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Investigating the Potential of Water Treatment Sludge for Improvement of the Geotechnical Properties of Gypseous Soil

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Keywords:
Geotechnical Properties; Gypsum Soil; Improvement; Soil Stabilization; Waste Treatment Sludge.

Highlights:

- *Improving the properties of gypsum soil using water treatment sludge WTS.*
- *The engineering properties of gypsum soil were considered experimentally.*
- *The percentage of gypsum in the soil sample was calculated based on the weight loss during burning.*

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Abstract: Water treatment sludge (WTS) has in recent years been used for improvement in geotechnical properties of soil. The present study has been taken up to establish whether WTS can be used for the improvement of gypseous soil by assessing its effects on the geotechnical properties. Soil samples were collected from the study area while WTS were locally obtained from a water treatment plant. Chemical and physical properties, mineral compositions, particle size distribution, water content, and Atterberg limits of soil and WTS were determined. The laboratory test was performed by employing laboratory testing to investigate the effects of different percentages of WTS on the strength, compressibility, collapsibility, and compatibility of the soil at different curing times. The results obtained showed that WTS influenced the geotechnical properties of gypseous soils significantly. Improvements in the strength, compressibility, and collapsibility were shown. The best application rate of WTS was suggested on the basis of the possible improvements in the geotechnical properties. From the study's outcomes, it could be concluded that the use of WTS may be an alternate and economic material for the improvement of geotechnical properties of gypseous soil.

دراسة إمكانية استخدام الحمأة الناتجة عن معالجة المياه في تحسين الخصائص الجيوتقنية للترب الجبسية

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الخلاصة
أصبح استخدام حمأة معالجة المياه (WTS) لتحسين الخصائص الجيوتقنية للتربة مجالًا شائعًا للبحث في السنوات الأخيرة. الهدف من هذه الدراسة هو دراسة جدوى استخدام WTS في تحسين خصائص التربة الجبسية من خلال دراسة تأثيرها على الخصائص الجيوتقنية. تم جمع عينات التربة من منطقة الدراسة، حيث تم الحصول على عينات WTS من محطة معالجة المياه المحلية. تم قياس الخواص الكيميائية والفيزيائية والتركيبات المعدنية وتوزيع حجم الجسيمات ومحتوى الماء وحدود Atterberg للتربة وWTS. أجريت تجارب معملية لاستقصاء تأثيرات إضافة نسب مختلفة من WTS مع أوقات معالجة مختلفة على قوة التربة، وقابلية الانضغاط، وقابلية الانهيار، وخصائص الانضغاط. أظهرت النتائج التي تم الحصول عليها أن إضافة WTS له تأثير إيجابي على الخصائص الجيوتقنية للتربة الجبسية، مع ملاحظة تحسن في القوة، الانضغاطية، وقابلية الانهيار. تم تحديد المحتوى الأمثل لـ WTS المضاف بناءً على مقدار التحسين في الخصائص الجيوتقنية للتربة الجبسية. تشير نتائج الدراسة إلى أن WTS قد يكون حلاً عمليًا وفعالًا من حيث التكلفة لتحسين الخصائص الجيوتقنية للتربة الجبسية.

الكلمات الدالة: حمأة معالجة النفايات، التربة الجبسية، الخصائص الجيوتقنية، تثبيت التربة.

1.INTRODUCTION

Soil stabilization is one of the most common engineering processes used to improve the physical properties of weak soils in order to satisfy any specified engineering requirements. Various mechanical as well as chemical methods are adopted for such purposes. However, researchers and engineers have resorted to the use of waste materials as possible stabilizing agents in an effort to address geo-environmental problems and waste disposal issues [1]. In the procedure of selection of stabilizing agents, it is vital to take into account several factors like the effectiveness, cost, and availability (Economically and environmentally beneficial factors). For example, sludge stands to be an option following the trend that its supply is widespread, a quantity that is expected to grow along with the size of city-based wastewater treatment facilities [2]. Water treatment sludge (WTS) is the residual material that results from the uniform washing of filters and decanters in water treatment plants (WTPs). In a typical WTP, raw water undergoes various treatment processes, including disinfection, fluoridation, pH correction, filtration, decantation, flocculation, and coagulation, to produce potable water. These processes involve adding several chemicals, such as fluorine, lime, coagulants, and chlorine. Coagulants, including polymeric, falum, and erric, induce the gathering of impurities at the sedimentation basins' bottom and filters. These basins and filters are periodically washed, leading to WTS production. To put it differently, WTS (waste treatment sludge) is a significant waste stream currently and soon, given that it constitutes 0.2% to 5% of the treated water volume and the global demand for drinking water is projected to increase by 1% annually [3]. WTS is in the form of a liquid or slurry and contains 2 to 15% oven-dried solids. Biosolids are a type of water-treatment sludge that resembles oven-dried solids and typically comprise 50 to 70 percent of the bulk solids' weight. The volume of water treatment sludge is ever on the rise worldwide every year, and the increased demands on virgin materials mean that recycling and recovery of biosolids are critical in attaining a sustainable society. Iraq has more than 2 million tons of biosolids stored in depots or lagoons, with 66,700 tons produced yearly [4]. In 2019, the experiment done by Mosallaei et al. [5] explored the impact of incinerated water treatment sludge (WTS) as an additive on the shear strength parameters of gypseous soil. Increase in the ratio of WTS was discovered to have considerable impact on the magnitudes of cohesion and internal friction angle for gypseous soil. Moreover, increase in the quantity of WTS saw an enlargement in the cohesion value and a reduction in the internal friction angle. Mohr-Coulomb line exhibits that the soil's shear strength increases for small stress magnitudes and lessens for larger stress ones. From the research, it can be clarified that WTS augmented the collapsible soil shear strength, and the best WTS proportion was 4%, as adding extra than that slightly affected shear strength. In 2021, Boscov et al. conducted an experimental investigation to evaluate the geomechanical properties of soil, i.e., waste-to-soil (WTS) mixtures, including permeability, shear strength, and deformability properties. The results showed that these mixtures were effective multipurpose geomaterials. Additionally, initial environmental examinations suggested their environmental feasibility, although additional research is required to validate these findings. Prospective work should encompass leaching tests, practical conditions simulation for every determined application, and addressing additional contaminants, including pharmaceuticals, hormones, and microorganisms. Applications with low soliciting stresses are well-suited for WTS mixtures. Nonetheless, the low sludge contents were the only means to achieve the minimum shear strength required for earthworks.

Therefore, there is a need for further research to identify additives that can create good all-purpose geomaterials. Additionally, the paper stresses the importance of investigating the WTS properties and characterizing them in rheological and geological terms to evaluate their suitable reutilization in developing countries at every stage, including mixing, transportation, and obtaining environmental licensing [6, 7]. Mohsin et al. [8] experimented on AL-Ramadi soil, poorly graded sand (SP), with a gypsum content of approximately 36%. After treatment with water treatment sludge (WTS), the soil was classified as SP-SM. Adding WTS significantly impacted the soil's physical and mechanical properties. The plasticity index of the soil increased with the proportion of water treatment sludge, reaching a maximum when 20% of the dry weight of gypsum soil was water treatment sludge. The results also showed a positive relationship between the proportion of water treatment sludge and unconfined compression strength. The unconfined compression strength and cohesiveness parameters significantly improved when applying 10% and 20% of water treatment sludge. Additionally, the compressive strength of all sewage sludge components increased with curing time, particularly when 20% of water treatment sludge was used and treated for 14 days. There are three names for current soil (gypsum soil): the first name is gypseous soil, containing some gypseous. The second one is 'gypseous soil,' which is uncommon in synthesizing the soil. The third one is 'gypseous soil,' used for the soil that has the largest gypseous percentage [9]. Pure gypseous contains 32.5% calcium oxide, 20.9% combined water, and 46.6% Sulphur trioxide. While the gypseous salts in Iraq range between 0% to 80% as great limits [10]. Gypsum, in its initial state, consists of $CaSO_4.H_2O$. The forms and their represents are:

- $CaSO_4$ is called anhydrite.
- SO_3 represents sulfate.
- H_2O is water.

Gypseous soils are widely found in semiarid and arid regions of Iraq. It is found in the Euphrates River basin and covers 20% of Iraq [11]. The classification of gypseous soil was explained by Ref. [12] according to the gypseous content, as shown in Table 1.

Table 1 Classification of Gypseous Soil According to the Gypseous Content [9].

Gypseous Content as a Percentage (%)	Classification
3.0-10	Slightly gypseous
10-25	Moderately gypseous
25-50	Highly gypseous
3.0-10	Slightly gypseous
<50	Gypseous

Fattah et al. [13] grouted the gypsum soil using acrylate liquid. The author observed that grouting the soil with the above liquid decreased the compressibility by 60 to 70%, while the collapse potential decreased by 50 to 60% compared to untreated soil. Al-Gharbawi et al. [14] investigated improving the characteristics of gypsum soil by employing magnesium oxide in combination with the treatment of carbonization. Their results implied that including 10 % magnesium oxide and carbonation treatment with 3 hr may reduce the collapse potential by 77%. Mohamad et al. [15] studied the effects of adding high-reactivity attapulgite to gypsum soil. The study results reported that by the addition of 5 to 40% of High Reactivity Attapulgite, the collapsibility was reduced by 13% to 90%, and the unconfined compressive strength improved from 88 to 271 kilopascals. Kamil et al. [16] carried out a test model with the use of test samples measuring 600×600×600 mm on the effect of adding WTS in soil gypsum with 37% gypsum content. The findings achieved were adding WTS in the upper layer (50 mm) reduced the factor of the collapse reduction by 86%. The use of industrial waste is common and very popular when it comes to the stabilization of soil. Most industrial waste is harmful to the environment, and it is best to get rid of it by using it for the stabilization of the soil. Saving biodiversity, disposing of waste, enhancing soil characteristics like increasing strength and stability, decreasing compressibility, and keeping the natural soil are all advantages of using waste in stabilizing the soil. Another advantage is the ability to build cost-effective structures. Therefore, this study used WTS as a recycled material to improve shear strength and stability and decrease compressibility.

2.MATERIALS AND METHODS

2.1.Materials

According to the gypsum map distribution in Iraq, the sample was taken from Ramadi, specifically the University of Anbar, at a depth of 1.5 m, where the soil is sandy with gypsum content ranging between (34-40%). The sewage sludge was taken from the big Ramadi water project site at Latitude 33° 26.372' North and Longitude 43° 16.152' East. WTS was investigated and generated at conventional-treatment WTPs in AL-Ramadi (Fig. 1). The WTS samples were collected immediately after centrifuge dewatering. According to the Theory of Sampling, a protocol was devised to obtain representative samples [17]. Then, implementing the experimental work on gypsum soil, i.e., taken from the University of Anbar at a depth of (1-1.5), filled with bags, and taken to the soil laboratory in the University of Anbar, to conduct physical and chemical tests. Table 2 represents the soil index properties, and Table 3 represents the WTS physical and chemical properties.

Table 2 Index Properties of Soil.

Property	Standard Designation	Value
Soil type	ASTM C117	Poor Sand
Specific Gravity (Gs)	ASTM D854	2.41
Moisture content	ASTM D2216	8.7%
Gypsum Content	SORB\R6	34%

Table 3 Physical and Chemical Properties of WTS.

Property	Standard Designation	Value
Specific Gravity (Gs)	ASTM D854	2.62
Total Sulfate Constant (SO_3)	BS 1377-3	0.246%
Gypsum Content	SORB\R6	0.529%

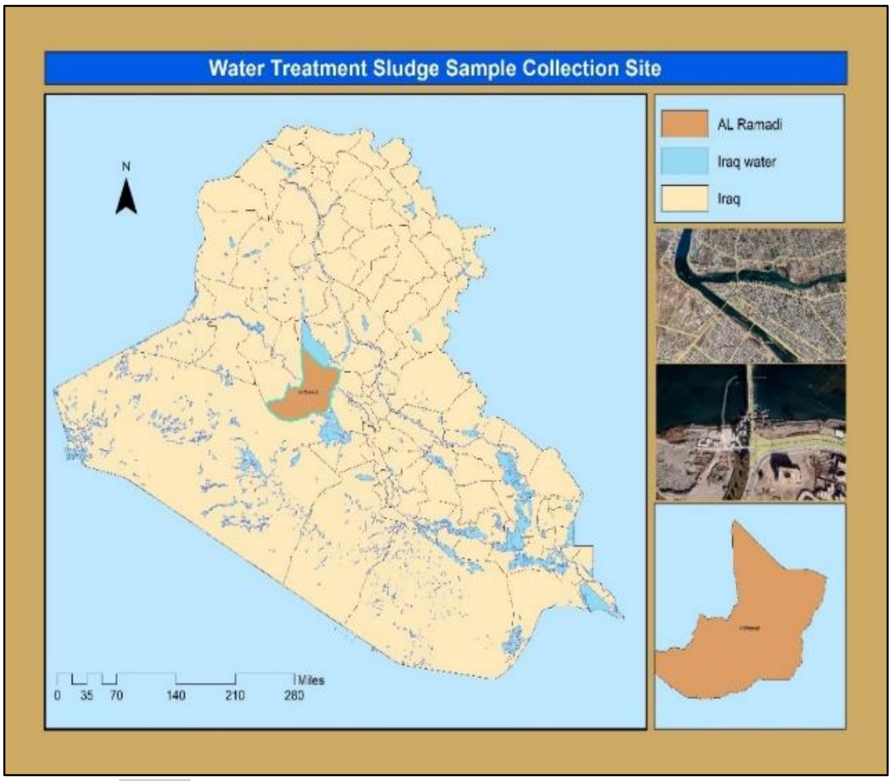


Fig. 1 Shows the Location of the Ramadi Project Station for Collecting WTS Samples.

2.2.Methods

2.2.1.Compaction Test According to ASTM D1557 (ASTM, 2003)

This test was conducted according to the modified Proctor method to obtain the maximum dry density and optimum moisture content. The soil passed through No. 4 sieve to ensure uniform distribution of the particle size. So, the different contents of water varying from 2% to 18% were mixed with the soil, prepared in a specific dimension of mold, and compacted in five layers of twenty-five blows in each. The prepared mold samples from the wet soil were then dried in order to give the moisture content of the soil and the density of the soil. This was repeated for each water percentage in order to determine the best density and moisture content of the soil. The density of soil is high, which is 17.8 kN/m3, and the soil is compact with mass per unit volume being high. The quantity of moisture is 9.5%; this means the soil has a small quantity of water. The text outlines an experiment that sets down the influence of different percentages of sludge added to gypsum soil with respect to density and moisture content. In the test, the gypsum soil was infused with sludge at 10%, 15%, 20%, 25%, and 30%. The gypsum soil weight was estimated, and the related percentage of sludge was added. Thereafter, the water of varied content level (4%, 8%, 10%, 12%, and 14%) was added further to get to the most favorable density and moisture content. The experiment results have shown that the density of the soil increases while the moisture content of the soil decreases with an increase in sludge percentage up to 20%. With the increase in sludge percentage to 20%, the soil density would have improved while its moisture content would have reduced. However, after 20%, the soil density increased, and moisture content increased. This is a sign that incorporating more than 20% of sludge impacted the soil density and the soil's moisture content. The experiment's findings have significant implications for stabilizing and improving soil using sludge [19].

2.2.2.Collapse Test According to ASTM D5333 (ASTM, 2003)

The weight required depending upon the mold density and size with the dimensions of a diameter of 5 cm and a height of 2 cm was taken in preparing the dry gypsum soil from Sieve No. 4 according to ASTM D5333 (ASTM,2003). The sample was mixed and placed inside the mold, stacked on five layers, and placed inside the device, and a load of 1 kg equivalent to 50 kPa started shedding. After an hour. the reading was taken, and a load of 1 kg was added to become 100 kPa, and after an hour, the reading was taken, and the weight of 1 kg was added to become 150 kPa, and after an hour, the reading was recorded to reach 200 kPa. Then, water was added to the mold, and after 24 hours, the reading was taken. Then, 400 kilopascals were added and took a reading. 800 kilopascals were added until the descent stabilized, and the reading was taken. Cp can be calculated from [20].

$$Cp = \frac{de}{(1-eo)} \times 100 \quad (1)$$

where:

Cp The specific heat capacity of a material at constant pressure.
d The material density.
e The material mass.
o The specific heat capacity of water.

$$E = \frac{(H_o - H_s)}{H_s} \quad (2)$$

where:

E The machine efficiency.
H_o Heat entering the machine.
H_s Heat coming out of the machine.

$$V_s = \frac{Md}{pw} \quad (3)$$

where:

V_s The specific volume of a material.
M The material mass.
d The material density.
p_W The weight density of water.

$$H_s = \frac{V_s}{A} \quad (4)$$

Where:

H_s The fluid head.
V_s The specific volume of the fluid.
A The cross-section area of the pipe.

As for the examination after adding sludge, 10, 15 and 20% of the sludge were mixed with a percentage of the gypsum's total weight and left for a treatment period of 3 days, a week, and a month; the examination was conducted in the same way as the highest.

2.2.3.Unconfined Compression Test According to ASTM D2166 (ASTM, 2013)

The dry gypsum soil was prepared from Sieve No. 4 and stacked in a modified manner, where the template with dimensions of 12.8 cm and a height of 6.3 cm was used. The soil was placed on five layers, each layer 29 strokes. After preparing the form, it examined the device [21].

$$E = \frac{Nb*Nl*W*H}{V} \quad (5)$$

E: Energy
N_b: Number of blow per layer
N_l: Number of layers
W: Hamer weight
H: Height of drop
V: Mold volume

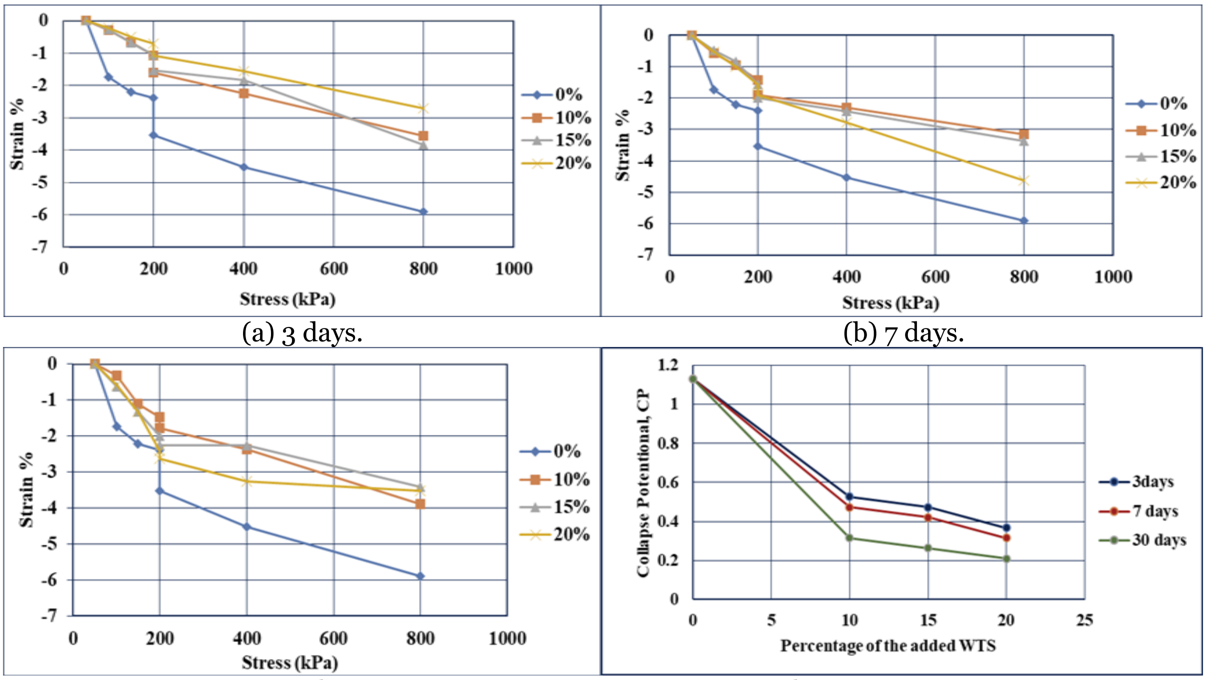
3.RESULTS

3.1.The Collapse Potential (CP) of the Gypseous Soils

The collapse potential of gypseous soils was studied using the double oedometer test, showing that the collapsible settlement occurred due to gypsum dissolution in water and subsequent softening of soil particle bonds. The collapse potential increased progressively with applied stress due to continuous gypsum dissolution and slipping of soil particles to a denser state. Compared to single collapse tests, double oedometer tests provided more uniform results but required fewer specimens when determining collapse potential at different stress levels, as shown in (Figs. 2 (a), (b), (c), and (d)). Additionally, the collapse potential obtained from the double oedometer tests at a stress level of 200 kPa was relatively greater than the collapse test when adding WTS samples due to adding water at the beginning and subsequent increase in dissolved gypsum. Furthermore, comparing the collapse potential obtained from the double oedometer and actual collapse tests showed that the former was greater. Adding 20% of WTS to specimens yielded little gypseous soil collapsibility. This behavior is consistent with other studies conducted by Al-Mukhtar and Al-Obaidi [22], Seleam [23], and Saaed et al. [24], as shown in (Figs. 3 (a) and (b)).

3.2.Compaction Curves Gypseous Soil Influenced by Adding WTS

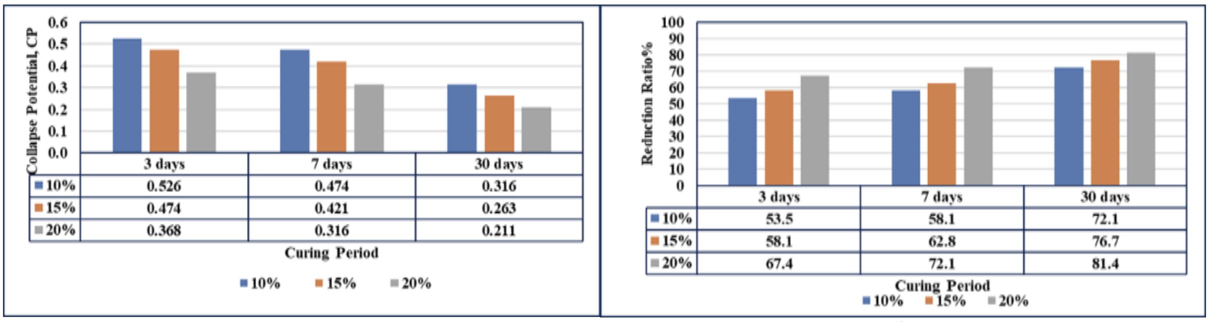
Figure 4 (a) illustrates the compaction curves of gypsum soil mixed with different contents of (WTS), while Fig. 4 (b) shows the variation of Maximum Dry Unit Weight (MDU) and Optimum Moisture Content (OMC) by adding WTS to gypseous soil. The information shows that when the percentage of WTS added to the gypseous soil was between 15% and 20%, the MDU reached its maximum value. Additionally, the OMC ranged from 11.6% to 10.93% in this range of WTS addition, which indicates that adding WTS to gypseous soil in these proportions can improve the soil's compaction properties, which can be beneficial for various engineering applications, such as soil stabilization and construction projects. Although the provided search results do not directly discuss the specific topic of compaction curves of gypsum soil mixed with WTS, they provide some insights into soil stabilization and compaction characteristics of different soil mixtures. These studies highlight the importance of understanding the effects of adding various materials to soils to improve their engineering properties.



(a) 3 days. (b) 7 days.

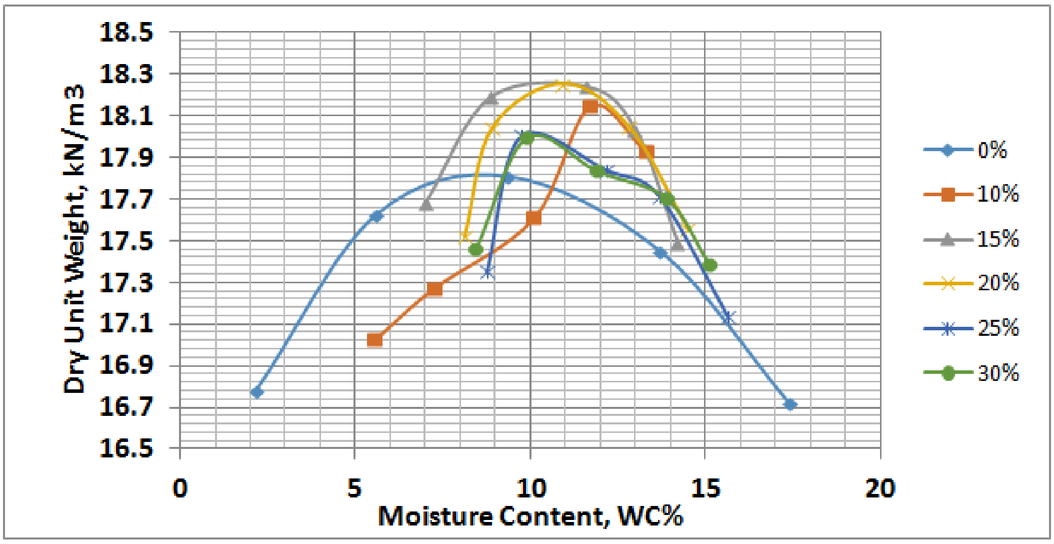
(c) 30 days. (d) WTC Comparison.

Fig. 2 Oedometer Test (OT) for Different Curing Periods with WTC Comparison Among them.

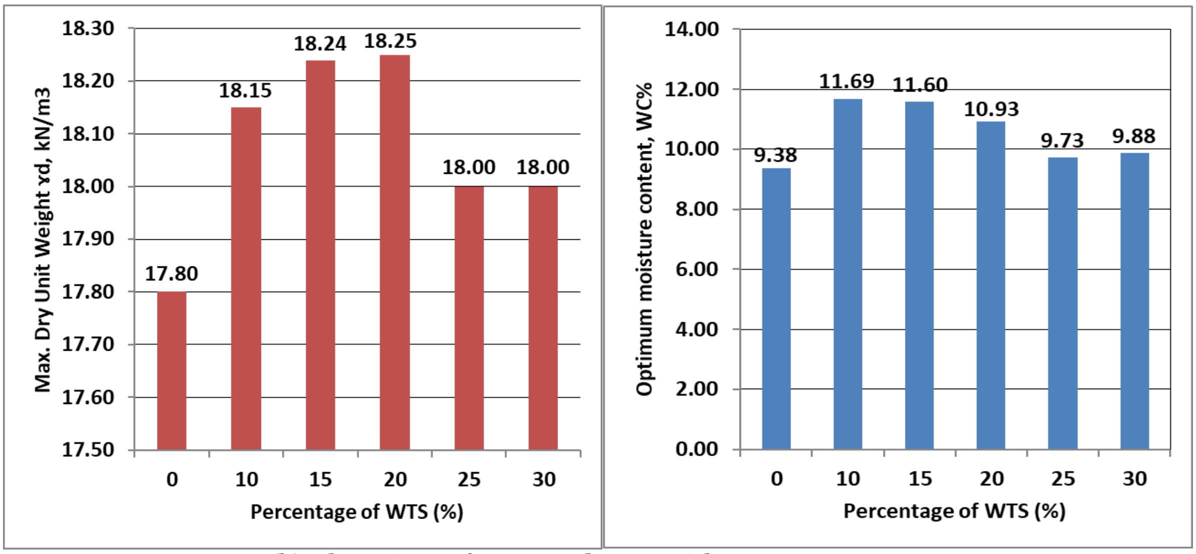


(a) (b)

Fig. 3 (a) Variation of CP with Percentage of WTS, and (b) Variation of Reduction Ratio with Percentage of WTS at Different Curing Periods.



(a) Compaction Curves of Soil Mixed with Diverse WTS Proportions.



(b) Alterations of MDU and OMC with WTS Percentage.

Fig. 4 Results of Compaction.

Table 4 The XRF Test's Results.

No.	Mineral/compound	Gypseous Soil	WTS	Gypseous Soil with WTS		
				10%	15%	20%
1	Alumina (Al_2O_3)	0.017	0.722	0.2929	0.1342	0.2110
2	Fe_2O_3	0.2851	4.383	2.087	1.750	2.298

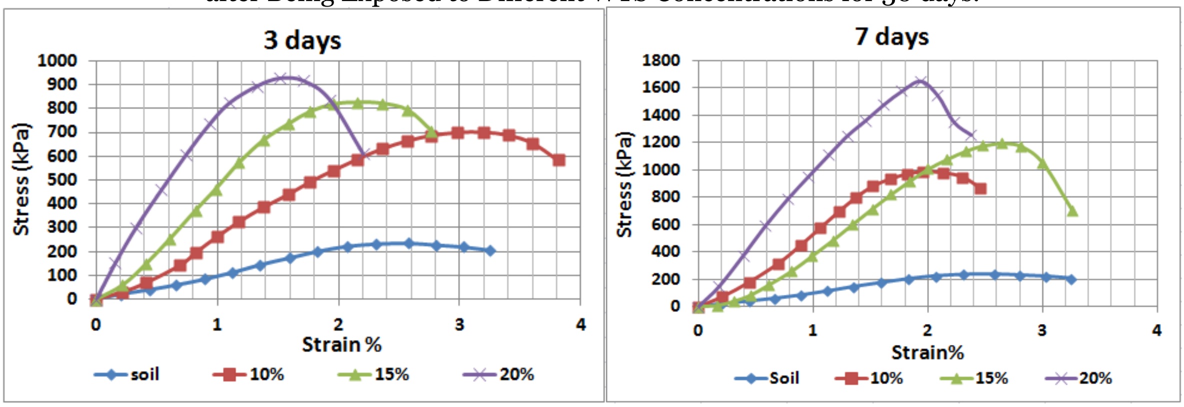
The concentration of two minerals (alumina and iron oxide) in the gypseous soil and gypseous soil with (WTS) at distinct concentrations (i.e. 10%, 15%, and 20%) is presented in Table 4. The results, therefore, reveal that the concentration of alumina and iron oxide increased with WTS concentration. The outcomes of the present study are consistent with what previous studies found, as WTS is positively enhanced by the properties of soil. For instance, the finding by Qasemi et al. [25] indicates that incorporating WTS into the soil increases the content of some minerals like iron, aluminum, and calcium. The percentage of these minerals in the soil is increased with the addition of WTS, probably as a result of the high percentage of these minerals as natural components in WTS. When WTS is decomposed in the soil, the percentage of these minerals ascends. Along this line, Shukla et al. [26] in their study showed that incorporation of WTS into soil can make the soil fertility better by an increase of some nutrients percentage, water retention, and microbial activity. These improvements in soil properties could quicken plant growth and then heightened the crop productivity of agriculture. As a whole, the outcomes achieved in this study imply that the percentage of some minerals could be increased by adding WTS to gypseous soil, which might have a beneficial effect on soil properties and plant growth. Nevertheless, further research into the best WTS content for diverse types of soils in different environmental conditions, while, on the other, its possible adverse effects should be assessed.

3.3.Unconfined Compressive Strength of Gypseous Soil and WTS

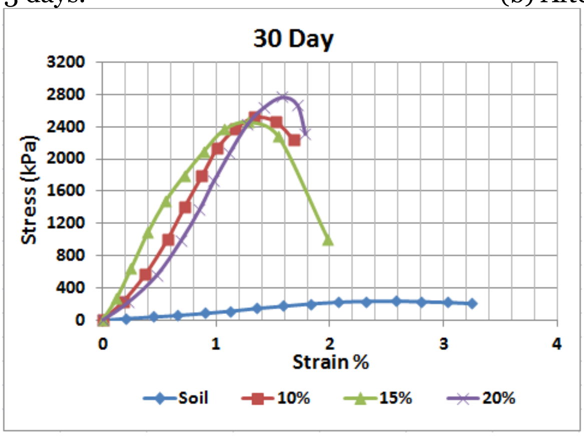
The unconfined compression test is the most used method of soil shear testing because it is one of the quickest and cheapest shear strength tests. It is primarily used on unsaturated, cohesive soils. The unconfined compression test is strain-controlled. When the soil sample was loaded at a constant rate, the pore pressures (water within the soil) changed too quickly to dissipate. As a result, it is typical of soils on construction sites where the rate of construction is rapid, and the pore waters do not have time to dissipate. Figure 5 shows the failure behavior of soil specimens mixed with different percentages of WTS cured for 30 days during an unconfined compressive strength test. The UCS of the natural soils shows much variation (fluctuating between 235.8 and 2770.9 kPa) despite the different quantities of the added WTS, as shown in (Figs. 6 (a), (b), and (c)). The decrease in the void ratio of the soil samples elucidates the elevation in strength values with WTS content.

(a) 10%. (b) 15%. (c) 20%.

Fig. 5 The Failure Behavior of Soil Specimens in an Unconfined Compressive Strength Test Changed after Being Exposed to Different WTS Concentrations for 30 days.



(a) After 3 days. (b) After 7 days.



(c) after 30 days.

Fig. 6 Stress-Strain Relationships at Unconfined Compressive Strength for Different Percentages of WTS and Different Periods.

Figures 7 and 8 present the outcomes concerning the unconfined compressive strength of soil samples, considering diverse WTS content and different curing conditions. With an extended curing period, WTS-containing and WTS-free mixes exhibited an increase in unconfined compressive strength. Soil samples with WTS displayed higher unconfined compressive strength values than those without WTS. This behavior can be attributed to the faster hydration rate, which causes the more pronounced reaction between the soil and WTS. Saberian et al. [27] inspected the effect of WTS on the clayey soils' engineering properties. They concluded that WTS, when added to the soil, enhances the compaction properties by showing the higher maximum dry density with lower values of the optimum moisture content. Also, Taha et al. [28] studied the influence of WTS on the sandy soil geotechnical properties. They observed that with the increase in the WTS in the soil, the maximum dry density increased and the optimum moisture content decreased, thus increasing the compaction properties of the soil. In another study by Li et al. [29] examined the impact of WTS on the mechanical properties of expansive soil. Their results revealed that the increase in strength was further validated with the introduction of WTS into the soil, which resulted in reduced compressibility and hence showed better compaction features.

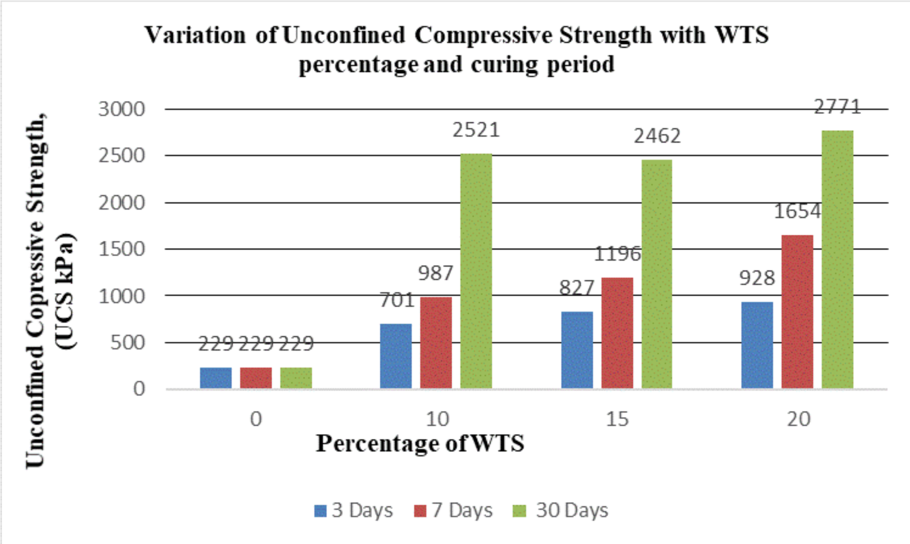


Fig. 7 Variation of Unconfined Compressive Strength with WTS Percentage and Curing Period.

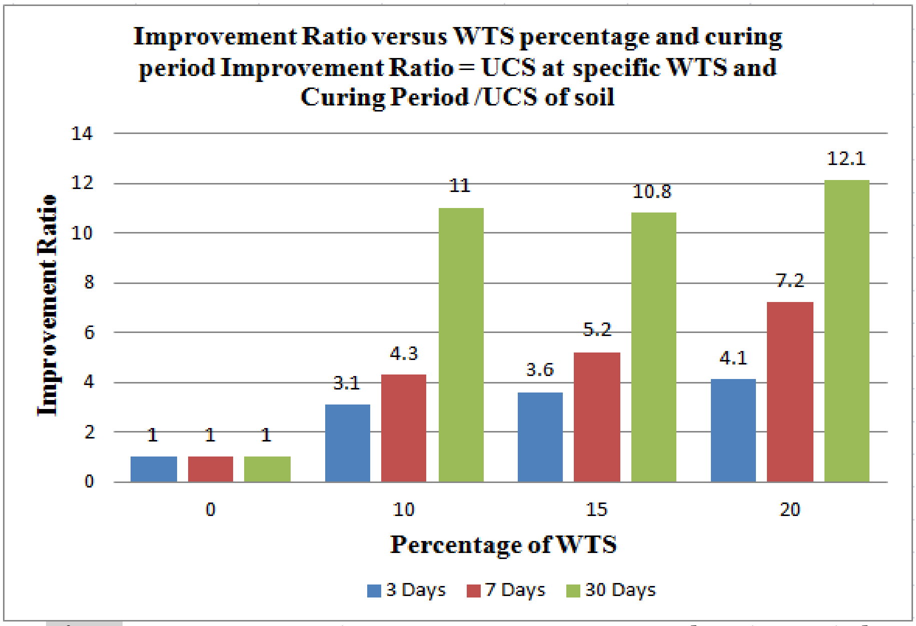
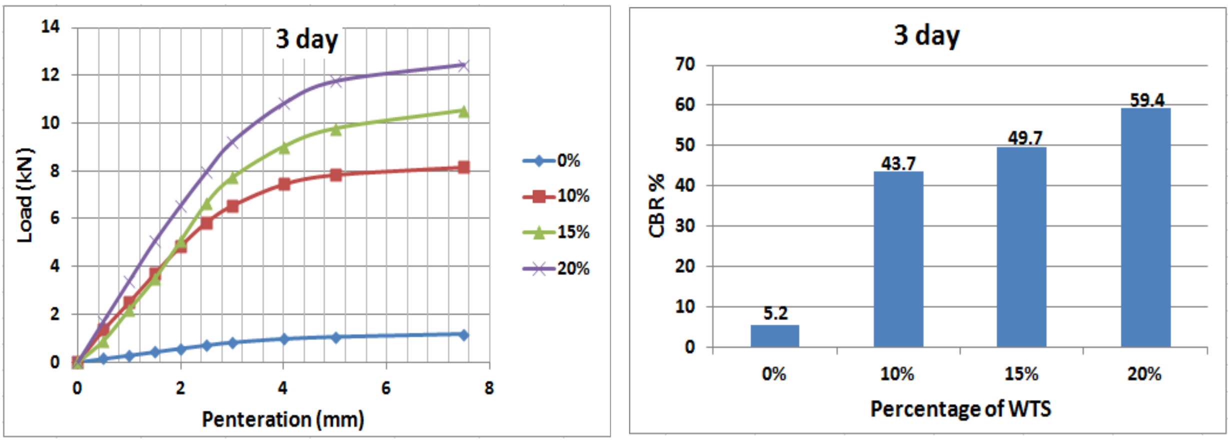


Fig. 8 Improvement Ratio Versus WTS Percentage and Curing Period Improvement Ratio = UCS at Specific WTS and Curing Period/UCS of Soil.

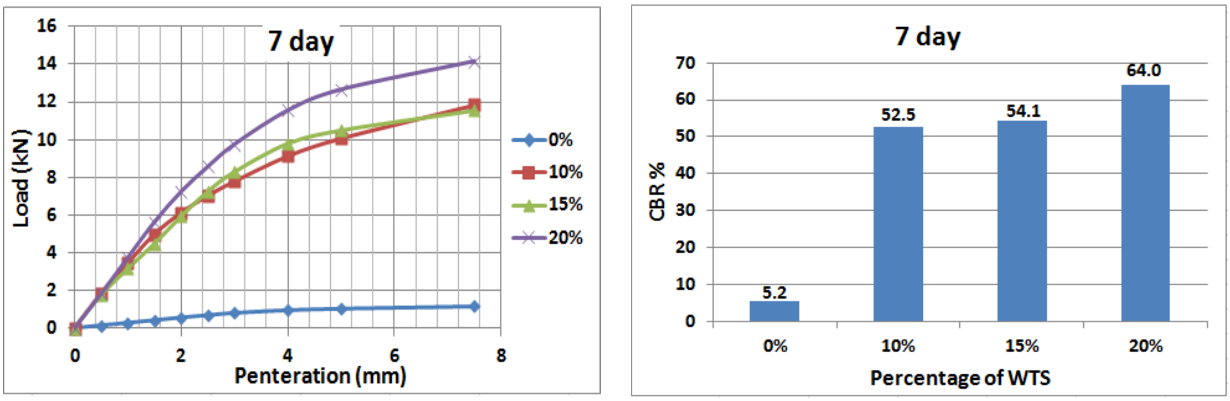
The unconfined compressive strength value increased up to its maximum observed for the soil samples that contained 20% of WTS after the 30-day period of curing, revealing the considerable apparent effect of WTS content (Fig. 7). The strength of the 7-day cured soil samples treated with 15% WTS came second among the treated soils, while that of the soil treated with 10% WTS and 3 days cured came the lowest. The reduction in the unconfined compressive strength of the soil samples was attributed to the reason of existence for the unreacted gypsum particles, which is a lightweight material with specific gravity 2.41. Further, it was observed that the texture of the soil samples was affected by adding the gypsum content. Thus, the size of the macro pores was increased with increasing content of the WTS content, which subsequently reduced the unconfined compressive strength. On the other hand, the WTS content further contributed to the reactions for the formation of the cementitious materials, and that made changes in the unconfined compressive strength.

3.4. Results of CBR Test on Gypsum Soil and WTS

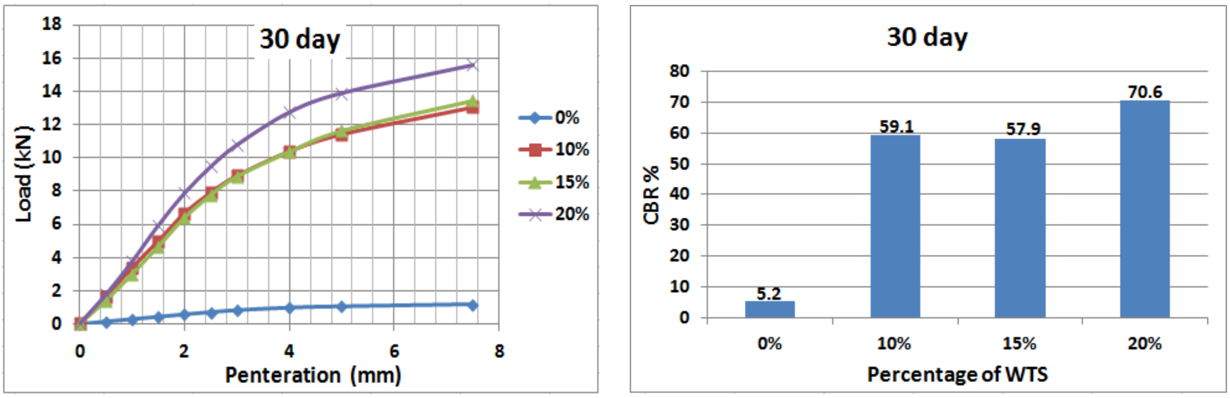
The results indicate that California Bearing Ratio (CBR) improvement by Water Treatment Sludge (WTS) addition to the soil can be significant in view of different percentages of WTS and time interval. The CBR values raised with percentages of added WTS in the soil and with the increment of curing time, indicating improvement in soil strength and stability. For instance, if there is no WTS added, the CBR value is just 5.2. Alternatively, the CBR value was enlarged to 43.7 after three days when 10% WTS was inserted, and it was more improved to 52.5 after seven days and 59.1 after 30 days. The CBR values also augmented to 49.7 and 54.1 after three and seven days with 15% addition of WTS, respectively, and to 57.9 and 70.6 with 15% and 20% addition of WTS after 30 days, respectively. This therefore clarified that both the strength and stability of the soil ascends with higher WTS content and curing time. This work concord with previous studies on the utilization of different additives to stabilize soils. For example, Zhang et al. [30] found out that adding waste rock powder to loess soil significantly enlarged the shear strength and deformation of the loess soil, thus the slope stability was enhanced. Lastly, this research findings and past studies go on to portray that the WTS addition is effective at improving the properties of the soil and augmenting the stability of the geotechnical structures. The best ratio and the application method for WTS should be thus estimated before extensive utilization in geotechnical engineering projects, which must be based on the exact soil properties and environmental conditions. Likewise, Wang et al. [31] explained that the WTS affected the load-deformation behavior of cement-stabilized soil. They observed that the addition of WTS leads to the improvement of deformation modulus, but the peak strength and stiffness of the mixture were reduced. This was because according to the authors, WTS was lubricant particles that offer a little resistance to the sliding and reorientation of the soil particles under load. In contrast, some researchers found that WTS had a positive effect on the mechanical soil properties. For instance, Wang et al. [32] studied the use of WTS as aggregates replacing natural aggregates in asphalt mixture. They found out that through the use of WTS, the rutting resistance and moisture susceptibility for the asphalt mixture should be improved. Similarly, another study by Huang et al. [33] evaluated the effect of WTS on the mechanical behavior of recycled concrete aggregate (RCA) stabilized with cement and fly ash. The results showed that adding WTS increased the compressive strength and stiffness of the RCA-cement-fly ash-WTS mixture while reducing its deformation and creep characteristics. The load-deformation curves with the corresponding deformation-time curves of selected mixtures were obtained from the compaction test. By generally viewing these (Fig. 9 (a)), relatively high deformations developed at the first loading cycles. Repeated load applications caused the permanent deformation to decrease slightly between a given two subsequent loading cycles and eventually decrease to the lowest levels at the end of the test. Depending on the composition of the mixture, it required about 15 – 50 loading cycles to attain the stable state, at which the permanent deformation due to the last five loading applications becomes very small and can be neglected. Adding WTS affected the specimen's response by increasing the number of load applications to reach a stable condition, which may be owed to the increased compressibility of soil-WTS mixtures due to the rearrangement of WTS grains under plunger load, as demonstrated in Figs. 9 (a), (b), and (c)).



(a) 3 days.



(b) 7 days.



(c) 30 days.

Fig. 9 Load-Deformation Curves and Deformation-Time Curves of Selected Mixtures Obtained from the CBR Test for Various Periods.

4.DISCUSSION

The results of the present paper confirmed that waste treatment sludge (WTS) can potentially enhance the engineering properties of gypseous soil. The studies conducted in this research provide insights into the effect of the addition of different materials to the soils in order to improve their properties, including the analyses of XRD and XRF to determine the presence of minerals in gypseous soil and WTS. The results showed that the concentration of some of the minerals, such as alumina and iron oxide, increased with WTS concentration since WTS contains some of the minerals as natural components. So, when WTS decomposes in the soil, it releases these minerals into the soil. Adding WTS to soil can further enhance soil fertility by increasing the percentage of some nutrients, water retention, and microbial activity. Such changes in soil properties might enhance and raise plant growth rate, and in agricultural lands, this would increase crop productivity. The soil was also subjected to the compaction test, an indication of the correct density and moisture content relevant to the soil used for construction of the road. The team that is constructing the road will then be in a position to tell from this the best soil compaction and moisture control for the road for it to be safe and last long. Furthermore, the research also looks into an experiment carried out on the different proportions of WTS added to gypseous soil, the curing period in terms of unconfined compressive strength (UCS) and the California Bearing Ratio (CBR). The test results indicate that the addition of WTS into the soil greatly increased the UCS and CBR at different percentages of WTS and time intervals. The CBR values gradually increased with an increase in the percentage of WTS added to the soil and increase in the curing periods since it indicates a development of the strength and stability of the soil. In general, the results showed that the addition of WTS to the gypseous soil has increased the percentage of some minerals in this area, which may favor soil properties and the growth of plants. However, further study is needed in order to describe the proper WTS content for every kind of soil under different environmental conditions, and even to estimate the expected negative impact of the application of WTS.

5.CONCLUSIONS

The conclusions include:

- The incorporation of waste treatment sludge (WTS) in gypseous soil has been found to be one way of improving its engineering properties.
- The addition of WTS increased mineral concentration and the fertility of the soil, as well as strengthen it, making it more stable. The percentage of Alumina (Al2O3)

and Fe_2O_3 enlarged from 0.017% and 0.2851% for natural soil to 0.2110% and 2.298%, respectively, when inserting 20% of WTS into the soil.

- The study provides a formula to calculate the percentage of gypsum in a soil sample based on weight loss during burning.
- The article further shows that the proper soil compaction and the control of moisture for use in road construction must pass through the compaction test. The MDU enlarged from 17.8 kN/m³ to 18.25 kN/m³ when adding 20% of TS. In addition, the OMC increased to 11.69% when 10% of WTS was added, compared to 9.38% for natural soil.
- The addition of WTS at different percentages and curing periods shows an increase in the unconfined compressive strength (UCS) and California Bearing Ratio (CBR) for the gypseous soil from the experiment. The values of UCS and CBR ascended to 2771 kPa and 70.6%, respectively, which were obtained with a 20% WTS addition and a 30-day curing period.
- Further research is recommended to determine optimal WTS concentration for different soil types and environmental conditions.

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