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IMPROVEMENT OF THE CYCLIC LOADING RESPONSE OF STABILIZED EXPANSIVE SOILS

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ABSTRACT

This research aims to investigate the active behavior of expansive soils stabilized with ground granular kiln slag (GGBS) and cement-activated slag (GGBS/C) subjected to cyclic loading. Key active parameters shear modulus, Young's modulus, damping ratio, and deviatoric stress are basically assessed, complemented by Fourier Transform Infrared Spectroscopy (FTIR) analysis to characterize the underlying chemical mechanisms. Untreated expansive soils exhibit very low stiffness and strength, making them highly susceptible to cyclic degradation. The results show that stabilization with GGBS and GGBS/C substantially improves the mechanical stability: Young 's modulus increases by 5200 % to 7200 %. And this is key: and shear modulus increases by 2000 % to 5700 %, while the damping ratio decreases by more than 90 %. Resistance to deviatoric stress also increases, increasing by 440% to 545% depending on the limiting stress. Also increasing the confining pressure from 100 to 300 kPa further strengthens the stiffness and cyclic resistance, resulting in more stable performance under repeated loading conditions.

KEYWORDS

Stabilization, Activated Slag, Loading-Unloading, Ftir, Dynamic Behavior.

1. INTRODUCTION

Expansive soils, characterized by a high proportion of expansive clay minerals such as montmorillonite, exhibit marked swelling and shrinkage behavior. Their properties are basically very sensitive to variations in water content: when wetted, it undergoes large changes in volume (Al-Soudany, 2018; Gheris and Hamrouni, 2020). In many cases, prolonged exposure to moisture will further damage the soil structure, increasing internal pressure and deformation. Which can in the end lead to foundation cracking and structural failure (Gupta and Kaur, 2019). In other words, that's the gist of it. Under cyclic loading, this sensitivity to water becomes worse. As expansive soils become increasingly brittle and deform due to particle rearrangement driven by internal stress redistribution; Repeated loading cycles further reduce strength and Stiffness,accelerating soil weakening over time (Nguyen and Fatahi, 2018). To reduce these limitations, traditional stabilizers such as Portland cement and lime have long been used to improve the geotechnical properties of expansive soils. Lime reacts chemically with clay minerals to reduce plasticity and increase strength, while cement increases cohesion and reduces permeability (Al-Soudany, 2018). To be honest, more to be specific lime promotes flocculation and coagulation of clay particles, (in most cases) which compacts the soil matrix and strengthens interparticle bonds (Wild et al., 2017). That's the long and short of it. While Cement produces calcium silicate hydrate (C–S–H) in the presence of water,providing the binding strength necessary for construction applications (Siddique, 2019).Given the environmental and economic disadvantages of conventional stabilizers, (usually) industrial by-products such as ground granular furnace slag (GGBS) and fly ash have emerged as long-lasting alternatives, offering effective stabilization at lower costs and reducing the environmental change of disposal (Garg et al., 2019). Among other things, GGBS has proven to be very effective: as a cement byproduct of steelmaking. GGBS not only stabilizes expansive soils but also reduces their swelling potential (Hayal et al., 2021). Plain and simple, In a straightforward manner, GGBS combined with an alkaline activator results in a cementitious compound, which significantly enhances the strength and durability of soils (Shi et al., 2016) The results of the study confirm that using GGBS improves compressive strength and durability properties of the soil (Sharma and Sivapullaiah, 2020). More recently, studies have been conducted on different waste materials that can serve as soil stabilizers and by that means widen the possibilities of geotechnical solutions (Mehsin, 2025). Overall, the incorporation of stabilizers improves the expansive behavior of soil by reducing water absorption and plasticity while increasing load-bearing capacity, by doing that ensuring long-term structural stability. If you think about it, in specific, the addition of GGBS to expansive clay soils reduces the plasticity and swelling potential while increasing the bearing capacity. Also higher confining pressures have been shown to increase the dynamic response and stiffness of treated soil, by doing that further increasing its resistance to deformation due to repeated loading (Kavazanjian and Ghazavi, 2020).So yeah, that's the idea. For what Ghazavi's worth, cyclic triaxial tests confirmed that confining pressure plays an important role in soil behavior under stress, by doing that increasing stability. Increased confining pressure provides greater resistance to deformation during repeated loading, such as that induced by traffic or earthquakes (Chen et al., 2019). The treatment of expansive soils significantly enhances dynamic parameters under cyclic loading by improving shear wave velocity and dynamic strength, thereby increasing their ability to withstand repeated loading and limiting permanent deformations (Zhao and Liu, 2018). Furthermore, the reduction in the accumulation of plastic deformations significantly reduces the risk of failure after multiple loading cycles (Khosravi and McCartney, 2017). It was found that adding lime and fly ash to expansive clay soils significantly increased shear wave velocity, dynamic stiffness, and resistance, while reducing plastic deformation, thereby improving soil durability under dynamic stress (Fattah and Al-Karkhi, 2017).Stabilization of expansive soils with synthetic resin was shown to enhance energy dissipation capacity and reduce resonance, thus increasing stability against cyclic vibration and shock wave transmission damping (Bahadori and Fakhari, 2020). The behavior of clayey soils and the influence of bituminous binders on them have also been examined (Fang and Daniels, 2020). While previous studies have focused mainly on the chemical and static stabilization of expansive soils, the dynamic response under cyclic loading and varying confining pressures, especially with GGBS and GGBS/C(cement-activated slag), remains insufficiently investigated. The objective of this work is to demonstrate the effectiveness of using different percentages of GGBS and GGBS/C in stabilizing expansive soils with respect to their dynamic behavior under cyclic loading. At the same time, the effect of confining pressures on this behavior is analyzed in order to understand how these conditions alter the reaction of the stabilized soil to dynamic loading. The combination of these two aspects helps to attain a better understanding of the obtained improvement in the mechanical characteristics of the treated soil and of its applicability for different environments subjected to alternating loading cycles.

2. MATERIALS AND TEST METHODS

2.1. Materials

Soil samples were taken from depths of 1.50 to 3.50 meters which is the depth that foundations for buildings go in shallow ground. To put it simply that is the point. And this is important: the soil we looked at is classified as CH, which means it is plasticity clay according to the Unified

Soil Classification System (USCS). This type of soil Soil has a coefficient (Cg) of expansion of 0.075 which means it swells and shrinks a lot when it gets wet or dry. This Soil needs to be stabilized so that new buildingsre safe. Table 1 summarizes the physical, mechanical, and chemical properties of soil samples. The cement used in this study was Portland CEM II/CPJ 42.5, supplied by Hadjr Essoud Cement Company (Annaba. Which, when you think about it, makes perfect sense. Algeria); The chemical composition and Main elements are detailed in Table 2. Plain and simple, GGBS, provided by El-Hadjar company (Annaba), is produced by cooling molten slag with a high-pressure water jet, producing a gray granular material. This rapid cooling process induces a glass-like microstructure that increases the reactivity and binding efficiency of the additive. The chemical composition of GGBS is also presented in Table 2

Table 1. Physical, Mechanical and chemical properties of the studied soil

Parameters	Value
Bulk density (g/cm^3)	1.83
dry density (g/cm^3)	1.45
Specific Gravity	2.7
Liquid Limit, LL(%)	55
Plastic Limit, PL(%)	26
Plasticity Index, PI (%)	29
2mm (%)	99.42
0.08mm (%)	95.77
USCS Classification	CH
Maximum Dry Density(g/cm^3)	1.55
Optimum Moisture Content(%)	23.66
C(bar)	1.358
Φ(˚)	23
W(%)	26.3
PC(BAR)	0.606
Ct	0.213
Cg	0.075
Carbonate (%)	30.24
Gypse (%)	15.1
Insoluble (%)	31.51

Table 2. Chemical composition of GGBS and cement

Minerals	GGBS	Cement
SiO2	40.3 (%)	21.32 (%)
CaO	39.7 (%)	64.25 (%)
AL2O3	7.08 (%)	5.69 (%)
Fe2O3	0.99 (%)	2.39 (%)
MgO	6.79 (%)	1.27 (%)
SO3	0.67 (%)	1.86 (%)
MnO	3.25 (%)	-
P2O5	0.01 (%)	-
ZnO	0.01 (%)	-
Loss on ignition	-	2.67 (%)
Insoluble residue	-	0.3 (%)

IR samples were scanned using a PerkinElmer FTIR spectrometer. Figs.6 and 7 present the FTIR spectra of the studied soils, where several important functional groups were identified.Absorption bands at 1000-1100 cm^{-1} indicate the occurrence of the Si-O stretching vibrations of the clay mineral silicates (Madejová et al., 2017). The presence of alumina is confirmed by Al–OH bending vibrations appearing between 900 and 950 cm^{-1} (Plevova et al., 2020). The peaks appearing in the ranges of 500-800 cm^{-1} are related to the silicate lattice vibrations, which testify about the crystallinity of the clay minerals. Carbonate groups give rise to bands in the range of 1500-1700 cm^{-1} and indicate possible interactions between the stabilizers and soil minerals. Changes in the intensity and position of the bands indicate the mineralogical variability of soils and the effects of stabilization techniques employed as well (Jozanikohan and Abarghooei, 2022).

2.2. Sample preparation

Soil samples underwent an oven-drying process at a temperature of 105 °C for 24 hours and grinding process to obtain a uniform particle size. Then GGBS was pulverized in a mill operated by KHD Humboldt Wedag AG (Germany) to obtain a fineness of 4,000 cm^2/g to improve its activity during stabilization and ensure quicker pozzolanic reactions. Seven mixtures were obtained: one unmodified control mixture and six modified mixtures with the addition of GGBS in the amounts of 4%, 8%, and 12% respectively. Another modified mixture was obtained with the usage of GGBS/C which was received by mixing 85% GGBS and 15% cement. The option of 85/15 was chosen from the results of a prior study (Djouimaa et al., 2021) since it was shown to help in activating the latent hydraulic properties of GGBS. This amount of cement gives enough alkalinity to initiate pozzolanic reactions, and the high amount of GGBS is going to secure sustainability and cost effectiveness. After that distilled water was added to reach the optimum moisture content according to the results of the Proctor test that helps to determine the maximum dry density. The samples were received from the mixture using cylindrical molds (100 mm high × 50 mm in diameter). Finally, the samples were covered in plastic wrap to avoid losing moisture and were kept at room temperature till the moment of tests.

2.3. Cyclic triaxial test

The Dynatriax triaxial system (Wykeham Farrance) at the Infrares laboratory in Mohamed Chérif Messaadia University, Souk Ahras, Algeria was used in performing cyclic triaxial tests Fig. 1. The specimens were placed in a triaxial cell, where it is possible to apply vertical and lateral stresses while controlling drainage and consolidation conditions. The cyclic loading was preceded by the application of confining pressures which were kept constant during the entire testing process: 100, 200, and 300 kPa. The testing was done in line with ASTM D3999 standard under undrained conditions; the value of the consolidation ratio (Kc)=1 and the value of the Poisson’s ratio = 0.5. Sinusoidal waveform with 0.5 Hz frequency was employed to imitate the loading by vehicles on roads, since this frequency resembles typical stress caused by vehicles on weak subgrades.By applying cycles of compression and tension, the dynamic stresses influencing the soil were replicated. The axial deformation was continuously measured in real time and analyzed in order to determine the response of the soil. Furthermore, the effect of the percent of GGBS, the confining pressure and the number of load cycles on the soil behavior was studied.

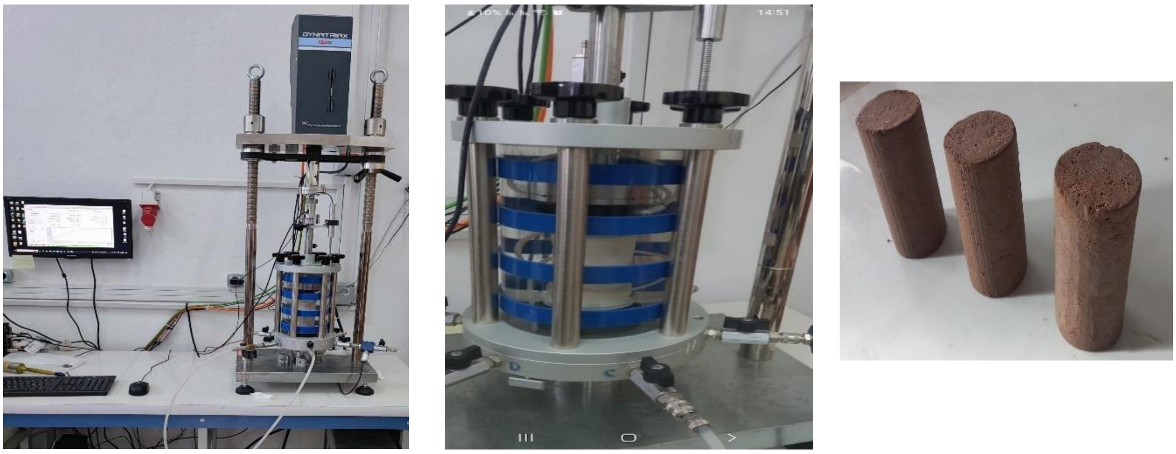
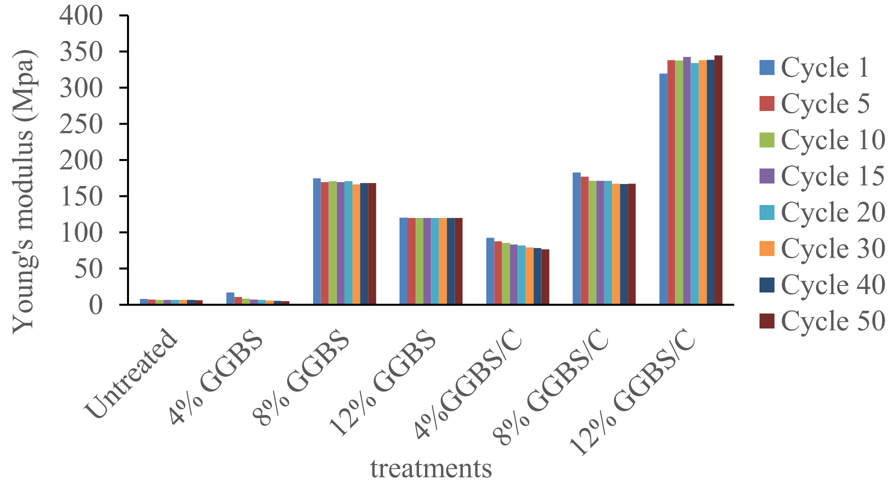


Fig. 1. Triaxial apparatus and prepared soil specimens

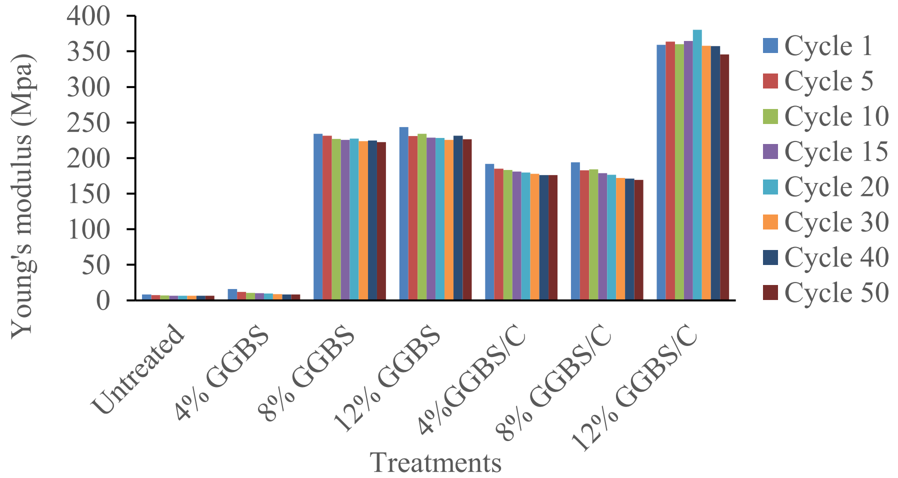
3. RESULTS AND DISCUSSION

3.1. The effect of GGBS and GGBS/Con Young's modulus

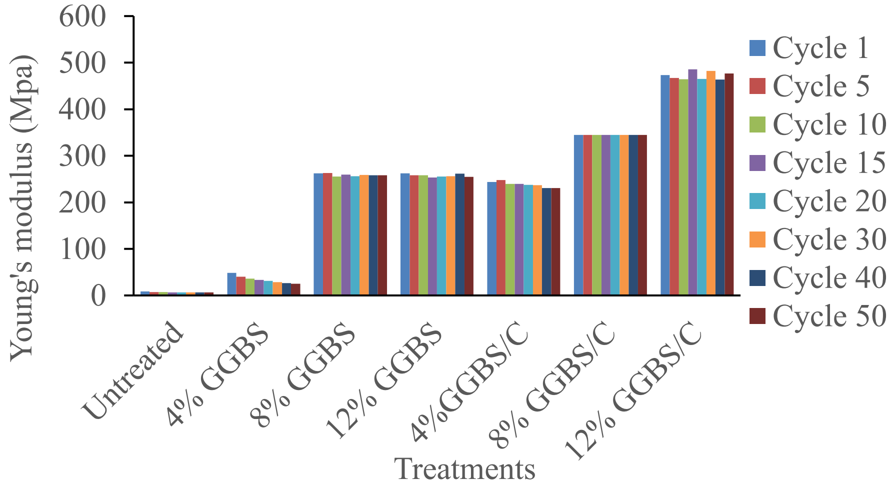
Figs. 2(a-c) show the Youngs values we got for soils that were treated with 4 percent, 8 percent and 12 percent GGBS or GGBS/C. We did this under confining pressures of 100, 200 and 300 kPa after the soil went through 50 load cycles. The soil that was not treated has a low Youngs modulus. It is 6.48 MPa at 100 kPa. The soil stays weak when we increase the confining pressure. This shows that the soil is not very stiff. When we add 4 percent GGBS to the soil the Youngs modulus of the soil increases. It goes from 4.99 MPa at 100 kPa to 24.84 MPa at 300 kPa. This is an improvement of about 283 percent compared to the soil that was not treated. When we add 8 percent GGBS to the soil the Youngs modulus of the soil goes up a lot. It goes from 169.74 MPa to 258.34 MPa. This is a gain of about 3884 percent compared to the soil that was not treated. We see something when we add 12 percent GGBS to the soil. The values go from 119.81 MPa to 254.99 MPa. This is an increase of 3834 percent. The biggest improvement we see is when we add 12 percent GGBS/C to the soil. The Youngs modulus of the soil is 344.62 MPa at 100 kPa. It goes up to 477.06 MPa at 300 kPa. This is an increase of, about 7260 percent compared to the soil that was not treated which had a Youngs modulus of 6.48 MPa.



(a) under confining pressures of 100Kpa



(b) under confining pressures of 200Kpa



(c) under confining pressures of 300Kpa

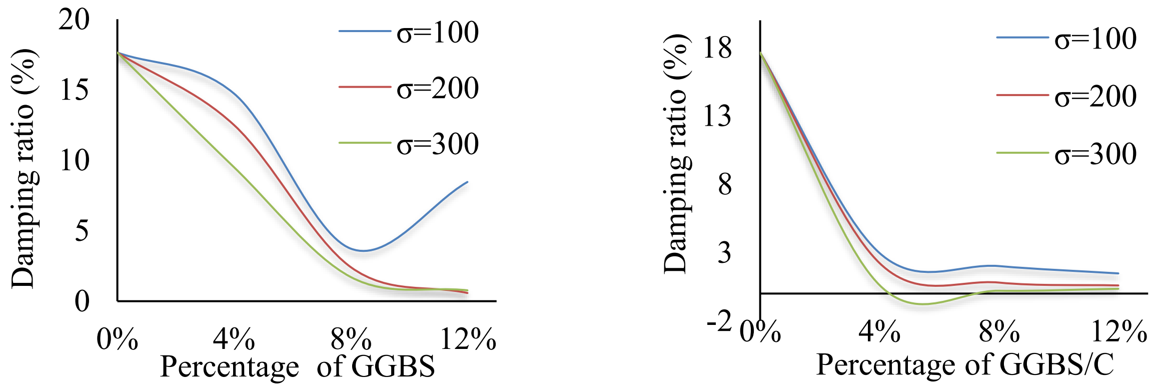
Fig. 2. Effect of GGBS and GGBS/C on Young's modulus with different confining pressures

The soil got a lot better. This is because of two things that work well together. First there are these reactions and the hydration of GGBS/C that make cementitious compounds like C-S-H and C-A-H. These compounds form bonds between the particles and make the soil stiffer. Second when the pressure on the soil is increased the spaces between the particles get smaller.

The particles lock together better which stops them from slipping and makes the soil act more like a strong elastic material. The GGBS and the way it works with the soil is really important here. These two things together are the reason why the Youngs modulus values were so high in this study. This is what other people have found too like (Kumar et al., 2019; Reddy et al., 2020; Phanikumar and Sharma, 2021). They all saw that the soil got a lot stiffer when they used GGBS and cement-activated GGBS and put amounts of pressure, on it.

3.2. The effect of GGBS and GGBS/C on the damping ratio

The damping ratio, which indicates the ability of soil to dissipate energy under dynamic loading, significantly declined after treatment. Fig. 3 shows how the damping ratio varies with confining pressure in terms of different treatment percentages. Note that there were only three discrete additive contents investigated (4%, 8%, and 12% of GGBS and GGBS/C); thus, the x-axis shows not the continuous variable but specific test points.



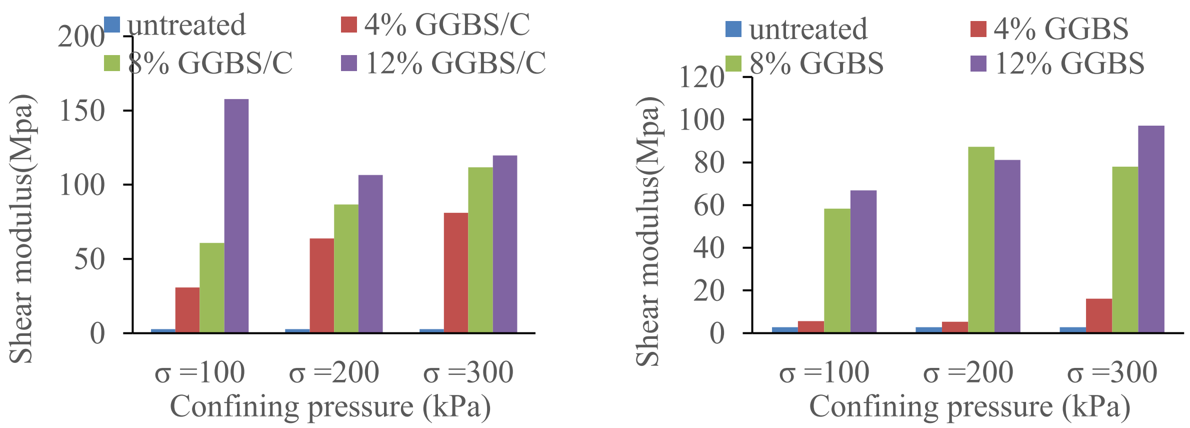
(a) Soil treated by GGBS **(b) Soil treated by GGBS/C**

Fig. 3. Effect of confining pressure on damping ratio with different treatment percentages

The untreated soil had a damping ratio of 17.63% with 100 kPa, which decreased to 12.49% with 200 kPa and to 9.5% in case of 300 kPa after 50 cycles of the experiment. With 8% GGBS, the damping ratio reached 4.23% with 100 kPa, and 2.42% with 300 kPa, indicating a reduction of about 76% in the case of treated versus untreated soil. Going to the case of 12% GGBS/C, the obtained values were even lower, as they reached 1.48% with 100 kPa, 0.60% with 200 kPa and 0.35% with 300 kPa, thus presenting the reduction exceeding 90%. The drop in the damping ratio that was observed in connection with GGBS and GGBS/C treatment can be explained by the increasing stiffness of the soil and by the more elastic and strong contacts established between the soil grains under confinement conditions.Higher confining pressures lead to a reduction of the void ratio and increase interlocking, while the presence of GGBS/C allows for the formation of cementitious materials (C–S–H and C–A–H), which enhance the resistance to inelastic slip. The combined process reduces the hysteresis loop and lowers damping ratios, indicating a better performance of soils in terms of elastic recovery. The results obtained correlate well with previous investigations. (Fattah and Al-Karkhi, 2017) demonstrated that lime-fly ash stabilization of expansive clays results in the reduction of damping ratio. Similarly, (Khosravi and McCartney, 2017) showed that geopolymer-stabilized clays exhibited decreased hysteretic damping due to enhanced elastic recovery. More recently, (Güllü and Khudir, 2019) and (Estabragh et al., 2021) highlighted that chemical stabilization typically results in damping ratio reductions of 70–90%, in agreement with the present results.

3.3. The effects of GGBS/C and GGBS on the shear modulus

At a confining pressure of 100 kPa, the untreated soil exhibits a shear modulus of about 2.7 MPa . With 4% GGBS, the initial modulus increases to 5.6 MPa (+107%), although it decreases to 1.7 MPa after 50 cycles. At higher contents, improvements are much more pronounced: 58 MPa with 8% GGBS (+2048%) and 67 MPa with 12% GGBS (+2381%) Fig. 4(b). When cement activation is introduced, the effect becomes remarkable: 12% GGBS/C attains 158 MPa (+5748%) and remains virtually unchanged after 50 cycles (159 MPa).At 200 kPa, the performance of 4% GGBS is not sustained under cyclic loading, while 8% and 12% GGBS maintain significant gains. Cement-activated mixtures show superior stability Fig.4(a); for example, 12% GGBS/C increases from 106 MPa to 112 MPa (+3826% to +4044%), and 8% GGBS/C oscillates between 76 and 86 MPa (+2715% to +3085%). At 300 kPa, the effect of GGBS is maximized: 78 MPa with 8% GGBS (+2789%) and 97 MPa with 12% GGBS (+3493%). With cement activation, values are even higher, reaching 111 MPa for 8% GGBS/C (+4011%) and 120 MPa for 12% GGBS/C (+4344%). No doubt that although the mixture with 12% GGBS/C leads to the highest absolute stiffness, GGBS and GGBS/C methods have been significantly recognized due to the shear modulus improvement at increased confining pressure and cyclic stability.



(a) Soil treated by GGBS/C **(b) Soil treated by GGBS**

Fig. 4. Effect of confining pressure on the shear modulus values

The remarkable increase in shear modulus can be attributed to the effects of both stabilization and confinement on the soil skeleton. The use of GGBS and GGBS/C modifies the soil microstructure by covering and cementing clay particles, resulting in improved interparticle adhesion and producing a change from a deformable clay matrix to a stable load-bearing structure. Thus, under cyclic loading, the bonded structure produces higher resistance to deformation because of the confinement pressure in the soil.The synergy between chemical bonding and mechanical confinement thus results in a significant improvement in shear stiffness. Comparable improvements have been reported in recent works. (Fattah et al., 2017) observed increases up to +2000% in lime–fly ash stabilized clays, while (Khosravi and McCartney, 2017) showed improvements between +1000% and +1900% for geopolymer-treated expansive soils. More recently, (Güllü and Khudir, 2019) and (Estabragh et al., 2021) reported increases ranging from +1500% to +3000% with chemical stabilizers. The present study, showing gains of +2000% to over +5700%, is therefore consistent with these findings and lies at the upper end of reported performances.

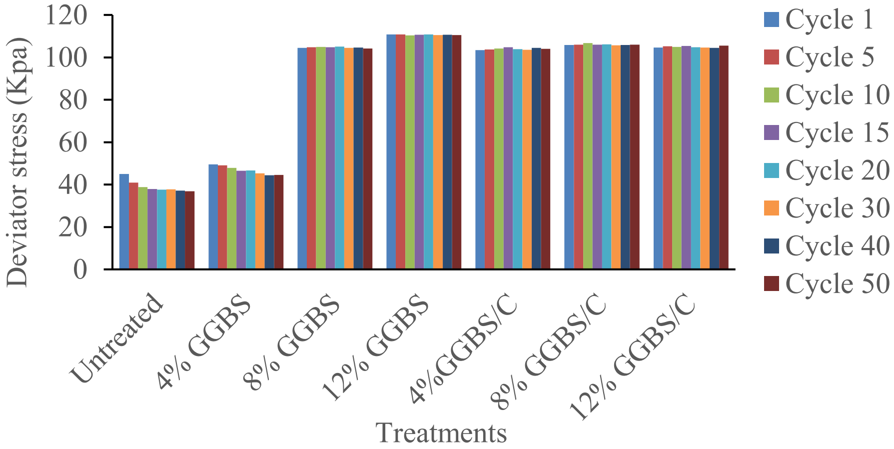
3.4. Effect of GGBS and GGBS/Con deviator stress under varying confining pressures

At a confining pressure of 100 kPa, samples treated with 12% GGBS/C achieved a maximum deviatoric stress exceeding 104 kPa, as shown in Fig. 5(a).

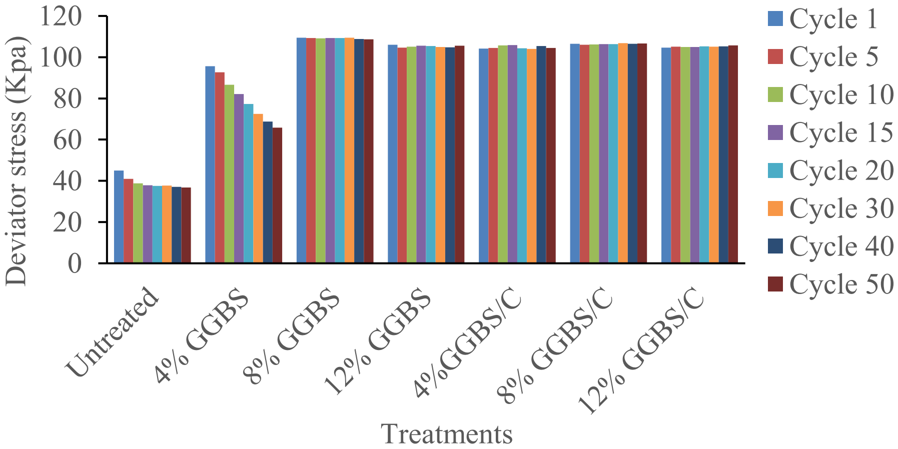
At a confining pressure of 200 kPa, the stress values for GGBS-stabilized samples reach 95.61, 109.47, and 105.96 kPa, corresponding to increases of +442%, +521%, and +501% compared with the untreated soil at 100 kPa. Under GGBS/C treatment, the stress attains 104.15 kPa (+490% relative to untreated soil) and remains nearly unchanged after 50 cycles, as illustrated in Fig. 5(b). at a pressure of 300 kPa, stabilized soils continue to have excellent performance under cyclic loading: the mixture with 8% GGBS/C attains the value of 107.33 kPa (+509%) during the first oscillation and stabilizes at approximately 113.66 kPa (+545%) after 50 oscillations (in accordance with Fig. 5(c)). This clearly shows that GGBS and GGBS/C improve stress resistance during cyclic loading, with mixtures based on cementing substances showing better stability throughout oscillation cycles.

The improvement observed in cyclic stress resistance has two underlying factors responsible for it. The induction of higher confinement pressure allows for greater particle locking and packing of soil particles itself; therefore, allowing for lower amount of deformation of the material under repetitive loading operations. Secondly, GGBS/C improves the reactivity of the cement via the formation of binders (C–S–H and C–A–H) that bind particles together and reduce slip at the surface of contact. As a result of the synergistic action of mechanical confinement and chemical bonding, soils can take high levels of stress even after cycling a number of times. Such outcomes were previously reported by some researchers: (Fattah et al.,

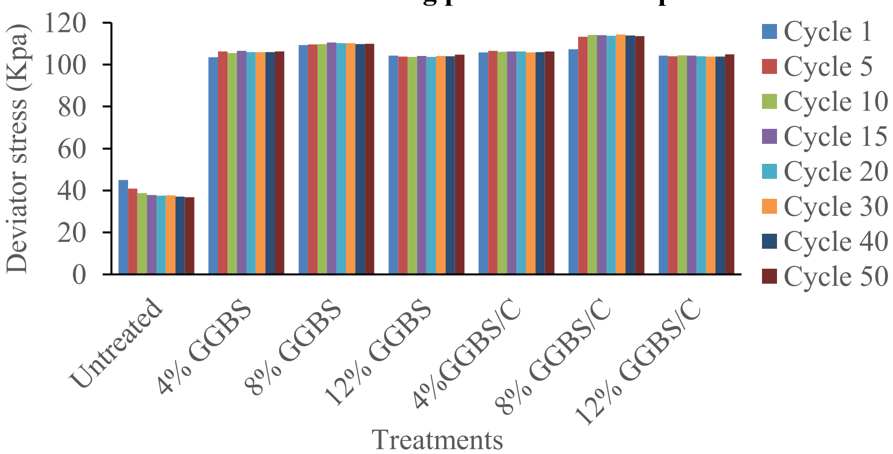
2017) noted an increase of cyclic stress by +200–300% for lime–fly ash stabilized soils, (Güllü and Khudir, 2019) witnessed an increase of cyclic strength of clays by +250–400% thanks to GGBS treatment, while (Estabragh et al., 2021) presented the findings of +300–500% for cementitious materials. The results of the present study, which are equal to increases of +440–545%, confirm earlier results and expand on them., highlighting the dual contribution of confinement and cementitious bonding in improving cyclic stress resistance.



a/ under confining pressure of 100Kpa



b/ under confining pressure of 200Kpa

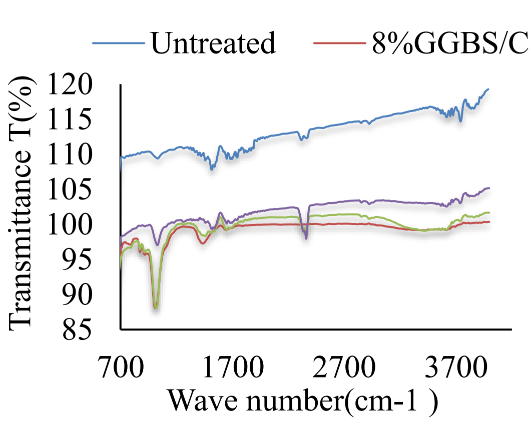


c/ under confining pressure of 300Kpa

Fig. 5. Effect of GGBS and GGBS/C on deviator stress with different confining pressure

3.5. Infrared (IR) Spectra Analysis

As depicted in Fig. 6, the increase in GGBS leads to the decline in the transmission, suggesting the better chemical stabilization effect with the minimal transmission recorded at 12% of GGBS. This decreased transmission indicates that soil minerals interact more intensively with GGBS, resulting in the formation of materials like C-S-H and C-A-H gels. At 8% of GGBS, the influence is moderate, while 4% GGBS experience the minimal interaction. In Fig. 7, GGBS/C stabilized soil shows that for all percentages, the transmission values are lower than before, so cement activation leads to the strong pozzolanic process. The presence of more C-S-H and C-A-H gels at 12% GGBS/C explains the great improvement in the mechanical properties discussed above, including the greater shear modulus and cyclic strength. In short, FTIR shows the molecular connectivity, which makes it possible to achieve increased stiffness and durability.



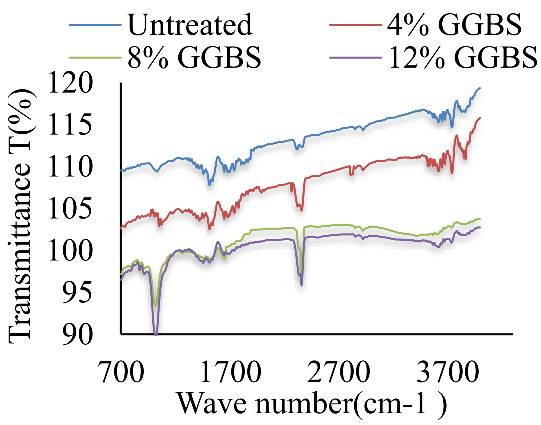


Fig. 6. Ftir analysis for soil treated with GGBSFig.7. Ftir analysis for soil treated withGGBS/C

4. CONCLUSIONS

This study's results can be summarized in the following points:

- The triaxial test reveals the role of GGBS being mixed in the amount of 8-12% leading to the increase in soil's stiffness up to +2600% at 100 kPa in comparison to the untreated soil and to the prevention of deformations caused by cyclic loading, especially at multiple confining pressures. Thus, the use of GGBS improved the soil's ability to withstand varying loads in terms of its dynamic resistance.

-The use of treatment with GGBS/C leads to an even greater impact with the increase of stiffness being +7260% relative to untreated soil at 300 kPa.

-GGBS/C stands out at 300 kPa in terms of dynamic loading ability when compared to GGBS, which means that the cement-activated formulations form a harder and denser structure and would yield positive performance under cyclic loads.

-The results obtained through FTIR support the theory of degradation of expansive minerals in clay and formation of new functional groups in soil treated with GGBS/C.

-In general, both GGBS and specifically GGBS/C have a positive effect on the dynamic load behavior, durability of repeated loading, and control over residual deformation, with the improvement percentages between +2000% and +7000% compared to standard untreated soil.

- The obtained results make it evident that GGBS/C treatment is suitable for use in infrastructure as foundations, roadways, and for other constructions dealing with cyclical or dynamic loading.

5. RECOMMENDATIONS

Based on the experimental results, the use of GGBS and cement-activated GGBS significantly enhances the cyclic performance of expansive soils. Although the degree of improvement generally increases with additive content, the findings indicate that 8% GGBS/C offers an optimal balance between mechanical performance and cost efficiency, since higher contents (12%) provide only marginal additional gains relative to the extra material cost. For practical applications, an additive content of approximately 8% GGBS/C is therefore recommended. It should be acknowledged that statistical analysis would further strengthen the validation of these results. However, due to the complexity and long duration of cyclic triaxial testing, as well as equipment constraints, tests were carried out on representative samples without replicates. To improve reliability, the obtained results can be compared with similar data found in the literature, which confirms the tendency found. Further research should also focus on conducting multiple trials and performing statistical calculations to verify the obtained results.

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