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Stabilization of Sandy Soils by Bentonite Clay Slurry at Laboratory Bench and Pilot Scales

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Abstract: Sand is one of the most abundant, naturally occurring materials in many parts of the world, which is used in local rural areas in infrastructure projects such as in the construction of low volume paved and unpaved road layers due to their availability at low cost and scarcity of other suitable construction materials. Several geotechnical solutions for sand stabilization have been undertaken to improve their properties in order to overcome erosion, failure of pavements under traffic loading, embankments, cuts and excavations caused by failures of sand structure. In this investigation, bentonite clay–water slurry was used due to its cohesive and eco-friendly nature to improve sand strength by the means of manual injection in the laboratory and pilot scales. Sand was stabilized using variation of bentonite clay contents, 0%, 1%, 2%, 3%, and 4% (by weight of dry sand), at different curing times: 0 days, 1 day, 2 days, and 3 days. Direct shear tests were conducted to determine shear strength parameters for sand before and after stabilization process. Furthermore, a transparent polypropylene box (60 cm × 40 cm × 30 cm) was used in this study as a larger scale for sand stabilization technique by applying manual grouting of bentonite clay–water slurry to the sand mass. A mechanical shaker was used at 100, 200, 300, and 400 rpm for 10 min at each stage to test the stability of sand in addition to using a Scanning Electron Microscope (SEM) to obtain images for stabilized sand and Ground Penetrating Radar (GPR) to scan soil mass before and after stabilization. The test results showed that a slurry composed of 3% of bentonite clay additive with 10.3% added water by weight of dry sand mass are the optimum amounts for the stabilization process, which provides a substantial resistance to shear forces.

Keywords: sand road layers; bentonite clay; slurry; stabilization; shear strength; curing; grouting; georadar; mechanical shaking

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1. Introduction

Sand is one of the main type of soils which has garnered the direct attention of researchers due to its abundant existence in various sites [1]. To overcome the weakness of sandy soils, adding a foreign agent or using a mechanical stabilization method can be used to improve the properties of soil [2]. Soil stabilization can improve the performance of soil to increase its strength and bearing capacity.

The cohesionless soil can be given some cohesion by the rearrangement of soil particles and decreasing the voids between the particles by adding fine particles between them and increasing the density; then, the required properties can be improved. The chemical combinations available due to the additives can also generate new bonded materials, which can provide the soil mass with better engineering properties. Several materials were used as stabilizers in the literature for sandy soils such as bentonite [3], ceramic tile waste [4], geopolymers, fly ash and lime [5], and bentonite and lime [6].

The stabilizing processes of sand were illustrated by Zang et al. (2015) which can be summarized as sand grains stacking incompactly in the nature, meaning that the grains are cohesionless because their junctions are unfixed, which makes the grains easy to slide along one another. When sand-fixing material containing binding particles is sprayed onto the surface of sand, it gets into the cores of sand by seepage. During the seepage, the material fulfils two actions: enveloping the grains to form water films and filling the gap among the grains. Then, along the area of water evaporation, the material gradually cures to become solid. In the end, an irregular matrix made up of cured sand-fixing material is formed in the sand pores, uniting the loose sand grains tightly as a uniform sand–material network [7].

One of the additives that can be used for stabilization purposes is bentonite clay, which is composed mainly of the clay mineral montmorillonite. Most bentonite deposits are formed by the alteration of volcanic ash, mainly in damp or wet conditions, or by the decomposition of primary rocks in water; the color of bentonite deposits varies according to location [8]. A fundamental property of bentonite clay is water absorption, and the level of hydration and swelling depends on the type of exchangeable ions contained, with different hydrophilic and solvating powers [3].

There have been several attempts to stabilize sand by bentonite, for example, Czaban et al. (2013) studied the effect of bentonite on the agriculture, sand due to a lack of nutrients and weak water storability [9]. Their results indicated that adding bentonite led to increases in the organic carbon and nitrogen, consequently, increasing the fertility of sand for agriculture. Likewise, the findings by Muhammad and Siddiqua (2019) indicated that the compressive strength of silty sand was improved by adding bentonite clay [10].

Using bentonite in the literature as a stabilizing agent for coarse-grained and fine-grained soils confirmed the improvement in their properties. For instance, Gueddouda et al. (2008) studied the hydraulic conductivity and shear strength of dune sand–bentonite mixtures. The hydraulic conductivity of the dune sand–bentonite mixtures decreases with the increasing percentages of bentonite, because bentonite adhered onto the sand particle surfaces and filled up the voids, which resulted in a narrow water flow path and hence a decrease in hydraulic conductivity. The results showed that the shear strength of sand bentonite mixtures decreases with bentonite additions; the friction angle is inversely proportional to additional bentonite, and the addition of bentonite led to increasing the cohesion because of the high content of fine particles (less than 2 μm) [11].

The effect of adding 1% and 2% nano-soil after a ball-milling process for a sedimentary residual soil obtained from a site within the campus of University Kebangsaan Malaysia (UKM), was studied. Each nano-soil was added to its original soil to study its own effect. The researcher studied the properties of original kaolinite, montmorillonite and UKM soil concerning their liquid limit, plastic limit, plasticity index, and specific surface before and after the addition of the nano-soil. Laboratory results showed that there was an increase in liquid limit and plastic limit values after adding the nano-soil and it led to a decrease in the value of the plasticity index. The average compressive strength showed a significant improvement when adding milled soil. The researcher noticed that a small number of crushed particles or nano-soils can provide significant improvement in the geotechnical properties of soil [12]. Sand stabilization potential using bentonite and lime was studied and a series of laboratory tests were performed on this soil: Compaction and Unconfined Compression Strength (UCS). The studied mixtures were prepared for the tests by using 5%, 10% and 15% bentonite with lime added at percentages of 1%, 2% and 3%. The results showed substantial improvements in the results of UCS with addition of 15% bentonite and 3% lime. Meanwhile, further addition of bentonite and lime in dune sand causes compaction difficulties, as the mix becomes sticky [6].

Several experiments were performed to stabilize dune sand with ceramic tile waste by mixing the compositions of dune sand with ceramic tiles wastage as admixture, and it was found that with increasing percentages and particle sizes of admixture the stabilization of dune sand was achieved [4]; moreover, the addition of fly ash improved the shear strength of sand to be used as an embankment material for road infrastructure material [13].

Increasing the bentonite content in sandy soil led to an increase in the cohesion and decrease in the angle of internal friction angle with a small amount [14]. In general, the shear stress for sandy soil at failure increased when increasing the bentonite content, and the cohesion of sand–bentonite mixtures increased to 3.34 kPa, 22.9 kPa and 70.6 kPa when sand was mixed with 10%, 20% and 30% bentonite, respectively. The internal friction angle increased, and cohesion decreased with increasing curing time [15]. Other researchers concluded that there is a significant increase in shear strength due to the use of bentonite and good improvement when lime was used with a limited amount of micaceous sand [16].

Bentonite slurry is widely used in various projects due to its excellent engineering properties. The behavior of slurry infiltration, especially filter cake formation, is directly related to the effect of slurry. The results illustrate that the bentonite slurry with guar gum could immediately form an external filter cake with an infiltrated zone. The external filter cake formed again with a denser bentonite clay platelet network after excavation in the condition of relatively short excavation distance. Therefore, this kind of slurry could rapidly stabilize the excavation surface in slurry-driven shield tunneling [17]. The infiltration of pressurized bentonite slurry in saturated sand has been investigated in two laboratory setups and the transition from mud spurt to filter cake formation depends on the infiltration velocity according to the literature [18].

The stabilized sandy soil with bentonite slurry will resist the infiltration of water through it due to the reduction of permeability (k). In terms of bentonite content, the addition of more than 3% bentonite via slurry injection and mixing with the sands was successful in reducing the k of the unmixed sands (9.4×10^{-3} cm/s $\leq$ k $\leq 5.4 \times 10^{-2}$ cm/s) by as much as four orders of magnitude, to values less than 1.0×10^{-6} cm/s [19].

From the above thorough revision, one can notice that most of the literature focused on studying the effect of using bentonite as a soil-stabilizing agent by mixing it using different percentages, as well as soil stabilizers, in a bench scale. Additionally, no attention has been paid to the effect of grout technique used by these studies.

In this study, the bentonite clay–water slurry was used for sand stabilization in two phases, a batch test to find the optimum bentonite content using the shear strength of soil as a reference, in addition to examining the curing effect by studying the strength variation of the stabilized soil with time, and the grout application technique using the GeoRadar scanner to test for bentonite grout distribution in addition to using a mechanical shaker to test the stability of grouted sand in a pilot scale.

2. Materials and Experimental Program

2.1. Soil Properties

Poorly graded natural Sweileh sand (80% SiO_2, 18% kaolinite clay and other minerals) with bulk density of 1624 kg/m^3, in addition to poorly graded natural silica sand (quartz 99% SiO_2, with impurities of clay minerals; kaolinite and illite) with bulk density of 1480 kg/m^3 were collected from 25 cm depth at different locations in Jordan and transported to the laboratory to undergo several laboratory tests; both sands were untreated pass sieve US no. 4, and their strength parameters are given in Table 1.

Table 1. Shear strength parameters for Sweileh and silica soils.

Sand	Natural Sweileh Sand	Natural Silica Sand
Friction angle (°)	26.31	30.75
Cohesion (kN/m^2)	33.11	26.14

2.2. Additive Properties

The bentonite used in this study is a light brown soluble hydrophilic bentonite powder as shown in Figure 1; it is a pass US sieve no. 200 with 2.6 g/cm^3 specific gravity, 10% water content, 410 m^2/g surface area, and 180% absorption. Figure 2 shows the X-ray diffraction pattern of the additive that indicates a clear presence of the predominant mineral of montmorillonite while Table 2 shows its elemental analysis using the X-ray fluorescence analysis of the additive. Montmorillonite, halloysite, and opal are the major constituents of the used bentonite clay as indicated by the XRD analysis while silica (Si) and aluminum (Al) are the major elements as indicated by XRF.

Table 2. XRF elemental analysis of used bentonite.

Element	Percent
Si	68.5
Al	12.4
Ca	4.9
Cl	3.4
Fe	3.4
Na	2.4
Mg	2.1
S	1.4
K	0.9
Ba	0.2
Mn	0.1
Ti	0.08
P	0.04
Zn	0.02
Cr	0.02
Ni	0.009
Rb	0.008

Figure 1. Sample of the used bentonite.

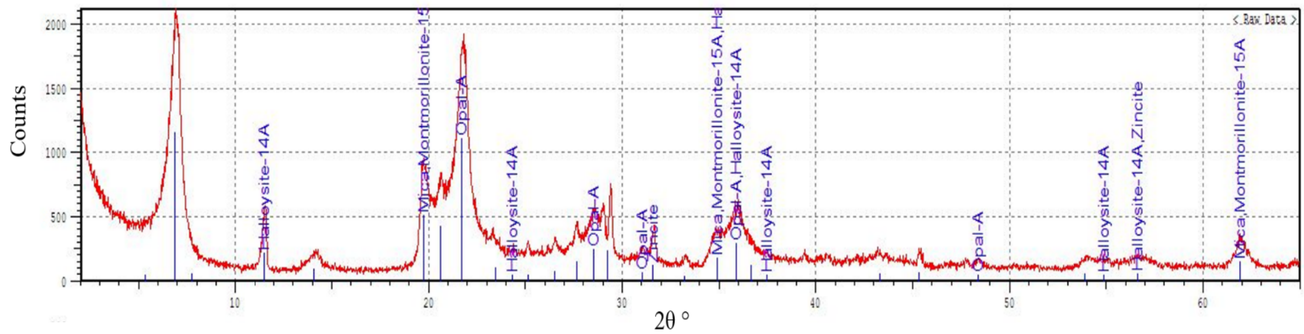
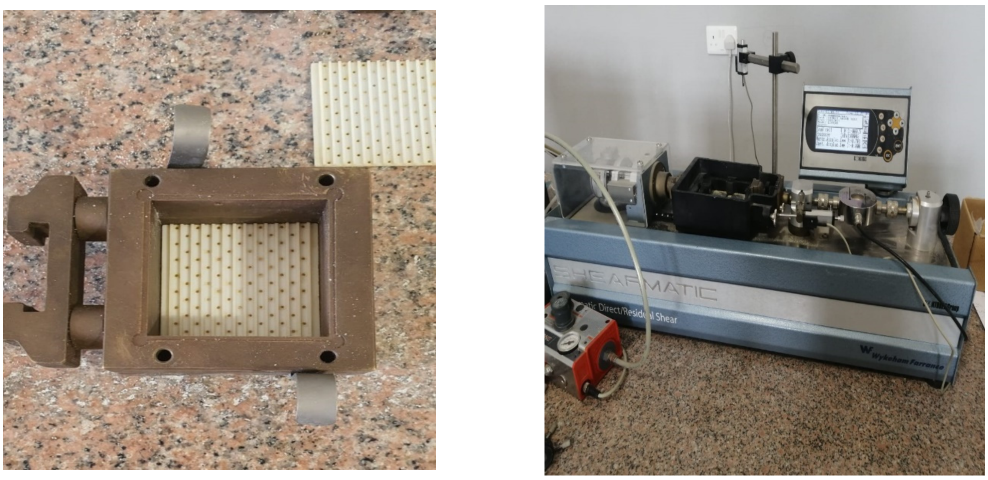


Figure 2. XRD of bentonite clay used in this study.

3. Experimental Program

3.1. Bentonite Clay–Water Slurry Preparation

The bentonite clay–water slurries were prepared by mixing bentonite clay and tap water in varying proportions by weight. Varied volumes of water were used to mix with bentonite; 10 mL, 12 mL, 15 mL, and 18 mL; thereafter the bentonite was added at percentages of 1%, 2%, 3% and 4% by the weight of dry sand that filled a shear box of 60 mm × 60 mm × 20 mm, as shown in Figure 3a.



(**a**) (**b**)

Figure 3. The shear strength device used in this study: (**a**) Shear box (60 mm × 60 mm cm × 20 mm). (**b**) Shear strength device.

Bentonite clay–water slurry was prepared by placing water in a beaker, then the bentonite was added gradually to the water and stirred instantaneously with a spatula until a homogeneous solution was reached. Bentonite clay was added to water gradually and stirred manually, and after that it was mixed by an electric mixer for 3 min (to prepare larger amounts of slurry) in order to remove all clusters to obtain a homogenous mixture. The bentonite clay–water slurry was added to the sand and mixed thoroughly. After performing 48 trials of bench tests (three samples for each mixture were prepared) to find the volume of water to be mixed with bentonite clay, based on the ease of mixing, application, and highest shear strength (as shown in the results), the volume of water was estimated to be 12 mL of water. The dry mass of sand in the shear box was used as the basis for determining the optimum amount of tap water required to be added to the bentonite clay to form the slurry and then to be injected to the sand mass. The bentonite–water slurry was prepared as a percentage of dry mass of sand, then it was added to the amount of water (12 mL per 115.5 g of sand to fill the shear box). Then, the mixtures were subjected to a direct shear test at a rate of 1mm/min in the shear strength device to determine the shear strength parameters of the soil samples.

3.2. Direct Shear Test

A direct shear test was performed according to ASTM D3080/D3080M–11 (Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions) [20] after sieving soil samples on a US sieve No. 4. A stress–strain curve was plotted for each soil sample before and after the addition of the stabilizer.

Stabilized soil samples by bentonite was prepared for curing at 1 day, 2 days and 3 days, in order to find the effect of stabilizer directly after application with different periods of time at room temperature (24 °C) in order to reflect the field conditions without rainfall or vibrations. The samples were prepared in made-up stainless-steel molds (each mold consists of two parts—two square halves—with the same dimensions of the shear box and fixed with an elastic to easily separate them in order to place the soil sample in the shear box, as illustrated in Figure 4). The prepared soil samples in the molds were left at room temperature. After the mixing process, SEM images were obtained using a QUANTA FEG 450 at various magnifications as shown in Figure 5a,b, which revealed the presence of bentonite clay (platy shapes on the surface). Additionally, it can be seen how the stabilizer filled the pores and coated the sand grains resulting in a denser filler, narrower pores, and more uniform surface that increased the density of the sandy soils and provided the desired improvement in sand strength.

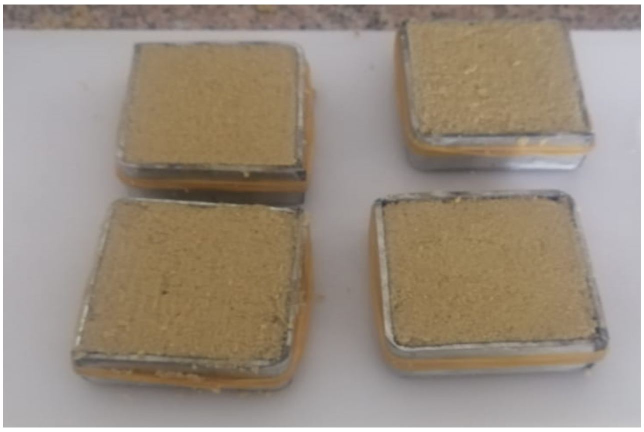
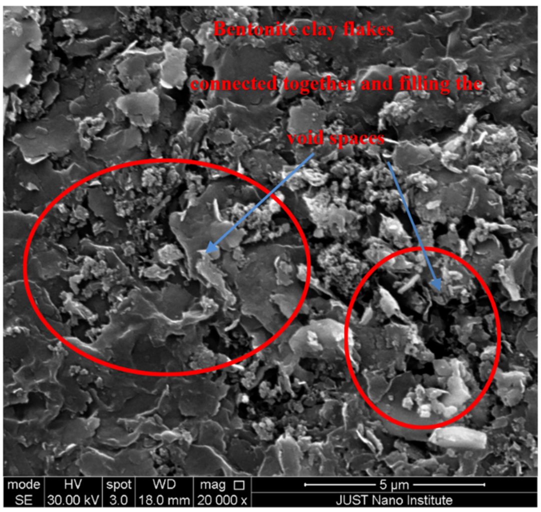
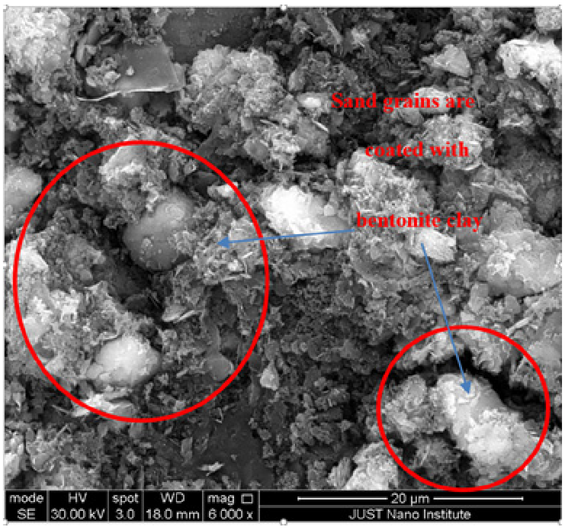


Figure 4. Samples of stabilized sand in molds.



(**a**)

Figure 5. *Cont.*

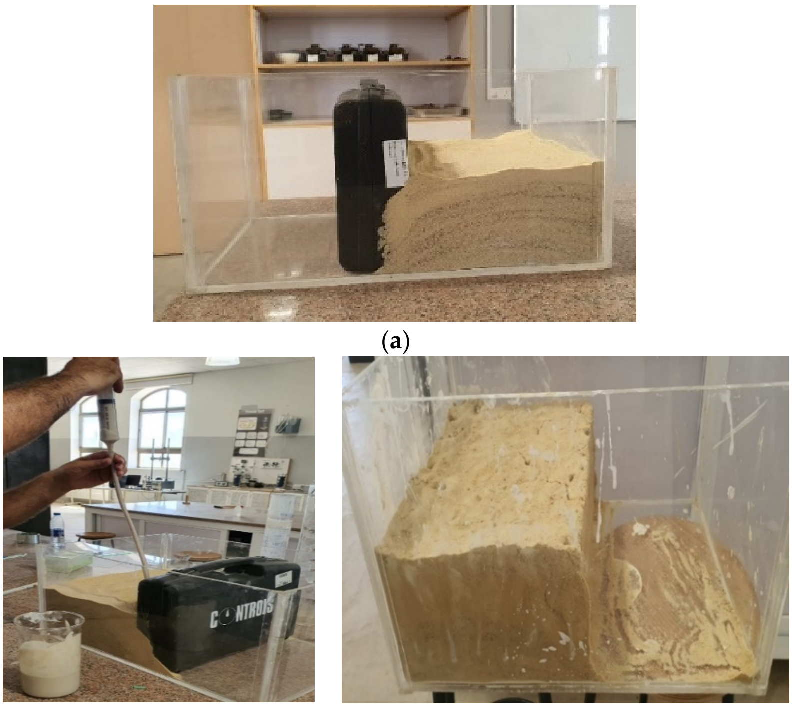


(**b**)

Figure 5. SEM images of stabilized sand with bentonite clay–water slurry. (**a**) SEM image of a stabilized sand mass surface (20,000 mag). (**b**) SEM image for the middle part of stabilized sand (6000 mag).

3.3. Pilot Scale

A transparent polypropylene box with dimensions of 60 cm × 40 cm × 30 cm was customized and manufactured with extra support at the box corners to be used in this study for larger scale of sand stabilization using manual bentonite–water slurry injection technique. To prevent the sand from failing, as shown in Figure 6a, the box was filled partially with 30 kg of sand using a vertical solid plastic barrier in front of the sand to support the loose sand behind it.



(**a**)

(**b**) (**c**)

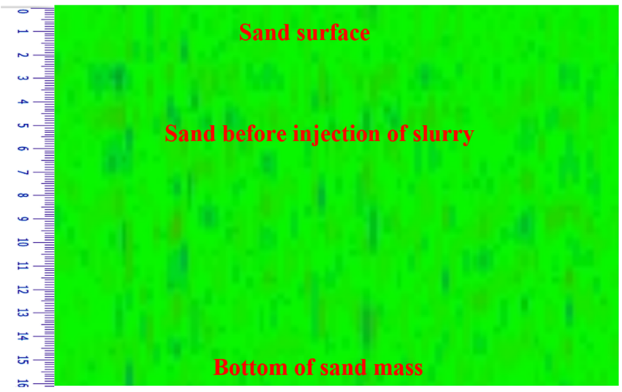
Figure 6. Box filled with sand and supported with barrier before and after injection process. (**a**) Box filled with sand and supported with barrier. (**b**) Bentonite injection process into sand. (**c**) Box filled with sand and supported with barrier.

A transparent plastic tube of 10 mm diameter (outside) and 8 mm diameter (inside) and a 100 mL syringe were used; the top area of the sand was divided into squares of 4 cm × 4 cm, the tube was manually inserted in a vertical direction in the sand in each corner until it reached the bottom, then the injection process started next to the barrier (the first row of squares) by filling the syringe with the bentonite slurry and injecting it slowly in stages by pulling the tube whenever sufficient slurry was injected, until it reached the surface. A similar process was repeated all over the area of sand in each corner of the squares starting from the front row to the back rows as shown in Figure 6b.

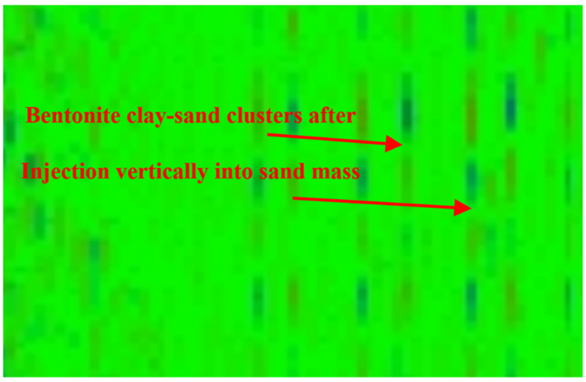
Then, the stabilized sand was left in room temperature for 1 day; the same process was repeated and cured for 2, and 3 days. The 3 day stabilized sand (Figure 6c) was tested using a mechanical shaker at 100 rpm, 200 rpm, 300 rpm, and 400 rpm for 10 min at each stage.

Oerad Easyrad ProPack Ground Penetrating Radar (GPR) is used in this study as a nondestructive method to scan soil mass, which uses a pulsed dipole GPR (consists of a transmitter, a receiver, antennas, battery, cables, and a processing IPad-software) with an excellent penetration depth designed to survey, detect and predict geophysical phenomena in terms of the soil condition, as well as to detect objects such as cables and pipes, and voids and cracks; the equipment setup is illustrated in Figure 7a.

(**a**) GPR setup.



(**b**) Radargram for sand before slurry injection.



(**c**) Radargram for stabilized sand.

Figure 7. GPR setup and Radargram for non-stabilized and stabilized sand in pilot scale.

Figure 7b,c show a ground penetrating radargram performed on the soil mass (scan in-depth vertically where green color represents sand mass) before and after stabilization with bentonite clay–water slurry. The vertical columns after stabilization indicate the presence of the grouted bentonite clay–water slurry in the sand and the distribution of the slurry around the grouting area forming bentonite–sand clusters, which has improved the sand ability to resist shear forces during shaking process using the mechanical shaker.

4. Results and Discussion

4.1. Optimum Volume of Water to Be Added

Figure 8 shows the shear failure envelopes for sand masses containing 10 mL, 12 mL, 15 mL and 18 mL of added water to 115.5 g of dry sand; shear strength parameters were obtained, then, the shear strength of stabilized sand samples were calculated. Based on results, the quantity of 12 mL of water (10.4% of dry weight of sand) was selected to be applied as it provides the maximum shear strength, ease of application, consistency, and ease of mixing on bench tests.

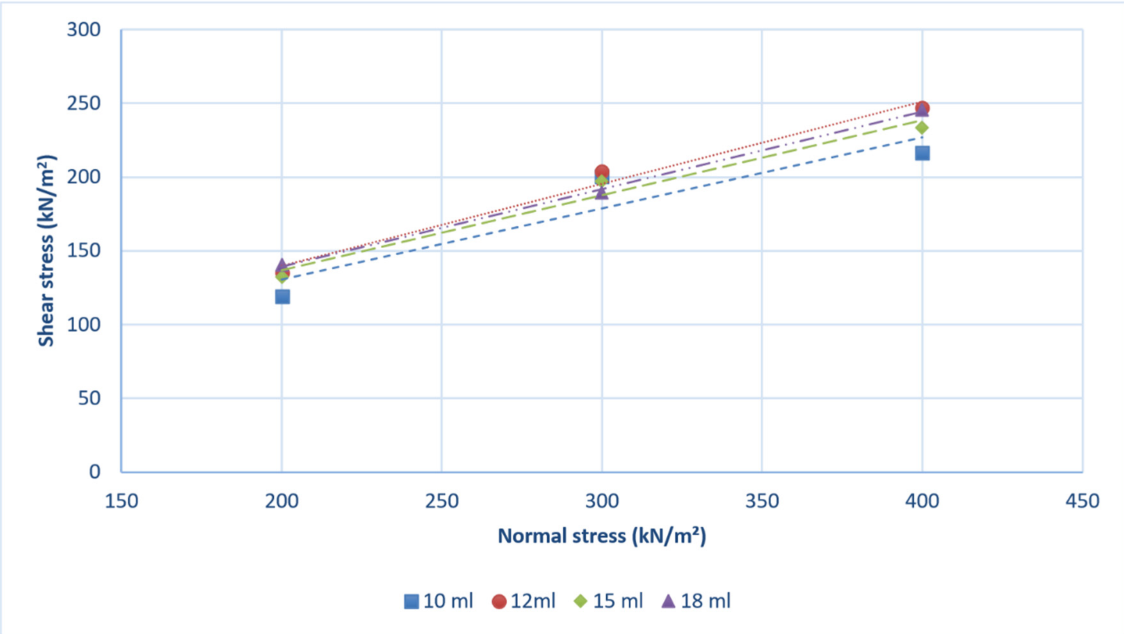


Figure 8. Shear failure envelopes for Sweileh sandy soil using various volumes of water.

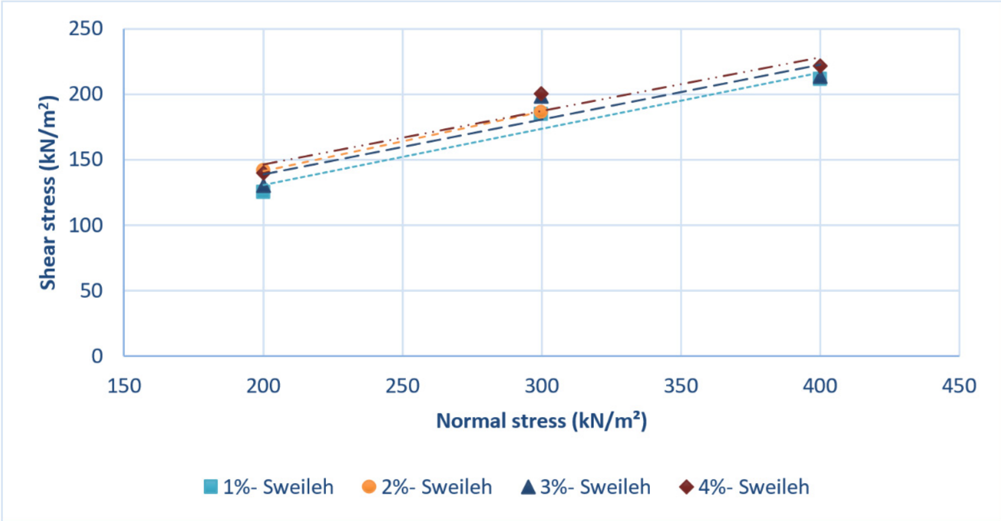
4.2. Optimum Amount of Bentonite Clay to Be Used in the Slurry

In order to find the best quantity of bentonite clay to be used as an optimum amount of the stabilizer, a shear strength test was conducted with different amounts of bentonite clay: 1%, 2%, 3% and 4% by dry weight of sand. Figure 9 shows the shear failure envelopes for the stabilized sand with varied amounts of bentonite clay–water slurry. The experimental tests for sand indicate (Figure 9a,b) that 4% bentonite content provides the greater shear strength of soil for Sweileh sand. The shear strength of sand increased by 28%, 18.2%, 6.1%, and 6% for 4%, 3%, 2%, and 1% bentonite, respectively, compared to non-stabilized Sweileh sand. Adding bentonite more than 4% by weight of dry sand was very difficult in terms of slurry preparation and grouting process because the slurry became very thick which made it very difficult for the injection process within the sand mass; this was the reason to stop at 4% bentonite clay content.

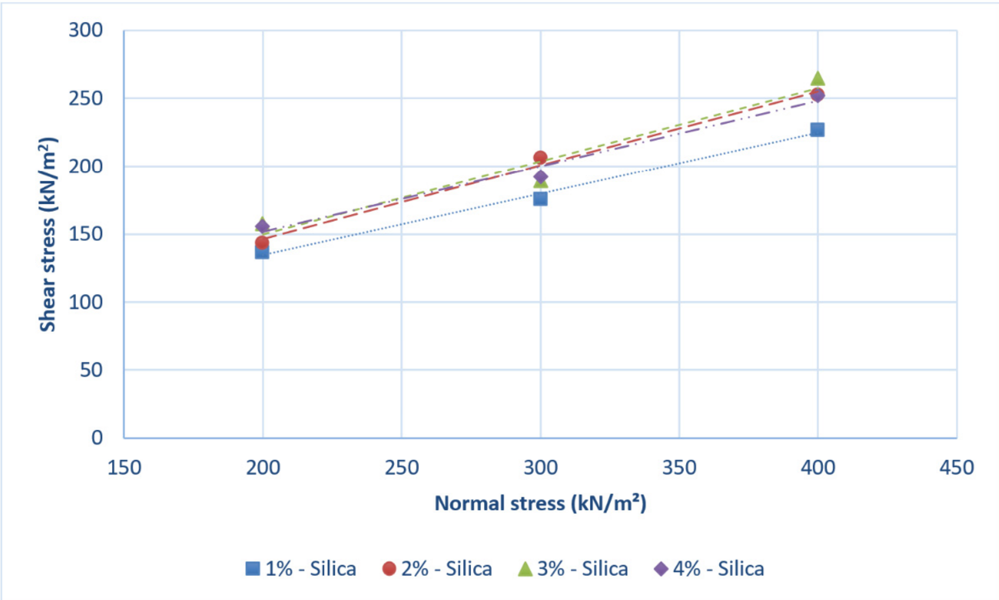
However, for silica sand 3% bentonite clay–water slurry grout was chosen to be the optimum amount of stabilizer which provides greater shear strength as indicated by Figure 9b with the grey dotted line with 12.5% higher shear strength compared to non-stabilized silica sand.

It is worth mentioning that the cohesion term increases with the increase of bentonite clay content in the mixture. Nevertheless, for both types of sands the friction angle decreased with the bentonite addition because of the reduction in friction between sand particles due to the existence of bentonite clay, which filled the voids and coated the sand particles causing the reduction of friction between sand grains. In case of silica sand, the friction angle dropped when increasing the bentonite clay content in the slurry from 28.2° for 3% bentonite content to 25.8° for a bentonite clay content of 4%. In the case of

Sweileh sand, the friction angle dropped slightly from 22.7° to 22.3°. The reason for this slight drop in Sweileh sand can be attributed to the higher amount of clay in its natural constituent. However, in the case of silica sand the impurities (clay content) were less than for Sweileh sand.



(**a**) Sweileh sand.

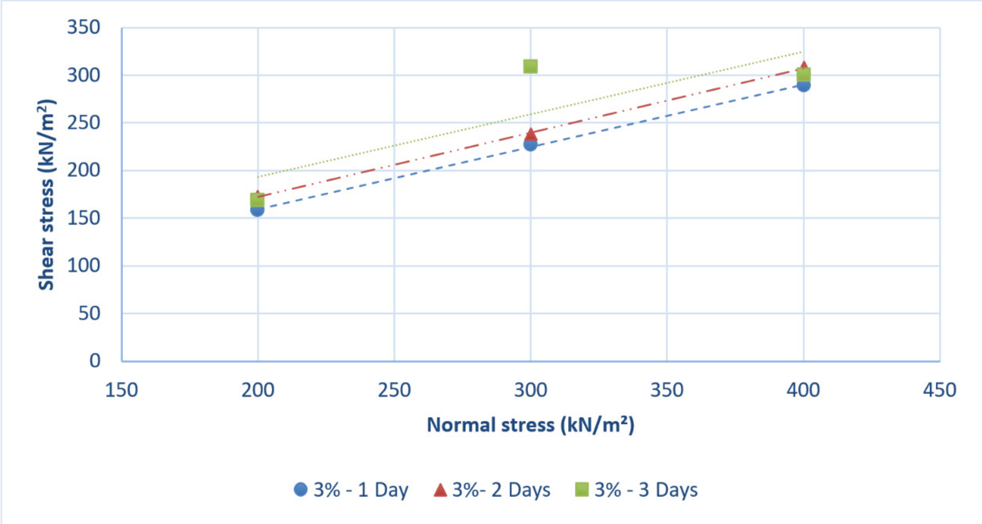


(**b**) Silica sand.

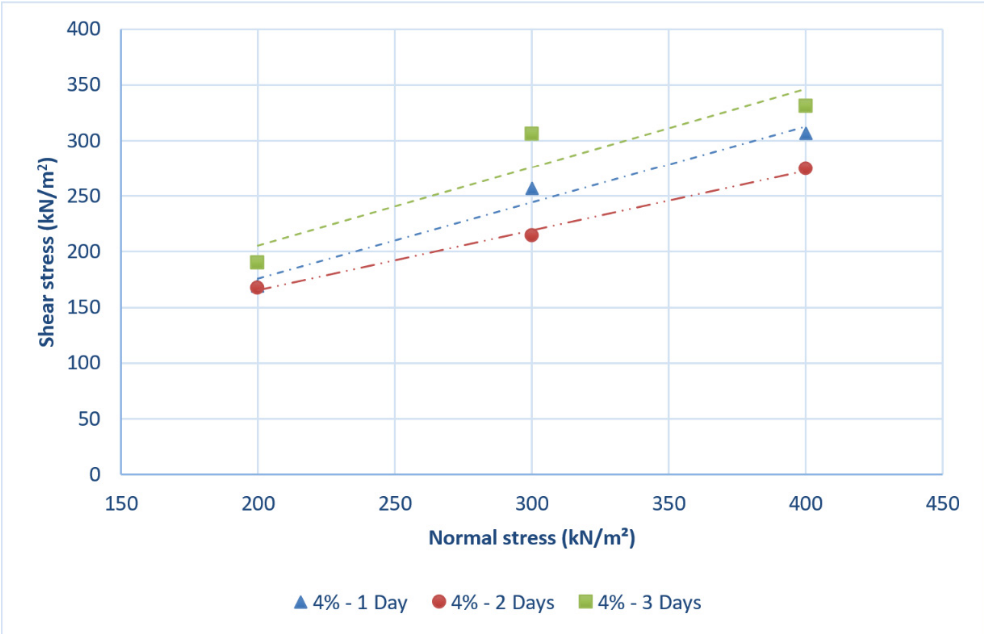
Figure 9. Shear failure envelopes for (**a**) Sweileh, and (**b**) silica sandy soils using various amounts of bentonite clay.

4.3. Curing Stage for Stabilized Sand with 3% and 4% Bentonite Clay–Water Slurry

In order to find the time effect on stabilized sand mixtures, a shear strength test was conducted on Sweileh sand at different time periods; 0 day, 1 day, 2 days, and 3 days with different amounts of bentonite clay additive, namely 3% and 4%. Figure 10a,b reveal the shear failure envelopes after the curing process for 3% and 4% bentonite, consequently. The tests result reveal that the curing time is an important factor which has a direct influence on the shear strength of soil; 3 days of curing for both percentages of bentonite(3% and 4%) indicates a higher shear strength compared to the 1 and 2 day curing times. This can be attributed to the evaporation of water from soil mass leaving sand–bentonite clusters, which contribute to increasing the bonds between sand–sand particles that led to the shear strength increase, therefore a higher ability to resist shear forces.



(**a**) Curing of Sweileh sand stabilized with 3% bentonite clay.



(**b**) Curing of Sweileh sand stabilized with 4% bentonite clay.

Figure 10. Shear failure envelopes after curing for Sweileh soil using: (**a**) 3% bentonite clay; (**b**) 4% bentonite clay.

Table 3 shows the values of friction, cohesion, and total shear strength of soil at different curing periods. Figure 11 shows the shear strength with curing period in days which shows that the curing time is a significant parameter to improve the stabilized soil to shear forces specially at 3 days curing time, which increased the shear strength by 31.6% and 27.9% for 3% and 4% bentonite percentages, respectively, compared to tested samples directly after stabilization (without curing time).

Table 3. Shear strength parameters for Sweileh and silica sandy soils stabilized with various amounts of bentonite contents.

Bentonite Content %	**0%**		**1%**		**2%**		**3%**		**4%**	
	Sweileh Sand	**Silica Sand**	**Sweileh Sand**	**Silica Sand**	**Sweileh Sand**	**Silica Sand**	**Sweileh Sand**	**Silica Sand**	**Sweileh Sand**	**Silica Sand**
Friction angle (°)	26.31	30.75	23.29	24.33	25.47	28.51	22.67	28.22	22.29	25.83
Cohesion (kN/m^2)	33.11	26.14	44.46	44.11	40.35	37.70	55.43	42.70	64.36	54.75
Shear strength (kN/m^2)	82.55	85.63	87.52	89.33	87.98	92.02	97.19	96.37	105.36	103.15

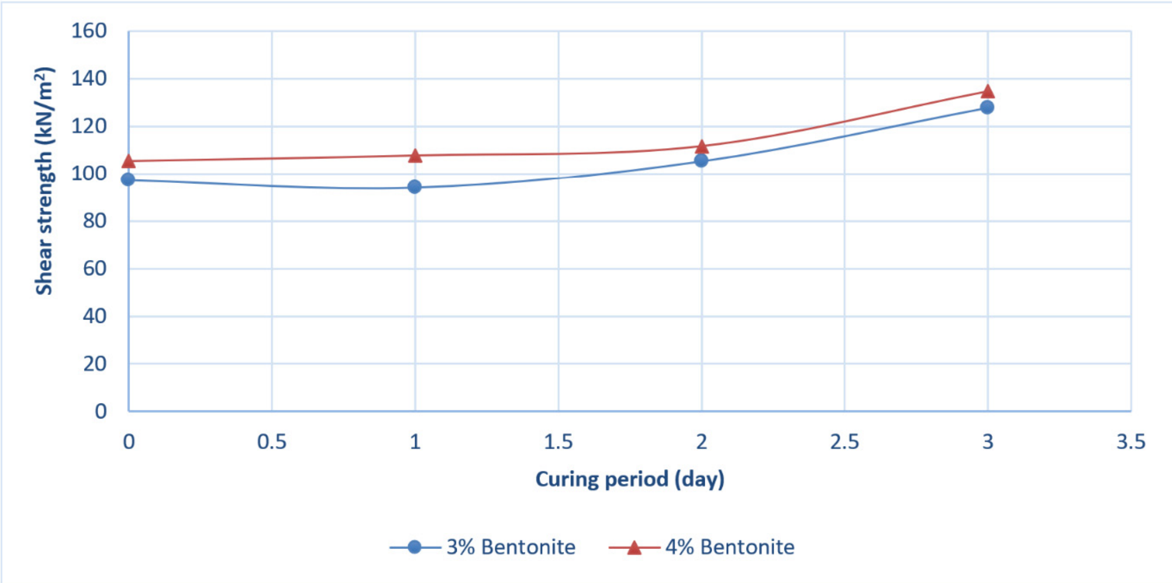


Figure 11. Shear strength values versus curing period for Sweileh sand stabilized with 3% and 4% bentonite clay.

It is important to explain that the bentonite powder (passed from sieve no. 200) enhances the strength by reinforcing the packing density, filling the spaces between sand particles and reducing the porosity. Therefore, an increase in internal friction between sand particles occurred by decreasing the amount of free water [21,22].

Bentonite leads to increases in the precipitated calcium carbonate ($CaCO_3$), which leads to the production of calcium ions (Ca^{+2}). Thus, ion exchange occurs between calcium ions (Ca^{+2}) and lower valance ions. Therefore, the sand particles will be flocculated and agglomerated [23].

After applying the shaking process to simulate shear forces or earthquakes for cured stabilized Sweileh sandy soil (after 3 days) by using a mechanical shaker at varied rpm capacities from 100 to 400 rpm for 10 min at each stage for stabilized sand with bentonite clay–water slurry (additive contents 3% and 4%), the results show that for both bentonite clay contents at 100 and 200 rpm, the shaking process for 10 continuous minutes at each rpm capacity had no effect on the stabilized soil and the soil mass remains intact as shown in Figures 12a and 13a; however, at 300 rpm shaking for 10 min, the soil starts to fall from the top part-cleft side (Figures 12b and 13b) yet for stabilized soil with 3% bentonite the amount of failed soil was not significant. At 400 rpm shaking for 10 min the soil mass collapsed partially (Figures 12c and 13c), and the amount of collapsed soil that was stabilized with 4% was much less than that stabilized with 3% bentonite clay. Although, after shaking the stabilized sandy soil with 4% bentonite clay for a total of 40 min (10 min each stage) at 100, 200, 300, and 400 rpm, the soil was intact.

(**a**) At 100 and 200 rpm. (**b**) At 300 rpm. (**c**) At 400 rpm.

Figure 12. Shaking the stabilized Sweileh sand with 4% bentonite clay at 100 to 400 rpm for 10 min each time.

(**a**) At 100 and 200 rpm. (**b**) At 300 rpm. (**c**) At 400 rpm.

Figure 13. Shaking the stabilized sand with 3% bentonite clay at 100 to 400 rpm for 10 min each stage.

4.4. Comparison between Current Study Results and Other Similar Studies

Previous studies are in line with the findings of the current study regarding the effect of bentonite clay additives to sand as a stabilizer on a bench scale. All results of research work determined that the bentonite clay addition resulted in a slight decrease in the internal angle of friction for sand and an increase in the sand cohesion. For example, Tawfiq (2009) used varied amounts of bentonite clay (2.5%, 5%, 7.5%, 10%) to stabilize poorly graded sand on a bench scale; the stabilized sand with 5% bentonite clay resulted in a friction angle of 53.2° and cohesion of 3.6 kPa compared with 54.6° and zero cohesion for sand without bentonite clay additive. Sadhwani et al., (2020) used 0%, 2%, 4%, 6%, and 8% bentonite clay additive to stabilize micaceous sands; they found out that the gain of strength was not significant beyond 4% bentonite clay addition. For example, for 15% mica in micaceous sand stabilized with 4% bentonite clay the friction angle of the mixture was 32.3° and the cohesion was 8.6 kPa, compared to 35.9° and zero cohesion for sand with 0% bentonite clay [16]. In the current study, 4% bentonite clay was selected as an optimum amount of additive to stabilize poorly graded natural Sweileh sand which resulted in a 22.29° friction angle and cohesion of 64.36 kPa compared with a 26.13° friction angle and 33.11 kPa cohesion for sand without bentonite. However, for stabilized poorly graded natural silica sand with 3% bentonite clay, the friction angle was 28.22° and cohesion was 42.70 kPa compared with a 30.75° friction angle and 26.14 kPa cohesion for silica sand without bentonite clay addition.

5. Conclusions

Based on the test results the following conclusions are drawn:

1. Bentonite clay powder can be considered as a good stabilizing agent as it fills the voids between sand particles, and decreases the amount of free water in the voids resulting in an increase of sand mass strength.
2. Slurry composed of 10.4% of water and 4% of bentonite clay by dry weight of sand is the optimum volume to be added for the stabilization process of Sweileh sand. For silica sand 3% bentonite content by dry weight of sand can be used as the optimum amount for slurry preparation.
3. Three days curing time increased the shear strength of the stabilized Sweileh sand with bentonite clay–water slurry by 31.6% and 27.9% for stabilization with 3% and 4% bentonite clay, respectively, compared to no curing time after stabilization.
4. Stabilized sandy soil with eco-friendly bentonite clay–water slurry offers an excellent resistance to mechanical shaking.
5. The cohesion of stabilized sand by bentonite clay–water slurry increased with a slight decrease in the internal friction angle of sand, which is in line with previous studies.

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