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Effect of rate of strain on the strength parameters of clay soil stabilized with cement dust by product

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Abstract. The primary goal was to assess how the addition of cement dust, a byproduct known to be harmful, could be used to stabilize clay. Various percentages of cement dust were added to soil samples, which were then subjected to triaxial testing at different rates of strain using an unconsolidated undrained triaxial machine. Six different rates of strain were applied to analyze the response of the clay under different conditions, resulting in 216 triaxial sample tests. As the percentage of cement dust in the clay samples increased, there was a noticeable increase in the strength properties of the clay, indicating a positive effect of cement dust on the clay's strength characteristics. Higher rates of strain during testing led to increased strength properties of the clay. Varying cement dust content influenced the impact of increasing the rate of strain on the clay's strength properties. Higher cement dust content reduced the sensitivity of the clay to changes in strain rate, indicating that the clay became less responsive to changes in strain rate as cement dust content increased. Potential for Clay Stabilization Cement dust proved the potential to enhance the strength properties of clay, indicating its potential utility in clay stabilization applications. Both higher percentages of cement dust and higher rates of strain were found to increase the clay's strength. It's essential to consider both the percentage of cement dust and the rate of strain when assessing the strength properties of clay in practical applications.

Keywords: cement dust; clay; rate of cement dust; rate of strain; undrained shear strength

1. Introduction

The rate of strain can significantly affect the strength properties of clay. Generally, clay's strength increases with the rate of strain, exhibiting higher strength under high strain rate conditions compared to low strain rate conditions. his behavior, known as strain rate sensitivity, is attributed to clay's deformation mechanisms, including plastic deformation, yielding, and cracking. The specific effect of strain rate on clay strength varies depending on the type of clay, its mineral composition, and the loading conditions. Hu *et al*. (2020) studied the effect of the rate of strain on the effect on strength properties of unsaturated compacted silty clays tested with the triaxial test. They used 11 rates of strain and 6 confining pressures. They concluded that the results showed that there were two types of strain rate values, which caused the peak strength to first decrease and then increase with strain rate under low confining pressures. However, under high confining pressures, the peak strength first followed the same trend as low confining pressure, but then it decreased with an increased strain rate. Additionally, the elastic modulus increased the strain rate. Additionally, the elastic modulus increased monotonically with strain rate under low confining pressures, but under high confining pressures, it first decreased and then increased. Mohammed *et al*. (2022) in their paper conducted unconsolidated undrained triaxial tests on Kombolcha town clay, Ethiopia to explore the effects of the rate of strain on strength properties. The rate of strain ranged from 0.38 mm/min to 1.14 mm/min. The results showed that there is a distinctive increase in the values, shear strength, angle of internal friction, and modulus when increasing the rate of strain. Zhu *et al*. (2019) investigated the effect of rate strain and temperature on the one-dimensional compression behavior of soils. They focused on the bonding degradation effect of soil structure on the time and temperature-dependent behavior of soft-structured clay. The strain rate and temperature dependency of pre-consolidation pressure are investigated in a double logarithm plane and a thermal viscoplastic model is considered. The results showed that the extended model can reasonably describe the effect of bonding degradation on the stain rate and temperature-dependent behavior of soft structural clay under one-dimensional conditions. Mamo *et al.* (2015) investigated the effect of varying strain rates on φ based on direct shear tests conducted on dry cohesionless soil prepared at four different densities. Their results revealed that the peak and residual φ are noticeably affected by variation in strain rate, with a more prominent effect being manifested for loose sands. Sabbar *et al.* (2017) studied adding a slag with different contents to strengthen the soil, using direct shear tests and unconsolidated triaxial tests on mixtures of Perth sand and slag. The results showed no significant differences in shear stress parameters when slag content rose from 4% to 6%. The unconsolidated undrained triaxial tests showed a distinctive increase in

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strength parameters with increasing slag content. Alzubaidi and Lafta (2013) investigated the effects of the rate of strain on stabilized clay with lime. Their study includes five strain rates (0.1, 0.8, 2.0, 4.0, and 7.0 %/min) and five lime contents (0, 3, 6, 9 and 12 %). The results for natural soil showed that the undrained shear strength, the initial modulus of elasticity and the cohesion increase significantly as the strain rate increases, while for soil–lime mixture, the undrained shear strength, initial modulus of elasticity, and the cohesion increase to a maximum and then decrease as the strain rate and lime content increase. Zhou *et al*. (2019) stabilized the expansive soil with fly ash and lime to explore the effect on the strength properties of expansive soil . The test results deduced, suggest that, after 5% lime is added based on fly ash, the plasticity index of the expansive soil decreases by 64.9%, the free swelling ratio is reduced to about 10%, the unloading swelling ratio is reduced to nearly 4%, and the stabilized soil no longer exhibits the expansive property. Hussain and Hussaini (2023) utilized the discrete element method (DEM) to simulate a series of three-dimensional direct shear tests to investigate the shear behavior of railway ballast and its interaction at the microscopic level under a multitude of loading conditions. The results indicate how shear resistance and volumetric changes in the ballast assembly are affected by normal stress, shearing rate, particle size distribution (PSD), and shear box size. Li *et al*. (2023) stabilized soft soil using bio-cementitious mortars consisting of microbially induced carbonate precipitation and ordinary Portland cement. The results showed that the cohesion and internal friction angles of microbially induced carbonate precipitation-treated soft soil were greater than those of remolded soft soil. The unconfined compressive strength (UCS), elastic modulus, and toughness of C-MICP-treated soft soil with high moisture content (50%, 60%, 70%, 80%) were improved compared to traditional cement-soil mixtures. Bagriacik *et al.* (2023) utilized marble and granite waste to stabilize clay soil. They mixed marble and granite waste with cement and clay soil to improve the shear strength properties. The results revealed that the bearing capacity of the clay soil increased by approximately 71% when using marble and granite waste and cement additives. Moreover, the consolidated settlement values of the clay soil decreased up to 6 times compared to the additive-free case. Mukherjee and Pathak (2023) developed a numerical solution to employ a recently proposed visco-plastic constitutive model to explore the rate-dependent mechanical behavior of Toyoura sand under drained triaxial loading conditions. The simulation results indicate that the rate-induced strength increase is highest for the dense state, and such strength enhancements remain nearly independent of the applied confinement level. Pereira *et al*. (2023) carried out several unconfined compression strength and split tensile strength tests in sandy soil from the Leiria region (Portugal), using the machine learning tool Neural Pattern Recognition of the MATLAB software. A prediction of these two parameters based on six input parameters was made. The results obtained with recourse to a Bayesian regularization-backpropagation algorithm are highly positive, with a forecast success percentage over 90% and a very low root mean square error. Ghadr *et al.* (2023) investigated the potential use of C3S cement to enable durable cementation. They explored the prospects of using PP fiber alongside C3S cement, scopes for partial replacement of C3S cement with plant-based nano-silica, and evolution of binders. The results showed that Nanobiosilica provides an opportunity to reduce the C3S content and transition highly compressive organic clays into an engineered, open-structured medium with compressive strength exceeding 0.5 MPa across strains from peak to 1.5 times peak. Chhun and Yune (2023) studied the compressive strength of cement-stabilized soil using electrical resistivity measurement. In their study, they developed an equation for compressive strength using electrical resistivity measurement based on its reliability, time effectiveness, non-destructiveness, and cost-effectiveness. Shabani *et al.* (2022) used biopolymers to improve the geotechnical behavior of sandy soil. The stabilized sand treatment was investigated by performing unconfined compressive strength tests, California bearing ratio tests, as well as wind erosion tests. A microstructural study was conducted via SEM images, revealing that the biopolymer coated the sand particles and formed a strong network. Zhou *et al.* (2022) carried out different dynamic loading tests on three different rocks and bituminous coal.

They found that the dynamic compression strength of rocks and bituminous coal is much greater than the static compression strength. Additionally, the dynamic compression strength and dynamic increase factor of the rocks both increase linearly with the increase of the strain rate, while those of the bituminous coal are irregular due to the characteristics of multi-fracture and heterogeneity. Moreover, the absorbed energy of the rocks and bituminous coal both increase linearly with an increase in the strain rate.

As a literature review, no previous work tackles the use of cement dust to stabilize the soil and study the effect of rate of strain. The existing research explores the use of cement dust, a byproduct with known harmful effects, as a potential stabilizing agent for clay soil. Through triaxial testing, the researchers investigate how varying percentages of cement dust and rates of strain affect the strength properties of the clay. The findings that increasing cement dust content leads to enhanced strength properties in the clay, while higher rates of strain during testing further increase its strength. Additionally, higher cement dust content reduces the clay's sensitivity to changes in strain rate, suggesting a more consistent response under different loading conditions. The current research purpose is to provide a more comprehensive understanding of the effectiveness and practical implications of using cement dust for clay stabilization. The current work aims to incorporate field studies, environmental impact assessments, and long-term performance evaluations to provide a more holistic perspective on the feasibility and sustainability of this stabilization method.

2. The physical properties of the tested Soil

The soil studied in the present research was brown silty clay located south of Baghdad (Hussain 2002), the physical properties are shown in Table 1. The grain size distribution of the soil is shown in Fig. 1. The graph shows that the soil consists of sand with 1.7%, silt 76.3%, and clay 22%.

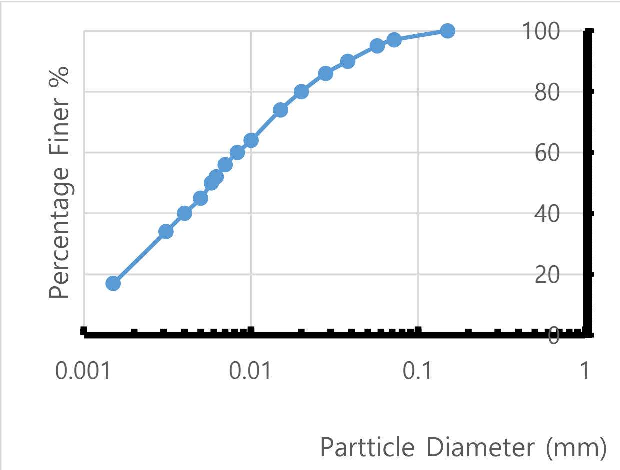

Fig. 1 Grain size distribution of Baghdad soil

Table 1 Physical properties of the clay

Description	Value
Specific Gravity	2.73
Liquid limit %	42
Plastic limit %	26.26
Plasticity index %	15.74
Max dry density (Kg/m^3) (modified compaction test)	1870
OMC %	16
AASHTO soil classification	A-7-6 (18)
Unified soil classification	CL

3. Chemical properties of the soil

Table 2 shows the chemical properties of the soil, also X-ray diffraction was conducted, the results showed that Quartz and Calcite are the dominant minerals, in addition, some other minerals such as Dolomite, Montmorillonite, Feldspar, Chlorite, and Gypsum are also presented.

Table 2 Chemical Properties and Mineralogical Composition of the Soil

Description	Value
PH value	7.72
SO_3 (%)	0.69
Total Soluble Salts (%)	1.61
Organic content (%)	0.32
CI (%)	0.04
$CaCO_3$	30
SiO_2 (%)	45.03
Fe_2O_3 (%)	3.62
CaO (%)	23.1
MgO (%)	5.25
Gypsum $CaSO_4.2H_2O$ (%)	1.38
Mineralogical Composition Quartz, Calcite, Feldspar, Dolomite, Chlorite , Mica,Mont ,Chlorite, Kaolinite	

Table 3 Chemical Analysis of Cement Dust

Chemical composition	%
Silica SiO_2	14.1
Alumina Al_2O_3	4.7
Iron Fe_2O_3	1.97
Lime CaO	40.17
Magnesia MgO	2.79
Sulfuric Anhydride SO_3	5.35
Putasso K_2O	3.23
Soda Na_2O	1.61
Chlorides Cl	1.82
Loss on Ignition	24.26
Total	100

4. Cement dust

The cement dust was collected as a side product from the factory of cement. The chemical properties of the cement dust are shown in Table 3. The cement dust was stored in a dry place before the specimens' preparation and mixing with soil. Distilled water was used in the preparation of the mixture of all the specimens.

5. Specimens preparation

The specified cement dust content expressed in percent of the dry soil weight was added to the dry soil and mixed thoroughly to a uniform color. The measured amount of distilled water to produce the optimum moisture content of the soil was added to the mixture and kept mixing for five minutes. The measured amount of distilled water which represents the optimum moisture content (deduced from compaction tests) was added to the mixture. The modified proctor tests were used to determine the maximum dry density and optimum moisture content of the mixed soil. The compacted mixtures were removed from the molds, wrapped with a plastic sheet, labeled, and stored in a desiccator at room temperature (25°C). All the specimens were transferred to the triaxial machine for testing after curing for 7 days. After the curing period, the plastic sheet was removed, and the specimen was weighed. The maximum loss in moisture during the curing period was found to be 0.7% which is insignificant and can be neglected.

6. Cement dust content with different rates of strain

Three different values of cement contents were used, these values were 5%, 10%, and 15%, the percentages represented the dry weights of cement dust from the total weight of the stabilized soil. The stabilized samples have been tested with five different rates of strain, these were 0.2, 0.8, 2.0, 3.0, 4.0, and 5.0% per minute as shown in Table 4. All samples were tested with unconsolidated

Table 4 cement dust and Rate of strain %

Cement Dust percentage % Stabilized clay	Tested Rate of strain %per Min.
5%	0.2,0.8,2,3,4 and 5
10%	0.2,0.8,2,3,4 and 5
15%	0.2,0.8,2,3,4 and 5

undrained triaxial tests. The significance of conducting tests under unconsolidated undrained (UU) conditions lies in its ability to simulate specific scenarios relevant to certain engineering applications, despite its rarity in practical engineering. Here's why this condition might be chosen:

A. Emulating Rapid Loading Scenarios: In certain situations, such as during seismic events or rapid construction processes, soil may experience sudden and significant loading without undergoing prior consolidation. Testing under unconsolidated conditions allows researchers to simulate these rapid loading scenarios and assess how the soil responds without the confounding effects of consolidation.

B. Assessing Immediate Stability: In engineering projects where time is critical, such as emergency response situations or temporary constructions, it may be necessary to evaluate the immediate stability of soil without waiting for consolidation to occur. Testing under unconsolidated conditions provides insights into the immediate strength and stability of the soil, helping engineers make timely decisions.

C. Characterizing Sensitive Soils: Some soils, such as clays with high sensitivity to disturbance, may undergo significant changes in behavior during consolidation. Testing these soils under unconsolidated conditions allows researchers to characterize their undisturbed properties and assess their response to loading without the influence of consolidation-induced changes.

D. Research and Development: In the early stages of research and development for new materials or construction techniques, testing under simplified conditions like unconsolidated undrained can provide valuable insights into fundamental soil behavior and the potential efficacy of new approaches before moving to more complex and realistic testing conditions.

While unconsolidated undrained conditions may not directly replicate real-world scenarios encountered in practical engineering, they serve as a valuable tool for controlled experimentation and fundamental understanding of soil behavior. By carefully interpreting the results obtained under these conditions and extrapolating them to practical applications, engineers can make informed decisions and develop more effective solutions for a wide range of engineering challenges.

The significance of selecting specific test conditions, such as the inclusion of various percentages of cement dust and the application of different rates of strain, lies in the need to thoroughly understand how these factors affect the strength properties of clay soil. Here's why these test conditions were chosen:

1. **Evaluation of Cement Dust Impact**: Cement dust is often considered a waste byproduct with potential environmental hazards. By incorporating different percentages of cement dust into the soil samples, the study aimed to assess whether this material could be repurposed for beneficial purposes, such as clay soil stabilization. Understanding how varying amounts of cement dust influence the clay's strength properties is crucial for determining its suitability for such applications.
2. **Assessment of Strength Enhancement**: The primary goal of clay stabilization is to improve its engineering properties, particularly its strength. Therefore, the study sought to determine whether the addition of cement dust could enhance the strength of the clay. Testing samples with different cement dust percentages allowed researchers to identify the optimal proportion for achieving the desired strength enhancement while minimizing potential adverse effects.
3. **Exploration of Rate of Strain Effects**: The rate of strain applied during testing can significantly impact the behavior of soil materials. By subjecting the soil samples to different rates of strain, the study aimed to understand how the clay's strength properties respond under varying loading conditions. This information is essential for assessing the stability and performance of clay in real-world scenarios where it may experience different loading rates due to environmental factors or construction activities.
4. **Comprehensive Understanding**: Conducting tests under a range of conditions provides a comprehensive understanding of the complex interactions between cement dust content, rate of strain, and clay behavior. This allows researchers to identify potential trends, correlations, and trade-offs associated with different test parameters, thereby informing more informed decision-making in engineering practices.

Overall, selecting these test conditions enables researchers to gain valuable insights into the efficacy and feasibility of using cement dust for clay soil stabilization, as well as the underlying mechanisms governing the behavior of stabilized clay under different loading conditions. This knowledge is essential for developing practical and sustainable solutions for geotechnical engineering applications.

7. Effect of rate of strain on strength properties of the tested soil

Experimental investigations on the undrained shear strength of natural clay soil, both before and after mixing with cement dust, were conducted at various rates of strain. Figs. 2 to 4 depict stress-strain curves for different rates of strain and cell pressures, indicating an increase in deviator stress with higher rates of strain. Notably, Fig. 5

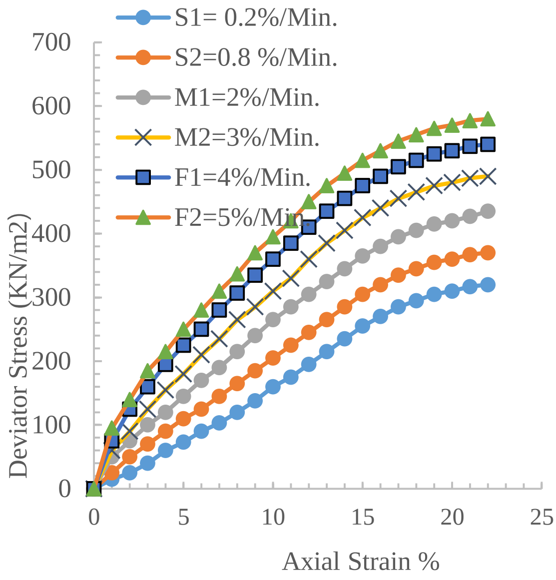

Fig. 2 Stress -Strain Curve for not treated Soil Under Cell Pressure 50 KN/ m^2

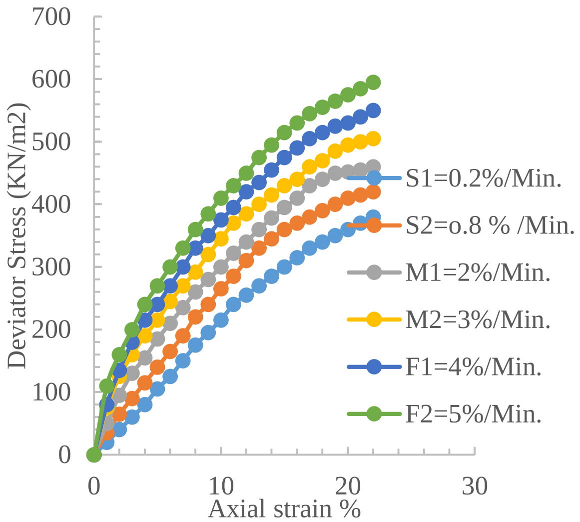

Fig. 3 Stress-Strain Curves for untreated Soil Under Cell pressure of 100 KN/m^2

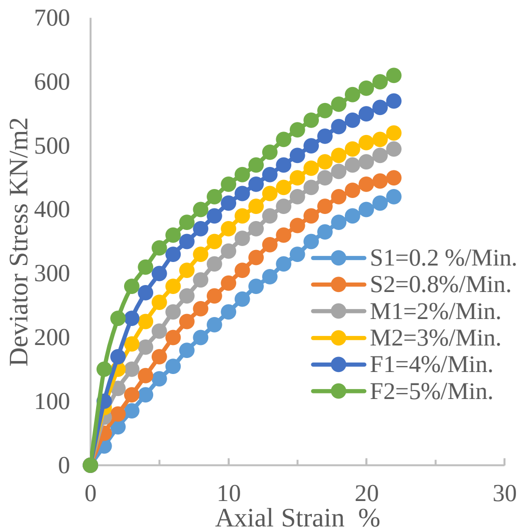

Fig. 4 Stress-strain curves for untreated Soil Under Cell pressure of 200 KN/m2

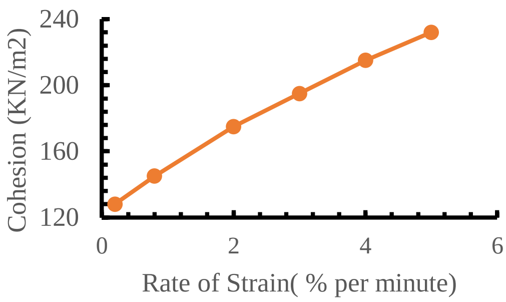

Fig. 5 Effect of rate of strain on cohesion of not-treated soil

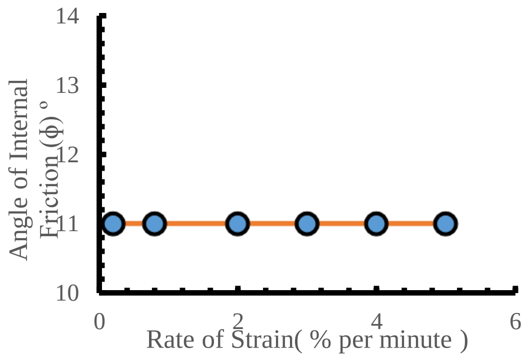

Fig. 6 Effect of strain rate on the internal angle of friction of natural soil

demonstrates a significant rise in undrained cohesion with increasing rates of strain, reaching up to 62% higher than the lowest strain rate. However, the angle of internal friction, as depicted in Fig. 6, remained unaffected by changes in the rate of strain. Tangent modulus values, illustrated in Fig. 7, exhibited a notable increase with higher rates of strain. Abdellaziz *et al*. (2022) explored the impact of strain rate variation on soil strength properties using eastern Canadian soils. Their findings highlighted a distinct increase in undrained shear strength and secant shear modulus with higher strain rates, with the extent of this effect correlating with shear strain amplitude and plasticity index. Hu *et al*. (2020) studied the intrinsic mechanisms of strain rate on unsaturated compacted silty clays through triaxial tests, revealing two critical strain rate values. These values caused peak strength to initially decrease and then increase with strain rate under low confining pressures, while under high confining pressures, peak strength followed a similar trend initially before decreasing with increased strain rate. Tahsin *et al.* (2020) investigated the effect of strain rate on polyester geogrids and found that higher strain rates resulted in increased measured strength and secant modulus. Nanda *et al*. (2017) conducted tests on

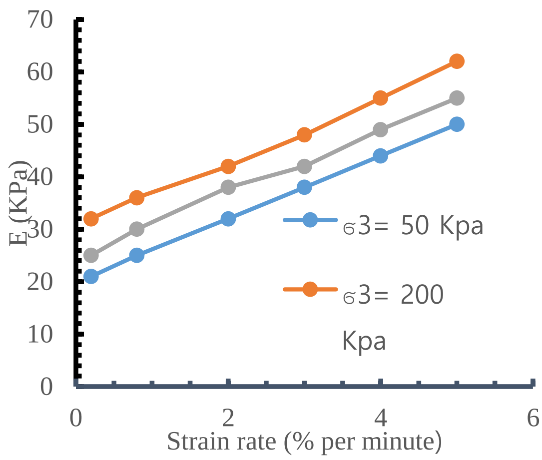

Fig. 7 Effect of Rate of Strain on the Initial Modulus for the Clay Soil

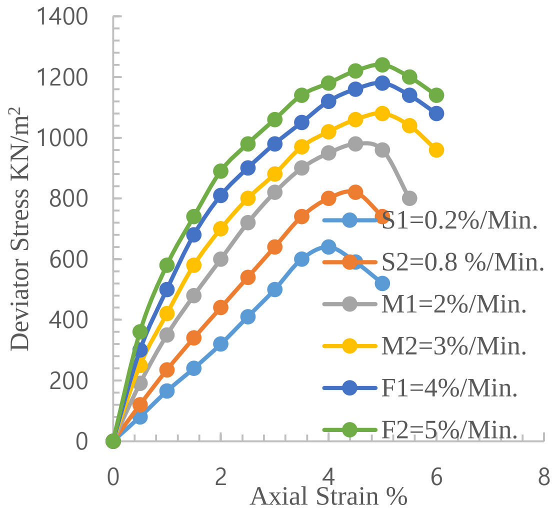

Fig. 8 Stress-Strain for soil-cement dust (5%) under cell pressure 50 KN/m^2

kaolin clay beds and found that resistance factor increased by 9% for every 10-fold increase in penetration rate. Liu *et al.* (2022) examined the effects of strain rate on characteristic stresses and acoustic emission parameters of rock under quasi-static compression. Their results showed a linearly positive correlation between characteristic stresses and the logarithm of strain rates, indicating an increase in characteristic stresses with higher strain rates.

Nanda *et al.* (2019) assessed the strain-rate effect on very soft soils, particularly in T-bar tests on soft offshore sediments. Their research revealed a 9% increase in resistance factor for every 10-fold increase in penetration rate, highlighting the strain-rate dependence of T-bar tests in very soft clay subjected to high rates of penetration.

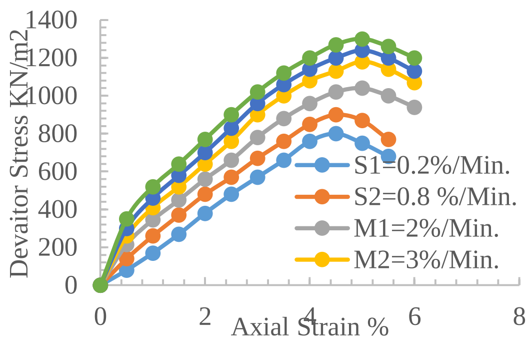

Fig. 9 Stress-Strain for Soil -cement dust (5%) under cell pressure 100 KN/m^2

8. Effect of rate of strain on stabilized soil mixed with different percentages of cement dust

The natural clay soil was mixed with three percentages of cement dust these are 5%,10%, and 15%, each type of stabilized soil was tested with 6 rates of strain to explore the effect of the rate of strain on strength properties of the stabilized soil with different percentages of cement dust.

As shown in Figs. 8 to 17, the stress-strain curves for soil mixed with 5%,10%, and 15% cement dust contents were tested at different rates of strain and different cell pressures.

Fig. 18 shows the distinctive increase in the results of the cohesion with the increase in both the content of the cement dust and the rate of strain The effect of the rate of strain and cement dust content on the angle of internal friction (ϕ) was also studied. Fig. 19 showed that as the cement dust content increases, the values of ϕ showed a distinctive increase as the contents of cement dust increases, while ϕ remains constant independent of the rate of strain for each cement dust content.

The effect of the rate of strain and cement dust content on the angle of internal friction (ϕ) was also studied. Fig. 19 showed that as the cement dust content increases, the values of ϕ showed a distinctive increase as the contents of cement

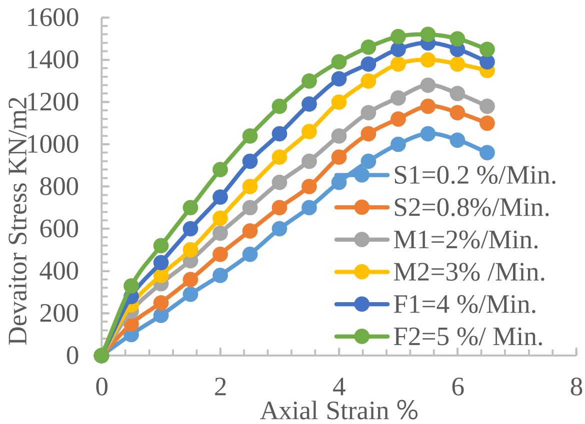

Fig. 10 Stress-Strain for Soil-cement dust (5%) under cell pressure 200 KN/m^2

dust increases, while ϕ remains constant independent of the rate of strain for each cement dust content on the angle of internal friction.

The values of the tangent modulus are also affected by

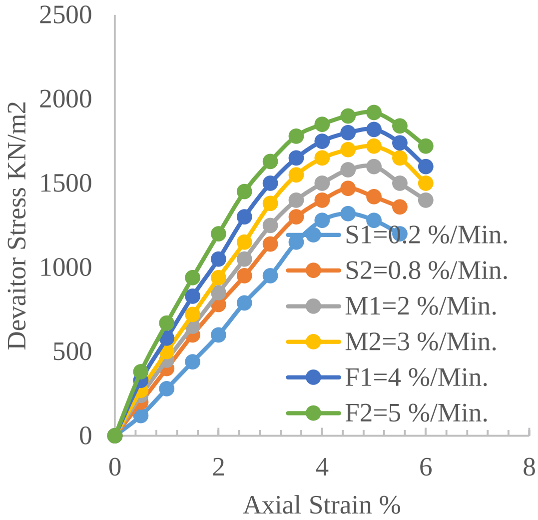

Fig. 11 Stress-Strain for Soil-cement dust (10%) under cell pressure 50 KN/m^2

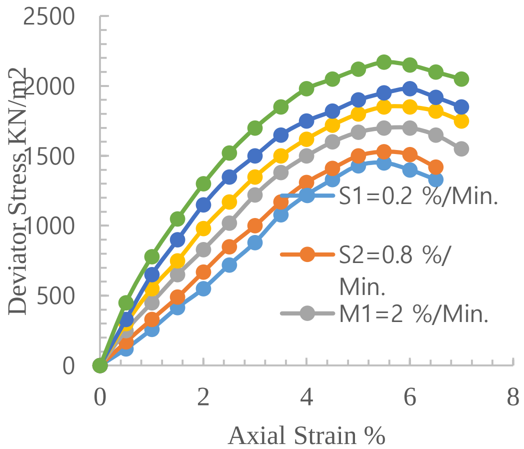

Fig. 12 Stress-Strain for Soil-cement dust (10%) under cell pressure 100 KN/m^2

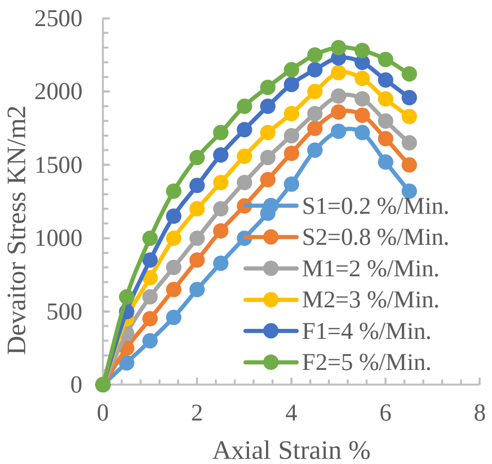

Fig. 13 Stress-Strain for Soil-cement dust (10%) under cell pressure 100 KN/m^2

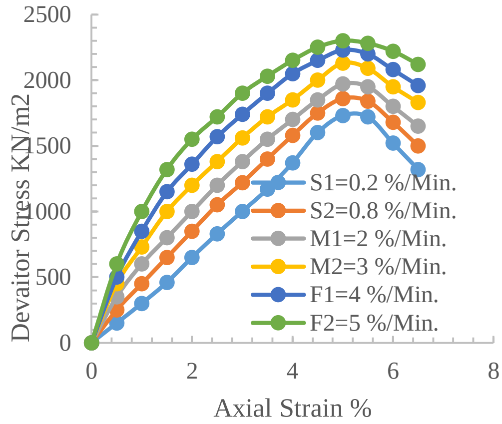

Fig. 14 Stress-Strain for Soil-cement dust (10%) under cell pressure 200 KN/m^2

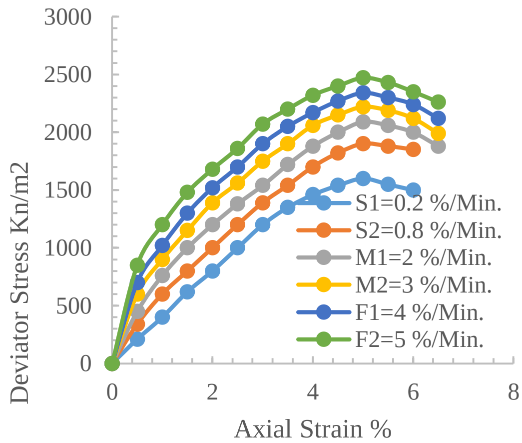

Fig. 15 Stress-Strain for Soil-cement dust (15%) under cell pressure 50 KN/m^2

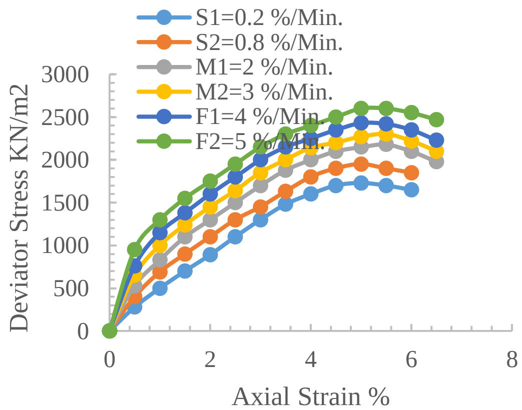

Fig. 16 Stress-Strain for Soil-cement dust (15%) under cell pressure 100 KN/m^2

both the rate of strain and cement dust content. As shown in Figs. 20-22 that the values of the initial Modulus increase with increasing both the rate of strain and cement dust contents. The values of initial modulus also showed a distinctive increase with increasing the cell pressure values.

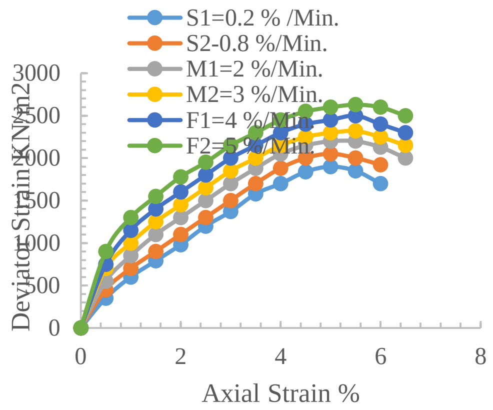

Fig. 17 Stress-Strain for Soil-cement dust (15%) under cell pressure 200 KN/m^2

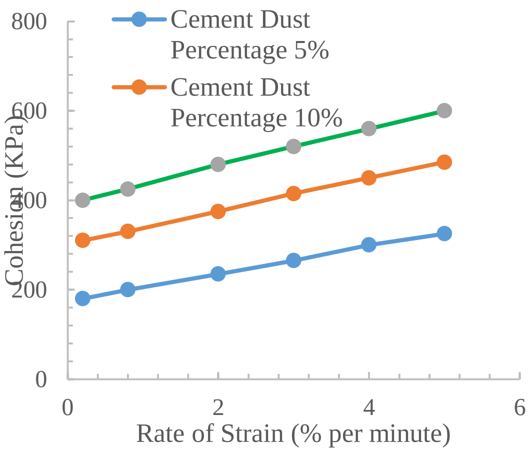

Fig. 18 Effect of Cement Dust percentages on Cohesion for Different Rate of Strain

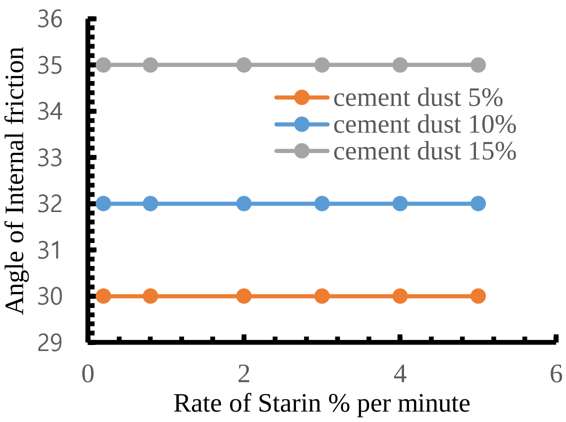

Fig. 19 Effect of rate of strain and cement dust

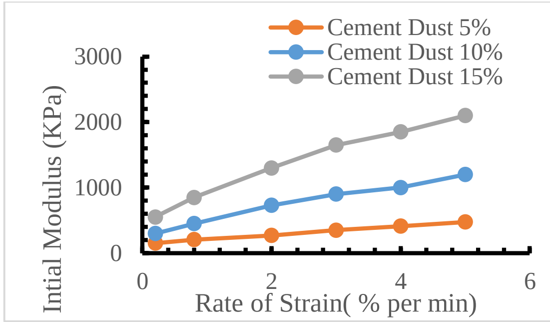

Fig. 20 Effect of Rate of Strain and Cement Dust content on initial Modulus with cell pressure of 50 KPa

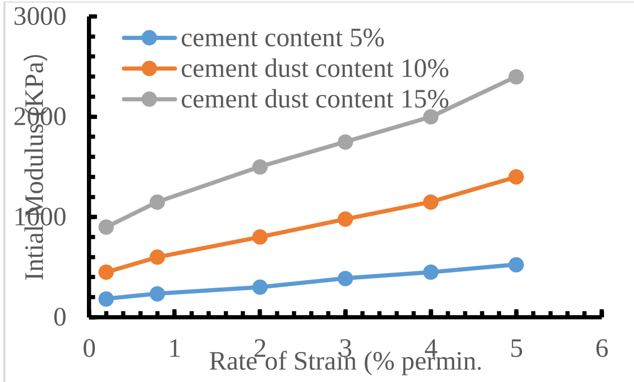

Fig. 21 Effect of Rate of Strain and Cement Dust content on initial Modulus with cell pressure of 100 KPa

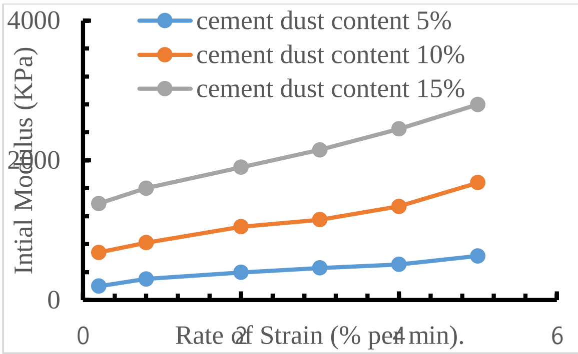

Fig. 22 Effect of Rate of Strain and Cement Dust content on initial Modulus with cell pressure of 200 KPa

8. Effect of cement dust on strength properties of the clay

The addition of cement dust with different percentages increases the cohesion, elastic modulus, and angle of internal friction, this is due to the bonding that creates between the particles of the clay.

As the percentages of the cement dust, the strength properties of the mixtures increase. various studies on the stabilization of different types of soil using cement-based materials. Du *et al*. (2020) focused on stabilizing expansive clay with different cement content. The researchers found that increasing the amount of cement improved the efficiency of controlling the expansion of the clay. Kumar and Singh (2017) used a cement kiln to stabilize weak soil and increase its strength. They added varying percentages of cement kiln cement, ranging from 0% to 30% by dry weight of the soil, and observed a significant increase in the strength properties of the soil.

Adeyanju and Okeke (2019) investigated the suitability of cement kiln dust (CKD) for stabilizing clayey soil extracted from a failed road section. The addition of 10% CKD to the clay soil resulted in the best mechanical improvement, with the unsoaked CBR (California Bearing

Ratio) increasing from 1.49 to 28.6% after a curing period of 7 days. Al-Gharbawi *et al*. (2023) studied, three percentages of lime, cement, and silica fume (5%, 7%, and 9%) were used to stabilize expansive soil. The research was divided into two sections: consolidation tests and grouting techniques. The results showed that the soil stabilized with different percentages of lime, cement, and silica fume exhibited a significant decrease in both free swell and swelling pressure compared to untreated soil. Additionally, the grouting technique using silica fume increased the bearing capacity of footings resting on the grouted soil by 64% to 82% for soil treated with 5% and 9% silica fume, respectively, compared to untreated soil. Solihu (2020) focuses on the suitability of ordinary Portland cement as a chemical stabilizer to enhance the strength and durability of sand for subgrade and base courses in rail track and road construction. The findings of the study suggest that ordinary Portland cement is indeed an effective chemical stabilizer for improving both the index properties and strength properties of soils. Pandey and Rabbani (2017) explored in their study that stabilizing the weak soil used for the construction of the road with cement improves the strength properties of the soil. Maichin *et al.* (2021) conducted a series of tests to evaluate the effectiveness of soil-cement stabilization with varying cement and FGD gypsum (Flue Gas Desulfurization gypsum) contents. Compaction tests were performed to assess the density and compaction characteristics of the stabilized soil. Unconfined compressive strength (UCS) tests were conducted to measure the strength development of the stabilized soil samples. Additionally, scanning electron microscope (SEM) analyses were carried out to examine the microstructural changes and identify the mechanisms responsible for the strength improvement. The results of the study indicated that the addition of FGD gypsum enhanced the strength of the stabilized soil. By adding FGD gypsum to the cement hydration system, more sulfate ions were introduced. These sulfate ions played a crucial role in the formation of ettringite and monosulfate, which are calcium sulfoaluminate hydrates. The presence of these hydration products contributed to the improved strength of the soil-cement mixture.

9. Discussion

The strengths of clay, soil not treated with cement increase with increasing strain rate in natural clay can be attributed to Pore Water Pressure built up, at higher strain rates, there may be less time for water to flow out of the soil pores. This can increase the effective stress in the soil, leading to higher apparent strength. Also in cohesive soils, an increase in strain rate can promote better particle-to-particle contact, enhancing the soil's ability to resist deformation. The clay may exhibit time-dependent behavior, such as creep or consolidation. At higher strain rates, these processes may have less time to occur, resulting in higher apparent strength. The angle of internal friction of natural clay showed no influence for the rate of strain , this may attributed the nature of clay soils that have a unique behavior due to their fine-grained particles and the presence of cohesive forces between these particles. These cohesive forces are primarily due to the electrochemical attraction between clay particles and the water films surrounding them. This cohesive nature of clay particles allows them to resist shear forces and maintain their structure even under relatively low strain rates. In clay soils, the cohesive forces between particles are much stronger than the frictional forces between particles. The clay particles do not have sufficient relative motion to significantly change the angle of internal friction. The tangent modulus may follow the same trend as the undrained shear strength as the rates of strain increases the values of tangent modulus increase, this is due to low response of the build-up of pore pressure with higher values of rate of strain.

The undrained strength of stabilized clay with cement dust increased significantly when both the percentages of cement dust and the rates of strain were increased. Specifically, it states that the strength increased by 82% when the rate of strain increased from 0.2% per minute to 5% per minute, while the cement dust content increased from 5% to 15%, with a cell pressure of 200 kN/m^2. This observation is consistent with the behavior of stabilized clay soils when subjected to cement stabilization. Increasing the rate of strain can result in higher apparent strength due to the rate-dependent behavior of the material. This can be particularly relevant in undrained conditions, where excess porewater pressure builds up rapidly, affecting the soil's effective stress and strength. Increasing the percentage of cement dust in the stabilized clay typically leads to greater cementation and improved strength. This is because a higher cement content provides more binding material to create stronger cementitious bonds within the soil matrix.

It appears that in the case of stabilized clay with cement, the angle of internal friction remained unchanged when the rate of strain was varied. However, there was a significant 17% increase in the angle of internal friction when the percentage of cement dust in the mixture was increased from 5% to 15%. This suggests that the addition of a higher percentage of cement dust had a positive effect on the material's resistance to shear or deformation, leading to an increase in its angle of internal friction. This change in behavior indicates improved stability and shear strength of the material with a higher cement dust content. The tangent modulus of this material increased significantly when both the percentage of cement dust and the rate of strain were increased when the percentage of cement dust in the stabilized clay increased from 5% to 15% and the rate of strain increased from 0.2% per minute to 5% per minute, the material's stiffness or strength (tangent modulus) increased significantly, by 103% under cell pressure 200 KN/m^2. This suggests that increasing the cement dust content and the rate of strain can enhance the mechanical properties of the stabilized clay, making it stronger under the given test conditions.

The study could be extended to include dynamic loading conditions for further research. Dynamic loading involves applying varying rates of strain or loading frequencies to the soil sample, which simulates real-world scenarios where the soil may experience dynamic forces such as vibrations from machinery, earthquakes, or traffic loads. Extending the study to incorporate dynamic loading conditions could provide additional insights into the behavior of cement-stabilized clay under dynamic loading, which is crucial for various engineering applications, including.

A. **Seismic Stability**: Understanding how cement-stabilized clay behaves under dynamic loading conditions can help assess its performance and stability during seismic events. This information is essential for designing structures and foundations in earthquake-prone regions.
B. **Pavement Design**: Dynamic loading from traffic loads can significantly affect the performance and durability of pavements constructed on clay soils. By studying the response of cement-stabilized clay under dynamic loading, researchers can optimize pavement design and construction techniques to enhance longevity and reduce maintenance costs.
C. **Machine Foundations**: Machinery operating on clay soils can generate dynamic forces that may affect the stability and integrity of their foundations. Investigating the behavior of cement-stabilized clay under dynamic loading can provide insights into the design and reinforcement of machine foundations to prevent settlement or failure.
D. **Environmental Remediation**: Dynamic loading can also influence the effectiveness of soil stabilization techniques in environmental remediation projects, such as landfill covers or contaminated site remediation. Studying the response of cement-stabilized clay under dynamic loading conditions can help assess its suitability for such applications and optimize remediation strategies.

By extending the study to include dynamic loading conditions, researchers can gain a more comprehensive understanding of the behavior of cement-stabilized clay in dynamic environments, leading to improved design guidelines, construction practices, and risk mitigation strategies for various engineering projects.

10. Conclusions

Based on the findings of the present research, the following conclusions can be drawn:

1. The rate of strain significantly influences the cohesion of clay soil, with an 81% increase observed when the rate of strain is increased from 0.2 to 5% per minute.
2. The angle of internal friction for the clay soil remains unaffected by changes in the rate of strain.
3. Initial tangent modulus values exhibit substantial increases with higher rates of strain, with increases of 135%, 120%, and 94% observed for cell pressures of 50 kPa, 100 kPa, and 200 kPa, respectively, when the rate of strain rises from 0.2 to 5% per minute. Additionally, initial tangent modulus values also increase with higher cell pressures, with increases of 52% and 24% noted when the cell pressure increases from 50 kPa to 200 kPa for strain rates of 0.2% and 5% per minute, respectively.
4. The addition of cement dust enhances the strength properties of clay soil, with increased cement dust percentages and strain rates resulting in notable improvements. Clay soil stabilized with 5%, 10%, and 15% cement dust displays cohesion increases of 41%, 150%, and 210%, respectively, compared to unstabilized clay soil, at a strain rate of 0.2% per minute. Similarly, at a strain rate of 5% per minute, cohesion increases of 40%, 110%, and 160% are observed for clay soil stabilized with 5%, 10%, and 15% cement dust, respectively. Soil stabilized with 5% cement dust demonstrates an 80% increase in cohesion when the strain rate rises from 0.2% to 5% per minute, while soil stabilized with 10% and 15% cement dust shows increases of 56% and 50%, respectively, under the same conditions.
5. While the angle of internal friction remains insensitive to strain rate changes, clay soil stabilized with 5%, 10%, and 15% cement dust displays substantial increases in the angle of internal friction compared to unstabilized clay soil.

These conclusions highlight the significant impact of both cement dust content and strain rate on the strength properties of clay soil, providing valuable insights for geotechnical engineering applications

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