

Evaluation of Structural Response in Cement-Treated and Reinforced Silty Clay under Dynamic Load

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ABSTRACT: The scarcity of building materials and the need for green construction worldwide open research opportunities in bio-based materials and focus on reducing carbon emissions and controlling greenhouse gases. To achieve this goal, Geotechnical engineering also plays a part in increasing the durability features of soil by adding different bio-based materials, also considering soils with subpar engineering characteristics. This study focuses on identifying dynamic characteristics of soil that are strain-dependent. Bagasse was used as the reinforcing agent (RA), and ordinary Portland cement (OPC) was used as the stabilizer. The selected soil is locally available clayey material, and samples were prepared with a defined range of additive proportions based on dry soil mass. The RA was added in the proportions of 0.2, 0.4, 0.6, 0.8, and 1%, while OPC was added at 2, 4, 6, 8, and 10%. The equipment used to test the characteristics is a Resonant Column, and the scenario considered for this study is machine vibrations. The loading frequency was considered as 30 Hz and strains as 0.0001%. An increase in shear modulus was observed on addition of bagasse and cement, but the damping ratio reduced on addition of cement, while bagasse helped in increasing the damping ratio. Specimens were prepared at the optimum moisture content associated with each additive content and tested at a confining pressure of 500 kPa. The experimental program compared untreated, reinforced, and cement-treated soils using sweep testing and free vibration decay. The results provide a basis for comparing the additives under the investigated conditions; further testing is needed before extrapolating these findings to other field conditions.

KEYWORDS: Cement, Bagasse, Shear Modulus, Damping Ratio, Machine Vibrations, Free Vibration Decay, and Sweep Test

1. INTRODUCTION

Construction experts may no longer ignore soils that were previously rejected for poor engineering properties when choosing appropriate building materials. This is because the supply of construction-grade soils is diminishing (Akinwumi et al., 2016; Ganapathy et al., 2017; Ravindran, Ganapathy, and Akinwumi, 2015). Fine soils pose significant challenges in geotechnical engineering, particularly for lightweight structures, because they tend to swell and shrink with changes in moisture content, and to make these soils workable, their stabilization is required. (Silvani, da Silva, and Guedes, 2024).

To improve soil durability, lime is effective for stabilizing clayey soils; however, it should be replaced with a more sustainable, environmentally friendly material because of its high cost and the significant greenhouse gas emissions associated with its production (Laveglia et al., 2022). The addition of fiber is common, and for that purpose, different fibers have been used in mud composites for decades (Kumar et al., 2021).

Currently, strengthening soil with bio-based or raw materials is a growing area of research in civil engineering, and for that purpose, the utilization of several fibers that are considered waste is incorporated into the soil in different manners, and their effects are noted under several testing conditions. This study focused on the inclusion of bagasse, a raw material from sugarcane, and OPC, a product used in the construction industry. The properties tested in this study are shear modulus (G) and damping ratio (D) under a loading frequency that matches the real conditions of machine vibrations and pulsations generated through the movement of reciprocating machines like diesel and gas engines, compressors, etc., along with their effects on maximum dry density through compaction tests.

Bagasse fibers are inexpensive, low-density, and eco-friendly materials. They share mechanical and physical characteristics with other natural fibers, such as jute, sisal, pineapple, and coir fiber. It has several potential applications in the construction industry as a reinforcing component to support the subgrade beneath pavements (Dang, Khabbaz, and Fatahi, 2017). Previous studies (Dang and

Khabbaz, 2018; Dang et al., 2017; Danso, D Brett Martinson, et al., 2015; Moin and Qasim, 2023; Ouedraogo et al., 2023; Salih, Osofero, and Imbabi, 2020; Tello et al., 2022) found bagasse-reinforced soil effective under the testing conditions of density, absorption, thermal conductivity, California bearing ratio, flexural, and unconfined compressive strength but the response under dynamic loading is not adequately addressed (Zachariah and Jakka, 2025).

As compared to bagasse, cement is an admixture that acts as a binder in soil; this material reacts with water and forms hardened material that can bear heavy loads and resist environmental conditions (Okonkwo and Kennedy, 2023). Several studies revealed that cement can provide good strength to the soil and improve its bearing capacity, UCS, elastic modulus, and other mechanical properties (Ali, 2019; Hartono, Prabandiyani Retno Wardani, and Setyo Muntohar, 2018; Liu et al., 2022; Pongsivasathit, Horpibulsuk, and Piyaphipat, 2019; Shi et al., 2023). These studies also suggested using the quantity of cement in the range of 1 to 10% to stabilize the soil. The compound $\text{Ca}(\text{OH})_2$ is generated in the chemical reaction of cement and water, and during hydration, it contributes to the pozzolanic reaction. Hydration also leads to stiffness, hardening, and setting (Han, 2015).

M. M. Shalchian and M. Arabani (2023) provided details on fiber reinforcement in soil and concluded that compressive, shear (cohesion and friction), and tensile strength can be enhanced by 20–60% with cellulosic fibers; ductility, stiffness, toughness, and elastic modulus can also increase. Fibers can also reduce crack propagation, settlement, radial deformation, shrinkage, and swelling more than animal-based and mineral fibers because cellulose in plant-based fibers relates to mechanical strength, which is linked to the compressive strength, bearing capacity, shear, and tensile strength of fiber-reinforced systems.

In machine foundations, dynamic motion typically produces low amplitudes of movement, leading to relatively small soil strains, often less than $10^{-3}\%$. However, when a foundation experiences torsional loading, predicting its response can be challenging due to slippage

effects. This condition reduces stiffness and increases oscillations. Confining pressure plays an important role in controlling this phenomenon. If a backfill lags a stiff surface, the surface often leads to soil separation and significantly reduces effectiveness, so avoiding this high confining pressure is recommended. (ACI Committee 351, 2004)

As far as dynamic parameters are concerned, density plays an important role; shear modulus is mainly dependent on three factors: (1) confining pressure, (2) amplitude strains, and (3) density (Ishihara, 1996; Mog and Anbazhagan, 2022).

The existing literature highlights a significant research gap. Most prior studies have focused primarily on soil stabilization techniques under static loading, with limited exploration into dynamic load responses. Current research mainly examines the dynamic properties such as shear modulus and damping ratio under parameters like low frequencies, strain amplitudes, and confining pressures. Notably, the influence of consistent or repeated loading, which better simulates real-world scenarios, remains largely underexplored. This study addresses this gap by examining ground improvement techniques using locally available materials, focusing on the soil's response under controlled combined loading conditions. The findings aim to contribute novel insights into soil behavior under realistic loading environments, offering both regional relevance and broader applicability to geotechnical practices in similar soil contexts globally.

The scope of this study is to provide a comparison of the effects of reinforced soil and cemented soil under machine vibrations. This study is not limited to investigating the effects of RA and OPC on shear modulus and damping ratio. It also examines the coupling effect of these two characteristics on peak amplitude strains. The optimum content obtained from RA and OPC was further observed for damping characteristics under free vibration decay (FVD).

This study is limited to machine vibration and soil conditions as specified in Table 1 and Table 4. The actual field conditions are considerably more complex, with confining stress, loading frequency, cyclic stress amplitude, degree of saturation, and environmental conditions varying with depth and service environment.

2. MATERIALS AND METHOD

This study is centered in Pakistan. The soil and modifiers used in this investigation were procured from local vendors. The soil was sourced from Nooriabad, situated near the Indus Delta, as that area is rich in clayey soil patches, while bagasse and cement were purchased from local vendors. The materials are shown in Figure 1. The properties of the materials are mentioned in Table 1, Table 2, and Table 3.

The dynamic soil properties of remolded soil specimens were assessed in this work using combined resonant column and torsional shear (RCTS) equipment mentioned in Figure 2 under sinusoidal loading conditions (Unconsolidated Undrained tests)

The working principle of the resonant column is based on applied strain and frequency. The soil specimen has a fixed bottom pedestal that is free at the top and fixed at the bottom. Since the top of the specimen is not constrained, it can be excited with torsional vibrations using four magnets attached to the top cap at its free end (Darendeli, 2001; Lang, Li, and Chen, 2020). The testing follows the ASTM standard D 4015.

The calculation of shear modulus is based on the density and shear wave velocity (V_s); the shear wave velocity depends on the resonant frequency, which can be noted during excitation. At the same time, the damping is based on the cutoff frequencies at amplitudes of $0.707f_r$.

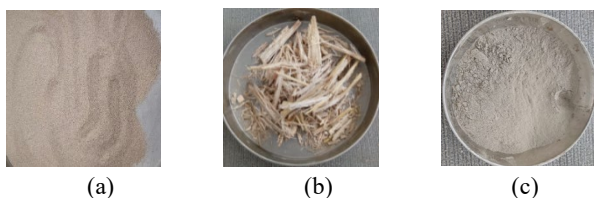


Figure 1 (a) base material (b) Bagasse (c) Cement

Table 1 Properties of selected soil

Properties	Value
Maximum dry unit weight	16.41 kN/m ³
Optimum Moisture Content	16.9%
Sand	3.08%
Silt	47.48 %
Clay	38.83 %
Colloids	10.61 %
USCS Classification	CL-ML
Liquid limit	27%
Plastic limit	19.3%
Plasticity Index	7.7
Specific Gravity	2.60

Table 2 Basic properties of Bagasse fiber used in this study

Properties	Value
Average diameter (D)	1.8 mm
Average length (L)	15 mm
Specific gravity (G)	0.326
Water absorption ratio (WAR)	815% (after 24 hours)
Tensile strength	43.29 MPa

Table 3 Chemical composition and compressive strength of Cement

Cement Sample	
Appearance	Grey fine powder
Specific Gravity	3.15
CaO	63.03%
SiO ₂	20.75%
Al ₂ O ₃	4.75%
Fe ₂ O ₃	3.78%
MgO	1.46%
SO ₃	2.45%
C ₃ S	54.6%
C ₂ S	18.3%
C ₄ AF	11.49%
LOI	2.68%
Compressive strength (3 days)	33.59 N/mm ²

2.1 Sample preparation

Past studies indicate that, when preparing samples with reinforcing agents, the amount of water added was equivalent to the optimum moisture content of untreated soil (Meng, Zhao, and Yang, 2020; Phan and Pham, 2018; Vincenzini, Augarde, and Gioffrè, 2021). To avoid moisture depletion, Danso et al. (2015) suggested using damp plant-based fiber in the soil matrix.



Figure 2 Resonant column loading cell

Moin and Qasim (2023) observed the OMC after each addition of damp bagasse fiber and used a similar OMC to prepare the samples. At first, a dry soil mass of 500 g was used to prepare the sample of standard size, 50 mm diameter and 100 mm height; then fibers were weighed at 0.2%, 0.4%, 0.6%, 0.8% and 1% of dry soil mass. Before mixing, the fibers were soaked in water for 24 hours to achieve maximum saturation and subsequently air-dried to reach a damp condition. This pre-treatment minimized water absorption by the fibers during sample preparation and prevented reductions in optimum moisture content and dry density. The damp fibers were then thoroughly mixed with the soil at the OMC of the specified additive content to obtain a homogeneous mixture. Remolded specimens were prepared in a split mold by using the moist tamping technique.

A similar preparation technique was applied for the cemented samples. The OMC was identified for each additive content, and the samples were prepared accordingly.

Prepared samples were wrapped in plastic, cured for 7 days in a desiccator, and dried at room temperature for 2 days. 2 samples were prepared for each proportion.

The prepared samples are shown in Figure 3 and Figure 4.

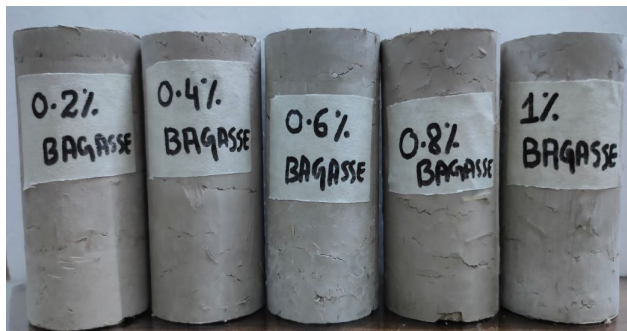


Figure 3 Prepared samples of Reinforced soil



Figure 4 Prepared sample of Cemented soil

2.2 Research design

The testing parameters decided for each loading scenario are listed and mentioned in Table 4. First, the sample behavior is observed under forced vibration scenarios, and then the optimum sample will be considered for testing in free vibration decay.

Table 4 Research Design with details

Research Design	
Applied frequency	30 Hz (Ishihara, 1996; Prasad, 2014)
Confining pressure	500 kPa (Hosseini, 2014)
Amplitude strains	0.0001% (Prasad, 2014)
No. of cycles under Sweep and FVD tests	20
% of Reinforcing agents	0.2, 0.4, 0.6, 0.8 and 1.0%
% of Ordinary Portland Cement	2, 4, 6, 8 and 10%
Dynamic properties tested in sweep test	Shear Modulus (G), Damping ratio (D), and peak amplitude strain (γ)
Strain range applied on optimal content in FVD to determine the damping effect	0.0001 to 0.001%

3. RESULTS AND DISCUSSION

3.1 Effect on maximum dry density and optimum moisture content

Figure 5 represents the compaction results of cemented soil with the comparison of untreated soil; it has been noted that cement increased the density of soil by 17.6%, and it also increased the optimum moisture content due to the hydration process for strengthening. The minimal increment was attributed to particle packing (Ali, 2019). Mixture particles tend to absorb water, while finer content improves particle packing, which increases maximum dry density. (Mollamahmutoglu and Avcı, 2018; Yousefi, Jahanian, and Azadi, 2020)

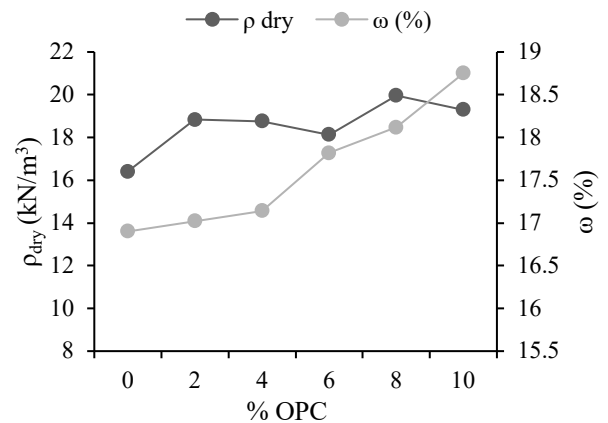


Figure 5 Effect on density and optimum moisture content on addition of OPC

On the other hand, it is noted that the presence of lightweight material in soil decreases its density. A slight increment of 4.7% was observed on the addition of 0.6% fibers to the same soil; the results of adding bagasse fiber and its effect on density and moisture content were reported previously by Moin and Qasim (2023). Similar trends have been observed in past studies (Bawadi et al., 2020; Meng et al., 2020; Soundara and Kumar, 2015; Wu, Li, and Niu, 2014). The small increase in fiber content is due to the additional mass introduced into the soil, but adding more will decrease the soil mass and ultimately affect the density of the reinforced soil matrix.

3.2 Effect of additives on shear modulus of soil

The shear modulus of untreated soil was 8.64 MPa, and the maximum value was 12.581 MPa, which was 46% higher than that of untreated soil. It was noted that the addition of 0.6% bagasse, while cement

increased it up to 11.69 MPa with the addition of 8%, as mentioned in Figure 6. These results align with the previous study by Wu et al. (2023) for untreated soils.

The development of cementitious hydration products, primarily calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), enhances interparticle bonding and contact rigidity within the soil matrix. This improved soil structure restricts particle movement during cyclic loading and increases resistance to shear deformation, increasing the shear modulus from 8.64 MPa to 11.69 MPa.

Randomly distributed bagasse fibers function as reinforcing bridges between soil particles, limiting their relative movement and developing tensile resistance under cyclic shear loading. This interaction between the fibers and the surrounding soil improves stress transfer throughout the soil matrix, thereby increasing its resistance to shear deformation and resulting in a higher shear modulus. At higher fiber content, there is a risk of clogging in the soil-fiber matrix (Chen et al., 2015; Alcan and Çelik, 2023; Zafar et al., 2023).

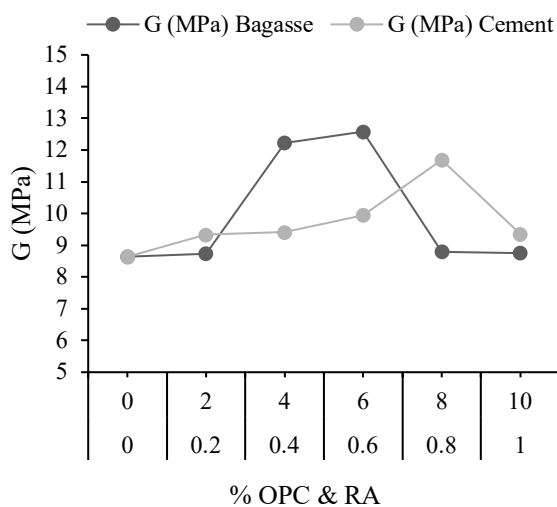


Figure 6 Effect of additives on shear modulus

3.3 Effect of additives on damping ratio of soil

Figure 7 shows that the damping ratio was enhanced by 10% with the addition of fibrous material, while cement reduced it by 8%. The damping increased because fiber enhanced resilience against crack

propagation. Fibers can tie soil cracks, dissipating additional energy during loading cycles. With the addition of cement, calcium silicate hydrate and alumina silicate hydrate produced rigid bonding and transformed the soil into a stiffer matrix, simultaneously limiting the vibration-absorption mechanism. The results reported in Figure 7 follow the same trend observed by Zhao et al. (2021), Reehana et al. (2023), and Amir-Faryar and Aggour (2016).

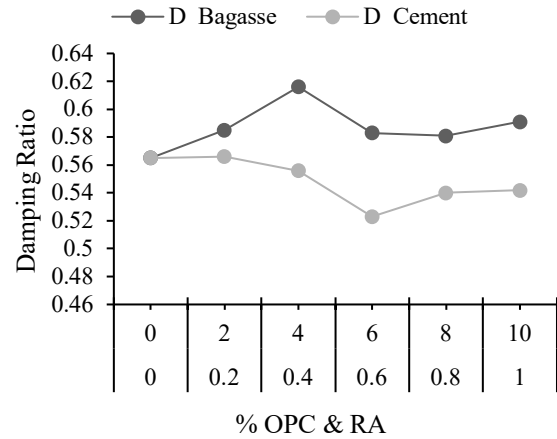


Figure 7 Effect of additives on the damping ratio of soil

3.4 Coupling effect of dynamic characteristics on peak amplitude strains and selection of optimal content

Table 5 and Figure 8 show that both additives helped lower the strains. The increase in shear modulus provides stiffness in the soil and lowers the risk of deformation, while a high damping ratio helps in dissipating the energy; if one is going to decrease, then it provides support to other characteristics.

Cemented soil showed the maximum G with the addition of 8%; this addition increased the shear modulus by 35.3%. It reduced the amplification by 12%, and the value of the damping ratio decreased with the addition of cement. Moreover, reinforced soil showed a 42% increase in G and a 10% increase in D, and it positively affected amplification by 14%.

Diaz-Rodriguez and Lopez-Molina (2008) provided details about the strain threshold limits in clayey soils, and it has been noted that for most of the clayey soils, the threshold strains are in the range of 1×10^{-5} to 5×10^{-5} under the small strain regime.

Table 5 Summary of the test results under sweep testing conditions

% RA	% OPC	Bagasse			Cement		
		G (MPa)	D (%)	γ	G (MPa)	D (%)	γ
0	0	8.64	0.565	3.89e-05	8.64	0.565	3.89e-05
0.2	2	8.74	0.585	3.43e-05	9.336	0.566	3.70e-05
0.4	4	12.23	0.616	3.41e-05	9.417	0.556	3.72e-05
0.6	6	12.581	0.583	3.45e-05	9.949	0.523	4.05e-05
0.8	8	8.8	0.581	3.64e-05	11.69	0.540	3.47e-05
1	10	8.76	0.591	3.40e-05	9.356	0.542	3.98e-05

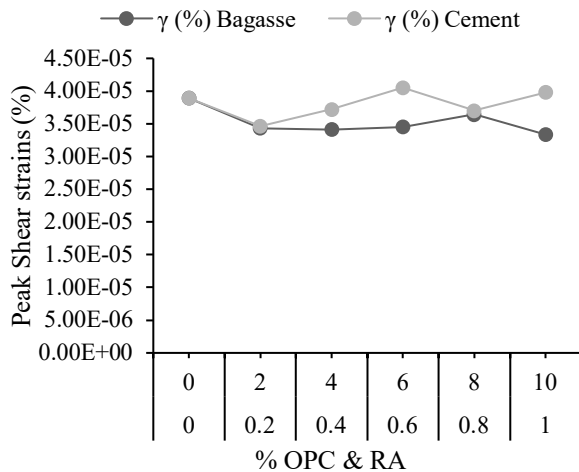


Figure 8 Effect of additives on peak amplitude strains

3.5 Response of optimal content under free vibration decay (FVD)

From the above testing, it has been determined that adding 0.4% bagasse and 8% cement reduced the amplification and provided strength to the soil, so the free vibration decay tests were conducted on a small strain range (0.0001 to 0.001%) (Diaz-Rodriguez and Lopez-Molina, 2008). The damping ratio increased with strain; cemented soil and reinforced soils both increased the soil damping ratio. These results for cemented soil align with the findings of Lang et al. (2020), which observed that energy dissipation depends on wave propagation in soil; weakly cemented samples show greater energy loss than hardened, stiff material. This behavior is also observed in the results mentioned in Figure 9.

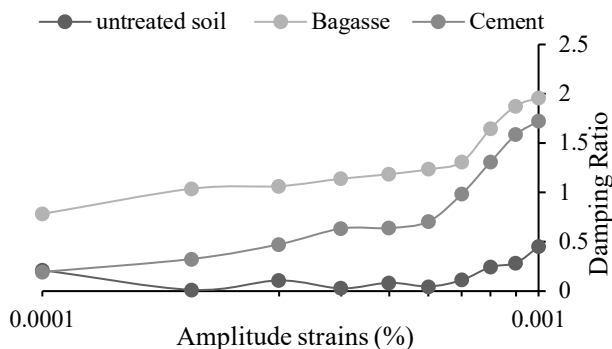


Figure 9 Change in Damping ratio with increment in amplitude strains

4. CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions of this study, together with practical recommendations for engineering applications, are summarized as follows:

1. When bagasse is mixed with clay soil at an optimal rate (0.4% by dry soil mass), it can increase the shear modulus of the soil, as a high amount of increment in fiber can lead to a poor soil matrix. Hence, mixing fiber under optimal conditions is significant, as it increases both characteristics and reduces the peak strain amplitude under the designed loading condition.
2. The addition of cement leads to an increase in the stiffness of soil due to its binding properties, but it reduces the damping characteristics of soil. Although the maximum increment in shear modulus was observed with the addition of 8% of dry soil mass, and the minimum peak amplitude strain was identified with the addition of 2% of dry soil mass,

where a minor increment was observed in the values of damping ratio and shear modulus. The difference in the recorded peak amplitude strain is 6.5%.

3. The damping ratio and strain relationship formed with the free vibration decay mode illustrated that reinforced soil D increased with an increase in strain as compared to cemented soils and untreated soils.
4. Although both stabilizers reduced the strain amplification, bagasse fibers exhibited superior vibration diminution owing to their flexible reinforcing mechanism and enhanced energy dissipation through fiber–soil interaction, which is why they are recommended for vibration-sensitive geotechnical structures like machine foundations, pavement subgrades, and other similar cyclic loading structures.
5. Under the investigated confining pressure and loading frequency, the optimum bagasse content improved the shear modulus and damping characteristics of the soil, suggesting its suitability under comparable loading conditions. Likewise, cement stabilization increased soil stiffness, indicating its applicability where enhanced stiffness is required under similar testing conditions.
6. The measured improvements in shear modulus and damping ratio should be interpreted within the adopted experimental conditions and should not be directly extrapolated to all field situations. Further investigations covering a wider range of confining pressures, frequencies, and environmental conditions are recommended to establish more comprehensive design guidelines.

5. ACKNOWLEDGMENTS

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6. DECLARATION OF INTEREST

The authors declare no conflict of interest.

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