Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 624.1

DOI: 10.34910/MCE.124.6

Shear strength and chemical properties of soft clayey soil treated with magnetized water

S.I. Jawad [1,2], M.O. Karkush [1]

[1] *University of Baghdad, Baghdad, Iraq*
[2] *Bilad Alrafidain University College, Diyala, Iraq*

✉ *mahdi_karkush@coeng.uobaghdad.edu.iq*

Keywords: magnetized water, magnetic field, shear strength, soft soil, vane shear, unconfined compressive strength

Abstract. Design criteria of any type of foundation are mainly depending on the shear strength of the soil founded on/in it. In this research, investigation of the effect of magnetized water (MW) on shear strength and chemical properties of soft clayey soil was investigated. The shear strength of soft soil before and after treatment by MW was measured by an unconfined compressive strength test (UCST) and vane shear test (VST). Tap water used to treat the soft soil was modified by different magnetic field intensities (2000, 4000, 6000, and 8000 Gauss). Two-time intervals were used to conduct the shear strength tests for all intensities: first, after 7 days of treatment of the soil by MW, and second after 14 days. The circulating of MW through soft clayey soil samples for 7 days shows increasing the unconfined shear strength by 17, 39, 42, and 45% for soil treated with MW of intensity 2000, 4000, 6000, and 8000 G, respectively compared to the reference soil sample treated under the same conditions with tap water (TW). Increasing the duration of treatment up to 14 days showed increasing in the UCS of soft soil by 35, 49, 92, and 120% for soil treated with MW of intensity 2000, 4000, 6000, and 8000 G, respectively. On the other hand, the shear strength (S_{uv}) measured by the vane shear device increased with increasing the intensity of the magnetic field for the same duration of treatment. The magnetized water technique can be considered as a promising and sustainable technology to be employed in geotechnical engineering to improving the geotechnical properties of soil.

Citation: Jawad, S.I., Karkush, M.O. Shear strength and chemical properties of soft clayey soil treated with magnetized water. Magazine of Civil Engineering. 2023. 124(8). Article no. 12406. DOI: 10.34910/MCE.124.6

1. *Introduction*

Iraq is one of the countries that have significant ratios of regions formed by sedimentation deposits, especially in the middle and southern regions. This stratigraphy consists mainly of weak soils classified as soft to very soft, which often make unfavorable conditions for construction activities. Therefore; the assessment and design of any geotechnical structures requires a good knowledge of the most important engineering issues such as the bearing capacity and settlement of these challenging types of soils. Depending on the cohesion (c) and angle of internal friction (ϕ), the shear strength of soil can be affected by several factors such as the liquid and plastic limits and the water and clay content [1]. Many criteria were adopted in order to consider the soil as soft, such as the high tendency to flow, the high plasticity behavior, saturation conditions, and also consistency index (Ic) < 0.75. Moreover, a wide range of techniques has been used to improve the geotechnical properties of soft soils such as grouting and stone columns which are considered popular techniques to reinforce the underlying foundation of the structures [2]. Sand compaction pile (SCP), dynamic compaction (DC), prefabricated vertical drain (PVD), and microbially induced calcite precipitation (MICP) are also recently used to improve soft soils [3,4]. The rapid increase in population and growing infrastructures made the requirement of problematic soils, therefore, geotechnical engineers make a challenge to improve the soft soils in order to be used for many infrastructures facilities.

Many studies were conducted to investigate the variation of shear strength of soft soils after using different improvement techniques. Additives such as cement and lime [5], the common agents adopted as a binder for improving the strength of soil and ground improvement can be used as an additional mixture with Nano-MgO to improve strength properties and micro-structure of soft soil with a significant resulting role in unconfined compressive strength of stabilized soil [6]. Additionally, the vertical drains and pre-loading can be used to improve disturbed zone containing soft soil deposits [7]. Many categories of chemical and mechanical stabilization methods have been applied to various types of problematic soils, these types of methods are mainly based on vibration, loading of soil, soil grouting, admixtures, and other methods [8,9]. General soil stabilization methods of soft soil concluded that the soft soil properties and the strength characteristics can be improved significantly by using additives other than using mechanical stabilization methods which were depending on the decreasing voids ratio in the soil by compaction [10,11].

The current study focuses on the application of magnetized water (MW) as green technology which has an increasingly significant effect on many fields of science. In general, water can be found at the nanoscale as clusters which can be affected by factors such as temperature, pressure, and the forces applied to it [12-14]. As the water is subjected to a magnetic field, certain properties of this water will be altered, due to alteration in the water cluster and consequently the water density. Therefore, many variations in these anomalous and unique properties of water occur at the macroscopic level (the hydrogen bonds and van der Waals forces will change due to the conditions of exposing the water to the dominant existing magnetic fields [15-17]. Studies on the treatment of water magnetic field stated that the hydrogen bonds get stronger when subjected to the magnetic forces, that is to say, the increase in the energy of hydrogen bonds directly reflects the increase in the surface tension of the water [18-20]. The majority point of the study considers the MW as an environmentally friendly technology in the remediation of water and consequently the improvement of soil properties depending mainly on the bonds among soil particles as well as the intensity of the magnetic field applied to the modified water.

Various laboratory tests have been conducted to investigate the influence of using MW to improve some properties of construction materials (e.g. soil and concrete) with various purposes and different intensities of magnetized water. The previous studies showed that the MW is considered a factor that can enhance the fresh-state and hardened-state properties of the concrete when using the small intensities of magnetization technique (0, 6000, 12000, and 18000 Gauss) as well as the improvement of the mechanical performance of the concrete due to the decrement in the numbers of pores and getting more dense concrete with MW [21,22]. It has also been shown that MW can be used as an injection fluid in oil fields to substitute the extracted oil [23]. In the field of soil mechanics, the MW is used to enhance the chemical and swelling properties of expansive soil type treated by MW with several intensities of magnetic fields (500, 1000, 1500, and 2000 Gauss). The treatment by MW led to a decrease in the liquid limit and free swelling by a significant amount, resulting in the mitigation of the potential of expansive soils [24]. MW technology proved sufficient satisfactory effects in many fields of science such as agriculture, medicine, and engineering.

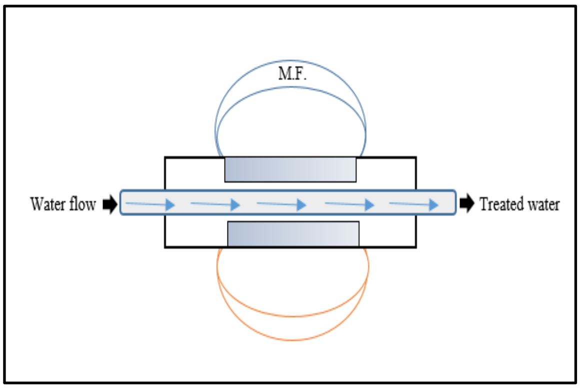
The shear strength of soil refers to the resistance of soil particles to sliding along each other when subjected to shear stress. It is related to the bonding between soil particles and the frictional forces that act between them. The shear strength of soil is influenced by various factors such as particle size, shape, surface roughness, mineralogy, water content, and compaction. It can be determined using various laboratory tests such as the direct shear test, triaxial shear test, vane shear test, and unconfined compression test. Overall, the shear strength of soil is an important property that influences the stability and behavior of soil in different geotechnical applications, such as foundation design, slope stability analysis, and underground excavations. The overall objective of the current study aims to investigate the influence of using several intensities of MW on the chemical properties and shear strength of the soft clayey soil for two-time intervals of the treatment process. The shear strength of soil was measured by the unconfined compressive strength test (UCST) and vane shear test (VST) after 7 and 14 days of treatment by MW.

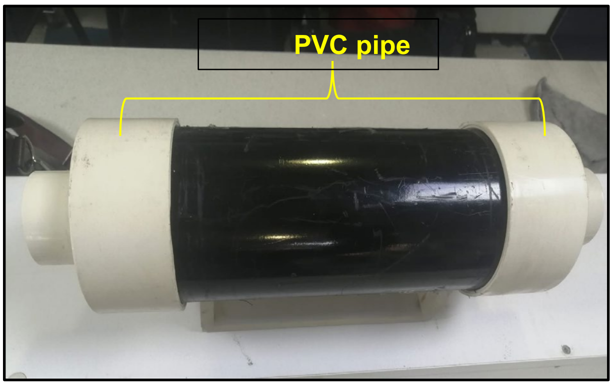
2. Materials and Methods

The material used herein basically includes the water and the soil samples. In this study, tap water was used for the treatment of soft soil.

2.1. Magnetic Water Technique

Magnetized water is generally obtained by passing water through a magnetic field to induce some alteration in the properties of the selected water type. The manufacturing of water magnetization equipment consisted of two Poly Vinyl Chloride (PVC) pipes, the first pipe of 25 mm in diameter and has a different length to transport the water from the pump to the tank of water and passes through the second pipe of a larger diameter which contains the magnetic rocks. The ends of the second pipe are closed by a plastic cover as shown in Figure 1 (a,b). The schematic diagram of a physical model of the water magnetization system is shown in Figure 2. The magnetic devices were placed in a way that provided the ease of the circulation route of the water in the container of soil. The water passes through the magnetic field of several intensities (2000, 4000, 6000, and 8000 Gauss) by a plastic pipe of 12 mm diameter. The magnetizing system consists of magnetic rocks, a container made of PVC with a submersible pump of 25 watts, a head of 1.8 m, a flow rate of 1000 l/h, and connecting PVC tubes. The container was filled with tap water and circulate in the magnetic field for a two-time duration; firstly, the water circulated for 7 days through the magnetic field and increased the time of circulation up to 14 days, and test the soil samples after each treatment.





a b

Figure 1. (a) Schematic diagram of magnetic device represent the inflow section, the magnets, and the outflow section and (b) magnetic device.

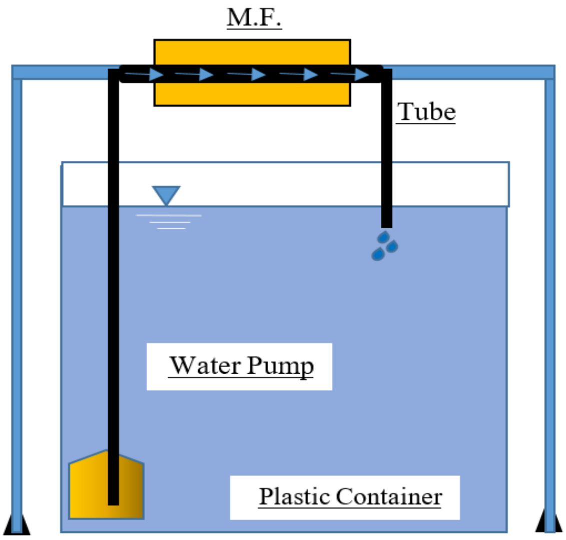


Figure 2. Schematic diagram of water magnetization system.

2.2. Soil Tests

The shear strength of soil refers to the strength of the soil at the microscopic level, which is governed by the interactions between soil particles and the pore fluid. The shear strength of soil is an important parameter in geotechnical engineering, as it plays a key role in determining the stability and bearing capacity of foundations, slopes, and retaining walls. Experimental methods, such as direct shear tests, triaxial tests, and torsional shear tests, can be used to measure the shear strength of soil in the laboratory. However, it is important to note that the measured shear strength can be influenced by factors such as sample preparation, testing conditions, and the stress history of the soil. Therefore, it is important to carefully consider the testing methodology and interpretation of the results when evaluating the micromechanical shear strength of the soil.

In this study, the clayey soil samples were obtained from one of the residential complexes in Baghdad, Iraq. The soil investigation program included drilling a borehole extended to a depth of (1.5–2) m below the natural ground level. Subsequent analysis and laboratory tests were accomplished to determine the physical, chemical, and shear strength characteristics of the soil sample. However, the general classification of the natural soil result is clayey soil (CL) which is accomplished according to the unified soil classification system (USCS). The geotechnical properties of soil were examined before and after treatment by MW. Additionally, the laboratory tests were conducted according to the ASTM specifications, where the shear strength was represented by an unconfined compressive strength test (UCST), direct shear test (DST), and vane shear test (VST) were conducted according to ASTM D2166, ASTM D3080, and ASTM D4972 standards, respectively. The description of the soil and physical properties are given in Table 1. The results of shear strength tests conducted on the natural soil are listed in Table 2, which was conducted according to ASTM D2166 and ASTM D3080.

Table 1. Soil description and physical properties.

Depth, m	% Passing No. 200 sieve	γ_{wet}, kN/m^3	Natural water content, %	γ_{dry}, kN/m^3	LL, %	PL, %	PI, %	Gs	Fines, %		USCS
									Clay	Silt	
1.5–2.0	95	20.01	27.5	22.6	47	20	27	2.**75**	51.2	40.8	CL

Table 2. Results of undrained shear strength of natural soil.

Depth, m	UCST		DST		Consistency [25]
	q_u, kPa	c_u, kPa	c_u, kPa	φ, degree	
1.5–2.0	92.8	46.4	28	3	Medium

The current study focuses on determining the effect of the MW on the geotechnical properties of soft clayey soil. The aforementioned type of soil was prepared artificially from the natural clayey soil. Before preparing the soft soil, many tests were carried out to measure the relationship between the undrained shear strength of the soil and moisture content. Based on the results of tests shown in Figure 3, the soft soil used in this study can be prepared by mixing a moisture content approximately equal to 34% with natural clayey soil to produce a soft clayey soil has undrained shear strength, c_u = 40 kPa.

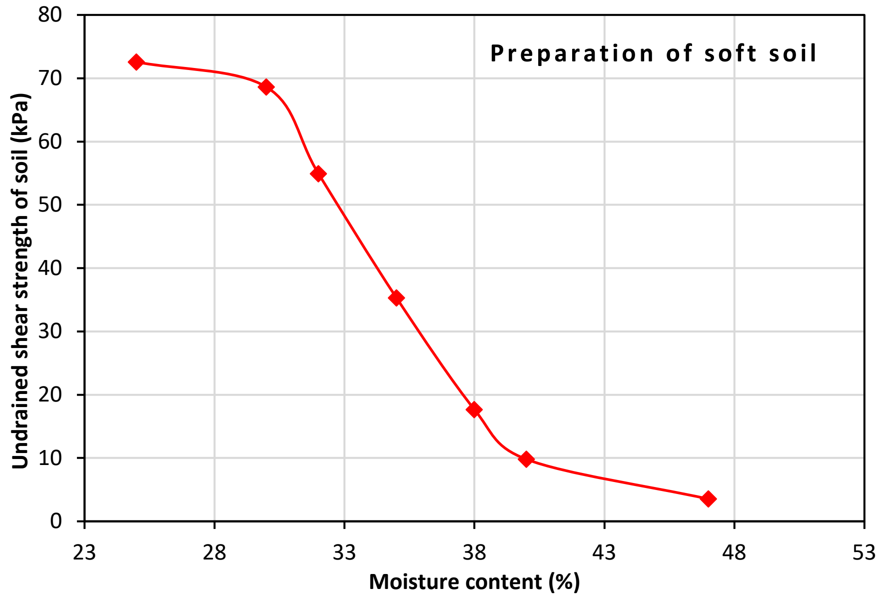


Figure 3. Variation of undrained shear strength versus water content for the remolded clay after 48 hrs.

3. Results and Discussion

The effect of magnetized water on the shear strength of soil is not well established and is currently a subject of ongoing research and debate. While some studies have suggested that magnetized water may have beneficial effects on soil properties, including shear strength, the results have been mixed and the underlying mechanisms of action are not well understood. One proposed mechanism is that the magnetic field may alter the structure and behavior of water molecules, leading to changes in soil structure and properties. Another proposed mechanism is that the magnetic field may enhance the activity of soil microorganisms and improve soil fertility, which could indirectly affect shear strength. However, these mechanisms have not been conclusively proven, and further research is needed to better understand the potential effects of magnetized water on soil properties and behavior, including shear strength. It is important to note that any claims about the effects of magnetized water on soil properties should be viewed with caution until they are supported by rigorous scientific evidence. In the meantime, established soil testing methods and principles should continue to be used for evaluating soil properties and behavior. The shear strength of soil samples was tested by the portable vane share device as well as the unconfined compressive strength test as shown in Figure 4. The chemical test of the soil had also been tested before and after the treatment by the magnetized water with different time duration and different magnetic field intensities.

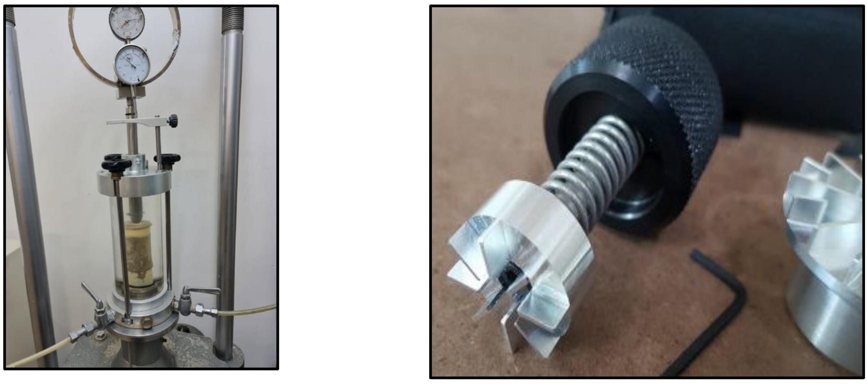


Figure 4. Unconfined compressive strength test (UCST) and portable vane shear test (VST) devices.

3.1. Influence of MW on Chemical Properties of Soil

The magnetic field applied to the water is thought to alter the structure and behavior of water molecules, which can affect the solubility and availability of soil nutrients and minerals. Some studies have reported that magnetized water can reduce the total soluble salt content of the soil, particularly in soils with high salinity. This effect is thought to be due to changes in the electrical charge and surface tension of the water, which can enhance the ability of the water to dissolve and transport nutrients while reducing the accumulation of salts in the soil. However, other studies have reported no significant effect of magnetized water on the total soluble salt content of the soil. The mechanisms of action are not well understood, and the results of studies on the effects of magnetized water on soil-soluble salt content have been mixed. In order to study the chemical alteration of the properties of soft clayey soil when treated with MW, the chemical tests listed in Table 3 were conducted on the soil samples before and after treatment. The analysis of variance showed that the effects of MW treatment on the chemical properties were significant under the highest intensity of 8000 G. Some studies have suggested that magnetized water can increase microbial activity in the soil, which could potentially lead to an increase in the decomposition of organic matter. This effect may be due to the increased solubility and availability of nutrients in the soil, as well as changes in the electrical charge and surface tension of the water. However, other studies have reported no significant effect of magnetized water on soil organic matter content (OMC) or decomposition rates. The mechanisms of action are not well understood, and the results of studies on the effects of magnetized water on soil organic matter have been mixed. The concentration of OMC decreased by 16.3% after 7 days and 26.2% after 14 days.

Table 3. Chemical test results were conducted on soft soil treated with magnetized water.

Property	7 days					14 days
	TW	2000 G	4000 G	6000 G	8000 G	8000 G
Organic matter content (OMC), %	4.35	4.25	4.01	3.78	3.64	3.21
Gypsum content, %	2.37	2.15	2.01	1.62	1.31	1.01
pH value	7.81	7.89	8.24	8.46	8.52	8.66
Sulfate content (SO_4), %	2.39	1.96	1.45	1.36	0.86	0.61
Total soluble salts content (TSS), %	4.47	4.11	4.06	3.65	3.16	2.64

Gypsum is a common mineral in soil and can play an important role in soil fertility and structure. There is limited research on the effect of magnetized water on the gypsum content of the soil. One study reported that magnetized water had no significant effect on the solubility or availability of gypsum in soil. However, the study had a limited sample size and further research is needed to confirm these results. Overall, more research is needed to better understand the potential effects of magnetized water on the gypsum content of the soil and to determine the optimal conditions and application methods for achieving any potential benefits. It is important to note that claims about the effects of magnetized water on soil gypsum content should be viewed with caution until they are supported by rigorous scientific evidence. Gypsum content decreased by 44.7% after 7 days and 57.3% after 14 days, respectively. The decrement in the sulfate content may be due to the decline in the solubility of the gypsum content in water, and increased rates of crystal growth and nucleation instead, which leads to the precipitation of gypsum.

Magnetized water has also been shown to affect the pH and conductivity of soil solutions, potentially influencing the availability of other nutrients and minerals. Some studies have reported that magnetized water can increase soil pH, while others have reported no significant effect. However, the results of studies on the effects of magnetized water on soil chemical properties have been mixed, and the mechanisms of action are not well understood. Further research is needed to better understand the potential effects of magnetized water on soil chemistry and nutrient availability and to determine the optimal conditions and application methods for achieving any potential benefits. Also, the pH value of the soil was influenced by the magnetic field of different intensities. The water treated with the magnetic intensity of 8000 G circulated through the soil, and the pH value gets also increased to about 8.34% after 7 days and 9.82% after 14 days, respectively. Increasing the value of the pH of the soil resulted from increasing the concentration of the hydrogen ions in the magnetized water.

The sulfate concentration in the soil was measured before and after treatment by different magnetic intensities and the analysis results showed the increase in the magnetic intensity for the treated water will cause a lower concentration measurement of sulfate 64% after 7 days and 74.48% after 14 days at the intensity of 8000 G. The total soluble salts (TSS) in the soil were decreased under the treatment by the magnetized water, as the efficiency of the magnetic treatment to reduce the concentration was 29.3% after 7 days and 36.9% after 14 days at the intensity of 8000 G. This is due to that the MW is working on increasing the leaching of the excess soluble salts due to that when water passes the magnetic field becomes more energetic and modifying the ability of the flow of the water, and dissolving slightly the soluble salts like carbonates, phosphates, and sulfates. However, other studies have reported no significant effect of magnetized water on the sulfate content of the soil. The mechanisms of action are not well understood, and the results of studies on the effects of magnetized water on soil sulfate content have been mixed.

3.2. Influence of MW on Shear Strength of Soil

On the other hand, the shear strength of soft soil has been measured by two tests, UCST and VST. Each has been conducted on soil samples before and after the treatment process by several intensities of MW. Each increment of the magnetic field intensity has led to increasing the shear strength of soft clayey soil. The tests can be grouped into two classes as varying the time of conducting tests after being treated by magnetized water. The soil was first tested when treated by MW for 7 days and the treatment continued for 14 days and then the soil was tested again. Figure 4 shows the influence of magnetic treatment on the unconfined compressive strength (q_u) of soft clay after 7 days of treatment which compared with that of the reference soil sample treated with tap water (TW). Generally, circulation of the water in magnetic field for 7 days and soft clay indicates an increase in q_u value by 52, 68, 43, and 45% for soil samples treated with MW of intensity 2000 G, 4000 G, 6000 G, and 8000 G, respectively.

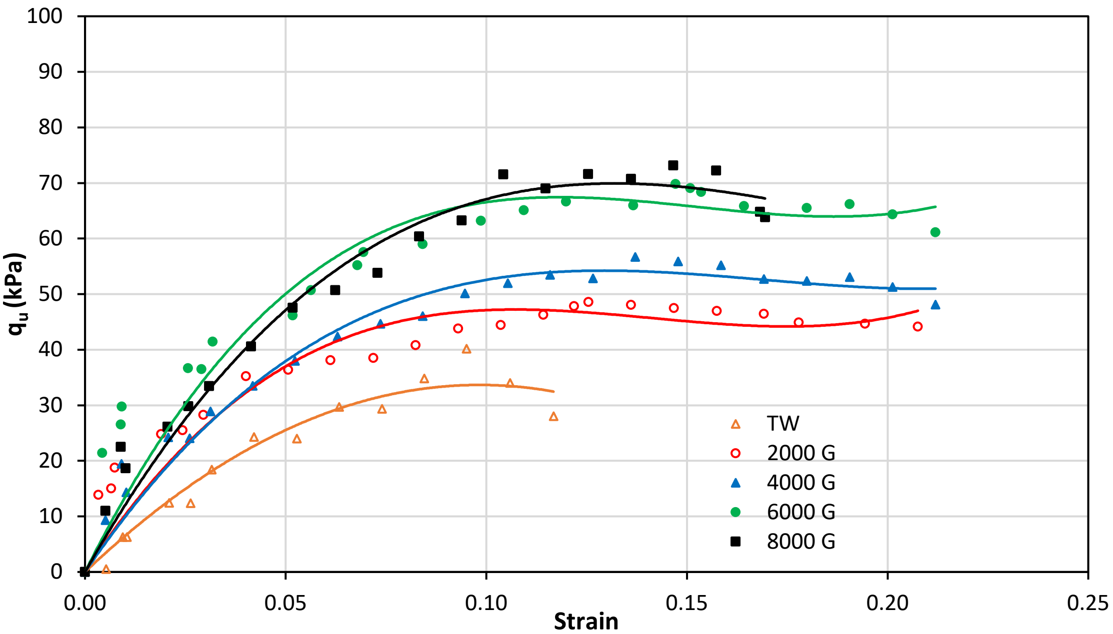


Figure 5. Variation of unconfined compressive strength with strain for soil samples treated with MW after 7 days.

Also, the unconfined compressive strength (q_u) of soft clayey soil was measured after 14 days of treatment as shown in Figure 5. Increasing the duration of treatment by MW from 7 days to 14 days showed increasing the unconfined compressive strength of soft soil by 21, 41, 74, and 82% corresponding to that treated with MW of intensity 2000 G, 4000 G, 6000 G, and 8000 G, respectively. The average of increasing q_u ranged from 1.25 to 2.65 times that gained after 7 days of treatment. It can be concluded that increasing the unconfined compressive strength of soil (i.e., the cohesion values) can be attributed to increasing the concentration of the salts and minerals in the pores of soil which provide additional internal bonds between the particles of soil. Also, decreasing the thickness of the double-diffusive layer causes a reduction in the antiparticle's repulsion force and increasing the attraction force between the soil particles.

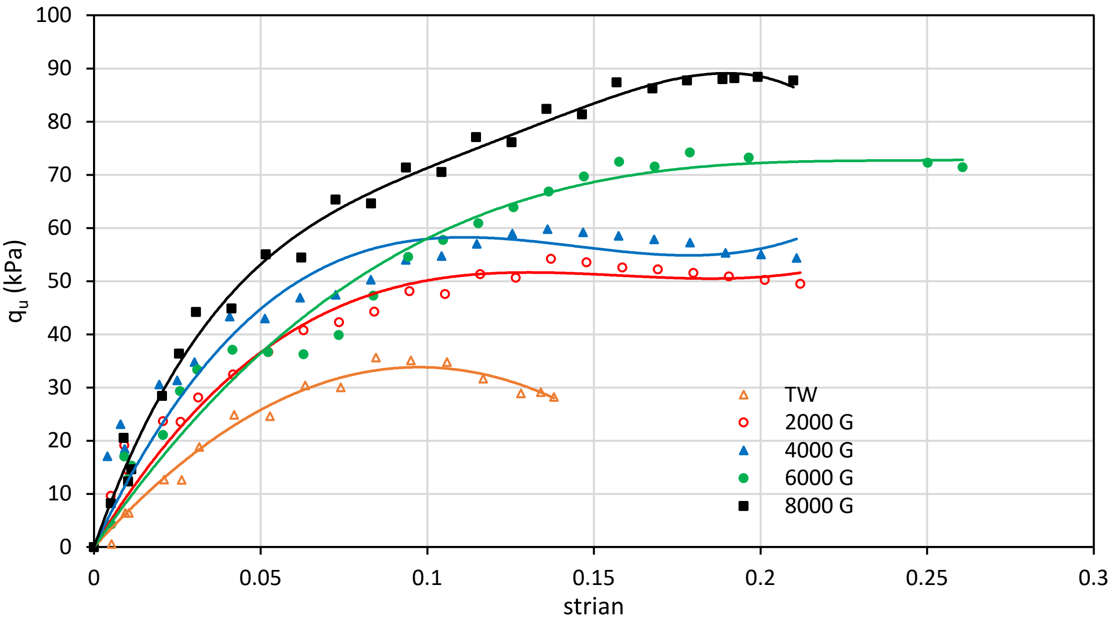


Figure 6. Variation of unconfined compressive strength with strain for soil samples treated with MW after 14 days.

The vane shear test is a type of in-situ test used to determine the undrained shear strength of soft soils. This test is particularly useful for cohesive soils, such as clays, silts, and muds. In the vane shear test, a four-bladed vane is inserted into the soil at a known depth and rotated at a constant rate. The torque required to rotate the vane is measured and used to calculate the undrained shear strength of the soil. The test is typically performed in situ, which means that the soil sample is not disturbed during the testing process. This makes it an ideal test for soft soils where disturbance can significantly alter the soil properties. The vane shear test is commonly used in geotechnical engineering to assess the stability of slopes, embankments, and other earth structures. It can also be used to evaluate the stability of shallow foundations and to determine the shear strength of soils for use in design calculations

Figures 6 and 7 show the variation of undrained shear strength (S_{uv}) measured by a vane shear device for soft soil samples treated with several intensities of MW after 7 and 14 days of treatment. The treatment of soft soil by MW of intensities 2000 G and 4000 G showed a slight increase in the undrained shear strength, but the soil samples treated with intensities of 6000 G and 8000 G showed a significant increase in the undrained shear strength (S_{uv}) of soft clayey soil. Based on the results displayed, there is a slight effect of treatment duration on the magnitude of undrained shear strength.

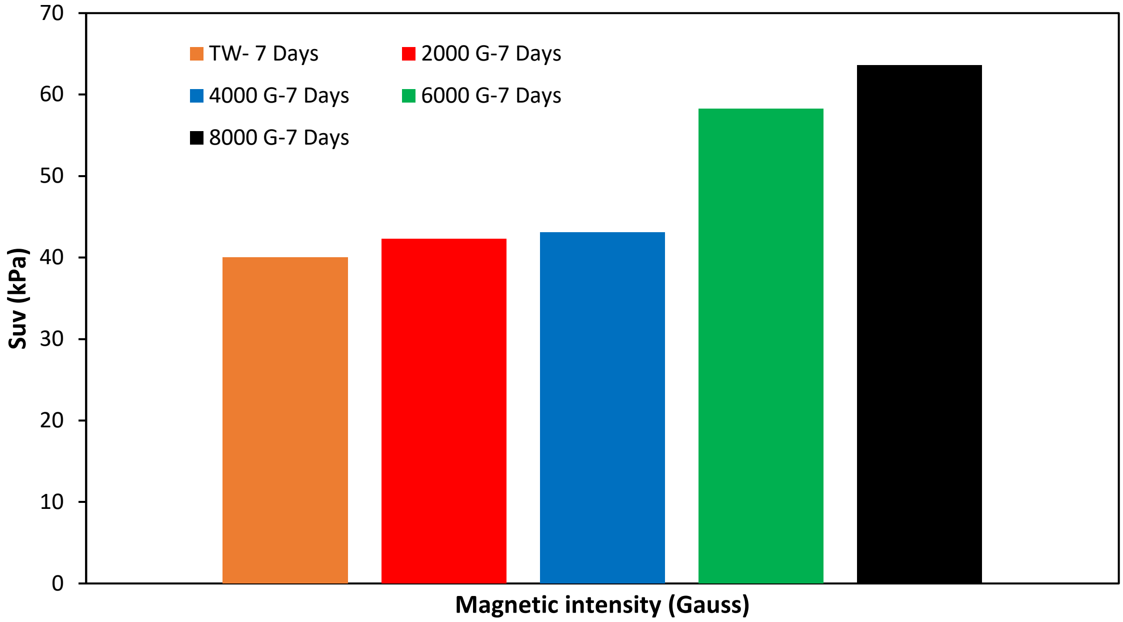


Figure 7. Results of vane shear tests after 7 days of soft clay samples treated by MW.

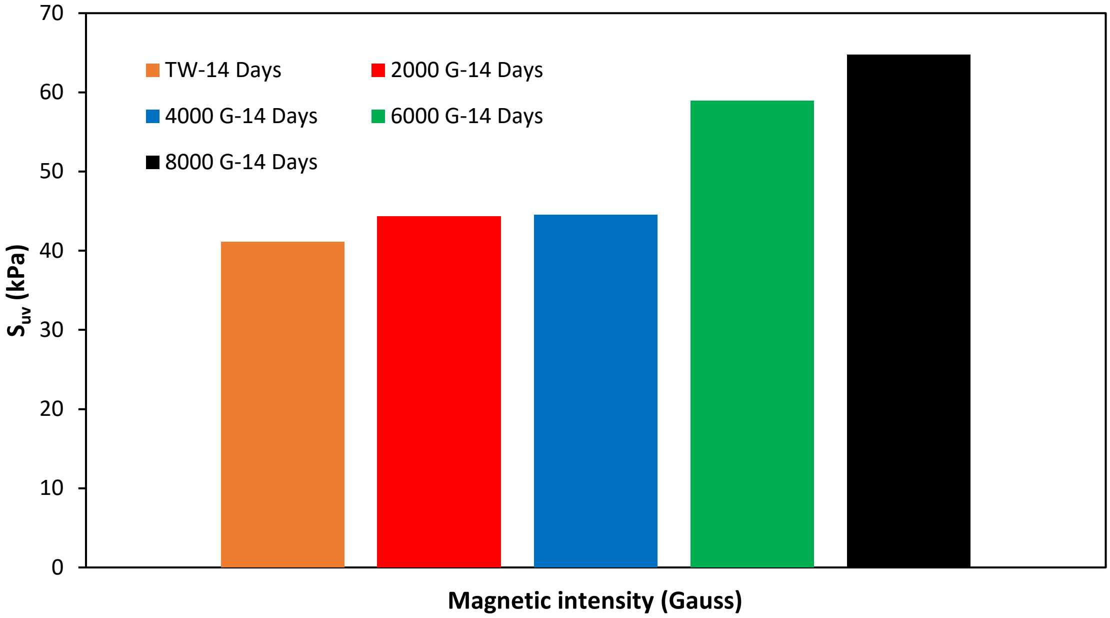


Figure 8. Results of vane shear tests after 14 days of soft clay samples treated by MW.

The summary of results of unconfined compressive strength (q_u) and undrained shear strength (S_{uv}) for soft clayey soil samples treated by several intensities of MW after 7 and 14 days of treatment are given in Table 4. The VST gives results of undrained shear strength higher than the unconfined shear strength test. Also, the rate of growth of undrained shear strength after 7 days of treatment is higher than that after 14 days of treatment, but still, the shear strength after 14 days of treatment is higher than that obtained after 7 days of treatment by MW.

Table 4. Summary of shear strength of soft clay treated by MW obtained from UCST and VST.

Soil sample	7 days					14 days				
	q_u, kPa	c_u, kPa	% change	S_{uv}, kPa	% change	q_u, kPa	c_u, kPa	% change	S_{uv}, kPa	% change
MW	34	17.00	0.00	40.00	0.00	35.11	17.56	0.00	41.10	0.00
2000 G	47.82	23.91	40.65	42.30	5.75	51.27	25.64	45.99	44.32	7.83
4000 G	53.47	26.74	57.26	43.10	7.75	58.93	29.47	67.80	44.51	8.30
6000 G	66.61	33.31	95.91	58.24	45.60	73.19	36.60	108.40	58.88	43.26
8000 G	70.69	35.35	107.91	63.60	59.00	88.19	44.10	151.11	64.71	57.45

4. Conclusions

The main objective of this work was studying the influence of several intensities (2000, 4000, 6000, and 8000 G) of magnetized water on the chemical properties and shear strength of soft clayey soil after 7 and 14 days of treatment by MW. Based on the results of this study, the following points can be drawn out:

- The influence of the magnetized water with different intensities also showed a significant variation in the chemical composition of the soil after 7 and 14 days.
- Water magnetization increased the alkalinity of the soil, where pH value increased from 7.81 to 8.52, but the OMC, gypsum, SO_3, and TSS contents decreased with increasing the intensity of MW due to adsorption and sedimentation of salts.
- The treatment of soft soil by MW improved the shear strength measured by UCST and VST, where the shear strength increased with increasing the intensity of the magnetic field.
- The shear strength of the soil was also increased as the curing time of the magnetized water circulation increased from 7 days up to 14 days.
- In general, the overall response of the treated soil depicts a promising and bright application of the magnetized water sustainability system used for alteration and improvement of the shear strength and chemical properties of soft clayey soil. The sustainable effects of using MW technique on the soil properties is not only limited to the cost, but also reduce using chemicals that could spread in the soil, which in turn would be very expensive and toxic. In addition, in large sites, the MW technique can be easily applied compared with other techniques. Furthermore, one of the main advantages of MW technique is the low cost, as it relies mainly on water circulating through a magnetized metal field device, and the validity of this device extends for many years.

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Information about authors

Saba Jawad, *Doctor of Technical Sciences*
ORCID: https://orcid.org/0000-0002-16579-0942
E-mail: saba@bauc14.edu.iq

Mahdi Karkush, *Doctor of Technical Sciences*
ORCID: https://orcid.org/0000-0003-1304-0303
E-mail: mahdi_karkush@coeng.uobaghdad.edu.iq

Received 07.04.2023. Approved after reviewing 29.04.2023. Accepted 29.11.2023.