Effects of controlled burn rice husk ash on the geotechnical properties of soil

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Abstract

Pozzolanic reactions of rice husk ash (RHA) entirely depend on controlled burning condition. The current study illustrates the effects of controlled burn RHA on the geotechnical properties of A-2-4 soil as per the American Association of State Highway and Transportations Officials (AASHTO) classification. The compactibility, bearing capacity, compressive strength, shear strength, and scanning electron micrographs were investigated as the important geotechnical properties of soil with 0%, 5%, 10%, and 15% of RHA admixtures considering the 7-day moist curing. The test results showed that the optimum moisture content increased, but maximum dry density reduced with the increment of RHA content. Soil with 5% RHA showed the increased percentage of California bearing ratio (39.5%), unconfined compressive strength (6.0%), modulus of deformation (56.3%), cohesion (11.8%), and angle of internal friction (6.3%) compared to untreated soil specimen which indicated that the application of burnt RHA at a controlled temperature enhanced the geotechnical properties of soil. Scanning electron microscopy image on soil with 5% RHA also observed the best microstructural development, which recommends that soil with 5% RHA can be used as a construction material for rural roads and pedestrian roads.

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Introduction

Rice husk ash (RHA), a natural carbon-based agricultural by-product, contains the highest amorphous silica among all agricultural wastes (Thomas, 2018). It has pozzolanic properties with a large specific surface, reacting with soil as secondary cementitious materials in the soil stabilization process (Sarkar *et al*., 2012). It is produced from paddy rice by milling process as rice husk and then formed as ash by burning process (Pode, 2016). The paddy rice production was 782 million tons worldwide in 2018 (FAOSTAT, 2020), and about 172 million tons of rice husk and 34 million tons of RHA were produced from the paddy rice in that year (Nahar *et al*., 2021). The chemical composition, particle size, pozzolanic reactivity, and silica state in RHA entirely rely on the burning conditions, temperature, and duration (Hwang and Chandra, 1996; Singh, 2018). Silica content in RHA shows the amorphous and crystalline state with different properties (Della, 2002). Crystalline silica is produced by uncontrolled burning or open burning of rice husk at a temperature above 800°C, which are low reactive or non-reactive silica minerals (Singh, 2018). On the other hand, amorphous silica is the best for pozzolanic reaction, formed by the controlled temperature at 600°C-700°C (Hwang and Chandra, 1996). The amorphous silica of well-burnt RHA in single-phase displayed a halo pattern with a peak at around $2\theta = 22°$ by the X-ray diffraction (XRD) test (Chandrasekhar *et al*., 2003; Al-Hasnawi and Al-Hydary, 2019; Nahar *et al*., 2021).

RHA waste creates environmental and health problems because of its disposal difficulties and absence of utilization (Pode, 2016). Concurrently, suitable construction sites are deficient due to rapid urbanization and industrialization, demanding feasible ground improvement techniques for untreated soil (Murthy *et al*., 2002). The strength and durability of engineering structures are affected by the geotechnical properties of soil (Roy and Bhalla, 2017). The usage of various chemical additives is one of the effective methods for improving the geotechnical properties of soil (Adhikary and Jana, 2016). Many researchers have discovered that adequately utilizing locally obtainable RHA as a pozzolanic material in ground improvement can decrease environmental degradation and construction price and increase soil strength properties (Alhassan, 2008; Jain *et al.*, 2020). Several studies have been conducted on soil with only RHA in ground improvement. Among these investigations, only Sarkar *et al.* (2012) and Ayininuola and Olaosebikan (2013) used the controlled burn and as-obtained RHA for soil stabilization. However, Rahman *et al.* (2014) and Rathan *et al.* (2016) took the uncontrolled burn and natural RHA; Alhassan (2008), Okafor and Okonkwo (2009), and Adhikary and Jana (2016) utilized the uncontrolled burn, ground, and sieved (by No. 200) RHA, but Jain *et al*. (2020) used the pulverized and sieved RHA by No. 4 sieve for soil improvement. Grinding is essential for open burnt RHA to attain the fineness and large specific surface area of RHA that can provide the best pozzolanic reactions, but it needs extra time and costs. The cost of producing RHA at a controlled temperature is cheap since computers can manage the temperature and burning speed, reducing labor costs and efforts (MIT, 2018). There is little research investigating the performance of a single RHA as a soil additive, where RHA was produced at controlled temperature and used as a secondary cementitious material with its natural form.

The key objective of the present study is to examine the influence of controlled burn and as-obtained RHA on the geotechnical properties of A-2-4 type soil. The present investigation is essential to inspire the application of an enormous quantity of RHA as a cement substitute for constructing the different civil infrastructures, particularly in rice-producing countries. A series of laboratory tests were performed, including standard Proctor compaction tests, California bearing ratio (CBR) tests, unconfined compressive strength (UCS) tests, consolidated-drained (CD) triaxial compression tests, and scanning electron microscopy (SEM) test on soil addition with 0%, 5%, 10%, and 15% of RHA considering 7 days of moist curing. The effects of various percentages of controlled burn RHA on compactability, bearing capacity, unconfined compressive strength, shear strength, and microstructure of soil are illustrated with discussions.

Materials and methods

This investigation used SM or A-2-4 type soil and as-obtained controlled burn RHA for specimen preparation. The soil sample was collected from Handa Area, Tsu City, Mie prefecture in Japan, and readymade RHA was collected from the Make Integrated Technology (M.I.T.) company, Osaka, Japan. The major properties of soil and RHA are shown in Table 1. The particle size distribution curve of soil and RHA samples is available in other studies (Nahar *et al*., 2021). According to the United States Department of Agriculture (USDA) classification system of soil particle size, the soil sample comprises approximately 29% coarse sand (0.50-1.00 mm), 36% medium sand (0.25-0.50 mm), 19% fine sand (0.10-0.25 mm), 4% very fine sand (0.05-0.10), 9% silt (0.002-0.05 mm) and 3% clay (<0.002 mm). Texturally, the soil is silty sand. The plasticity index (PI=7.8%) indicates the less cohesiveness of soil hence low swell and low expansive potential. The rice husk ash production process was operated in a factory building of M.I.T. Company using an industrial machine device. Only methanol solid fuel was used to ignite the rice husk, then it incinerated by itself. A computer controlled the incineration. About 150 kg (15-20%) of RHA was produced from 800-1000 kg rice husk. The RHA sample contains 1% coarse (0.50-1.00 mm), 13% medium (0.25-0.50 mm), 63% fine (0.10-0.25 mm), and 6% very fine particles.

All current research experiments were performed at the Experimental Station on Engineering Materials, Faculty of Bioresources, Mie University, Japan. A series of standard Proctor compaction tests, CBR test, unconfined compression strength tests, CD triaxial compression tests were conducted according to Japanese Industrial Standards (JIS) and Japanese Geotechnical Society (JGS) (Table 2). SEM tests were also performed for the microstructural change detection of the specimens.

The combinations of soil and RHA were prepared by taking the mixing percentage of soil with 0% (control), 5%, 10%, and 15% of RHA content. Three similar specimens for each mix type were prepared and tested for performing a CBR test, UCS test, and triaxial compression test. Soil and the required amount of RHA were manually mixed thoroughly in a big bowl with plastic gloves, and then water was mixed gradually into the dry admixtures. Lower than 2% from the measured optimum moisture content (OMC) from the compaction tests was added as the required water content of the soil-RHA combinations. All prepared CBR (unsoaked condition), UCS, and triaxial and SEM test specimens were moist cured for 7 days. Each testing procedure is described below.

Standard proctor compaction test method

The Standard Proctor compaction test was performed for measuring the OMC and maximum dry density (MDD) of control and soil-RHA combinations. The specimens of soil-RHA admixtures were compressed manually in a 10 cm diameter cylindrical and 1000 cm^3 volume compaction mold with a collar and a base. The admixtures were compacted into three layers, giving 25 blows per layer using a 2.5 kg rammer through a falling height of 30 cm. Approximately 551.8 KJ/m^3 was applied as compaction energy for each specimen.

California bearing ratio test method

The soil-RHA mix types were compacted in a CBR mold with a bottom plate, spacer disc, and mold extension. The diameter and height of the CBR mold were 15 cm and 17.5 cm, respectively. The admixtures were tamped into three layers with 67 blows per layer using an automated rammer with a mass of 4.5 kg, a diameter of 5.0 cm, and a falling height of 45.0 cm.

Table 1. Properties of soil and rice husk ash used in the study.

Particles	Parameters	Values
Soil particle	Optimum water content ($W_{opt.}$)	17.50%
	Maximum dry density ($\gamma_{dry\ max}$)	1.696 g/cm^3
	Specific gravity (ρs)	2.7 g/cm^3
	Sand (75 μm - 2 mm)	88%
	Silt (5-75 μm)	9%
	Clay <5 μm	3%
	Uniformity coefficient, C_u	9.84
	Curvature coefficient, C_c	1.02
	Liquid limit, LL	37.5%
	Plastic limit, PL	29.7%
	Plasticity index, PI	7.8%
	USCS classification	SM
	AASHTO classification	A-2-4 (0)
RHA particle	Burning temperature	650°C-700°C
	Burning duration	27 hours
	Average particle size	0.001 to 0.3 mm
	Specific gravity	2.12 g/cm^3
	Silica (SiO_2)	91.10%
	Carbon dioxide (CO_2)	4.35%
	Potassium oxide (K_2O)	2.40%
	Calcium oxide (CaO)	0.57%
	Alumina (Al_2O_3)	0.03%
	Others	1.55%

USCS, Unified Soil Classification System; AASHTO, American Association of State Highway and Transportations Officials.

Table 2. Conducted laboratory tests with followed standards.

Name of the experiment	Standard followed
Test method for soil compaction using a rammer	JIS A 1210:2010
Test methods for the California bearing ratio of soils in the laboratory	JIS A 1211:2010
Method for unconfined compression test of soils	JIS A 1216:2010
Triaxial compression test of soil	JGS 0520-0524:2010

The CBR values were calculated for the penetration depth of 2.5 mm using Eq. (1).

$$\mathit{CBR\ value}\ (\%) = \frac{\mathit{Load\ strength}}{\mathit{Standard\ load\ strength}} \times 100 \qquad (1)$$

Unconfined compressive strength test method

The UCS specimens of soil-RHA combinations were compressed in the mold with a diameter of 5.0 cm and a height of 12.5 cm. Each specimen was compacted into three layers, and each layer was tamped by 20 blows using a 4.9 cm diameter rammer, which had a mass of 1.0 kg with a falling height of 30 cm. The stress-strain relationship, UCS values, and elasticity of the specimens were determined from the stress-strain curve, where the strain was plotted on the X-axis and stress on the Y-axis. In the stress-strain curve, the peak value from stress (σ) is the UCS (q_u). The deformation modulus (E_{50}) of the specimens were measured by eliminating the initial and final non-linearities of the stress-strain curve, and it was calculated from the following equation:

$$E_{50} = \frac{\frac{q_u}{2}}{\varepsilon_{50}} / 10 \qquad (2)$$

where E_{50} is the modulus of deformation in MPa, ε_{50} is the compressive strain, and q_u is the maximum value from stress in kPa.

Triaxial test method

The triaxial test specimens were prepared using the same mold and techniques of UCS specimen preparation. The three confining pressures (50 kPa, 100 kPa, 150 kPa) were applied in this experiment. The cohesion (c) and angle of internal friction (φ) of triaxial test results were calculated using graphical and mathematical methods. The Mohr-Coulomb failure criterion was followed as a graphical technique, where specimens fail due to a critical combination of normal stress and shear stress. The equation for the failure envelope line is as follows:

$$\tau_f = c + \sigma_f \tan \varphi \qquad (3)$$

where, τ_f is the shear stress of the failure plane and, σ_f is normal stress on the failure plane. The following equation was also used to calculate the cohesion (c) and angle of internal friction (φ):

$$\sigma_a = \sigma_r \tan^2 (45 + \phi/2) + 2c \tan (45 + \varphi/2) \qquad (4)$$

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

Scanning electron microscopy test method

The SEM images of soil-RHA combinations in magnification 1000 times were selected to understand the microstructural changes of particles in the specimens. The SEM test samples were collected from triaxial test specimens in this investigation.

Results and discussion

Compaction characteristics

The OMC and MDD of soil with 0%, 5%, 10%, and 15% RHA combinations were measured from the compaction curves in Figure 1A. The variations of OMC and MDD of soil-RHA admixtures showed that the OMC increased, while MDD decreased with the increment of RHA in the soil mix (Figure 1B). The OMC of the untreated soil was 17.5%, and with the increase of RHA content, the OMC of the treated soil with 5%, 10%, and 15% RHA was 20.0%, 24.0%, and 28.2%, respectively. This happened due to the absorption of a massive amount of water by the surplus fine particles of microporous RHA in the soil-RHA mixtures (Singh, 2018). The MDD of the control specimen was 1.696 g/cm^{3,} and with the addition of RHA, the decreasing percentage of MDD for 5% RHA (1.545 g/cm^3), 10% RHA (1.436 g/cm^3), and 15% RHA (1.334 g/cm^3) was 8.9%, 15.3%, and 21.3% correspondingly. The declining tendency of MDD may be clarified by the difference of specific gravity between soil (2.70 g/cm^3) and RHA 2.12 g/cm^3). The RHA particles act as a filler in soil pore spaces due to their lower specific gravity compared to soil (Alhassan, 2008).

California bearing ratio test results

The load-penetration curves of soil with 0%, 5%, 10%, and 15% RHA combinations are shown in Figure 2A. The calculated

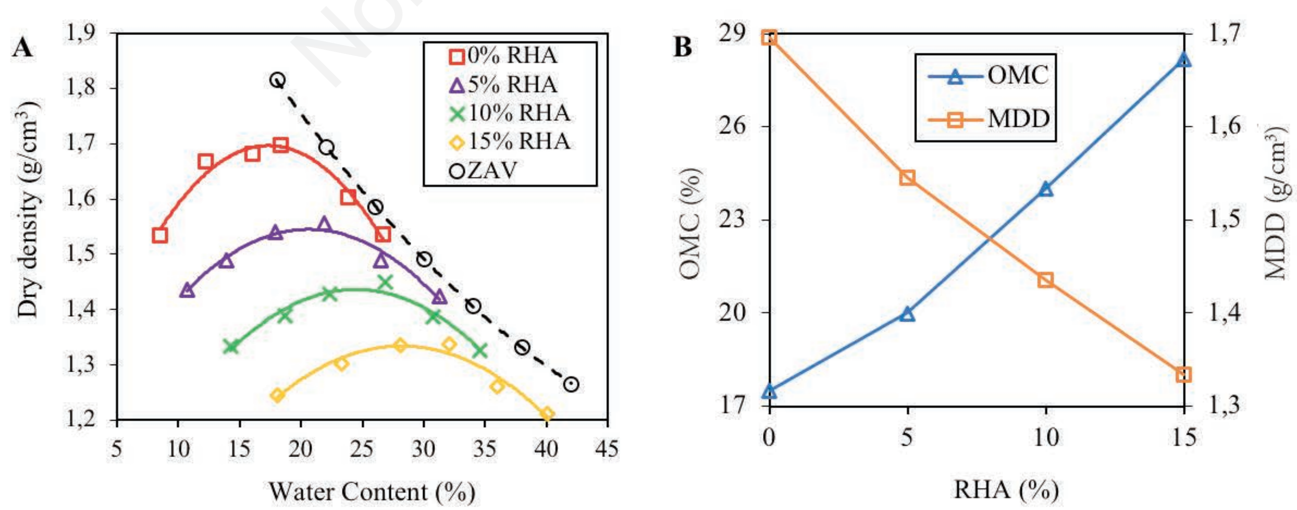

Figure 1. (A) Compaction curves, zero air void (ZAV); and (B) variation of optimum moisture content (OMC) and maximum dry density (MDD) of soil with 0%, 5%, 10%, 15% rice husk ash (RHA).

CBR value of control was 42.2%. The CBR value increased with 5% RHA and afterward declined at 10% and 15% RHA mixed soil. Soil with a 5% RHA combination showed the highest CBR value (58.9%), 10% RHA (47.0%) also exhibited an improvement of CBR value compared to control, and the CBR value for 15% RHA (36.3%) displayed the lower than control. The progress of CBR value for 5% RHA specifies the pozzolanic reactions among the substantial amount of reactive SiO_2, and a negligible amount of Al_2O_3, and CaO with water in the soil (Sarkar *et al*., 2012). The reduction in CBR value after adding 15% RHA may bedue to the

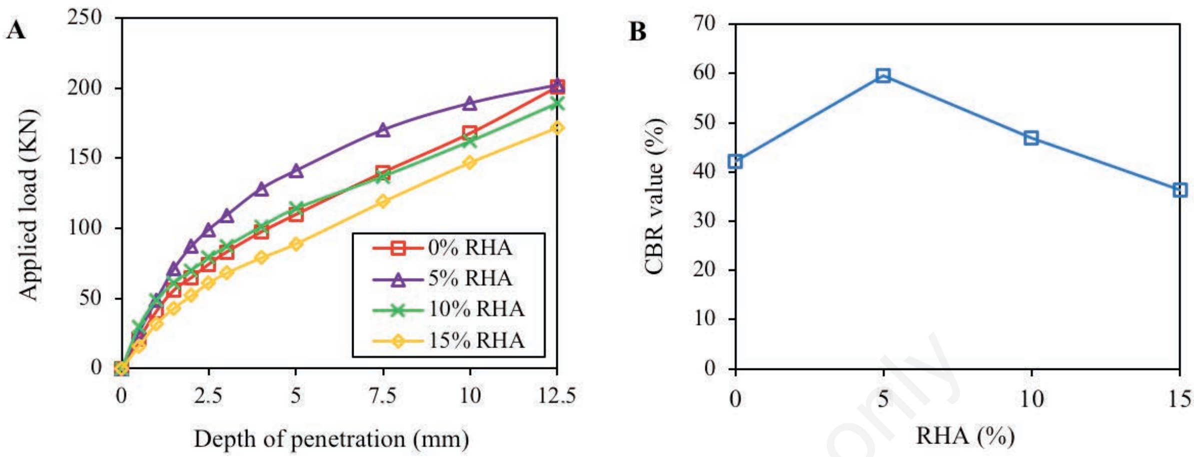

Figure 2. (A) Load penetration curves; and (B) California bearing ratio (CBR) value of soil with 0%, 5%, 10%, 15% rice husk ash (RHA).

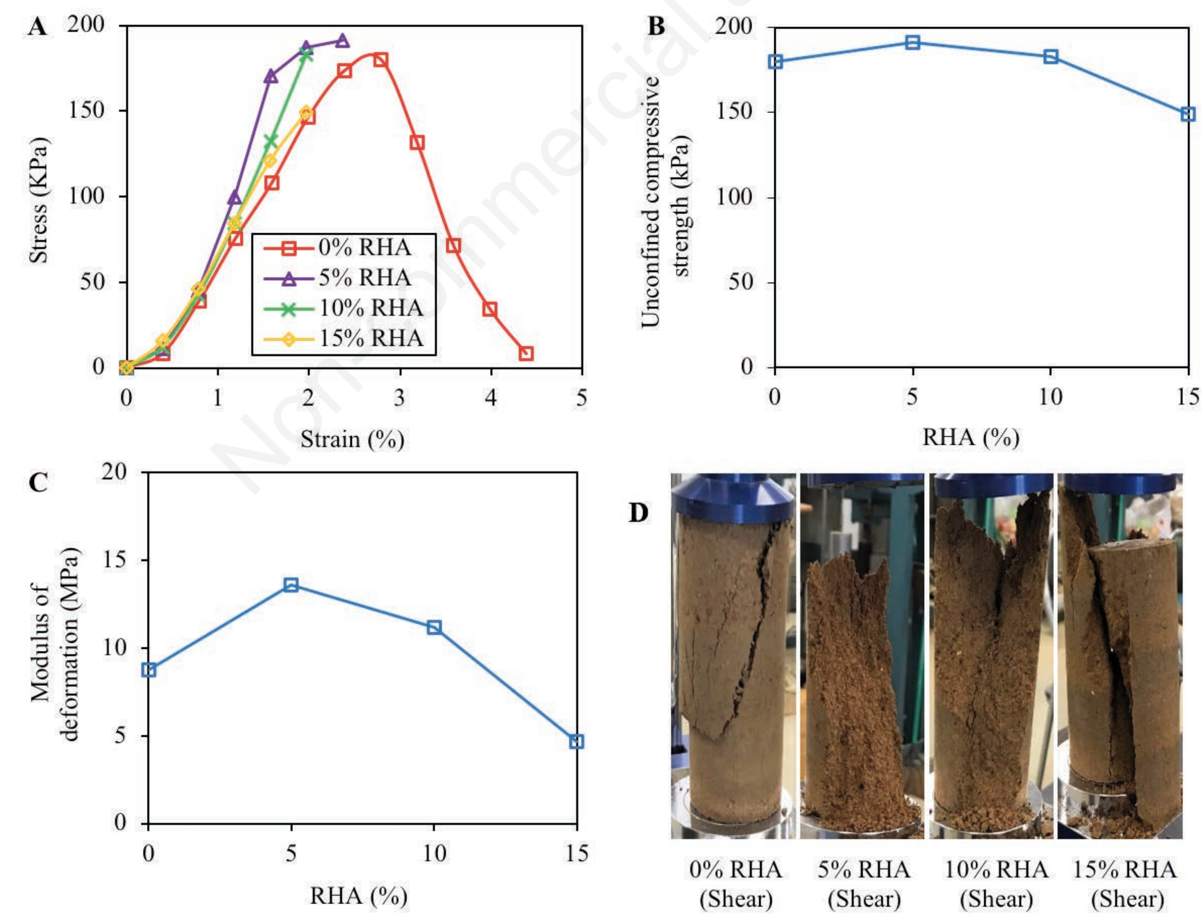

Figure 3. (A) Stress-strain relationship; (B) Unconfined Compressive strength (UCS); (C) Modulus of deformation (E_{50}); (D) Failure mode of soil with 0%, 5%, 10%, 15% rice husk ash (RHA).

extra RHA weakening the bonding between soil and pozzolanic materials in the mixtures (Alhassan, 2008).

Unconfined compressive strength test results

The stress-strain relationship curves of soil with 0%, 5%, 10%, and 15% RHA mix types are shown in Figure 3A. Each curve of this figure illustrates that the compressive stress increased with displacement until reaching the topmost value, then delivered a softening behaviour. It is noticed from Figure 3B and C that the addition of RHA showed an improvement of UCS value and modulus of deformation (E_{50}). Likewise, the results from the CBR test, the soil with 5% RHA showed the highest strength and elasticity (UCS=190.9 kPa and E_{50}=13.6 MPa) among all soil-RHA combinations. After the addition of 10% RHA, the UCS (183.1 kPa) and E_{50} (11.1 MPa) values decreased compared to 5% RHA, but these values are higher than the control specimen (UCS=180.0 kPa and E_{50}=8.7 MPa). Soil with 15% RHA showed lower UCS (149.2 kPa) and E_{50} (4.7 MPa) values than control. Shear failure mode was observed from the failure plane of all soil-RHA specimens. The addition of RHA exhibits a slight change in the properties from ductile to brittle nature (Figure 3D). Likewise, the improvement of soil bearing capacity with 5% RHA, the pozzolanic reactions, and mechanical interconnections of the particles of soil and RHA enhanced the UCS value of this soil-RHA combination.

Triaxial test results

The association between axial strain (ε_a) and deviatory stress ($\Delta\sigma = \sigma_a - \sigma_r$) of soil with 0%, 5%, 10%, and 15% RHA combinations are exhibited in Figures 4A-4D. The figures showed a common trend of stress-strain relationship, initially stress increased with the increase of strain, and after getting the topmost value, the stress followed softening behaviour. The angle of internal friction and cohesion of the control specimen was 32˚ and 76 kPa, respectively. It is noticeable from Figures 5A that soil with 5% and 10% RHA combinations improved the cohesion (c). The cohesion values for 5%, 10%, and 15% RHA were 85, 80, 72 kPa, correspondingly, whereas the angle of internal friction values was 34°, 33°, and 20° accordingly (Figures 5A-5B). Likewise, in the UCS and CBR test results, soil with 5% RHA achieved the highest shear strength properties, and soil with 10% RHA reached the second-highest strength. The soil with 15% RHA had lower cohesion and angle of internal friction values than the control specimen. All triaxial test specimens also exhibited shear failure patterns. The mechanism of pozzolanic reactions and strength development in different soil-RHA combinations have been explained in the CBR results section.

Scanning electron microscopy test results

The SEM test results of soil with 0%, 5%, 10%, and 15% RHA are shown in Figures 6A-6D. The untreated soil had a smooth and

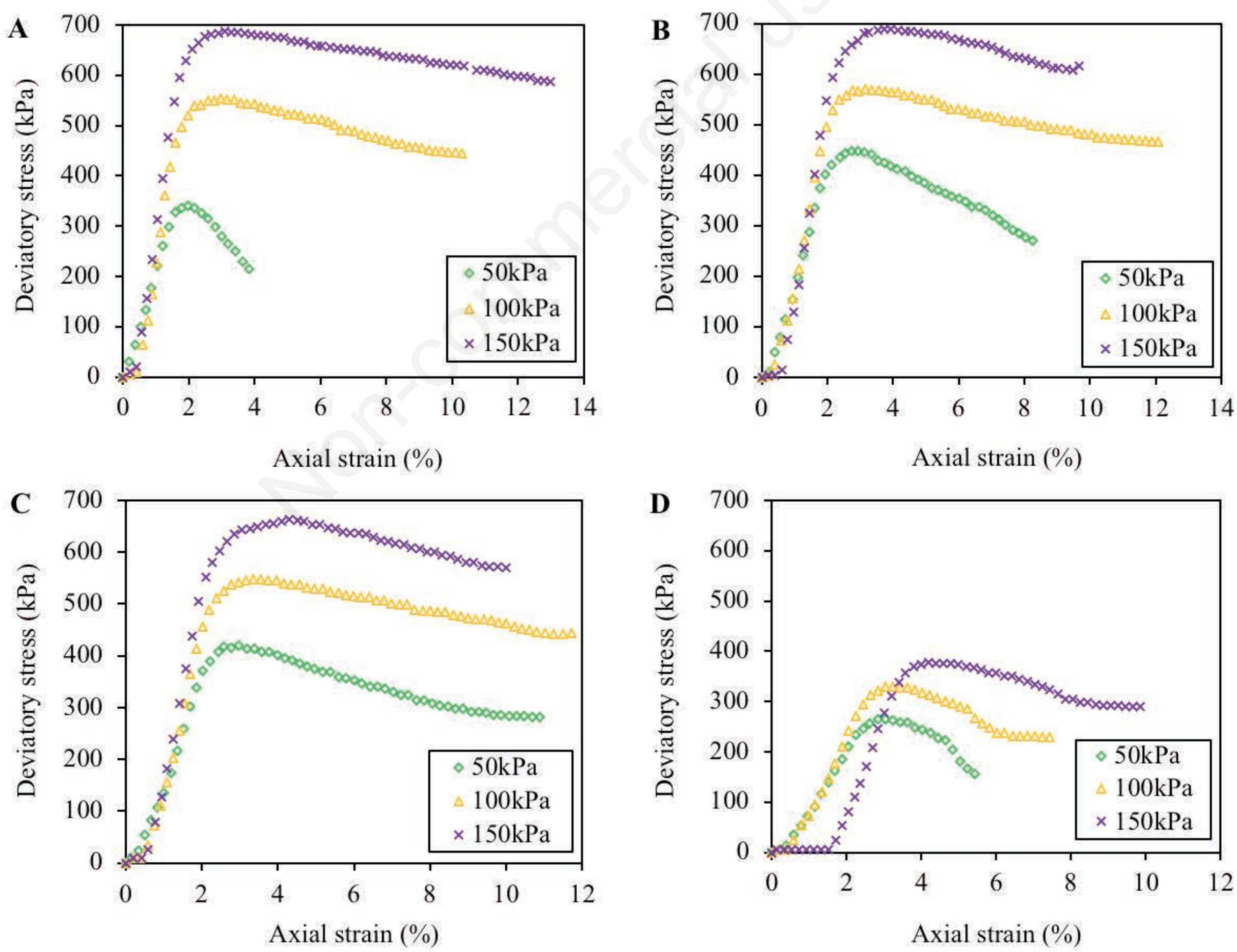

Figure 4. The axial strain (ε_a) and deviatory stress ($\Delta\sigma$) relationship of soil with (A) 0% rice husk ash (RHA); (B) 5% RHA; (C) 10% RHA; and (D) 15% RHA.

rough surface together with no spherical particles (Figure 6A). After adding RHA in the soil, the mechanical interconnection (Ramesh and Manjunatha, 2020) and pozzolanic reaction between the soil and RHA particles (Sarkar *et al.*, 2012) altered the microstructure of the soil. The surface roughness of treated soil increased with the increment of RHA content due to increased pore spaces compared to the control specimen. Soil with 5% RHA exhibited the best mechanical linkage between the particles of soil and RHA with pozzolanic reactions, resulting in the best microstructural and strength development (Figure 6B). Further

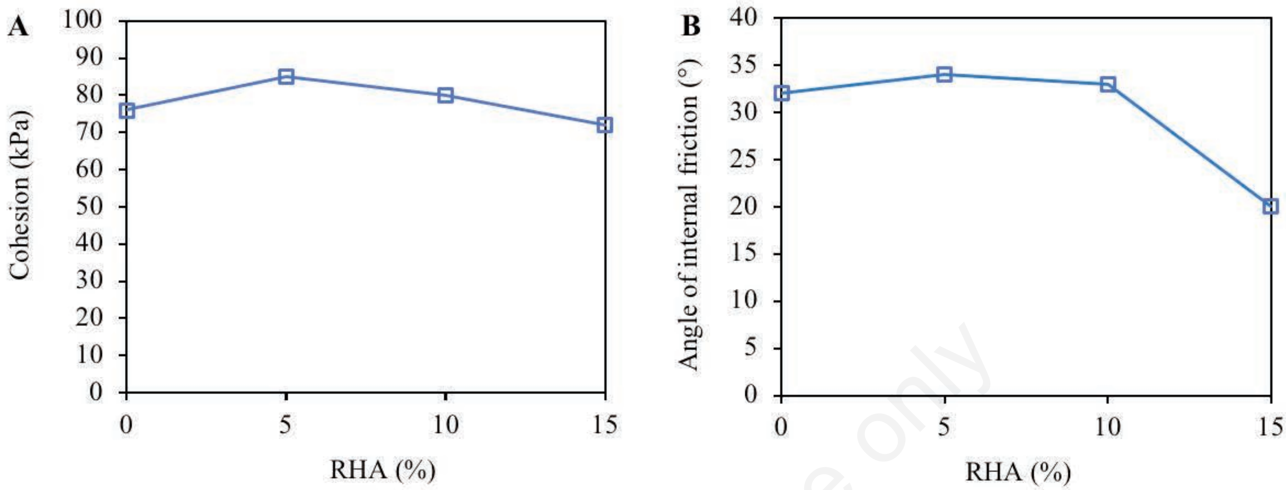

Figure 5. (A) Cohesion (c); and (B) angle of internal friction of (φ) soil with 0%, 5%, 10%, 15% rice husk ash (RHA).

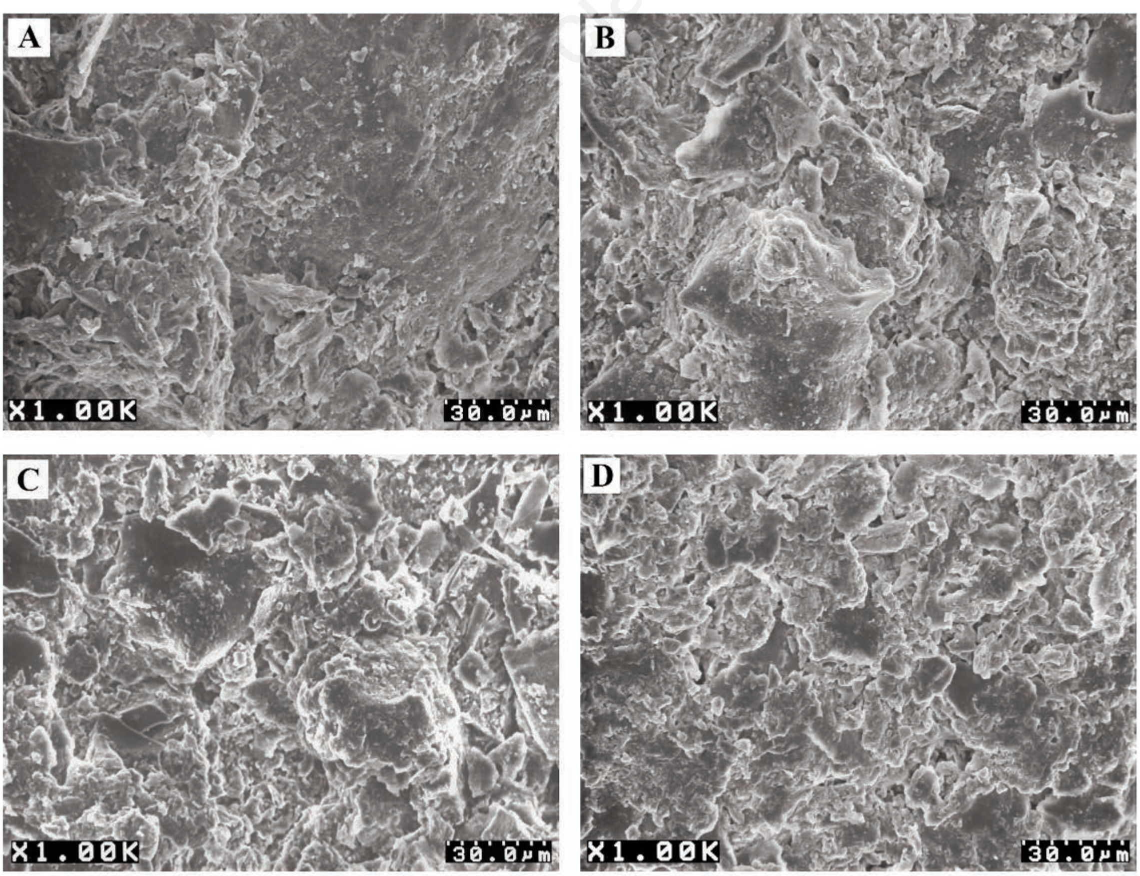

Figure 6. Scanning electron micrograph of soil with (A) 0% rice husk ash (RHA); (B) 5% RHA; (C) 10% RHA; and (D) 15% RHA with 1000× magnification.

addition of RHA increased the pore spaces, which inhibited the interlocking and pozzolanic reaction between soil and RHA particles, achieving less microstructural and strength development in the soil (Figures 6C-6D).

Conclusions

From the experimental investigation on the addition of burnt RHA at controlled temperature with soil, it can be concluded that soil with 0%, 5%, 10%, and 15% of RHA combinations influenced the compaction characteristics, bearing capacity, UCS, shear strength and microstructure of soil. The OMC increased, but MDD decreased with the increasing amount of RHA. The initial addition of 5 % RHA with soil showed the best improvement of geotechnical properties, and then these values declined with the increase of RHA. An increase of UCS value (190.9 kPa) and deformation modulus (13.6 MPa) for 5% of RHA was 6.0% and 56.3% respectively compared to the control specimen (UCS =180.0 kPa and E_{50}=8.7 MPa). CBR value increased by about 39.5% for the combination of soil with 5% RHA (58.9%), while the CBR of control was 42.2%. The increasing percentage of cohesion (85 kPa) and angle of internal friction (34°) of 5% RHA with soil was 11.8% and 6.3%.

The results showed the improvement of geotechnical properties of soil by utilization of RHA, which recommended that soil with 5% RHA can be used as a construction material for rural roads and pedestrian roads which can reduce construction costs and ensure environmental sustainability.

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