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Characterization of the Geotechnical Properties of Expansive Soil Improved by Sludge Waste

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ABSTRACT

Recently, a great rise in the population and fast manufacturing processes were noticed. These processes release significant magnitudes of waste. These wastes occupied a notable ground region, generating big issues for the earth and the environment. To enhance the geotechnical properties of fine-grained soil, a sequence of research projects in the lab were conducted to analyze the impacts of adding sludge waste (SW). The tests were done on both natural and mixed soil with SW at various proportions (2%, 4%, 6%, 8%, and 10%) based on the dry mass of the soil used. The experiments conducted focused on consistency, compaction, and shear strength. With the addition of 10% of SW, the values of LL and PI decreased by 29.7% and 38.5%, respectively. Also, with 10% of SW, the values of swelling percent (SP) and swelling pressure (SPR) decreased by 34% and 33%. On the other hand, SW content increase led to the rise in unconfined compressive strength (UCS) of the soil tested from 511kPa to 726kPa with the addition of 10% SW. Based on the findings, it can be confirmed that 10% SW in its natural state is notable for improving fine-grained soil strength and reducing the environmental hazard related to this waste type.

Keywords: Expansive soil, Geotechnical characteristics, Stabilization, Sludge waste, Swelling.

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توصيف الخصائص الجيوتقنية للتربة الانتفاخية المحسنة بواسطة نفايات المجاري

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الخلاصة

في الآونة الأخيرة ، لوحظ ارتفاع كبير في عدد السكان وعمليات التصنيع السريعة. هذه العمليات تطلق كميات كبيرة من النفايات. احتلت هذه النفايات منطقة بارزة من الأرض، مما تسبب في مشاكل كبيرة للأرض والبيئة. أجريت سلسلة من الاختبارات المعملية على تربة طبيعية ومخلوطة مع SW بنسب مختلفة (2%، 4%، 6%، 8%، 10%) بالكتلة الجافة للتربة المستخدمة. تشمل التجارب التي تم إجراؤها الاتساق والضغط وقوة القص. أسفرت نتائج الدراسة عن انخفاض حد السائل (LL) وحد البلاستيك (PL) ومؤشر اللدونة (PI) ومحتوى الرطوبة الأمثل (OMC) ونسبة الانتفاخ (SP) وضغط الانتفاخ (SPR) مع الزيادة في محتوى SW. ركزت التجارب التي أجريت على الاتساق والضغط وقوة القص. مع إضافة 10٪ من SW ، انخفضت قيم LL و PI بنسبة 29.7٪ و 38.5٪ على التوالي ، وأيضًا مع إضافة 10٪ من SW ، انخفضت قيم نسبة الانتفاخ (SP) وضغط الانتفاخ (SPR) بمقدار 34 ٪ و 33٪ على التوالي. من ناحية أخرى ، أدت زيادة محتوى SW إلى زيادة مقاومة الانضغاط غير المحصورة (UCS) للتربة التي تم اختبارها من 511 kPa إلى 726 kPa مع إضافة 10٪ من SW. بناءً على النتائج ، يمكن التأكيد على أن 10٪ SW في حالتها الطبيعية تتميز بتحسين قوة التربة الدقيقة وتقليل المخاطر البيئية المرتبطة بهذا النوع من النفايات.

الكلمات المفتاحية: التربة الانتفاخية، الخصائص الجيوتقنية، التثبيت، نفايات المجاري، الانتفاخ.

1. INTRODUCTION

Commonly in engineering projects, soils are very common materials. Soils can be used for construction projects such as embankments, highways, and railways. Clayey soils cover most ground surfaces (**Rashed et al., 2017; Behnood, 2018; Salih, 2020**). Clayey soil is a risky fine-grained soil in semiarid and arid areas. It is problematic for construction projects due to its susceptibility to swell over the wet season and shrink over the dry season. Expansive soils show a large volume variation because of moisture content changes, significantly damaging the superstructure built on them. Expansive soil's behavior (swelling and shrinkage) refers to the existence of montmorillonite minerals. So, if not properly amended, these soils are counted as a possible natural hazard that may result in widespread damage to superstructures (**Salih et al., 2022**). As a result, in some cases, improvement of unsuitable soil properties is necessary. To establish a solid foundation for structures, some fine-grained soils, such as expansive soils, can stabilize their weak geotechnical qualities (**Salih et al., 2022**).

Soil stabilization is a necessary part of the construction. Soil stabilization can be defined as a physical, chemical, biological, and/or combined procedure for changing in-situ soil to accomplish a technical goal. Improvements in soils involve soil bearing capability increase, tensile strength increase of natural soils, in addition to waste materials total performance to strengthen the roads surfaces (**kadhim et al., 2022**), and mainly reduce and control shrink-

swell, shear strength can be increased, and consequently, the sub-grade soil's ability to sustain pavement and foundations increased its load bearing capability.
Different natural and artificial substances have been employed to stabilize various soil types, including fly ash, hydrated and quick lime, steel slag, cement kiln dust, and crushed limestone or dust. (**Phanikumar and Sharma, 2007; Fattah et al., 2011; Pastor et al., 2019; Abdalqadir et al., 2020; Abdalqadir and Salih, 2020; Abdalla and Salih, 2020**). Similarly, the positive role of hydrated lime is achieved when it is used to improve weak geotechnical characteristics of clayey soils (**Abdalla and Salih, 2020**).
Waste disposal is a big challenge for all developing countries, which is fundamental because of the rising waste generation, the significant management cost, and the lack of understanding of responsible factors of waste management stages (**Agarwal, 2015**). Over the past few years, solid waste has significantly improved weak soils, such as expansive soils (**Sabat and Pati, 2014**).
Moreover, sewage sludge becomes common for soil improvement, such as sewage sludge ash (**Liu et al., 2012; Ingunza et al., 2015; Attom et al., 2017; Norouzian et al., 2018; Al-Adhamii et al., 2022**) and sewage sludge (**Amiralian et al., 2015; Pavani, 2016**). However, in the research, several stabilization aspects have not been focused on yet for different types of weak soils, such as utilizing SW in its natural state. Using SW in its natural state is notable and useful due to the terms of cost and energy to amend the soil's capacity instead of selecting the deep foundation option.
This study aims to utilize SW as a stabilizer material to improve some of the undesired geotechnical characteristics of expansive soil (CH soil). This study's purpose covered a laboratory testing program consisting of consistency, expansion, and unconfined compression experiments. The study will cover geotechnical characteristics changes such as Atterberg limits, expansion parameters, and unconfined compression properties.

2. STUDY METHODOLOGY

2.1 Used Natural Soil

The soil sample used in this study was taken from Bakrajo, Sulaimani City, northern Iraq, Sulaimani city with 35.5665234 N and 45.3568612 E, as shown in **Fig. 1**. The current study's fine-grained soil sample was taken at 1.5 meters below the ground level. To prevent any changes to the sample qualities owing to increased temperature, the soil sample was kept in plastic bags and transferred to a soil laboratory where it was first dried by air and then dried in an oven at 60 +/- 5 degrees Celsius (**Ikhlef et al., 2014; Sunil and Deepa, 2016**). Next, the oven-dried sample was crushed and passed through a No.4 sieve to expel the existing gravel fraction and prepare a homogenous sample. According to Table 1, the natural soil sample was classified as CH soil type. The rest of the geotechnical characteristics have been tabulated in **Table 1**.

Figure 1. Site locations map for selected soil sample.

Table 1. The physical and geotechnical properties of the natural soil sample.

No.	Physical and Geotechnical Properties		ASTM	Unit	Value
1	Particle Size Distribution	Sand (0.075mm - 4.75mm)	ASTM D422	%	13
2		Silt (0.005mm - 0.075mm)		%	36
3		Clay (< 0.005mm)		%	51
4	Atterberg Limits	Liquid Limit (LL)	ASTM D4318	%	55
5		Plastic Limit (PL)		%	29
6		Plasticity Index (PI)		%	26
7	Linear Shrinkage (LSL)		ASTM C356-10	%	15.36
8	Soil symbols		-	-	CH
9	Specific Gravity (G_s)		ASTM D854	-	2.71
10	Compaction Characteristics	OMC	ASTM D1557	%	17.2
11		MDD		(kN/m^3)	17.46
12	Swelling Percent		ASTM D4546	%	8.26
13	Swelling Pressure			(kPa)	171.6
14	Unconfined Compressive Strength (UCS)		ASTM D2166	(kPa)	511

2.2 Used Sludge Waste (SW)

Sludge waste, a common waste material, was selected as a binder element of the current study. It was obtained from the new campus station of the regional wastewater treatment plant in Sulaimani, Northern Iraq. The SW physical properties and chemical analysis are illustrated in **Tables 2 and 3,** respectively. The SW sample used in this research was crushed into a powder, then sieved through a No. 40 sieve, and after that, was used by 2, 4, 6, 8, and 10% as replacing mass from the dry mass of the natural soil sample.

Table 2. The physical properties of the utilized SW.

Properties	Sludge waste
Average particle size	0.2–0.5 mm
Surface area ($m^2\ g^{-1}$)	93.58
Color	Black
Morphology	Irregular
Bulk density ($g.cm^{-3}$)	0.56
True density ($g.cm^{-3}$)	1.53

Table 3. The chemical Composition of the utilized SW.

Chemical Composition	(SW) (w/w %)
Fe_2O_3	1.69
SiO_2	14.76
Al_2O_3	3.727
TiO_2	0.256
MnO	0.013
MgO	2.912
Chloride (Cl^-)	0.042
CaO	4.874
P_2O_5	1.875
Sulfate SO_3	1.497

2.3 Methods of Samples Preparation and Testing

After the required materials were prepared, SW was sieved on sieve No. 40 and mixed with the dry soil sample by replacing the allocated dry soil mass. Both dry materials were mixed thoroughly, the required amount of water was added, and then the mixture was thoroughly mixed. The mixture was then used to prepare the testing samples in the laboratory to obtain the geotechnical properties of the selected soil sample before and after SW addition in various percentages (as shown in section 2.2). All the samples of soil and SW were left for 24 hours after the preparation stage to be matured and then tested.

3. RESULTS AND DISCUSSION

3.1 Consistency Characteristics Improvement

SW carried out LL, PL, and LSL studies on soil samples that had been treated and untreated. The amount of LL and PI decreased by 29.7% and 38.5%, respectively, when SW was increased from 0% to 10%. In **Fig. 1**, the effect of SW on the parameters governing the consistency of fine-grained soil is amply illustrated. The value of LSL was also reduced from 15.35 % to 11.64 %, with the increase of SW from 0 % to 10 %; adding sludge waste reduced all those restrictions. This can be attributed to the fact that the soil absorbed less water because the soil mass was diminished due to applying SW. The thinning of the two layers of clay particles caused a decrease in LL, PL, and LSL values. This resulted from the cation exchange reaction, which increased the attraction between particles and caused them to clump together.

Additionally, soil clay minerals decrease as the percentage of SW in the soil combination increases. LL, PL, and LSL declined due to the soil mixture's diminished ability to retain water. This study's reduction trend with the percentage increase in SW on CH soil stabilized with SW ash is consistent (**Kadhim et al., 2022)**. The fine-grained soil was more affected by water than the coarse-grained soil. The outcomes of this study yielded a significant role of SW in decreasing the consistency parameters, especially LL (**Figs. 2 and 3**), which differ from the outcomes of the utilization of SW ash. Therefore, fine-grained soil had greater water absorption ability with sewage sludge ash percent increase, which may vary from the utilized SW in this study. LL and LSL values started to drop quickly between 2 - 4% SW, then decreased linearly. The SW percent increase caused the water absorption process to be reduced. Fine-grained soil absorbs more water due to the availability of clay minerals, which decreased due to the replacement by SW.

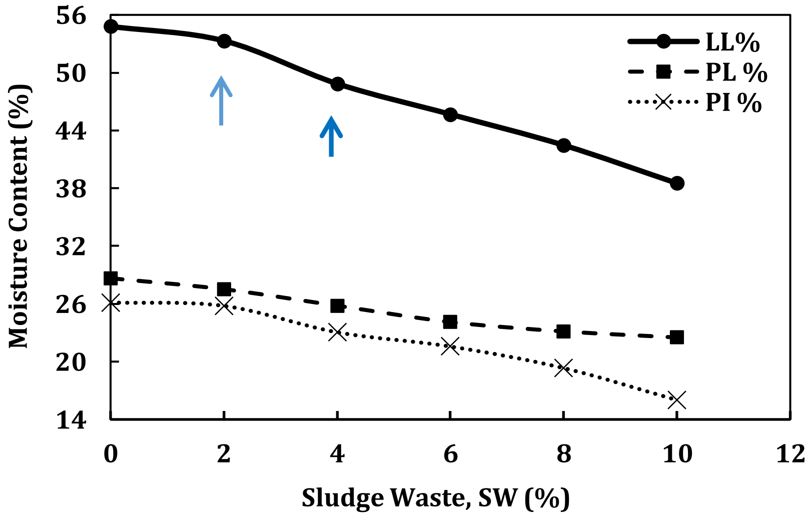

Figure 2. Variation of the liquid limit, plastic limit, and plasticity index when Sludge waste is included in varying amounts.

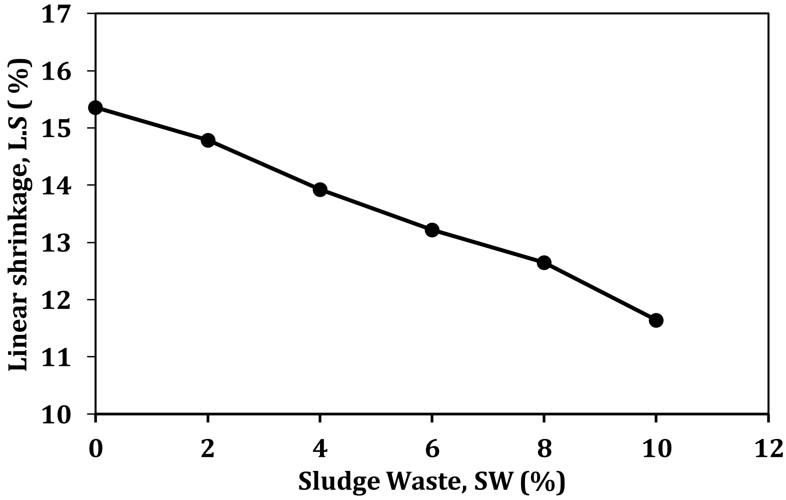

Figure 3. Variation of the linear shrinkage limit with different sludge waste content levels.

3.2. Swelling Characteristics Improvement

On soil samples that had been both untreated and treated, SPR and SP experiments were run. The values of SPR and SP were reduced from 171.6 kPa to 114.9 kPa and from 8.26 % to 5.45 %, respectively, with the addition of SW from 0 % to 10 %. (**Figs. 4 and 5**). The drop in SPR and SP values may be caused by influencing elements that influence the swelling process of expansive soil, such as the mineral makeup of the clay, the volume of non-clay material, the density of the soil, and the void ratio. So, the SW presence, a non-clay material, decreases the soil's content of clay minerals in the soil-SW mixture. Therefore, the expansive clay particles' total surface area decreases and can reduce the SPR and SP values. The outcomes of the current study on SPR and SP are consistent with the conclusions of (**Al-sharif and Attom, 2014)** on CH soil stabilized with SW ash. SPR and SP values started to drop quickly after adding 2% SW. The SW percent increase caused the absorption process of water to be decreased due to the reduction in the clay minerals percentage due to SW's replacement of part of the expansive soil sample.

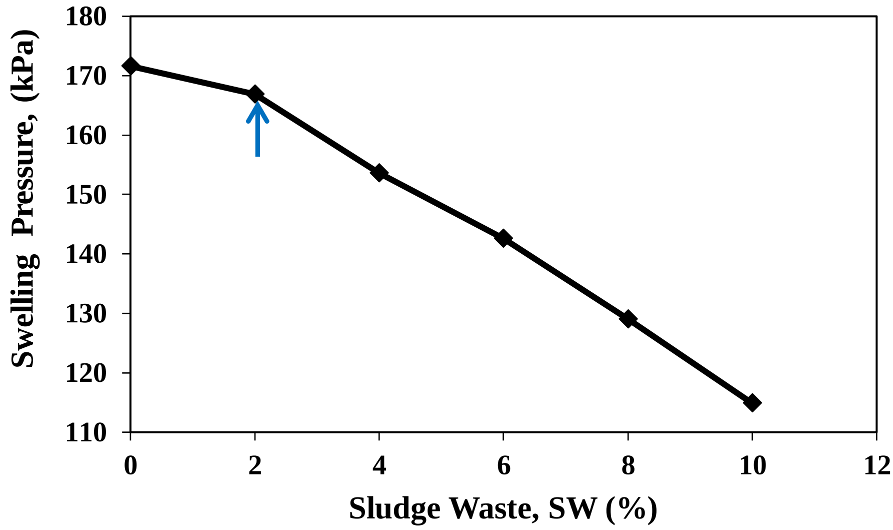

Figure 4. Variation of SP with various percentages of sludge waste.

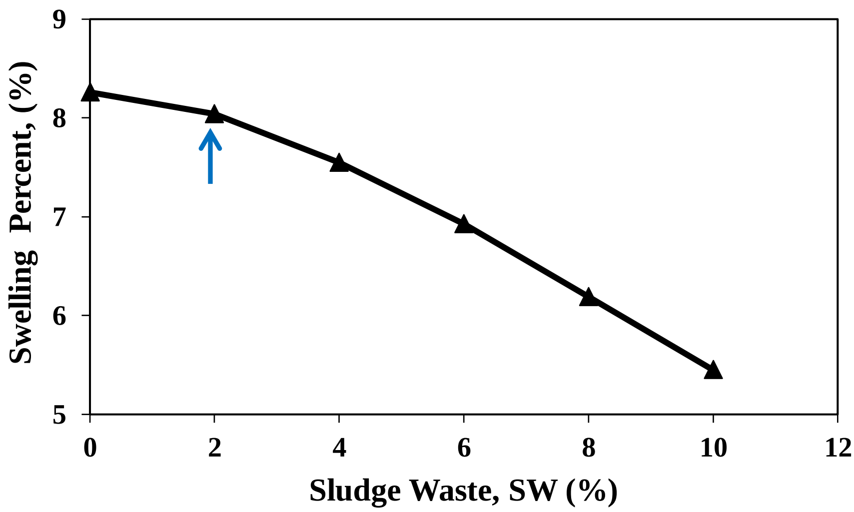

Figure 5. Variation of SPR with various percentages of sludge waste.

3.3. Unconfined Compressive Strength Improvement

The modified Proctor compaction test was conducted following ASTM standards (ASTM D1557) to arrange the samples for UCS tests and to acquire the maximum dry density (MDD) and ideal moisture content (OMC). The needed mixed samples were subjected to the UCS experiment following ASTM standards (ASTM D2166) to ascertain the unconfined compressive strength value (UCS). The UCS test sample preparation using compaction results for 0, 2, 4, 6, 8, and 10% SW.

With the increase of SW percent from 0% to 10%, the UCS value increased from 511 kPa to 726 kPa (**Fig. 6**). The increased UCS values are due to adding non-expansive material (SW) to the expansive soil, which decreased the clay minerals' amount in addition to a reduction in the void spaces among the soil particles. This soil's internal structural changes resulted in a stiffer structure, which showed higher compression capability. The current study on UCS aligns with the outcomes of (**Al-sharif and Attom, 2014)** on CH soil stabilized with SW ash. From **Fig. 7**, the SW in its natural state works significantly up to 10% to boost the UCS of the soil. This outcome indicates that the SW natural state improves the soil's UCS, which is better than the ash state as it achieved 8% (**Shafii and Noh, 2018**).

Fig. 7 shows the stress-strain curves, and it is obvious that when the SW percentage increases, the shear strain increases by a tiny percentage. Therefore, a 10% SW increases the UCS significantly. The untreated UCS of 511 kPa was enhanced to 726 kPa for 10% SW, as shown in **Figs. 6 and 7**. The gained strength because of SW is attributed to decreased soil porosity **(Consoli et al., 2019)**. However, the treated sample strain slightly increased due to the 10% SW content. The achieved results due to the SW percent increase for the ductility change in this study were well-matched with the outcomes of (**Eskisar, 2015; Nursit et al., 2017; Al-Jabban et al., 2019; Wahab et al., 2021; Kadhim et al., 2022)** studies on using cement for soil improvement.

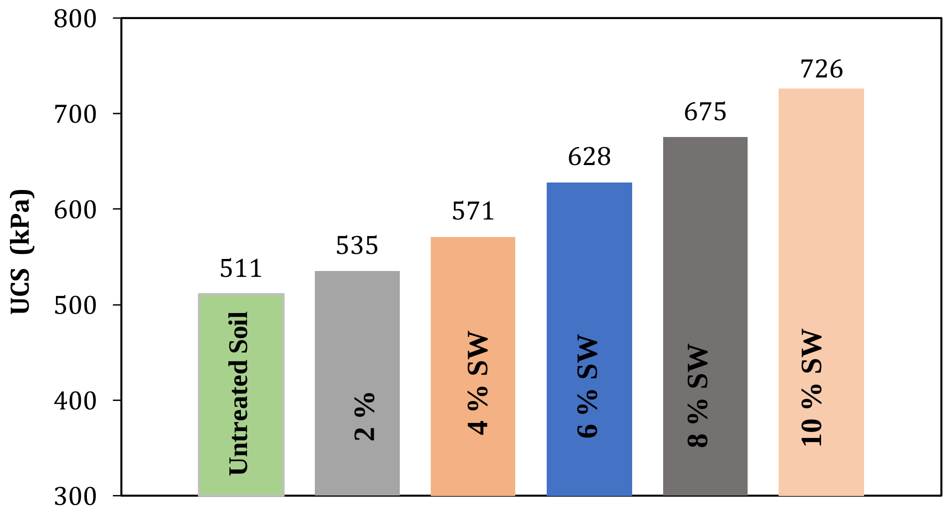

Figure 6. Variation of UCS with various percentages of SW.

In this study, the changes in the ductility of the sample mixed with 10% SW were not considerable, whereas the strength value notably increased. This feature is also evident in the failure shapes of the samples shown in **Fig. 7**, where the failure plane for the sample that received a 10% SW treatment is in the shape of a shear with bulging. As seen in **Fig. 7**, the bottom side of the untreated sample was only sheared in an inclined plane. The failure plane pattern discovered in the current study is well-matched with the outcomes achieved by **(Mengue et al., 2017)**, who worked on fine-grained soil treatment with cement.

The overall UCS data in **Figs. 5 and 6** reveal that SW increased compressive strength, which is attributable to SW filling soil particle pores and forming clods. The higher sample strength could be due to the presence of minerals like CaO and MgO (as seen in **Table 3**), which can form strong bonds with the clay minerals in the soil, thus leading to an increased UCS. This reveals that 10% SW in the soil is the best percent that forms cementing bonds.

To evaluate the deformability index (I_D = strain at failure for treated sample/strain at failure for natural sample) and soil's softening characteristics due to strain **(Sunil and Deepa, 2016)**, I_D value for 10% SW was depicted, which was 1.205. The introduction of SW to fine-grained soil resulted in larger deformability. This may be due to the SW particles' stiffness being weak compared to the natural soil particles, which, although resulting in higher strength due to the created cementing bond, caused larger deformability and flexibility properties, as shown in **Fig. 7**.

In addition, the major cause for the flexibility increase can be demonstrated that the utilization of 10% SW altered the structure of the soil, and the brittle property of the utilized SW was notable in controlling the blends. **Fig. 8** shows the different types of cracks in UCS samples after testing. Shear failure is significant in most cases of testing. However, for 2% and 10%, SW bulging failure was also noticed.

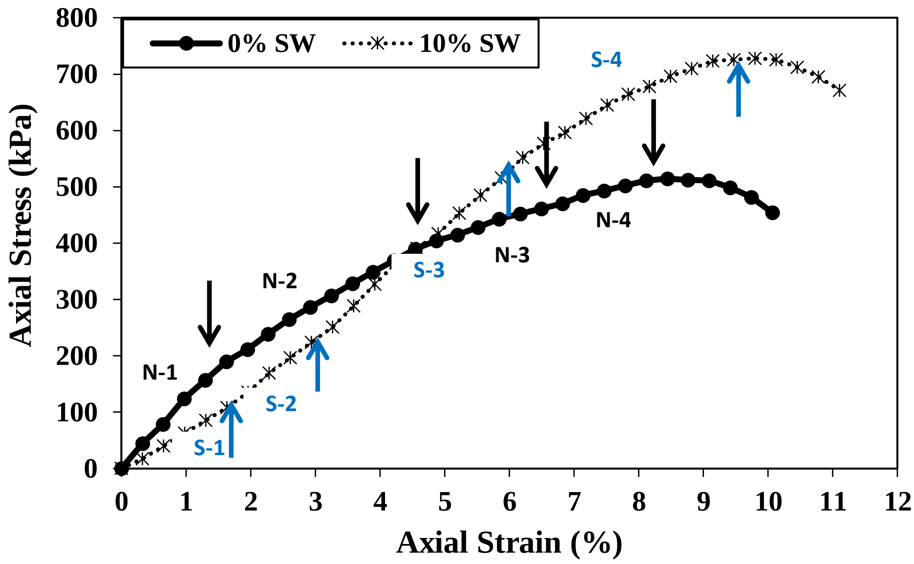

Figure 7. Comparison of stress-strain relations of two different SW percent.

It is discernible from the stress-strain curves may be divided into four stages: the compaction stage, two nonlinear rise stages, and the destruction stage. The trends of the stages for a natural sample and a 10% SW-treated sample are different. The 1st stage was due to the compacted voids among soil particles, which shows that the compressive strain is independent of SW content. The lower strain was recorded for the 1st and 2nd stages (S-1 and S-2), which means that the SW is more dominant in decreasing the strain. However, a slight decrease in strength was recorded. From the mid of the 3rd stage, the generated cementing bonds among soil particles due to the utilization of SW started to show its role in increasing the strong resistance.

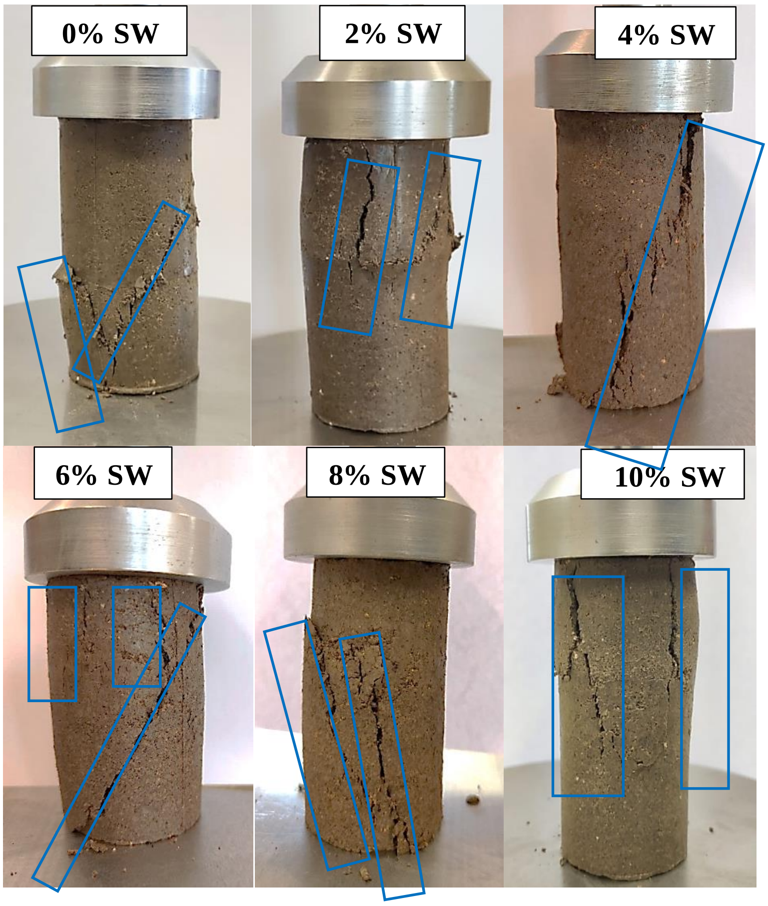

Figure 8. Different types of cracks in UCS samples after testing.

In contrast, the strain growth increased, which may be related to the SW particles' stiffness. Significantly, the used SW increased the strength later from the 3rd and ended by the 4th stage of the stress-strain curve compared to the natural state of the soil, which is evidence of SW's capability to improve the soil's stiffness by almost 30%. SW causes an increase in strength due to agglomeration, which in turn increases the maximum compression ability. SW mainly acts as a bond effect to decrease the stress concentration at the crack tip, which increases the sampling capability to minimize the shear plane to the upper side that showed a bit of bulging and shear failure (**Fig. 8**), which controlled the crack development and increases the peak strain growth.

4. CONCLUSIONS

Based on the obtained experimental test outcomes, this study yielded the following conclusions:

- Utilizing SW significantly improved the expansive (CH) soil to control and decrease the consistency characteristics: LL, PL, PI, and LSL. The LL, PL, and LSL values decreased by 29.7%, 38.75%, and 24.22%, respectively, with an increase in the percentages of SW from 0% to 10%.
- Adding SW (0% to 10%) significantly improved CH's expansive soil swelling characteristics, specifically SP and SPR. SP decreased from 8.26% to 5.45%, and SPR decreased from 171.6kPa to 114.9kPa, respectively.

- The incorporation of soil water significantly impacted the unconfined compressive strength of clayey soil, leading to an approximately 30% rise. The UCS values rose from 511 kPa to 726 kPa when the SW content went from 0% to 10%. There are superior results for the modified compaction characteristics, MDD, and OMC. Adding SW by percentages ranging from 2% to 10% improved MDD and OMC significantly.
- Consideration of SW plays a significant part in expanding (CH) soil's ability to manage an increasing number of undesirable geotechnical characteristics.
- The study found that using SW in its natural state is significant as a stabilization material for CH soil. There is no need to burn SW to make it in an ash state to stabilize CH soil, which in geotechnical applications can be successful.
- The stress-strain curve of fine-grained soil treated with SW can be divided into a compaction stage, two nonlinear rising stages, and a failure stage. Adding SW improves the failure mode and increases the strong resistance to a higher capability by around 30%.

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