].Salts have partially cemented the sand, which is typically very loose to medium compact. The lagoon sediments known as "muddy Sabkha" are primarily made up of sand- and carbonate-based mud's. The extensive ramification of names for things makes it more difficult to define Sabkha numerous Middle Eastern situations with high water tables [4]. The most accurate description of the[5] have reported on the sabkha system as the big (in dimension or size), flat saline, (horizontal terrains with slight, unnoticeable slopes)Aeration zones (due to the dry and hot environment), located either in coastal areas (referred to as coastal Sabkhas) or inland Sabkhas further inland (also known as continental or inland sabkhas) a lot of dry, semi-tropical nations [5].

The low shear strength and high compressibility of Sabkha soils are troublesome. Therefore, these soils provide a considerable risk of settlement and/or bearing capacity failure, and structures should not be erected on them. Due to the diversity and quantity of salts they contain, these soils display a broad range of behavior variations. Common salts include gypsum (Ca SO4 2H2O), calcium carbonate (CaCO3), calcium sulphate (anhydrite), and halite (NaCl) salt, once dried, functions as a binder that improves soil's shear strength and lowers its compressibility. When salt dissolves in water, it alters the soil structure, resulting in a loose and unstable matrix. This transformation increases the soil's compressibility, heightening the risk of collapse, while simultaneously reducing its shear strength. Numerous methods for enhancing the geotechnical properties of Sabkha soil have been extensively documented in academic literature [6]. Among these methods are grouting removal and compaction, geosynthetic reinforcement, vibroflotation, stone columns, dynamic compaction, removal and replacement, and preloading. The effectiveness of the augmentation approach is contingent on a number of variables, including the kind, quantity, and solubility of salts, soil permeability, temperature, and chemical qualities of groundwater.

Based on the soil's particle size, some studies have categorized sabkha soil into two groups: sandy Sabkhas and muddy Sabkhas. In most cases, muddy Sabkha (a kind of lagoon silt) is composed of a sand-based carbonate mud. Sandy sabkha is relatively loose to medium-density soil that occasionally has salts acting as a partial cement [7][8]. In Sabkha soils, high moisture concentrations, or "Sabkha brine," are commonly seen. Using ASTM D 4643, the water content of sabkha soils in the Arabian Gulf was calculated and found to be about 25%. (Al-Shayea et al. 2003) [9]. Additionally, it was discovered that the Sabkha soil in Sohar, Oman, had a natural water content of 25.64 percent (Al-Alawi et al. 2020) [10]. But Jizan Sabkha soil had a natural water content that varied from 16.7 to 63.5 percent [11]. According to Al-Homidy et al. [12], Sabkha soil has a natural water content that ranges from 8 to 65%. In general, climate circumstances and the kind of soil (i.e., coastal Sabkha or continental soil) influence the change of the natural water content.

1.1 Formation of the Sabkha

Sabkha is produced by the constant interaction of brines and sediment [13]. Minerals and sedimentary topographies are among the various aspects of Sabkha deposits linked to the original deposition framework. Several elements influence the creation of Sabkha, such as:

1. Climate consists of precipitation, humidity, temperature, and wind speed.
2. Geochemical: contains both minerals and brine chemistry
3. Geomorphological: groundwater table and surface gradient and
4. Hydrological: This may be an independent cause or effect of the first three.
5. Biological: consists of the burrowers and algal mats

The reactions that characterize Sabkha soil and its environs may be the consequence of the collaboration and interaction of the components above [14].

1.2 Chemical Stabilization

Al-Amoudi [15] investigated how two chemical stabilizing agents affected the density and compressive strength (unconfined) of Sabkha. Experience the flavor of Sabkha Lime and cement were used to improve the soil quality in eastern Saudi Arabia. They used five doses on soil samples collected at two moisture levels (16 and 22 percent) (0, 2.5, 5, 7, and 10 percent). Following standard compaction tests and sample preparation, unconfined compressive strength was evaluated repeatedly during curing. In all cases, the findings show that a moisture content of around 30 percent is best, and that increasing the cement content raises the maximum dry density. Sabkha mixtures stabilized with lime did not have a noticeably greater maximum dry density than those that were not. Further, for cement additions of 7.5 and 10%, data reveal that the strength of cement-stabilized Sabkha rises even after 90 days of cure. Since Lime Sabkha mixes could not attain their full strength until 90 days after curing, this suggests that extensive curing is necessary to develop strength. Statistics indicate that cement plays a crucial role in maintaining the stability of Sabkha at its natural moisturelevel.The solidification of Sabkha resulted in a progressive enhancement of its structural integrity over time.Al-Amoudi et al. [16] looked at how adding dust from limestone, cement, and lime altered Sabkha's salty and dry characteristics. It came from an eastern Saudi Arabian area. After 7 days, we subjected the samples to industry-standard compacted and unconfined compressive strength tests. Aiban et al. [17] evaluated the efficiency of lime-stabilized Sabkha Soil in Ras Al-Ghar. Saudi Arabia's Eastern Province. Lab experiments including soil characterization, compaction, unconfined, and triaxial compression were performed on soil samples collected at varying depths. There are noticeable differences in the moisture and lime content between cleaned and unwashed Sabkha soils. When soil samples were compacted at a higher moisture content than was desirable, they found that adding 5% lime boosted the soil's strength. They also found that the strength of the soil was affected by the amount of salt present, the curing regime, and the amount of moisture in the mold throughout the curing process. It was also shown that the maximum dry density and ideal moisture content of unwashed Sabkha were insensitive to the quantity of added lime, however for washed Sabkha, slight variations were seen. Many people prefer the unwashed kind of Sabkha because it has a more robust flavor due to the presence of salt. Additionally, when testing for strength, lesser moisture content yields better results. They claimed that adding a little amount of lime to Sabkha soils increased the strength, and that this improvement persisted even after 18 days of curing. Al-Amoudi [18] investigated Sabkha soil in Al-Qurayyah, Eastern Saudi Arabia, and found that lime and cement were successful in taming the soil's wild components. They used a range of 0%-10% lime and cement. The study analyzed the difference in stability between un stabilized and stabilized Sabkha at different degrees of moisture. The unconfined compressive strength and the Clegg impact value were used to get the CBR for this material. Maximum dry density was shown to rise as a function of cement %. However, the maximum dry density dropped as the lime proportion increased. No significant changes in the optimum moisture level were observed over the cement concentration range (from 0% to 7%) following addition. However, it was discovered that a slightly greater ideal moisture was achieved using 10% cement. When using lime as a stabilizer, the ideal moisture level of Sabkha was found to increase by 17% at lime concentrations of 0 and 3% and by roughly 20% at lime contents of 5, 7, and 10%. Strength was greatly improved by adding 3% cement to the Sabkha soil (from 809kPa without cement to 2667kPa with cement). The studies also reveal that cement may be utilized to increase the unconfined compressive strength and CBR of Sabkha soil to their maximum values of 500kPa and 533%, respectively. It was shown that adding lime to Sabkha soil did not significantly increase its strength or compressive strength. The pressure and pH levels went from 809 kPa and 111% to 1201 kPa and 164% after adding 10% lime. According to the results, cement was much more effective than lime in improving stabilized Sabkha's performance. They determined that cement was the ideal additive for making the Sabkha Soil more stable after conducting an analysis of the soil in the Al-Qurayyah area of Saudi Arabia. This study focused to use of SFM as chemical stabilizing for treating the Iraqi Sabkha soil.

2. Properties of materials

The innovative Schiff's base of furfural synthesis, and the soil (Sabkha) are all analyzed for their mineralogical, chemical, and physical properties. Scanning Electron Micrograph (SEM) image of sabkha soil used in this study Fig.1.

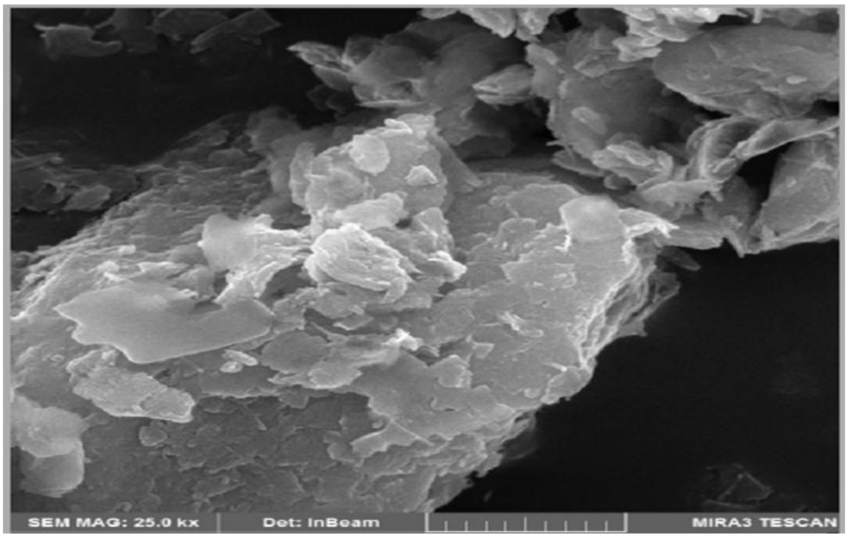


Fig. 1: Sabkha soil sample SEM image.

2.1 Sabkha soil

According to Table 1, the Total Dissolved Solids (TDS) in Sabkha brine maybe three to five times greater than in typical Arabian Gulf seawater.

Table 1. Sabkha brine and seawater Chemical analysis

Medium	Ion concentration (mg/mL)								PH Value
	Na^+	Mg^+	Ca^+	Si^+	Cl^-	So_4^{2-}	K^+	Hco_3^-	
Sabkha brine	68.5	11.4	1.64	0.03	15.7	6.02	3.11	0.1	6.7

Sea water	20.7	2.3	0.76	0.013	36.9	5.12	0.73	0.128	8.3

Table 2. Chemical composition of Sabkha soil

Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	LOI
%	33.1	12	5.4	18.8	10.8	6.2	8.8	18.8

2.1.1. Soil Samples Collection

The Sabkha soils of the area are shown using soil samples from the Samawah locality in southern Iraq. Sample sites are depicted in Fig.2. To improve the shear strength of Sabkha soil (by tightening bonds and keeping moisture in), a combination of (catalyst + furfural) is suggested as a possible chemical ingredient. Collecting soil and SFM samples is the initial stage. The physical and chemical properties of the soil and SFM are then determined experimentally. In addition, Atterberg limits and sieve analyses of the soil are computed. Third, the suggested mixtures have the maximum dry density and optimal moisture content. The proposed mixtures are then subjected to several tests for Unconfined Compressive Strength (UCS), direct shear, and triaxiality. As a fifth step, the California Bearing Ratio (CBR) of the allowed configurations by soaking them. The sixth step is to check the toughness of the mixtures that have been tested for strength and CBR. More precise information on each of the six occupations will be provided below.

Fig. 2: A map shows where the Samawah station is located.

2.1.2. Mineralogical analyses

Knowing the composition of a material's minerals might help one predict how it will act and react in different environments. The mineral content of soil and SFM is examined. The soil samples are first air-dried, sieved through a #10 sieve, and then thoroughly mixed to ensure uniformity. Then they are reduced to powder and passed through a #200 mesh screen. And next, after being mashed up, the soil spends 72 hours drying in an oven at 70 degrees Celsius [19]. The penultimate step is to conduct a mineralogical analysis on around 10 g of each soil sample. To determine the mineral composition of soil and SFM, X-ray diffraction (XRD) is used. The scientists used a Rigaku Ultima IV X-ray diffractometer for this study. The generator is set up for 40kV at 40mA at an angle of 6o to 90o (2q). In addition, samples that do well in durability and strength tests are produced and put through mineralogical analyses to pinpoint the specific chemical constituents that contribute to the improvement brought about by stabilization with various industrial by-products. Scanning electron micrograph Fig.1 and X-ray diffract gram Fig.3 of Sabkha soil from Al Samawaa. Quartz (75%) is the most abundant, followed by gypsum (12%) and halite (10%). High levels of quartz make this kind of sabkha soil non-plastic and fine-grained [20].

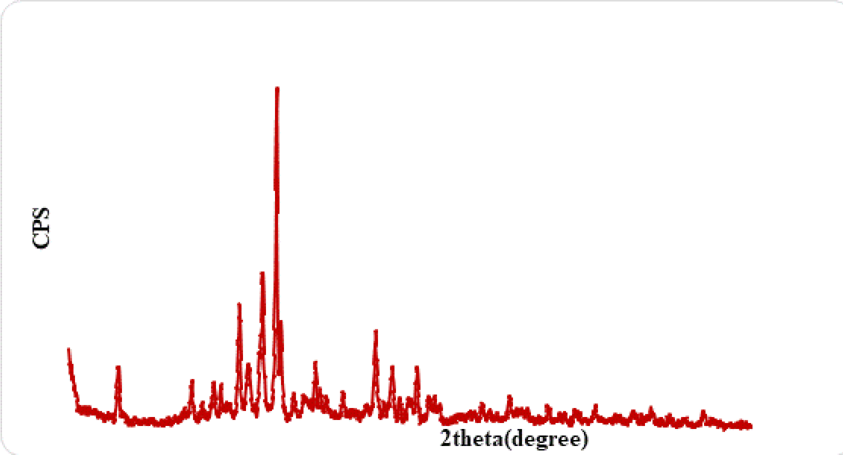


Fig.3:X-ray diffract gram for Sabkha soil sample

2.1.3. Specific gravity

The void ratio, unit weight of the soil, and particle size distribution can be determined using the specific gravity as a foundational parameter in soil mechanics. Since the recommended stabilizers have particle sizes smaller than 4.75 mm and the Sabkha soil sample goes through a #4 sieve, the specific gravity is computed according to [21]. To determine the average specific gravity, scientists evaluate each item's density of two "disturbed" dry samples. The Sabkha soil is allegedly baked at 70 degrees Celsius until a constant weight is reached [22]. The specific gravity of Sabkha soil is 2.71, which is less than the value of 2.73 supplied by [23] and between the values of 2.51 and 2.82 recorded by [24].

2.1.4. Atterberg limits

Each soil's plastic and liquid limits are determined in line with ASTM D424 (1954) and ASTM D423-66 (2017), using material passing a #40 sieve and brine sabkha. The moisture level at 25 blows is the liquid limit, but the moisture content necessary to roll the dirt to a thread of 1/8-inch (3.17-millimeters) is the plastic limit.

2.1.5. Grain size distribution

ASTM D422-63 is used to determine the particle size of Sabkha soil (1963). This evaluation is required for every soil analysis. In addition, the majority of soil classification schemes need it. There is also the option of using a dry or wet sieve. A typical dry soil sample is wet sieved by passing it through sieves of decreasing diameter (10, #20, #40, #60, #100, #140, and #200) until the water flowing through each sieve is clear. Unless otherwise specified in [24], Sabkha soil must be dried at 70 degrees Celsius to achieve a uniform weight. Drying the soil particles retained by each sieve and those that passed through the #200 sieve permits exact weighing of the remaining soil particles. By subtracting the weight of the dry soils from the weight of the sieves when they are empty, it is feasible to determine the percentage of material that goes through each sieve. The grain size distribution curves of Sabkha soil are shown in Fig.4. Dry and wet sieving processes yield distinct grain size distribution curves. Dry materials pass through the #200 sieve at a rate of 5.2%, whereas wet materials pass through at a rate of 33.7%. Washing considerably alters the quartz and soluble mineral content of sabkha soil, which may account for the observed variation in grain size distribution curves. Because water has a propensity to break down the bonds and ions between soil particles, wet sieving is much more effective than dry sieving. Due to the fact that a negligible proportion of particles in the examined soil passed through the #200 sieve, it is possible that it would be classified as either SM or SC under the unified soil classification system (USCS). Since its plasticity index (PI) is less than 4, collected Sabkha soil is classified as A-3 by the dry sieving technique of the American Association of State Highway and Transportation Officials and as SM by the United States Construction Specification (AASHTO). 32% of the wet-sieved material went through the #200 sieve, which is much more than the industry standard of 12%. Both SM and SC are capable of occurring in moist Sabkha, either might be present. Because they cannot be rolled into a thread smaller than 1/8 inch, all the sabkha soils investigated here belong to AASHTO Class A-3. The findings of the grain analysis experiments are shown in Fig.5. These findings demonstrate the need for a solvent that does not dissolve sabkha's ingredients. Researchers sought to mitigate the salt dissolution by combining SFM with Sabkha brine [25]. Figure 4 indicates that the SFM and Sabkha brine curves lie in the region's center indicated by the two "standards." Sabkha brine may be extracted from the same soil sample with reasonable ease. Sabkha brine is thus highly suggested for precisely testing the grain-size parameters of sabkha soils. The hydrometer method is an essential additional test for fine-grained soils. Since the specific gravity of distilled water varies with temperature, hydrometer studies on Sabkha soils cannot be undertaken. The hydrometer test for evaporitic soils will induce a dynamic change in specific gravity due to the dissolution of soluble salts [26].

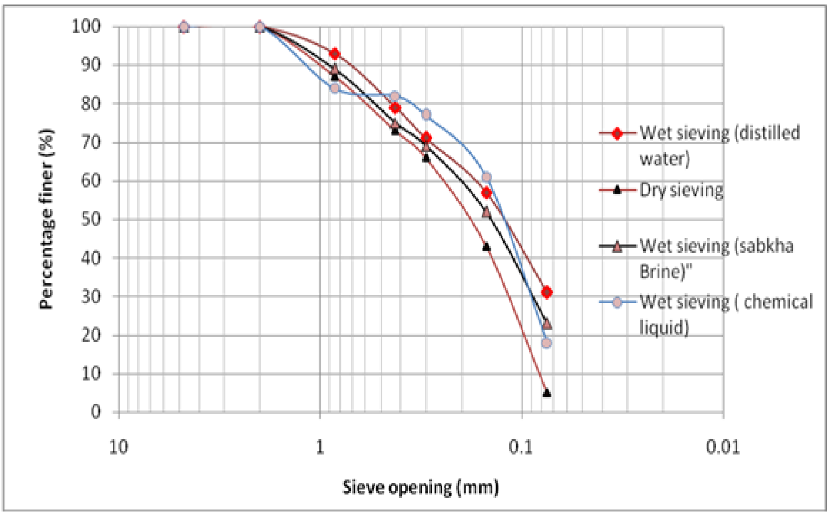


Fig. 4: Sabkha soil's grain size distribution of study samples.

2.1.6. Unit Weight

The unit weight of the Sabkha soil in the field are measured by using four steel pipes with a known inner diameter of 101 mm and a known length of 760 mm. The space between the steel pipes and the ground in the sabkha has been filled with soil. The pipes were sealed in plastic bags until they were needed for the tests. Figure 5 depicts a sample of Sabkha soil tested using SPT. Each pipe sample was transferred to its plate and weighed individually in the lab.Unit weight was determined by measuring the mass and volume of each sample. Five soil samples were taken from locations within five meters of each other and used to calculate the field unit weight of Sabkha soil to ensure accuracy. Table 3 illustrates the field's wet and dry unit weights and summarizes the results. While the field unit weight of Sabkha soil is typically 17.85 kN/m^3, its dry unit weight is typically 14.79 kN/m^3.

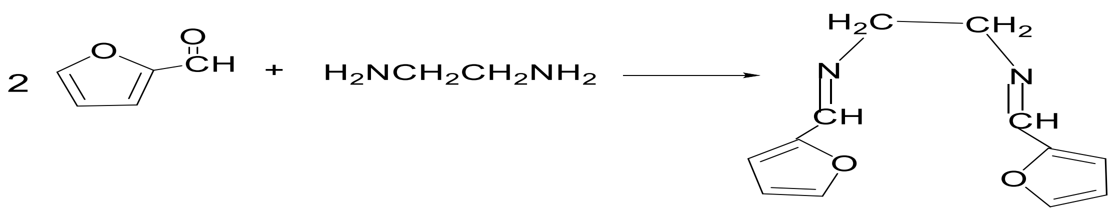
Fig. 5: A picture showing the nature and shape of soil.

Table 3. Summarizes of the findings, including moisture content, dry unit weight, and field unit weight.

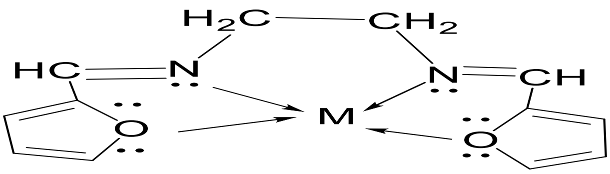
No. of sample	Unit weight (kN/m^3)	Water content %	Dry unit weight (kN/m^3)
1	18.99	21.9	15.57
2	16.71	18.3	14.13
3	17.91	23.1	16.17
4	17.36	23	14.11
5	18.52	18.7	15.6
Minimum	16.71	18.3	14.11
Maximum	18.99	23.1	16.17
Average	17.85	20.7	14.79

2.2. Chemical additives (Synthesis of new chelating Schiff's base of furfural)

16.55 ml (0.2mol) of furfural was dissolved in 25 ml of ethanol in a round-bottom flask ($C_5H_4O_2$). The ethylene diamine ($C_2H_8N_2$) solution, which was 0.1 moles in volume, was added very slowly over the course of 6.66 milliliters. The reaction mixture was maintained at a constant reflux for three to four hours. We acquired the oily yield by filtering away the particles after evaporating the ethanol from the reaction mixture.



In figures 6 ,7 and 8, the novel Schiff's base of furfural forming stable complexes with metal ions (M).



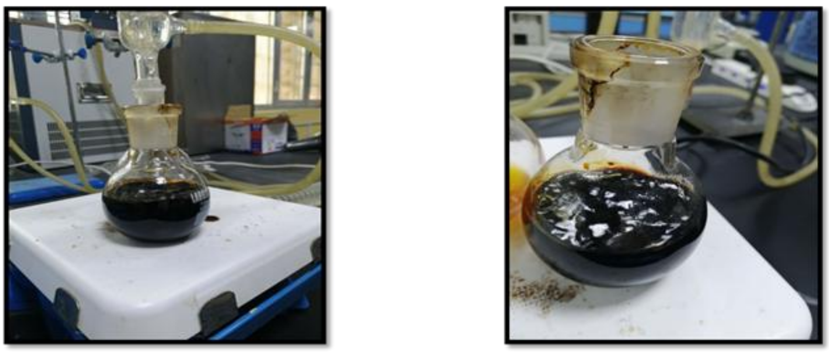


Fig. 6: The creation of stable compounds with metal ions using the novel Schiff's base of furfural (M).

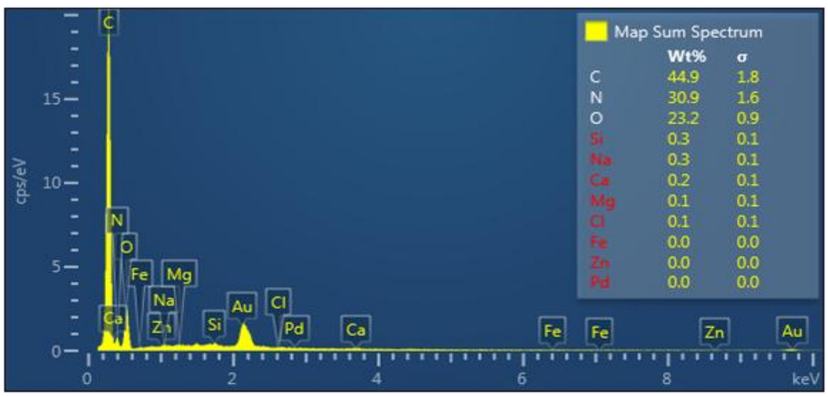


Fig. 7: EDX image of new chemical material (SFM).

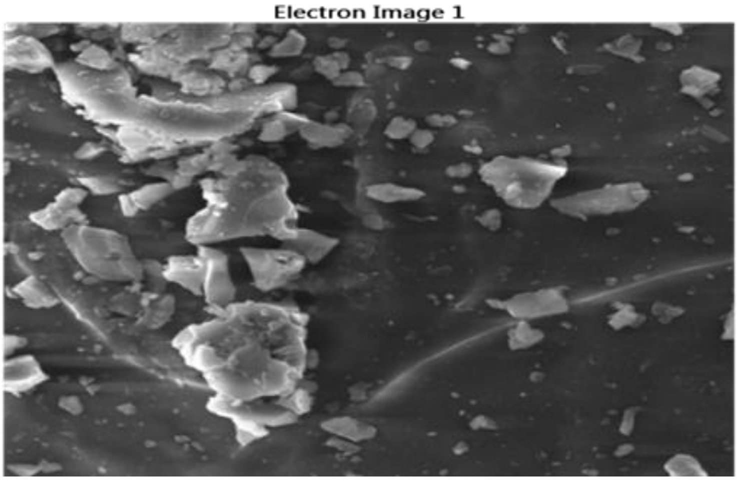


Fig. 8: SEM image of new chemical material (SFM).

3. Sabkha soil stabilized with new chemical material (SFM)

3.1. Establishing the relationship between moisture content and density

In line with ASTM D1557-12 [27], the optimum moisture content is calculated using a modified Proctor compaction test (2012). All experiments are conducted on Sabkha soil that has been treated with 2%, 4%, and 6% Chemical additive (SFM) (by weight of the dry soil). Initially, the dry Sabkha soil and Additive are combined for about one minute. The mixture is then agitated for a further three minutes to achieve the desired homogeneity, sealed in plastic bags to prevent moisture loss, and allowed to cure for seven days in a controlled laboratory setting (Table 4).

Table 4. Summary of the Sabkha soil compaction results.

Additive with sabkha and content	Maximum dry density MDD, (g/cm^3)	Optimum moisture content OMC, (%)
0% SFM	1.83	12.8
2%SFM	1.86	11.6
4%SFM	1.88	10
6 %SFM	1.99	9.6

The impact of SFM on the maximum dry density-moisture content relationship is investigated using modified Proctor compaction tests on Sabkha soil stabilized with and without SFM. In practice, SFM concentrations of 2, 4, and 6 percent are used. Table 4. The results of experiments for dry density and moisture content on Sabkha soil stabilized with and without SFM are shown in Fig.9. The maximum dry density of Sabkha soil increases as its SFM content rises, as seen in Fig.9.The greatest dry density of un stabilized Sabkha soil (at 0% additive) is 1.83 g/cm3, but the highest dry densities of stabilized Sabkha soil (at 2% and 4% concentrations) are 1.86 and 1.99, respectively. Table 4 illustrates that due to the presence of metal ions, the maximum dry density of soil with SFM is greater than that of Sabkha soil. Figure 9 shows a modest drop in ideal moisture content as SFM concentration increases. Ideal moisture levels for Sabkha soil stabilized with 2%, 4%, or 6% SFM are 11.6%,10% and 9.6% respectively, but optimal moisture levels for untreated Sabkha soil are only 12.8%. The SFM serves as a lubricant, shielding the surface from abrasion by coating dirt particles with an oily film (as seen by the drop in optimum moisture content). Table 4 demonstrates that adding SFM increases the maximum dry density of Sabkha soil, possibly due to the higher concentration of metal ions in SFM compared to those in the soil. In addition, the SFM works as an adhesive (cementing and coating agents). As SFM levels increase, the ideal moisture content in Sabkha soil varies due to varying gradations and covering particles.

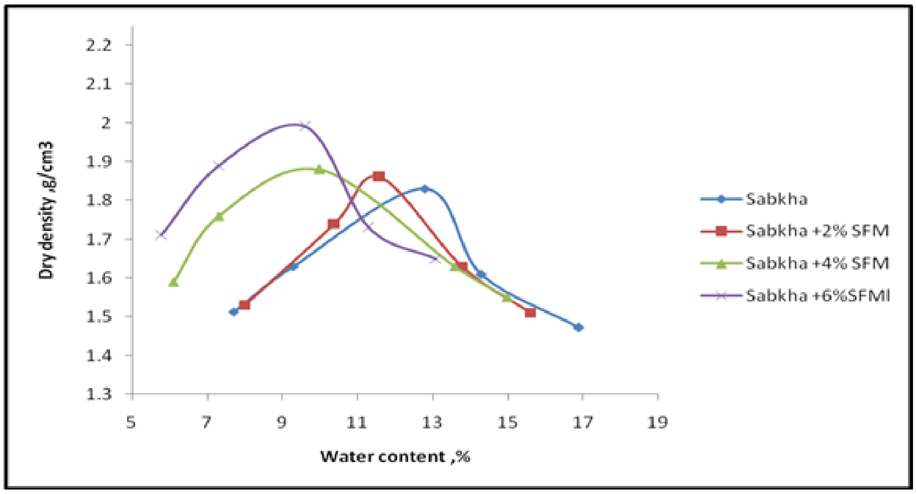


Fig. 9: Relationship between moisture content and dry density for sabkha soil stabilized with and without SFM.

4. Laboratory Testing Method and Outcomes

4.1. Preparation of the Sample

The SFM component was incorporated at concentrations of 2, 4, and 6% of the dry weight of the soil. Stabilizer and soil were mixed in a mechanical mixer for three minutes at the optimal moisture level until they were a uniform color, and then three layers of plastic were employed to keep the mixture dry. The wrapped samples are allowed to be cured for seven days in a laboratory setting maintained at (22 ± 3) degrees Celsius.

4.2. Direct shear test

The shear tests were carried out using a direct shear (shear box). Soil samples were tested in undisturbed and disturbed configurations to better capture the circumstances under which the soils were developed. As previously mentioned, the samples were collected in Shelby tubes without interference. The method was conducted in accordance with the standards established by ASTM D 3080. The test was run with a constant loading rate of 0.6 mm/min. Applying normal stresses of 50, 100, and 200 kPa. Figure 10 depicts experimental results from a direct shear test. A value of c' = 16.5 kPa was obtained for the cohesiveness angle, whereas 28.5 degrees was obtained for the internal friction angle. For best results, mix the disturbed soil samples with 2%, 4% and 6% stabilizer (SFM) (by weight of dry soil) at the optimum moisture level (mentioned in the compaction test results). Results show that when SFM concentration increases, so does friction angle. The angle of internal friction rose from 32.5 degrees to 34 degrees and then to 41 degrees after adding 2%, 4%, or 6% SFM to sabkha soil, respectively. The creation of many extremely stable covalently bonded silicates, aluminates, hydrated aluminates and hydrated silicates makes the processes involving silica and alumina so important.

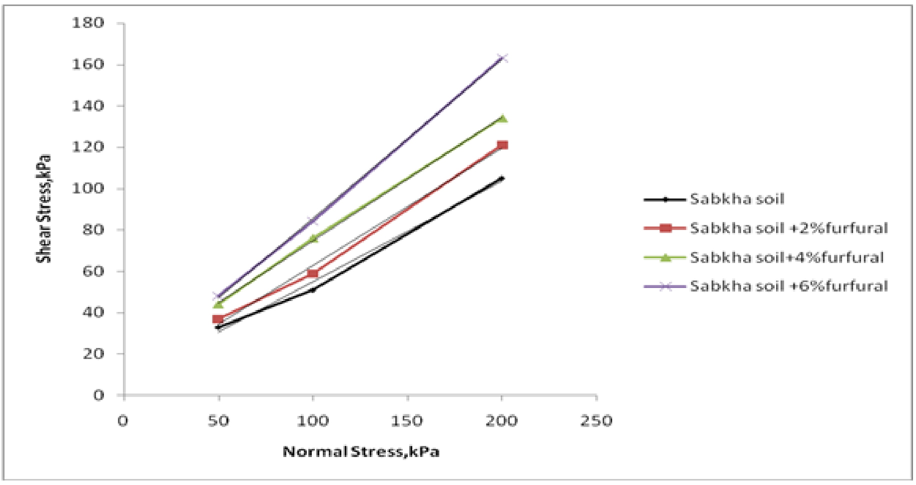


Fig. 10: Results of direct shear tests on several Sabkha - SFM combinations.

4.3. Unconfined Compressive Strength

UCS is calculated via the ASTM D2166/D2166M-16 techniques (2016) [28]. The compressive strength testing results are shown in Table 7 and Fig.11. As the amount of SFM grows, the unconfined compressive strength (qu) improves significantly compared to the value for untreated soil (qu = 74 kN/m2). Figure 11 demonstrates the correlation between UCS scores and SFM content. The data indicates that the UCS increases exponentially with increasing SFM density. 74.6 kPa,163 kPa,272 kPa, and402 kPa are the Unconfined Compressive Strengths (UCS) of Sabkha soil stabilized with 0%, 2%, 4%, and 6% SFM, respectively. In rigid pavements, Sabkha soil stabilized with 6% SFM may be used to create the subbase course, which exceeds the minimum strength requirement. Compared to the Sabkha soil utilized as a control, these improvements rose by 119% to 443%.SFM's interactions with water and the components of Sabkha resulted in the development of chemical binders, which are attributed for the improvements. The link between SFM dosage and the increase in qu supports this notion.

Table 7. Sabkha soil's unconfined compression strength after stabilization.

Stabilizer content	UCS %			
Sabkha soil (no additive)	Sample #1	Sample #2	Sample #3	Average
	73	77	74	74.6
2% SFM	163	166	160	163
4% SFM	271	276	270	272
6%SFM	405	403	399	402

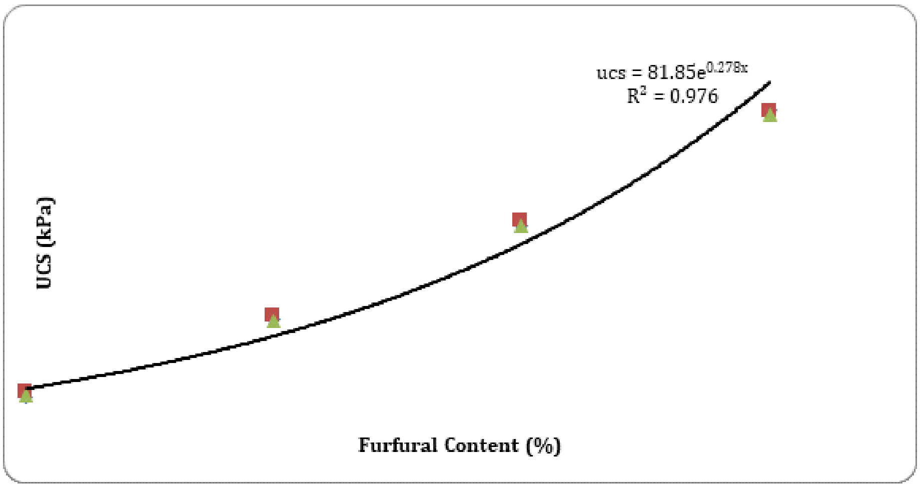


Fig. 11: The impact of SFM on the UCS of sabkha soil.

Using energy dispersive X-ray analysis, and scanning electron microscopy (SEM), Figures 12-14 show images(X-Ray) of Sabkha soil stabilized with (2%, 4%, and 6%) of SFM. Connectors and particle interactions may be seen. There are also holes of various sizes present. As seen in Figures17-19, the SEM of sabkha soil stabilized with 6% SFM reveals a decrease in voids. There are nonetheless still a few holes here and there. Due to its greater density, the latter mixture will likely have a higher UCS than sabkha soil stabilized with 2% SFM. The scanning electron micrograph of Sabkha soil treated with 2,4 and 6% SFM exhibits a platy structure and an isolated crystalline structure of gypsum (Figures15-17). The EDX picture reveals that the sample includes 0.71 percent Na, 7.36 percent Mn, 22.12 percent Si, 2.13 percent Cl, 9.42 percent Ca, and 3.15 percent Fe (Figures 12 and 13). Sabkha soil has a high concentration of chloride, the principal source of which is halite. The SFM is composed of Ca, Si, and Fe. Several regions of the SEM image of Sabkha soil stabilized with 6% cement (Fig. 17) exhibit a platy structure due to the hydration of SFM reflected in the fibrous needles (C-S-H). Figures 15 and 16 show an EDX picture of 4 and 6% SFM-stabilized sabkha soil, revealing the presence of Na, Mn, Si, Cl, Ca, and Fe in concentrations of 1.26, 8.45, 15.96, 1.64, 15.1, and 2.01%, respectively. Ca and Si are present owing to the injection of SFM, which generates a C-S-H gel.

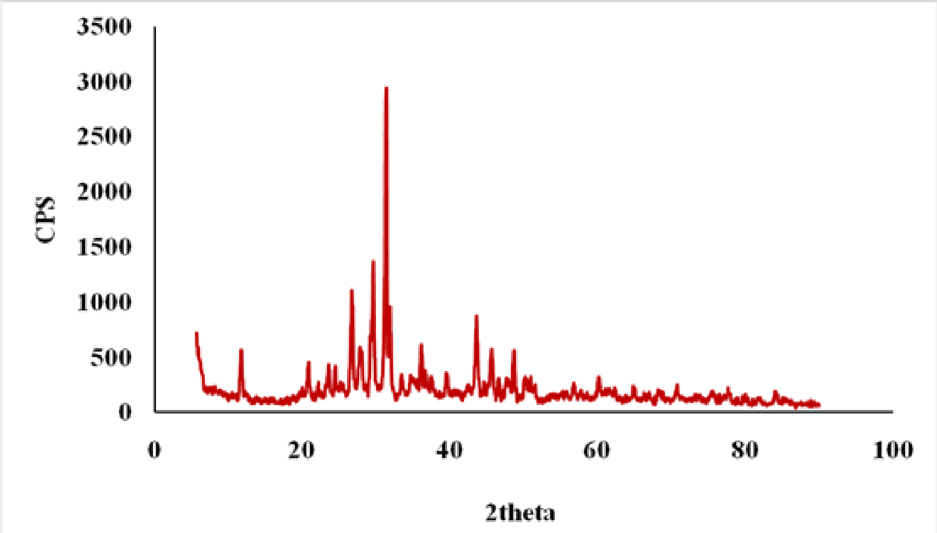


Fig. 12:X-Ray image of 2% SFM-stabilized Sabkha soil.

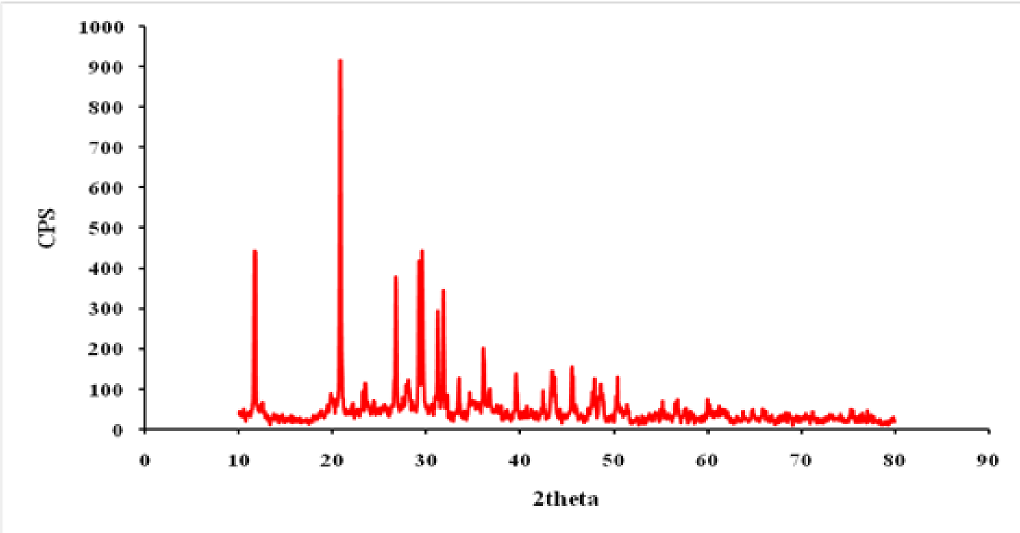


Fig. 13: X-Ray image of 4% SFM-stabilized sabkha soil.

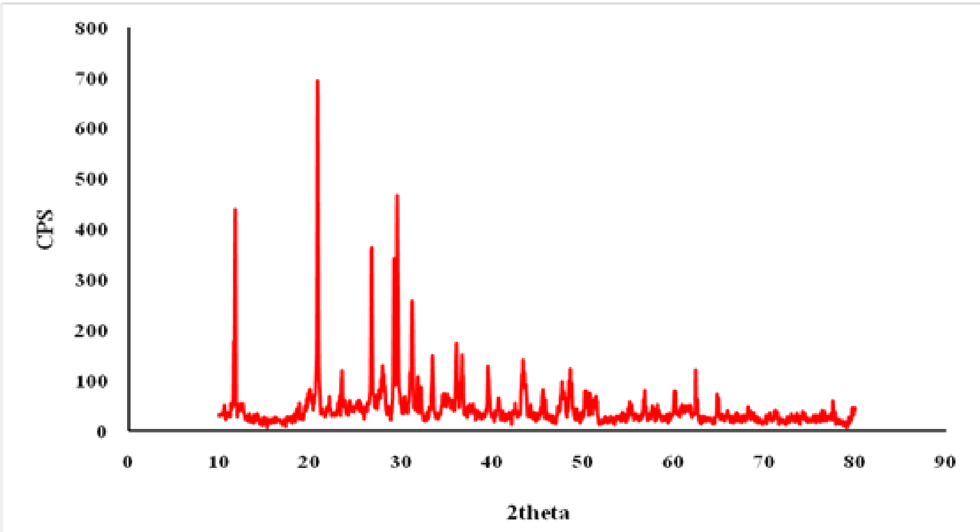


Fig. 14:X-Ray image of 6% SFM-stabilized Sabkha soil.

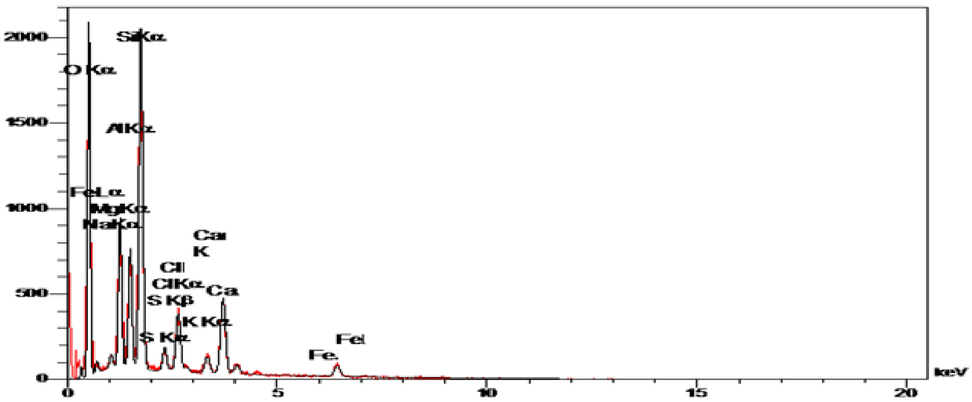


Fig. 15: EDX image of 4% SFM-stabilized Sabkha soil

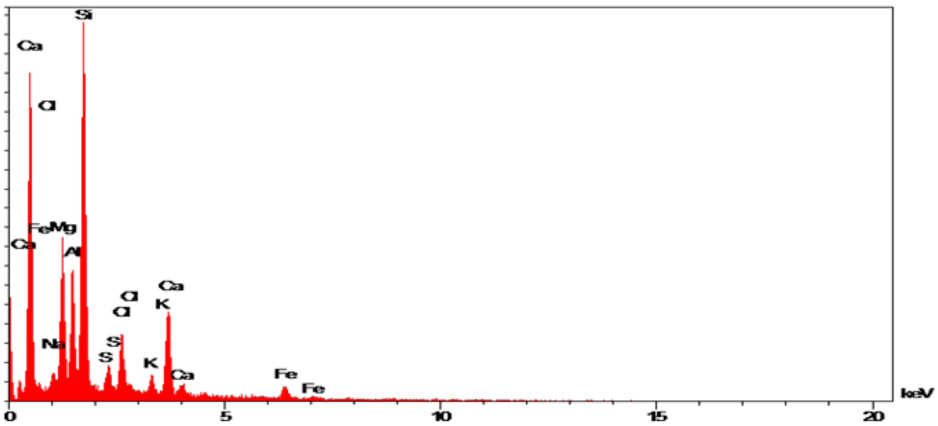


Fig. 16: EDX image of 6 % SFM-stabilized Sabkha soil

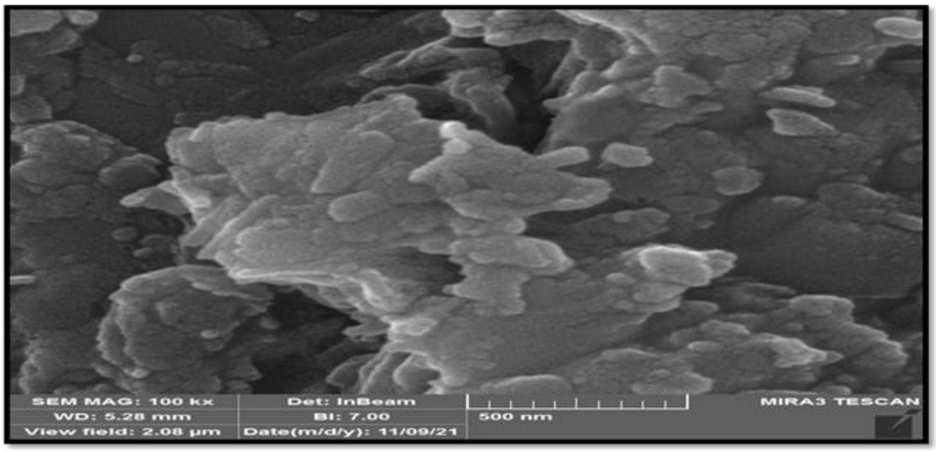


Fig. 17: SEM image of Sabkha soil stabilized with 4% SFM.

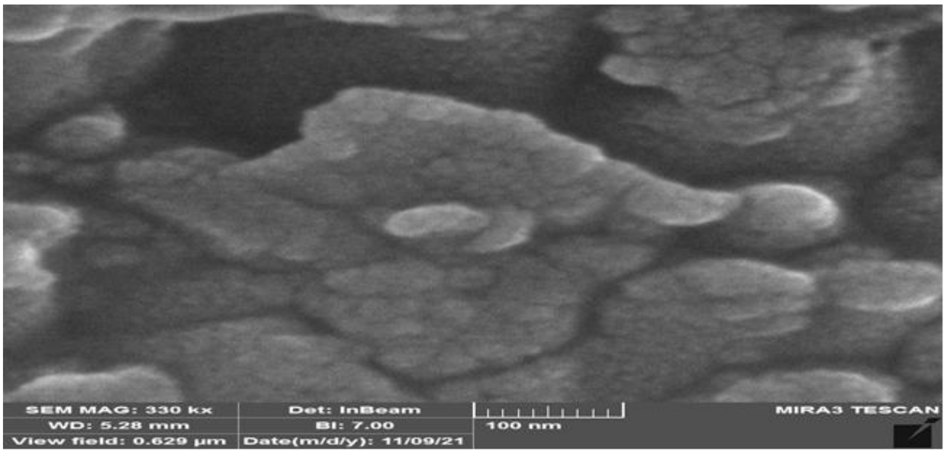


Fig. 18: SEM image of Sabkha soil stabilized with 4% SFM.

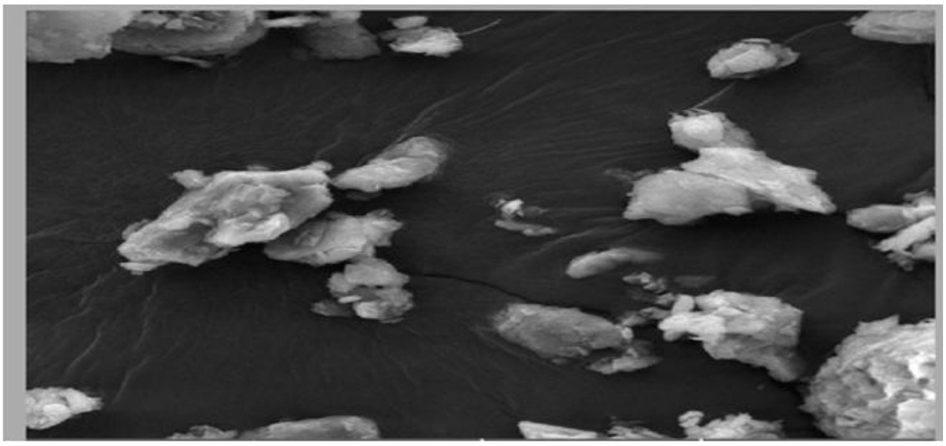


Fig. 19: SEM image of Sabkha soil stabilized with 6% SFM.

4.4. Triaxial test

An analysis of triaxial stress under unconsolidated conditions (CU) has been performed using triaxial testing on compacted, undrained soil samples treated with a 6% SFM additive. The compaction test determined the optimal water content for molding, and the samples were otherwise prepared according to Section 4.1. The consolidated undrained (CU) triaxial tests with pore pressure measurement were conducted following ASTM D 4767-11. Figure 20 illustrates the link between deviator stress and strain, while Fig.21 illustrates the relationship between excess pore water pressure (u) and strain for untreated soil. Figure 20 demonstrates the non-peaked, flexible nature of untreated soil. The stress at failure is considered to represent 15% of the maximum allowable strain of the material. At 1% strain, a steep stress-strain curve indicates a high initial tangent modulus. The soil exhibits a strain-hardening reaction at stresses of 3%, with modulus values close to zero. Strains having a modulus between 1% and 3% fall within an ideal range. A favorable result for increased pore water shows contractile activity during shearing. After reaching a high between 1.5% and 2.7%, u drops continuously. Figure 22 illustrates the relationship between deviator stress and strain, whereas Fig.25 illustrates the relationship between strain and excess pore water pressure (u) for the soil-SFM combination. The curves shown represent a 6% SFM mixture with a 7-day curing time. A notable rise in Figure 23 suggests that the soil is quite unstable. Normal failure stresses vary between 1.7% and 2.5%. Stabilized calcareous sand treated to the same quantity of cement displayed negligible brittleness [29]. As seen in Fig.21the extra pore water is positive in the range of 0.6–1% strain. However, beyond this range, it decreases dramatically and becomes negative upon failure. This is the expected reaction of a dilatant when anything goes wrong. Figure 24 depicts the effective stress route in untreated soil. The stress path starts vertically (p=0), then curves to the left and right, and eventually approaches the failure line asymptotically. To calculate the effective shear strength, φ= 37 and c= 0. According to [29], similar results were reported for silt treated with cement. Figure 25 depicts the effective stress route for the treated soil (6% SFM and seven days). When subjected to three confining pressures, the effective stress path begins as a straight line with a slope of 3 horizontal to 1 vertical before bending to the right and becoming asymptotic to the failure line. The critical state line (CSL) for unprocessed soil is also shown for equivalent purposes. As shown in the figure, adding SFM significantly increased the effective cohesiveness (C = 570 kPa) without affecting the effective friction angle (φ= 37). A similar conclusion has been obtained by several others [30, 31]. According to Lo and Wardani (2002) [32], the effective strength qualities of cemented silt may vary with the amount of applied pressure. They found that the CSL for SFM-treated soil for light confinement is identical to that of untreated soil (i.e., θ will be constant and C will grow).

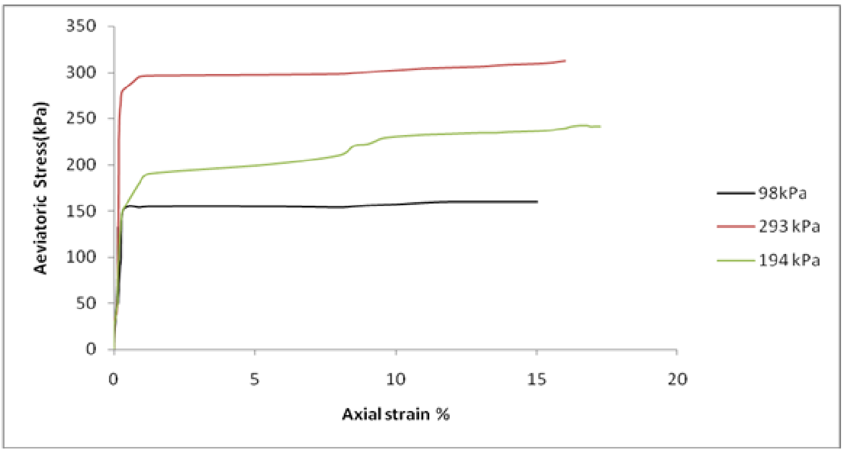


Fig. 20: Results of CU triaxial testing on untreated sabkha soil (stress-strain relationship).

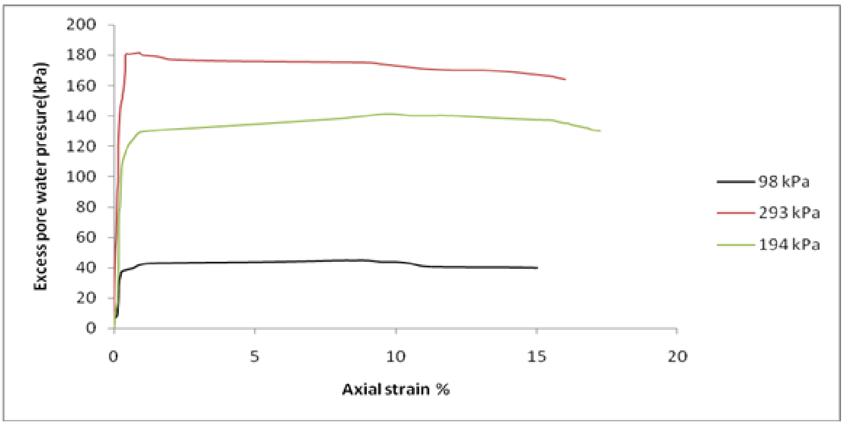


Fig. 21: Relationship between excess pore water pressure and strain (average back pressure = 780 kPa).

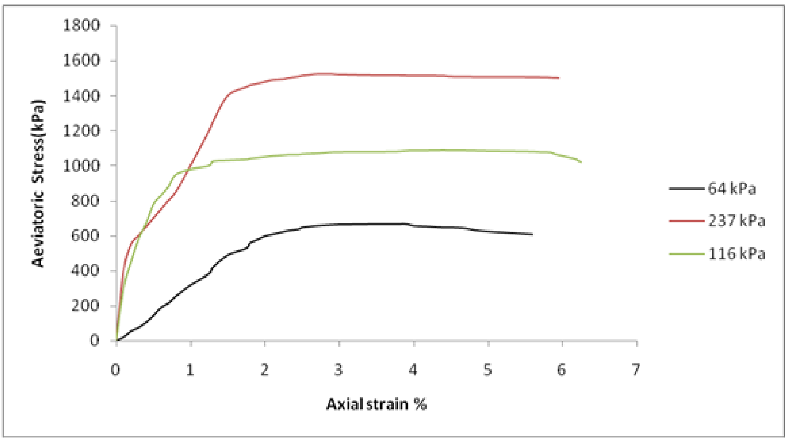


Fig.22: The stress-strain relationship determined by the CU triaxial test on treated sabkha soil (SFM = 6% and curing period = 7 days).

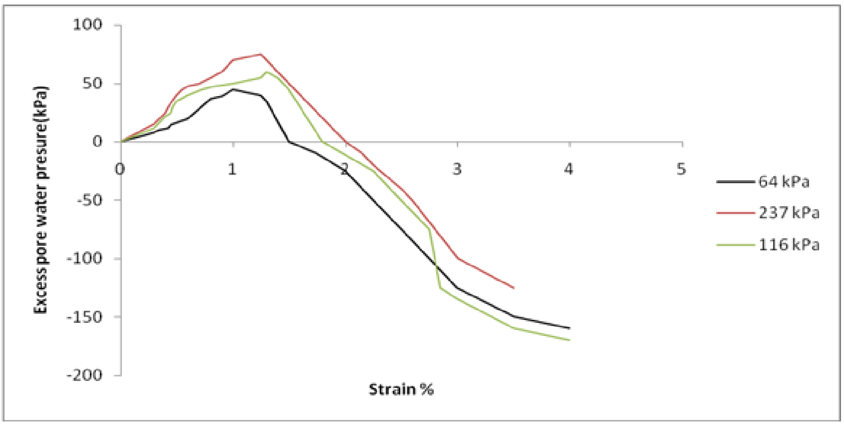


Fig. 23: Relationship between excess pore water pressure and strain (average back pressure = 600 kPa).

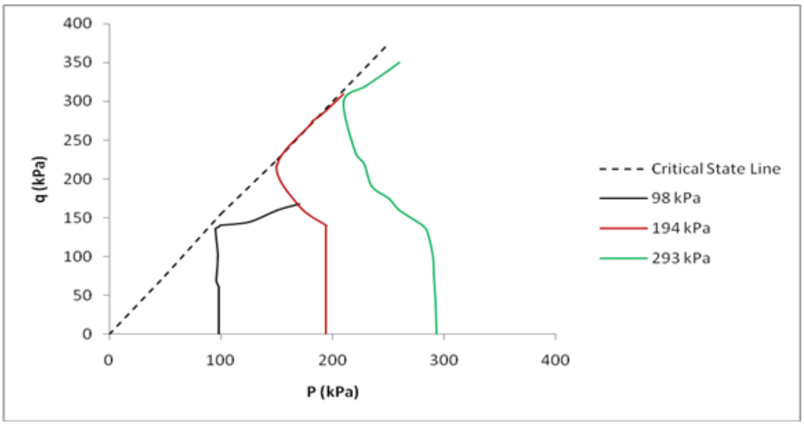


Fig. 24: Effective path of soil stress for untreated Sabkha.

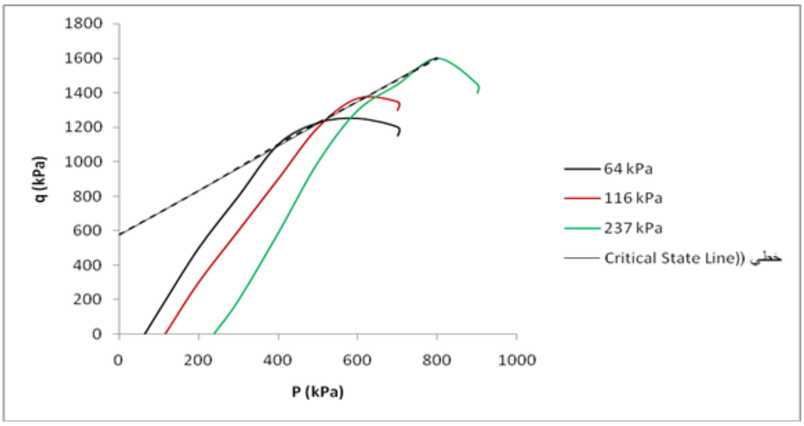


Fig. 25: Path of effective stress for treated sabkha soil (SFM concentration = 6% and curing duration = 7 days).

4.4. Soaked CBR test for stabilized Sabkha soil

CBR test samples of Sabkha soil are produced with stabilizer dosages that fulfill the ACI Committee's minimum strength requirements (2011) [33]. In addition, soil samples treated with 2%, 4% and 6% furfural are subjected to ASTM D1883-16 testing (2016) [34]. After samples are sealed, the laboratory has a 7-day curing period at (22±3) degrees Celsius. Before testing, the samples are steeped for 96 hours in ordinary tap water. To study the link between SFM addition and the soaked

CBR of Sabkha soil, soggy CBR tests are undertaken on Sabkha soil-SFM combinations and on Sabkha soil alone. There is mention of the flat, Sabkha soil. Figure 26 demonstrates that the soaking CBR of Sabkha soil increases as its SFM content increases. The soaking CBR is increased by 2%, 4% and 6% SFM, from 11% to 21%, 32%, and 58%, respectively. Adding any quantity of SFM significantly increases the saturated CBR of the sabkha soil in this study, making it a suitable material for use as a pavement foundation course. This study revealed that the soaking CBR of ordinary Sabkha soil is similarly 11%, showing that the soil is very water-sensitive. 11% was the initial CBR of ordinary Sabkha soil.

Table 7. The saturated CBR of the stabilized Sabkha soil.

Stabilizer content	Soaked CBR %			
	Sample #1	Sample #2	Sample #3	Average
Sabkha soil (no additive)	8	14	11	11
2% SFM	19	21	23	21
4% SFM	33	30	33	32
6% SFM	54	58	62	58

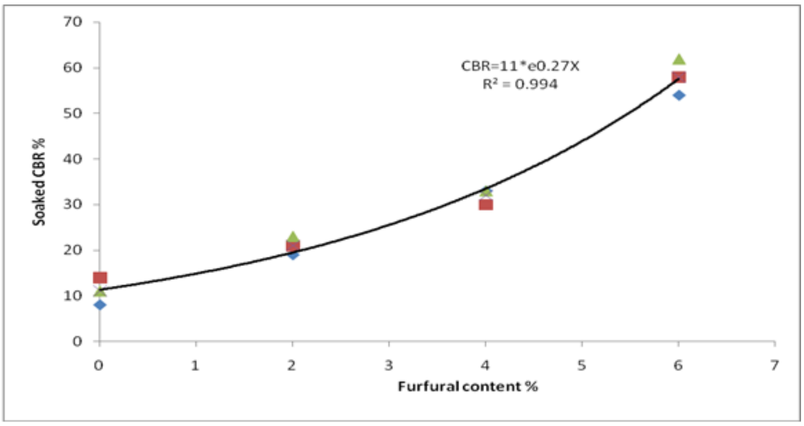


Fig. 26: Influence of SFM on the saturated CBR of sabkha soil.

4.5. Wetting and drying tests on stabilized Sabkha soil

After stabilization with the selected stabilizers, the stability of the Sabkha soil is examined using durability tests to see if it can withstand lengthy exposure to unfavorable circumstances. Only sufficiently potent mixtures are employed in trials. ASTM D559/D559M-15 [35] durability tests are done on Sabkha soil combined with 2%, 4%, and 6% furfural since these percentages all meet the strength criterion (2015). The findings of the compaction tests are used to determine the optimal moisture content for sample preparation. There are three of each manufactured item. In plastic bags, the samples are crushed and cured for seven days at room temperature. After 12 cycles of wetting/drying and brushing, it is possible to quantify the weight loss. Based on the findings, Sabkha soil stabilized with 6% SFM loses roughly 8.4% of its mass over time, whereas soil stabilized with 4% SFM loses approximately 10.5% and soil stabilized with 2% SFM loses approximately 15.4% of its weight. The measured weight loss is less than the maximum allowable weight loss of 14% as defined by the Portland Cement Association (PCA) and 11% as stated by the United States Army Corps of Engineers (USACE) for soils categorized as soils and SP with Pl 10, respectively [33]. In conclusion, from a strength and wetting and drying standpoint, Sub-base material for rigid pavements may be either 6% SFM-stabilized Sabkha soil or 4% SFM-treated Sabkha soil.

4.6. Toxicity and cost of a new material (SFM)

The new material contains the majority percentages in its composition of carbon, nitrogen and calcium, and the rest is percentages of silicon and sodium in small percentages are shown in fig. 8, and there are no harmful substances on the environment and organisms such as humans, animals and plants, so it is an environmentally friendly material based on EDX analyses for a new materials SFM, as for the cost of manufacturing this material, each liter of it is equivalent to nearly half dollar.

5. Conclusions

The city of Samawa in Al Muthanaa, Iraq, provided us with some delicious examples of Sabkha. Because it includes both silicate and carbonate minerals, the soil is classed as silty sand (SM). Two, four, and six percent SFM were used to stabilize the soil. The stabilized soil underwent testing, including compaction, strength, and durability evaluations. The following conclusion may be made in light of the findings provided in this paper:

1. The incorporation of SFM significantly enhances the shear strength of Sabkha. Additionally, there is a direct correlation between the quantity of SFM utilized and the curing duration, both of which influence the level of shear strength achieved. Especially 6% of SFM.
2. Within the restricted pressure range examined in this study, the SFM notably enhances the effective cohesiveness but has no impact on the effective friction angle
3. Un treatment Sabkha demonstrated ductile behavior, while the addition of SFM with percentages (2,4 and 6%) introduced dilatant characteristics at failure, making the material slightly brittle.
4. Stress-strain behavior and the effective stress path are distinctive features of cemented calcareous soils.
5. Micro-characterization techniques, including EDX, X-ray, and SEM, demonstrate that the enhanced presence of fibrous structures in the stabilized sabkha soil plays key role in the substantial improvement in Unconfined Compressive Strength (UCS), meeting the standards outlined by the Act Committee (2011) guidelines.
6.The durability test revealed that the stabilized Sabkha with 4% and 6% SFM exhibited minimal weight loss over time.

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