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VARIATIONS IN STRENGTH AND ELASTIC PROPERTIES OF COMPACTED FINE-GRAINED SOILS DUE TO CHANGE IN DEGREE OF SATURATION

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ABSTRACT

Fine-grained soils present challenges in construction due to their moisture sensitivity, which impacts the structure's stability. This study examines how saturation levels affect low-plasticity clay shear strength and modulus of elasticity. The standard proctor test assessed soil compaction for maximum dry density and water content. Unconfined compression tests determined the initial tangent modulus of elasticity, strain at failure, and undrained shear strength (Cu). Approach A: Soil samples are saturated by 20% gradually. Approach B: prepares samples at 100% saturation and gradually decreases them by 10% to achieve saturation levels. Results indicated saturation greatly affects Cu, modulus of elasticity, and strain at failure. Approach A reduces Cu gradually (18%) as saturation increases, but approach B reduces (67%) it sharply, especially at low saturation. Higher saturation increases strain at failure, exhibiting plasticity. Both approaches decrease modulus of elasticity as saturation increases. Undrained shear strength was higher in approach B specimens than in approach A.

KEYWORDS

degree of saturation, modulus of elasticity, shear strength, fine grained soil, unconfined compression test.

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1. INTRODUCTION

Geotechnical engineering projects frequently involve constructing earth structures with compacted soils. The shear strength of these soils is estimated through laboratory testing that simulates field conditions (Gitari and Mudzielwana, 2018). Changes in saturation levels markedly influence the mechanical and physical characteristics of compacted fine-grained soils, impacting their strength and elastic properties, which may result in structural failures (Martirosyan et al.,2022). Variations in saturation levels influence both shear and compressive strengths, with increased moisture content typically resulting in decreased cohesiveness and, thus, diminished overall soil strength (Ahmed et al., 2019). Unconfined compression tests are a fast and inexpensive approach to measure the shear strengths of cohesive and semi-cohesive soils based on total stress, whether undisturbed or reshaped and compacted. It is not ideal for loose or large-particle soils. Construction sites with quick construction and little pore water drainage benefit from this test (Güneyli and Rüşen, 2016). Higher moisture content significantly affected the fine-grained soils, and (Nagaraj and Muguda, 2019) found that as moisture levels rise, cohesion decreases, elasticity increases and the undrained shear strength decreases. According to (Wei *et al.*, 2019) water content has a significant impact on granitic soils shear strength, with variations observed in the clay loam layer. Low water content (7–14%) reduces shear strength, which affects soil properties and cohesion strength. (B.Salih, 2020) found that an increase in dry density led to a rise in the unconfined compression test (UCS) values, which in turn required the addition of some saturation between the soil particles. This relationship necessitates the addition of some saturation, as the void ratio is inversely related to soil strength. (Uyeturk and Huvaj, 2021) found that the strength of residual soils increased with the decrease of saturation (Sr), indicating a non-linear correlation between Sr and stress. They found that the S and average stress decreased while the shearing strength increased, indicating that the presence of S significantly impacts the mechanical behavior of compacted residual soils. (Gong *et al.*, 2022) studied the relationship between shear strength and water saturation. They found that silt has the highest decreasing rate of mean cohesion with increasing water saturation, while clay has the lowest. (Ma *et al.*, 2023) reported that the soil moisture content significantly influenced the mechanical strength and deformation characteristics of foundation soils for cultural relics. They found that increased moisture leads to decreased compressive strength and increased strain. (Yan and Meng, 2023)found that the soil's moisture content at 15, 18, 21, 4, and 27% significantly influences the shear strength of unsaturated soils, with higher confining pressure enhancing shear strength. (Waheed and Asmael, 2023) conducted a study on the correlation between soil modulus and cohesiveness in remolded soil specimens. The relationship between soil cohesion (Cu) and modulus of elasticity is significant. The results demonstrated a non-linear increase in soil cohesion due to the modulus of elasticity, indicating stress-strain characteristics and fine-grained soil strength. Additionally, it was shown that higher cohesion values lead to an increase in the modulus of elasticity in both remolded and undisturbed clay. Undisturbed clay exhibits a significantly higher modulus of elasticity compared to remolded clay, which highlights the impact of soil structure and composition, especially in stiff clay. This suggests that remolding changes the mechanical properties and stiffness of the soil.

In this research, the strength and deformation properties of fine-grained soil samples were explored by testing the number of specimens prepared at the same void ratio but at different values of the degree of saturation. Two approaches were adopted to achieve the required value for each specimen's saturation degree. Approach A: Soil samples are saturated by 20% gradually. Approach B: prepares samples at 100% saturation and gradually decreases them by 10% to achieve degree of saturation. The study investigates the effects of varying saturation levels on the shear strength and modulus of elasticity of low-plasticity clay, a type of fine-grained soil. This study seeks to fill this knowledge gap by evaluating how different degrees of saturation impact the undrained shear strength and modulus of elasticity of low-plasticity clay, where the study provides insights into the mechanical behavior of fine-grained soils under varying moisture conditions, which is crucial for improving the design and stability of structures built on such soils.

2. MATERIALS AND METHODS

2.1. Soil used

The soil sample used in this study was light brown fine-grained soil obtained from a rural area located southwest of Hilla City, Iraq. The particle size distribution curve shown in Fig.1. The soil was classified as [CL-Lean Clay], according to the Unified Soil Classification System USCS. The compaction curve (dry density vs water content) is shown in Fig.2. Standard proctor tests were conducted on the soil to obtain the soil compaction parameters, which are mentioned along with other index properties in Table 1.

2.2. Unconfined compression test

The unconfined compressive strength UCS test was performed according to ASTM-D-2166, as shown in Fig.3.a. The dimensions of the sample were 81 mm in height and 38 mm in diameter, as shown in Fig.3.b. The UCS test protocol is used; the unconfined compression test is typically used to evaluate clays undrained shear strength (Cu). Cohesive soils undrained shear strength equals half of the undrained compressive strength. Several unconfined compression test specimens were prepared at the same void ratio (e = 0.57), which resulted in the soil at its maximum dry density ($\rho = 1.72$ g/cm3) and selected values of degree of saturation. To achieve the required or target degree of saturation at which the specimen will be tested, two different approaches were adopted, namely approach A and approach B, as explained below:

1. Approach A: This approach prepares each specimen by adding the required volume of water to the appropriate mass of dry soil to achieve the desired degree of saturation. This approach prepared the specimens at varying degrees of saturation, ranging from 0 to 100% in increments of 20% (0, 20, 40, 60, 80, and 100%). In addition to that, a specimen prepared at the optimum water content gives a degree of saturation of 72.47%. Seven specimens were tested using this approach.

Table 1: physical and index properties of the soil

Property	Value	Specification
Specific gravity (Gs)	2.7	ASTM-D854-2010
Liquid limit (L.L)%	28	ASTM-D4318-2010
Plastic limit (P.L)%	20	ASTM-D4318-2010
Plasticity index (P.I)%	8	ASTM-D4318-2010
Sand (4.75mm -0.075mm)	13%	ASTM- D422-2010
Silt (0.075 mm-0.005mm)	47%	ASTM- D422-2010
Clay (<0.005mm)	40%	ASTM- D422-2010
Soil Classification	CL	ASTM-D-2487-2010
Maximum dry density g/cm^3	1.72	ASTM-D-698-2010
Wopt %	15.3	ASTM-D-698-2010

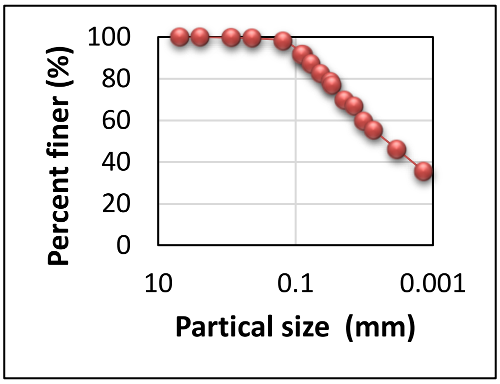


Fig.1. The soil sample's grain size distribution curve.

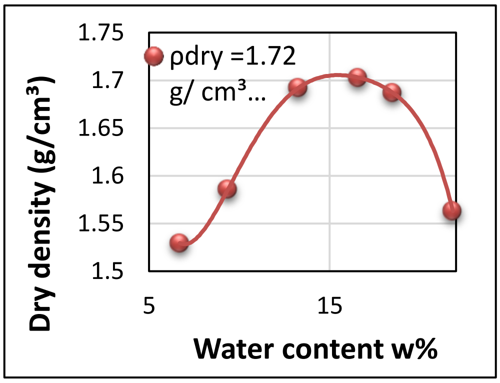
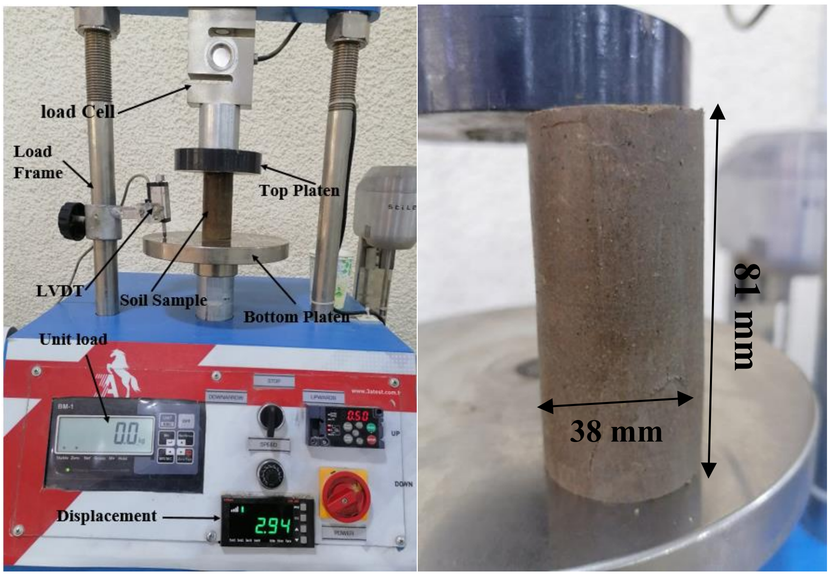


Fig. 2. Standard compaction test.

2. Approach B: In this testing approach, all specimens were prepared with a water content of 21.11%, resulting in a 100% degree of saturation. One of the specimens was immediately tested at 100% saturation, while the others were allowed to gradually lose moisture. The total mass of each specimen was monitored at appropriate intervals. Once a specimen reached the target degree of saturation (previously determined), it was then tested. This approach involved testing 12 specimens for degrees of saturation ranging from 100% to 0%, as well as a specimen prepared at the optimal water content (S = 72.47%).



(a) (b)

Fig. 3. (a) Unconfined compression device, (b) The specimen of the soil used in this test.

3. RESULTS AND DISCUSSION

from the results of the unconfined compression tests, the following parameters were determined for each tested specimen: -

1. The undrained shear strength Cu (kPa)
2. The strain at failure $\epsilon_f(\%)$
3. The initial tangent modulus E (MPa)

Value of these parameters are given in Table 2. The nature of variation of each parameter with the degree of saturation is given in the following paragraphs.

Table 2: The value of Cu, E, and $\epsilon_f\%$ with different degrees of saturation.

S %	Approach A			Approach B		
	c_u kpa	$\epsilon_f\%$	E MPa	c_u kpa	$\epsilon_f\%$	E MPa
0	583.49	1.23	86.26	3152.84	1.851	440.11
10				2402.63	1.48	388.31
20	392.27	0.74	80.68	2046.65	1.85	286.23
30				1494.53	2.1	190.54
40	388.34	1.23	52.63	1044.41	1.98	132.35
50				896.33	2.72	86.11
60	306.95	1.36	48.24	731.58	2.47	79.73
70				592.32	3.21	64.85
72.47	205.94	1.73	27.9	492.29	4.69	35.59
80	194.17	2.22	24.72	451.11	3.33	33.21
90				253.99	3.58	27.9
100	167.69	9.26	7.12	167.69	9.26	7.12

3.1. Effect the degree of saturation on undrained shear strength

The variation of Cu with S for the two approaches is shown in Fig.4. According to this figure, the following findings are obtained:

1. The value of Cu is decreased as S increases for the two approaches. The rate at which Cu is decreased with S will be expressed by the parameter α, which is the slope of the Cu vs S relation. For approach A, Cu decreased with S at an approximately constant rate of an average value of $\alpha = -4.1\ kPa$. This means that Cu is decreased by approximately 4.1 kPa for an increase of 1% in S. (Ma *et al.*, 2023) achieved the same findings in their research about the impact of moisture content on the compressive strength of soils. That is, moisture content increased, and soil particles formed aggregates, increasing cohesion and shear resistance. Low moisture content weakens interparticle cementation, leading to soil damage and plastic deformation. Increasing moisture content weakens soil damage and delays failure. On the other hand, two distinct values for α can be observed for approach B. In the initial range of S (from 0 to 40%), Cu decreased rapidly with S at an average rate of α = −50 kPa. Beyond S = 40%, the rate decreases markedly with an average value for α of −14.5 kPa. The negative sign indicates the inverse relation between Cu and S.

Regarding the most important case of the specimens at the optimum condition (S = 72.47%), Cu decreased from about 206 kPa at the optimum condition to about 168 kPa for approach B. This means that Cu was decreased by about 18% and 67% for approaches A and B, respectively. This remarks a radical reduction in shear strength as the soil becomes fully saturated after being prepared at its optimum water constant. Such reduction will substantially affect the stability of all soil problems designed on the pass of the soil strength determined from specimens compacted at their optimum water content.

2. The value of Cu for specimens prepared by approach B is higher than those prepared by approach A at the same degree of saturation, especially at the low range of S value (0- 40%). The rate of Cu from approach B to that from approach A ranges between 5.4 at S = 0 to 1 at S = 100%. At the optimum water content (S = 72.47%), this ratio was 2.39.

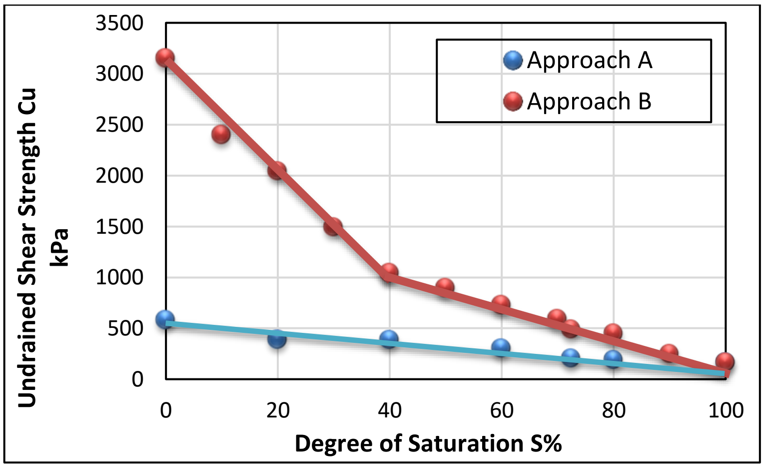


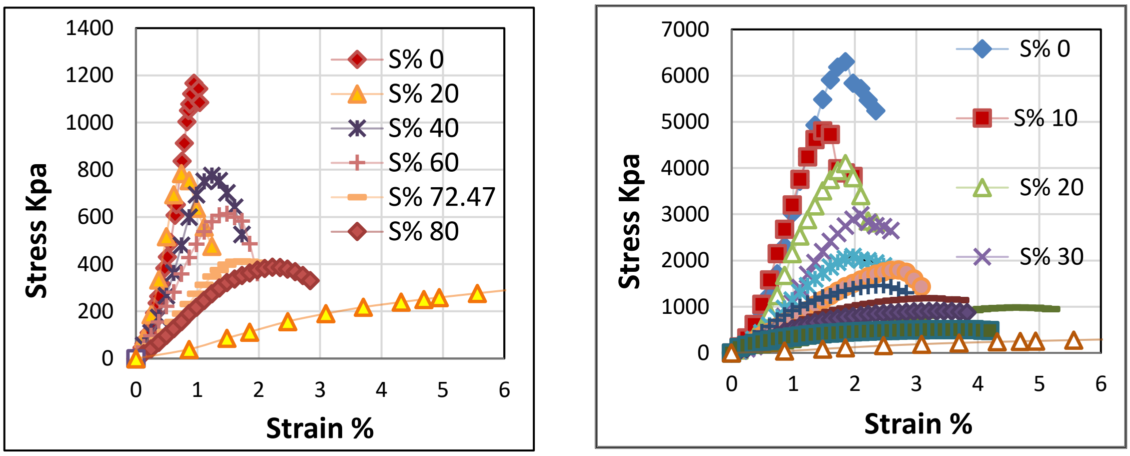
Fig. 4. The relationship between undrained shear strength and degree of saturation.

3.2. Effect of the degree of saturation on deformation properties

the effect of the degree of saturation on the deformation properties of the tested specimens will be explained through the shape of the stress- strain diagrams, the strain at failure ϵ_f and the modulus of elasticity E:

3.2.1. Shaped of the stress-strain diagram

The stress – strain diagrams of all tests conducted in this study are shown in Fig. 5. According to the curves shown in the Figure, it can be noted that at low degrees of saturation, the stress – strain curves show steep increase in Cu at initial part of the test to reach a maximum (failure) value at relatively small strain followed by a rapid decrease in Cu with further straining which indicates a brittle behavior with remarked failure surface for both approaches as shown in Fig.6.a. As S increased, the shaped of the stress – strain curves become flatter with less pronounced peak value and less pronounced failure plane. High saturation levels cause soil behavior to become more flexible; approach B in particular shows no clear peak point. Furthermore, during the final stage of the tests, the specimens bulged and no failure surface was identified as shown in Fig.6.b. This behavior can be attributed to the increasing influence of pore water within the soil matrix, which alters the effective stress conditions and promotes ductile responses.



Approach A Approach B

Fig. 5. Stress-Strain curves for approach A and B.

The findings suggest that as saturation levels rise, the soil particles experience reduced antiparticle friction and cohesion, facilitating a more uniform redistribution of stresses throughout the specimen. Consequently, the transformation from brittle to ductile behavior at higher saturations underscores the significance of moisture content in governing the mechanical properties of the soil.

3.2.2. Strain at failure ϵ_f

The strain at failure ϵ_f (in %) for all tests has been determined from the stress-strain diagrams, and the values are given in Table 2. The variation of ϵ_f with S is shown in Fig. 7 for the two approaches. It is clear from this Figure that the strain at failure, in general, increases as the degree of saturation increases, which indicates a more plastic behavior of the soil as the degree of saturation increases. Furthermore, strain at failure for approach B is higher than for approach A for the same degree of saturation except at S =100, where the two approaches had the exact value of ϵ_f. The ratio of ϵ_f for approach B to that for approach A was in the range of 1.5 (at S = 0, 80%) to 2.71 (at S = 72.47 optimum condition) with an average value of 1.93. The higher strain values at failure for approach B can be attributed to the initial saturation conditions, which promote a more even distribution of moisture within the soil. This even distribution likely makes it easier for the particles to rearrange and stick together under stress, making the soil more flexible. While higher saturation levels typically enhance shear and compressive strengths, leading to greater strain at failure, variations in effective stress and pore pressure at different saturation levels also affect mechanical behavior. Therefore, a dual approach that examines saturation and other mechanical properties is crucial for understanding soil behavior under various conditions.

(a) **(b)**

Fig. 6. Shapes of failure:(a) brittle (b) ductile.

3.2.3. Modulus of Elasticity

The modulus of elasticity is a fundamental property of the material that quantifies it is deformation due to applied stresses. It is defined simply as the slope of the stress-strain curve. Among the many criteria available to specify a value of the modulus for the materials with a non-linear stress-strain curve at its starting (initial) point. The value of the initial tangent modulus for all the tests included in this study has been determined (in MPa) and given in

Table 2. The variation of E with S for the two approaches followed in preparing the samples (approaches A and B) is shown in Fig. 8. According to this Figure, the effect of S on E is summarized in the following:

In general, the modulus E decreases with increasing the degree of saturation S for both groups of specimens prepared by approaches A and B. The rate by which E decreases with S will be quantitatively specified by the parameter β, which is the slope of the E – S relation, i.e. ΔE/ΔS (in MPa).

For approach A, the data indicate a more or less constant value of β throughout the range of S (0 – 100 %) with an average value of $\beta = -0.82$ MPa. This value indicates that E decreases by 0.82 MPa for a 1% increase in S. The negative sign indicates the inverse relation between E and S. (Waheed and Asmael, 2023) achieved the same findings in their research about the modulus of elasticity decreasing with increased moisture content. For approach B, two distinct trends can be observed. A rapid decrease in E with S occurs within the range of S (0 – 50 %) specified by an average value for the slope β of - 6.3 MPa. When the degree of saturation was increased beyond 50% (up to 100%), the rate of depression decreased, and the rate of change in an E with S can be expressed by an average value for β of -1.58 MPa. (Han and Vanapalli, 2017) obtained similar results from their study on the modulus of elasticity decreasing with increased moisture content. The modulus of elasticity increases as soil moisture content decreases, which means drier soils are stiffer. This is a crucial factor in geotechnical engineering, where maintaining soil stability is essential. Moisture levels significantly affect soil stiffness and compressibility, which in turn influence structural integrity. Additionally, environmental factors such as rainfall, humidity, and temperature can impact these properties.

Regarding the condition at the optimum water content, the E value decreases from 27.9 to 7.12 MPa for approach A and from 35.59 to 7.12 MPa for approach B as the specimen becomes fully saturated. This means that the value of E was decreased by 72.47% and 80% for approaches A and B, respectively, when the specimens became fully saturated in comparison with their condition at the optimum water condition (S = 72.47%). These findings show clearly to what extent fine-grained soil becomes compressible upon saturation.

As for the condition regarding the undrained shear strength, values of the modulus E for specimens prepared by approach B are higher than those prepared by approach A, with the same degrees of saturation. The difference is maximum at S = 0 and decreases as S is increased to zero at S =100%. The ratio EB / EA ranges between 5.1 to 1 for S = 0 and 100%, respectively. The average value of this ratio is 2.34. At the optimum condition, EB / EA was 1.28.

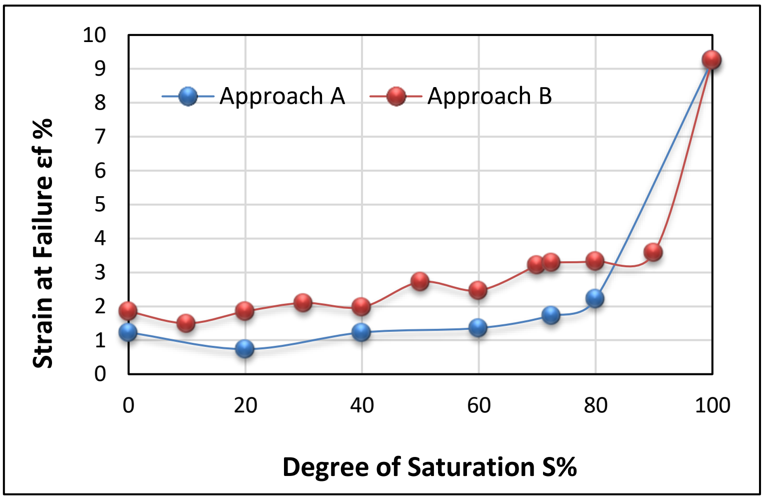


Fig. 7. Relationship between strain at failure and degree of saturation

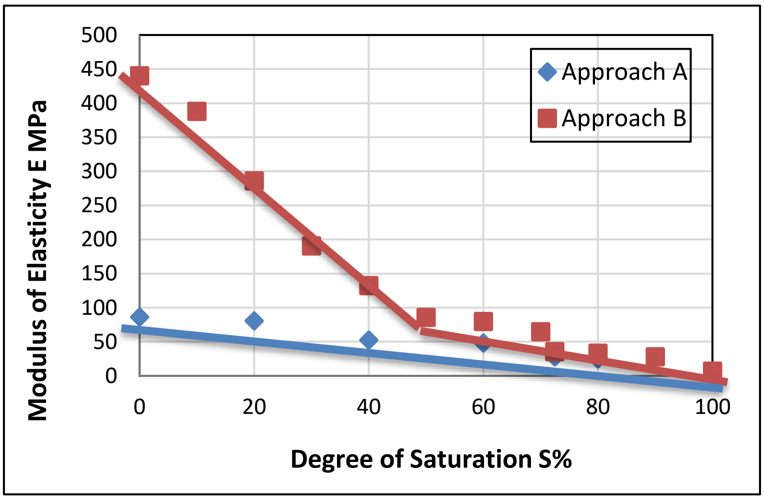


Fig. 8. The relationship between modulus of elasticity and degree of saturation for two approaches.

A review of the results presented above indicates that the specimens prepared by approach B are stronger and stiffer than those prepared by approach A at the same degrees of saturation and reach failure at higher strain. This can be explained by the fact that in approach B, the specimens were all prepared fully saturated initially and were let to lose moisture by natural evaporation until each reached the planned degree of saturation to be tested, except the specimens at S = 0, which was oven dried after its moisture come into stabilization due to room temperature drying. This process takes sufficient time (1 – 3 days), during which they preserve higher water contents, allowing physical-chemical reactions and bonds between water–active fine-grained soil particles, leading to this difference. It is concluded that preparing the specimens by approach B is more reliable and reflects the purposes behind this research more than those prepared by approach A.

4. CONCLUSIONS

This study provides critical insights into the relationship between soil saturation levels and shear strength, emphasizing the importance of understanding how varying degrees of saturation impact soil stability and mechanical properties. The experimental program concluded two approaches. Approach A: Soil samples are saturated by 20% gradually. Approach B: prepares samples at 100% saturation and gradually decreases them by 10% to achieve saturation levels. The findings highlight key factors influencing undrained shear strength (Cu) and offer valuable implications for geotechnical engineering:

• Saturation and Shear Strength: The research reveals that as saturation (S%) increases, the undrained shear strength (Cu) decreases significantly. Approach A reduces Cu gradually (18%) as saturation increases, but approach B reduces (67%) it sharply, especially at low saturation, with Approach B producing higher Cu values than Approach A, particularly at low saturation levels. This underscores the critical influence of saturation on soil stability.

• Strain at Failure: Both approaches demonstrate increased strain at failure with rising saturation, indicating that higher saturation levels lead to more plastic soil behavior. Approach B consistently shows greater failure strain than Approach A, except at full saturation, with strain ratios ranging from 1.5 to 2.71.

• Modulus of Elasticity (E): The study also shows that as saturation increases, the modulus of elasticity (E) decreases for both approaches, though Approach B experiences a sharper drop. The undrained shear strength of specimens in Approach B is significantly higher than in Approach A, with a strength ratio of 5.1 to 1.

These findings underscore the need for further research to explore a broader range of saturation levels and compaction methods. A deeper understanding of these interactions will enable more accurate predictions of soil behavior under varying conditions, leading to improved soil stability assessments and more effective engineering solutions in construction and infrastructure development.

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