Shear behavior of treated soil by rice husk ash and cement

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Abstract: Based on recent research, rice husk ash (RHA) is used as a secondary cementitious material for soil stabilization. The present study attempted to investigate the shear behavior of soil mixtures with RHA and a nominal cement dose. Triaxial compression and scanning electron microscopy tests were performed on specimens after moisture-curing for 1-day. The test results showed that all the soil-RHA-cement samples reached the maximum deviatoric stress value at 2%-3% axial strain, compared to 2.5%-5.5% for the untreated soil. Soil with 5% RHA and 0.6% cement admixture achieved the highest strength (677.5 kPa) under the confining pressure 150 kPa and the best microstructural improvement. It can be recommended as the optimum amount for practical purposes during designing and constructing different agricultural infrastructures.

Keywords: rice husk ash, nominal dosage cement, deviatoric stress and axial strain relationship, shear strength; cohesion, friction angle

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1 Introduction

Rice husk ash (RHA) is an agricultural waste abundantly obtainable in many rice-producing countries globally (Pode, 2016). The uncontrolled disposal of rice husk wastes in open places, roadsides, and riversides can create environmental pollution leading to public health problems due to local air pollution (Kumar et al., 2016). RHA has the highest amorphous silica (80%-95%) among all agro-wastes (Thomas, 2018). It can substitute cement as a secondary cementitious material in ground improvement to improve soil strength properties and reduce project cost, waste disposal, and environmental contamination (Xu et al., 2012). Using soil with RHA on its own does not give sufficient strength and stability to the soil due to the low pozzolanic substance (Choobbasti et al., 2019). Primarily, cement or lime additives are used with RHA for soil stabilization (Basha et al., 2005). Cement is widely used with many soil types, but lime is appropriate for clay soil (Hossain, 1986). After mixing soil with RHA, cement, and optimum water, calcium hydroxide is produced in the first step of the chemical reaction. Calcium silicate hydrate (CSH) and calcium aluminate hydrates (CAH) gels are formed in the second phase of the reaction, which creates bonding within soil particles, thus improving the soil's strength (Singh, 2018).

Many researchers have used RHA contents ranging between 5%-15% dry weight of soil mixed with cement percentage ranging between 2%-10% dry weight of soil or more to improve soil properties

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(Basha et al., 2005; Hossain, 1986; Rahman, 1987; Ali et al., 1992; Alhassan and Mustapha, 2007; Ahmad et al., 2018; Nguyen and Nu, 2020). Hossain and Sakai (2008) mixed less than 1% cement with clayey soil to improve soil strength, but the attained strength properties are not adequate for ground improvement by adding only cement. Several studies have been performed on RHA-cement stabilized soil, but very little or no work has been conducted to examine the effects of using RHA with minimal cement dosage. Technical and analytical study of soil treated with RHA and minimal dosages of cement provides excellent benefits for building eco-friendly structures, e.g., roads, dams, paddy field ridges, and other agricultural construction. Therefore, the present study presents the effectiveness of RHA with the nominal dosage of cement in developing the shear strength and microstructure of the treated soil. After one day of moist curing, all specimens were assessed by a consolidated drained (CD) triaxial test. The stress-strain relationship, shear strength, failure pattern, and microstructure development of soil mix with 5%, 10%, 15% of RHA, and 0.2%, 0.4%, and 0.6% cement are described in the study.

2 Materials and methods

2.1 Materials

Soil, as-obtained RHA, and ordinary Portland cement (OPC) were used in this study. The soil sample was collected from the Handa Area of Tsu City in Mie, and the readymade RHA was ordered from the Make Integrated Technology (M.I.T.) company of Osaka City in Japan. The significant properties of soil and RHA are presented in Table 1. The soil sample was silty sand texturally. The specific gravity of soil (2.70 g cm^{-3}) is higher than RHA (1.47 g cm^{-3}). The maximum dry density of soil was 1.696 g cm$^{-3,}$ and the optimum moisture content of the soil was 17.50%. The particle size distribution curves of soil and RHA is available in another study (Nahar et al., 2021). The particle size distribution curve of the soil specified that the soil was well-graded. About 86.97% of RHA particles passed through a 0.25 mm sieve, indicating an enormous number of fine particles in the RHA sample (Nahar et al., 2021). The OPC (Type I) was purchased from the market in Japan. The specific gravity of OPC is 3.15 g cm^{-3}. The OPC Type I comprises 62.7% lime, 21.7% silica, 5% alumina, 2.9% magnesia, etc. (Lee et al., 2014).

Table 1 Major properties of soil

Basic properties of soil		Basic properties of RHA	
Parameters	Values	Parameters	Values
Sand (75 μm - 2 mm)	87.9%	Burning temperature	650°C-700°C
Silt (5 - 75 μm)	8.9%	Burning time	27 hours
Clay < 5 μm	3.2%	Average particle size	0.001-0.3 mm
Specific gravity	2.70 g cm^{-3}	Specific gravity	1.47 g cm^{-3}
Liquid Limit, LL	37.5%	Silica (SiO_2)	91.10%
Plastic Limit, PL	29.7%	Alumina (Al_2O_3)	0.03%
Plasticity Index, PI	7.8%	Lime (CaO)	0.57%
USCS classification	SM	Magnesia (MgO)	0.16%
AASHTO classification	A-2-4	Carbon dioxide (CO_2)	4.35%

2.2 Preparation of the specimens

As a part of soil sample preparation, the soil was air-dried at 25°C temperature in a room and sieved to eliminate the undesirable leaves and roots from the soil. In this investigation, 10 combinations of soil-RHA-cement were made from the mixing proportions of soil with 0%, 5%, 10%, 15% RHA, and 0%, 0.2%, 0.4%, and 0.6% cement. Before adding water content to the soil-RHA-cement mixtures, about 2% water was reduced from optimum moisture content (OMC) to ensure better cement hydration (Table 2). The necessary amount of soil, RHA, and cement was gently mixed manually for 10 to 15 minutes in a large tray. All triaxial specimens were moist cured and reserved in a desiccator for 1-day.

Table 2 Mix types and mix proportions of soil, RHA, and cement in the mixtures

Sl. no.	Mix types	OMC	Index
1	Untreated soil	17.5	Control
2	Soil + 5% RHA + 0.2% Cement	21.0	S+5R+0.2C
3	Soil + 5% RHA + 0.4% Cement	21.3	S+5R+0.4C
4	Soil + 5% RHA + 0.6% Cement	21.5	S+5R+0.6C
5	Soil + 10% RHA + 0.2% Cement	25.1	S+10R+0.2C
6	Soil + 10% RHA + 0.4% Cement	25.3	S+10R+0.4C
7	Soil + 10% RHA + 0.6% Cement	25.5	S+10R+0.6C
8	Soil + 15% RHA + 0.2% Cement	28.8	S+15R+0.2C
9	Soil + 15% RHA + 0.4% Cement	29.0	S+15R+0.4C
10	Soil + 15% RHA + 0.6% Cement	29.2	S+15R+0.6C

Note: OMC denotes Optimum moisture content

2.3 Experimental method

The consolidated drained (CD) triaxial compression tests were performed for this investigation. The test is one of the most consistent techniques for determining soil shear strength (Rachmawati et al., 2020). The tests were performed following the Japanese Geotechnical Society (JGS 0520-0524, 2010) at the Experimental Station on Engineering Materials of Mie University in Japan. The schematic diagram of the triaxial cell is presented in Figure 1. The triaxial test specimens were prepared by manually compacting soil-RHA-cement admixtures in a mold, with a height and diameter of 12.5 cm and 5.0 cm, respectively, using a hand-rammer with a 4.9 cm diameter, a mass of 1.0 kg, and a falling height of 30 cm. Three specimens' layers were compacted, each receiving 20 blows. The consolidated drained tests were demonstrated under three confining pressures (50, 100 and 150 kPa).

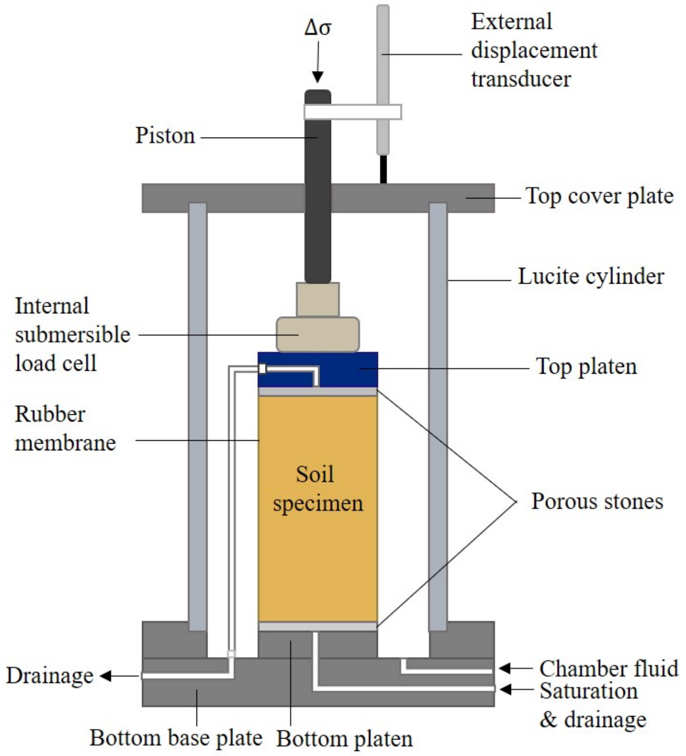


Figure 1 Schematic diagram of the triaxial cell

Both graphical and mathematical techniques were used to compute the cohesion (c) and angle of internal friction (φ) of triaxial test data. For the graphical technique, the Mohr-Coulomb failure criterion was used, in which specimens fail due to a critical combination of normal stress (σ_f) and shear stress (τ_f) The failure envelope line's equation is as follows:

$$\tau_{\mathrm{f}} = c + \sigma_f \tan\varphi \tag{1}$$

where, τ_f is the shear stress in kPa, and σ_f is the normal stress in kPa on the failure plane. The cohesion (c) in kPa and angle of internal friction (φ) in degree (°) were calculated using the following equation:

$$\sigma_a = \sigma_r \tan^2(45+\varphi/2) + 2c\tan(45+\varphi/2) \tag{2}$$

where, σ_a is the major stress, and σ_r the minor effective principal stress.

From compacted triaxial test specimens, SEM test specimens of soil-RHA-cement mix types were collected to detect the microstructure development and alterations of the particles in the specimens. All SEM images were taken at 1000-fold magnification and on a scale of 30 µm.

3 Results and discussions

3.1 Deviatoric stress and axial strain relationships of soil-RHA-cement combinations

The relationship between deviatoric stress and axial strain curves of control specimen and soil with 5%, 10%, 15% RHA, and 0.2%, 0.4%, 0.6% cement mix types are shown in Figures 2-3. It was observed that the behavior of the specimens was significantly affected by the addition of RHA and cement percentage. All specimens' deviatoric stress and axial strain curves showed that peak strength and brittleness behavior changed due to separate or combined effects of RHA and cement percentages. All the soil-RHA-cement specimens achieved peak value at 2%-3% axial strain except for the control specimen (Figure 3). The axial strains for all specimens decreased compared to untreated soil due to the addition of cement and RHA content (Rachmawati et al., 2020).

The ultimate deviatoric stress increased with the increment of cement content for the same amount of RHA (Figure 3). All soil-RHA-cement specimens achieved the highest deviatoric stress under the confining pressure of 150 kPa. However, the maximum deviatoric stress also diminished for all soil-RHA-cement combination types compared to the control specimen (Figure 2) except the S+5R+0.6C specimen (Figure 3c). Perhaps below 0.6% cement and more than 5%, RHA could not improve the soil's shear strength. The soil's surplus RHA (10% and 15%) and a low cement dosage (0.2% and 0.4%) prohibited cement hydration due to water absorption by the microporous RHA.

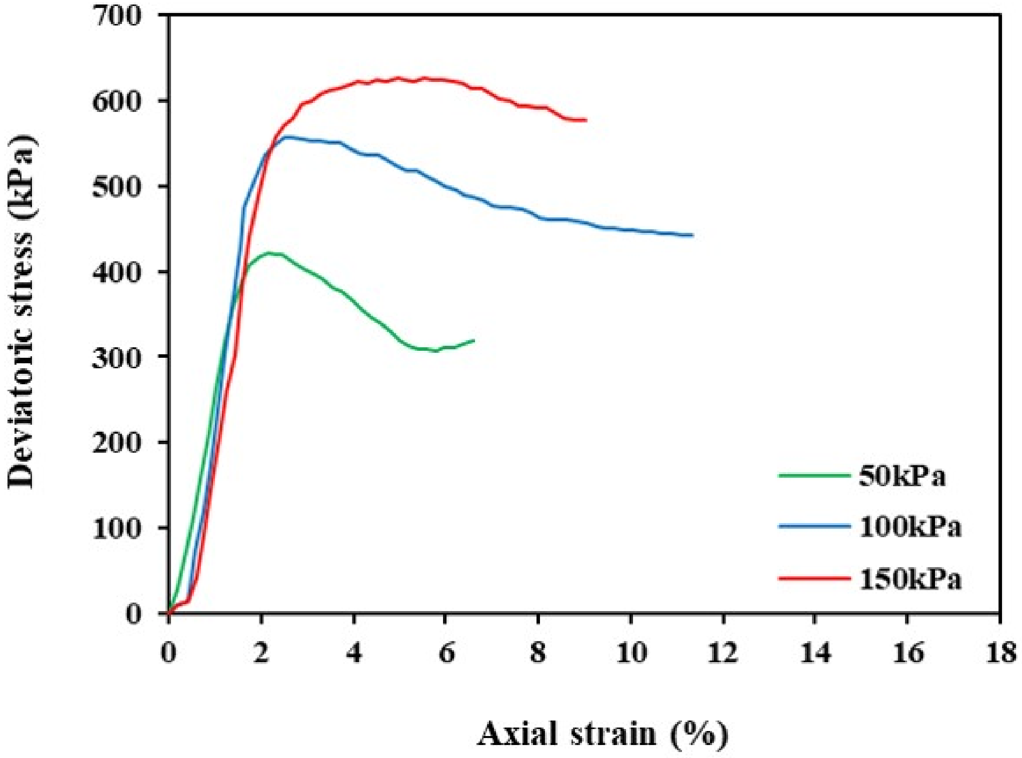
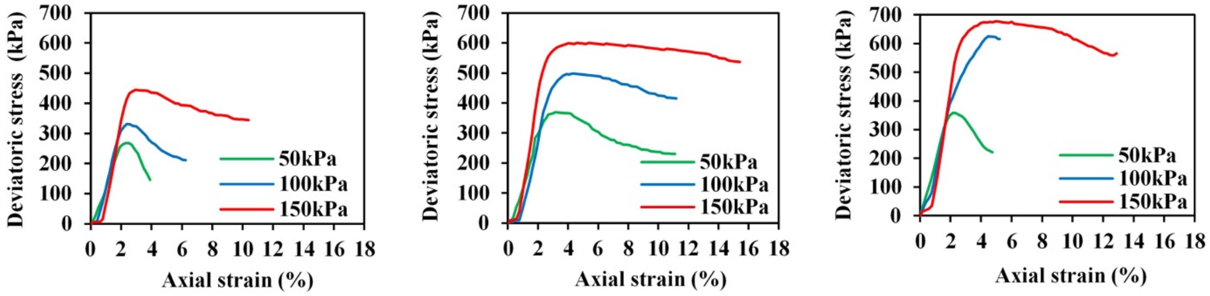
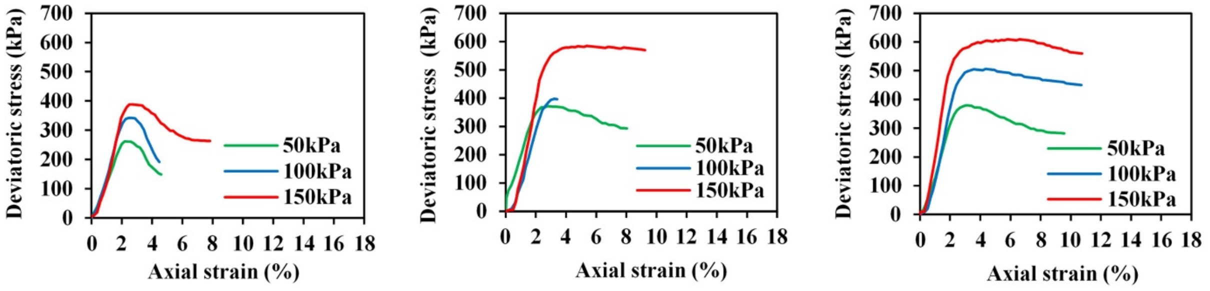


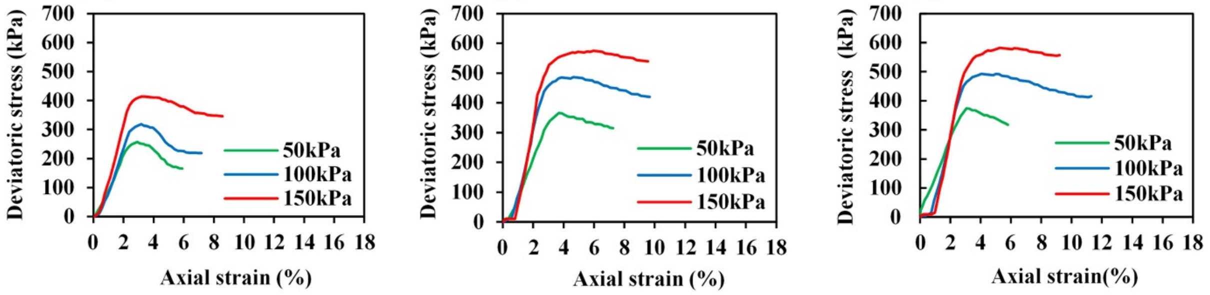
Figure 2 The deviatoric stress and axial strain relationship curves of the control specimen



(a) S+5R+0.2C (b) S+5R+0.4C (c) S+5R+0.6C



(d) S+10R+0.2C (e) S+10R+0.4C (f) S+10R+0.6C



(g) S+15R+0.2C (h) S+15R+0.4C (i) S+15R+0.6C

Figure 3 The deviatoric stress and axial strain relationship curves of various soil-RHA-cement combination types

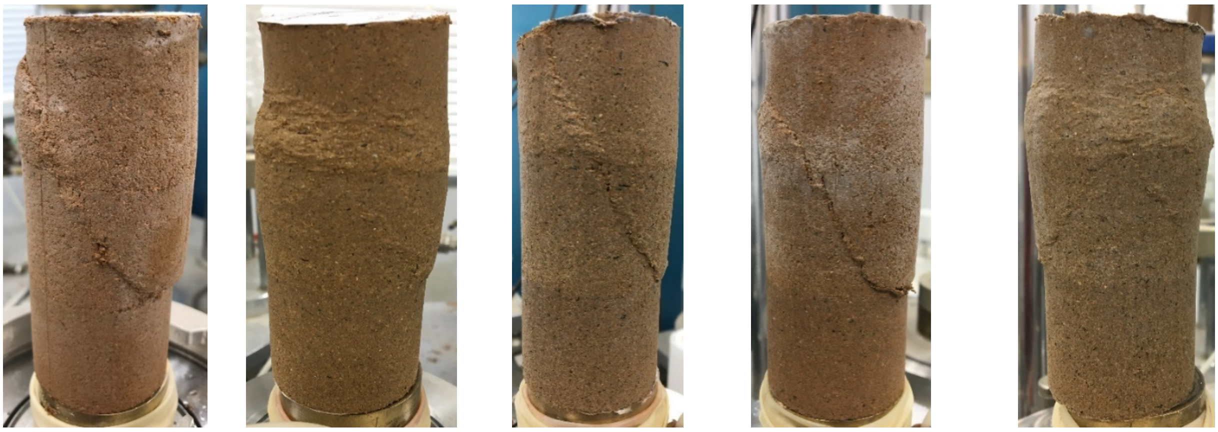
3 Shear strength of soil-RHA-cement combinations

The cohesion and angle of internal friction are the essential shear strength parameters. Using the maximum deviatoric stresses under the confining pressures 50kPa, 100kPa, and 150 kPa for all soil-RHA-cement specimens, the cohesion, and angle of internal friction were calculated. The maximum deviatoric stresses of all soil with RHA and cement combination types are represented in Table 3. Figure 4 exhibits the failure patterns of the various soil-RHA-cement combination types under 150 kPa confining pressure during consolidated drained triaxial compression tests. The untreated soil (control specimen) showed a simple shear failure after reaching the highest deviatoric stress of 625.9 kPa. The S+5R+0.4C, S+5R+0.6C, and S+10R+0.6C specimens also displayed a simple shear failure after attaining deviatoric stress of 600.5, 677.5, and 609.5 kPa, correspondingly (Table 3). The failure modes of the S+5R+0.2C, S+10R+0.2C, S+10R+0.4C, S+15R+0.2C, S+15R+0.4C, S+15R+0.6C specimens were mainly barreling with shear and single cone for some cases. The maximum deviatoric stresses for these specimens were below 600 kPa (Table 3) due to the low cement content (Amini and Hamidi, 2014) and the excess amount of RHA.

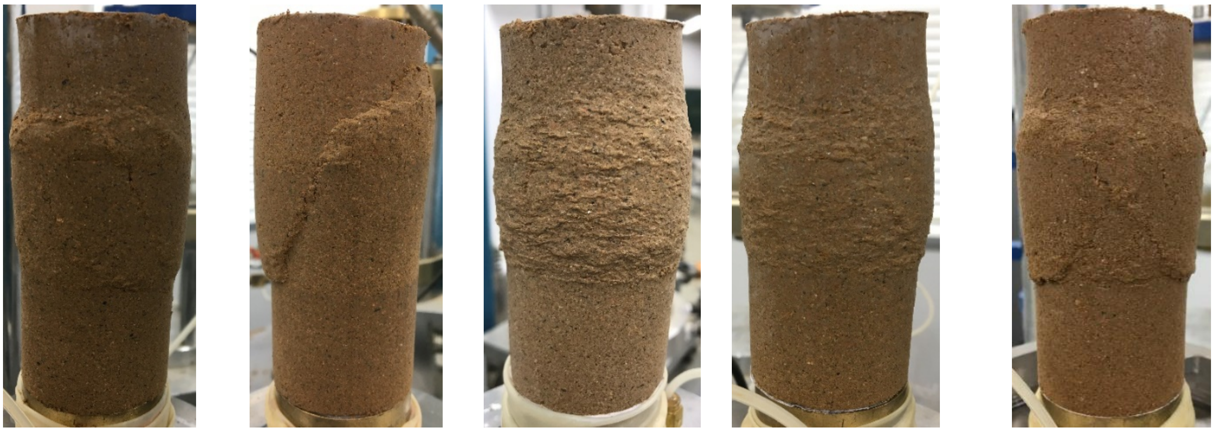
Table 3 Ultimate deviatoric stress of various soil-RHA-cement specimens

Mix types	Confining pressure		
	50 kPa	100 kPa	150 kPa
Control	420.8	556.9	625.9
S+5R+0.2C	267.8	330.5	444.5
S+5R+0.4C	368.9	498.5	600.5
S+5R+0.6C	357.7	625.2	677.5

Mix types	Confining pressure		
	50 kPa	100 kPa	150 kPa
S+10R+0.2C	261.9	342.5	388.5
S+10R+0.4C	371.4	397.3	584.7
S+10R+0.6C	379.5	505.7	609.5
S+15R+0.2C	257.0	318.4	414.4
S+15R+0.4C	365.5	486.1	574.9
S+15R+0.6C	373.7	492.2	581.7



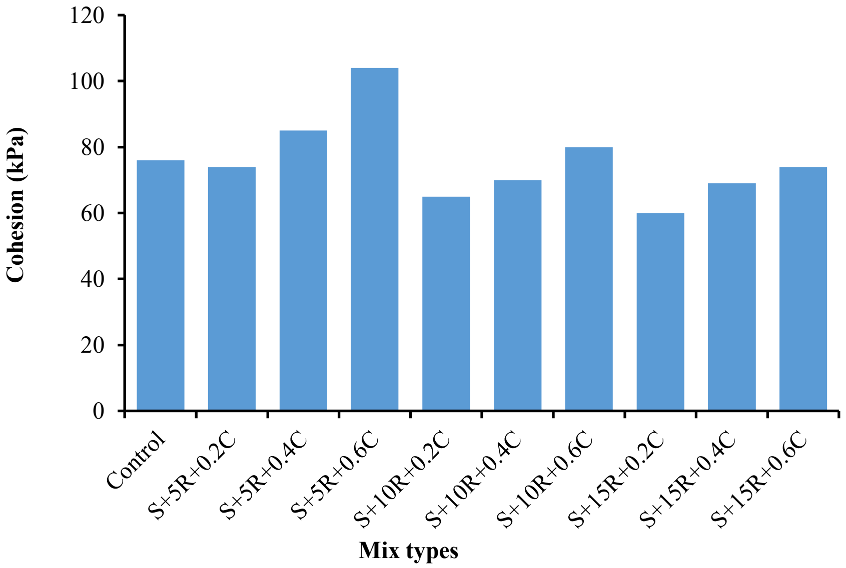
(a) Control (Simple shear) (b) S+5R+0.2C (Barreling with shear) (c) S+5R+0.4C (Simple shear) (d) S+5R+0.6C (Simple shear) (e) S+10R+0.2C (Barreling with single cone)



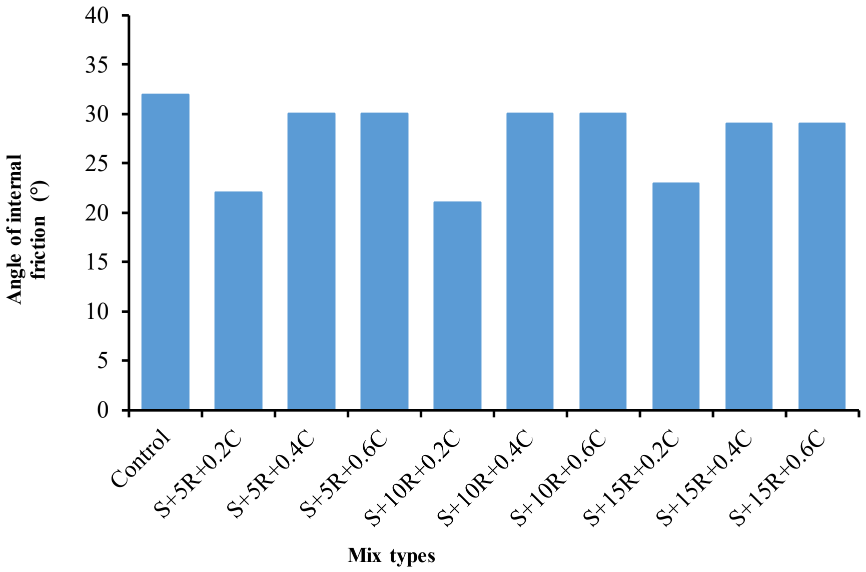
(f) S+10R+0.4C (Barreling with shear) (g) S+10R+0.6C (Simple shear) (h) S+15R+0.2C (Barreling) (i) S+15R+0.4C (Barreling with shear) (j) S+15R+0.6C (Barreling with single cone)

Figure 4 Failure modes of various soil-RHA-cement specimens under 150kPa confining pressure

Figure 5 shows the cohesion and angle of internal friction of all soil-RHA-cement mix types. The cohesion of untreated soil was 76.0 kPa. It was noticed that the cohesion was affected after adding the various ratios of RHA and cement in the soil (Figure 5a). Compared to the control specimen, an improvement in cohesion was observed for S+5R+0.4C and S+5R+0.6C samples. This improvement in cohesion can be attributed to the mechanical interlocking among the RHA and cement particles in the soil. The highest cohesion value was observed for the S+5R+0.6C specimen (104 kPa), and the percentage increase was 36.8% compared to the untreated soil. The cohesion values were reduced for the S+5R+0.2C, S+10R+0.2C, S+10R+0.4C, S+15R+0.2C, S+15R+0.4C, S+15R+0.6C specimens as the surplus amount of RHA and little amount of cement provided less mechanical linkage of the particles. This phenomenon increased the inter-particle distances among soil, RHA and cement particles. On the other hand, the internal friction angle values diminished for all soil-RHA-cement samples after adding the RHA and cement additives compared to untreated soil (32°) (Figure 5b). Perhaps, the fine particles of RHA and cement particles decreased the angle of internal friction due to the anti-synergetic action between the angle of internal friction and cohesion over time (Rachmawati et al., 2020; Hossain et al., 2006).



(a) Cohesion

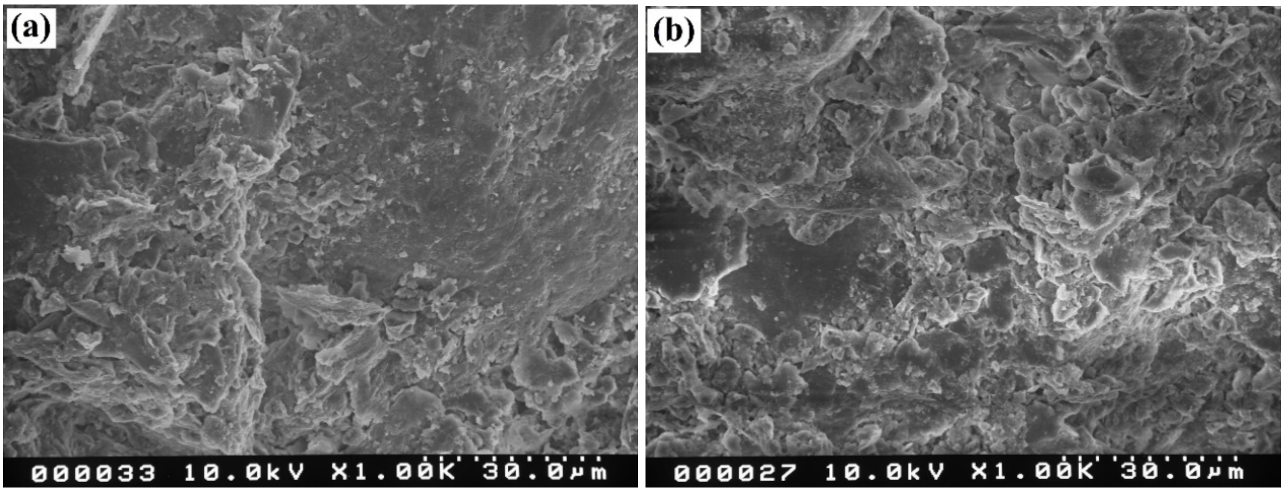


(b)Angle

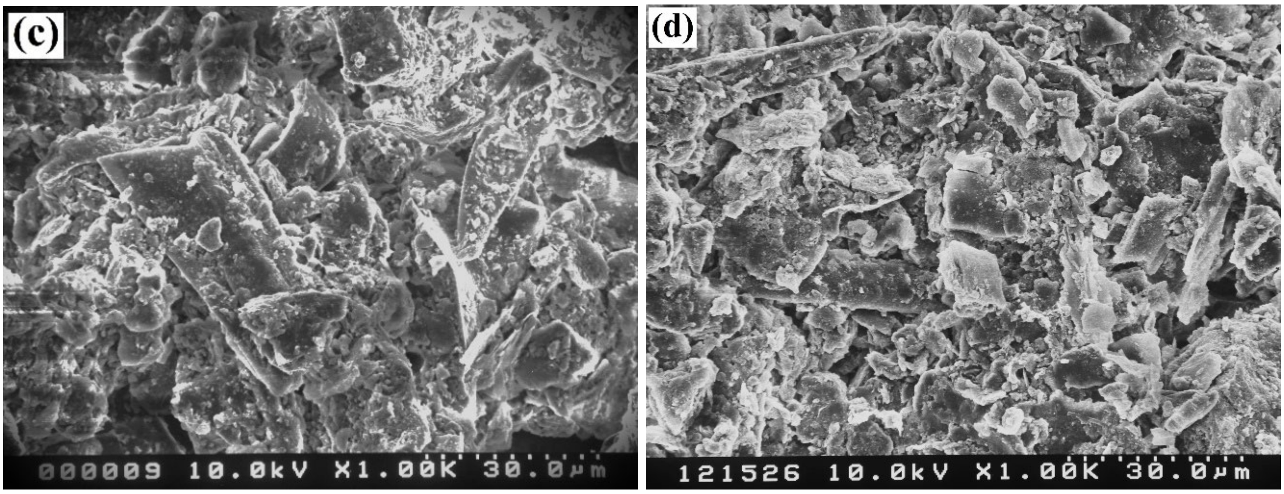
Figure 5 and of internal friction of various soil-RHA-cement combinations

3.3 Microstructural modification of triaxial test specimens

The SEM images of soil with 5%, 10%, and 15% RHA with 0.6% cement are displayed in Figure 6. It is observed from the pictures that the air voids in untreated soil were reduced after compaction (Figure 6a). Various amounts of RHA and cement altered the soil microstructure compared to untreated soil (Figures 6b-6d). Compared to the control specimen (untreated soil), the porosity of the S+5R+0.6C, S+10R+0.6C, and S+15R+0.6C specimens increased with RHA content (Figure 6). With the increment of RHA percentages for the same cement amount, the mechanical linkage of the soil, RHA, and cement decreased due to increased porosity. Simultaneously, the chemical reactions among SiO_2, Al_2O_3, and CaO were interrupted as the water was captivated by microporous RHA.



(a) untreated soil (b) S+5R+0.6C



(c) S+10R+0.6C (d) S+15R+0.6C

Figure 6 SEM images of specimens

4 Conclusions

The study investigated the shear behavior of A-2-4 type soil mixed with RHA and a nominal cement dosage, and the following conclusions can be drawn.

An improvement in shear strength was observed for the S+5R+0.6C specimen (677.5 kPa) compared to untreated soil (625.9 kPa).

The S+5R+0.6C specimen also attained the highest cohesion value (104 kPa) than the control specimen (76 kPa). The angle of internal friction for the S+5R+0.6C specimen was 30°**,** whereas the control specimen had 32°**.**

The angle of internal friction values of all combination types decreased compared to the control specimen.

The SEM image on the S+5R+0.6C combination showed the best microstructural development.

S+5R+0.6C combination can be used for some applications of ground improvement considering the curing period.

Using RHA with a nominal cement dosage, the results showed improved shear strength, cohesion, and microstructural development for the S+5R+0.6C specimen, which can be recommended for constructing rural roads, the ridge between paddy fields, and other agricultural infrastructures.

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Conflict of interest

The authors declare no competing interests, and the study has never been published or is currently being considered.

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