Effects of basalt fibres on strength and permeability of rice husk ash-treated expansive soils

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Abstract

The application of stabilised soil in agricultural construction works such as shallow foundation fills and subgrade material for farm roads is in demand due to the improved geotechnical properties. This study focused on improving the compressive capabilities and the permeability characteristics of rice husk ash (RHA)-treated clayey soils using basalt fibre. Basalt fibres are made from naturally occurring basalt rock, yet their use in soil stabilisation has not been realised due to limited research for its validation in ground stabilisation. Essential variables in the stabilised soil matrix included basalt fibre length (3 mm, 6 mm, and 12 mm), RHA percentages (5%, 10%, and 15%), and cement percentage (3%). In addition, the optimum moisture content of each admixture was determined by standard proctor compaction tests and reduced by 3% to prepare the specimens for unconfined compression strength test, constant head permeability test, and scanning electron microscope (SEM) test. It was observed that the unconfined compression strength of the RHA-basalt fibre stabilised clayey significantly increased when the specimens wet cure for 28 days.

Similarly, adding fibres into the soil improved the permeability coefficient. The SEM test showed a porous morphology that increased permeability. Furthermore, through SEM, the randomly oriented basalt fibres' portrayed the reinforcing phenomenon related to improved compressive strength and sufficient bearing capacity to support structures built upon this class of soils.

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Key words: Basalt fibre; soil stabilisation; permeability coefficient; unconfined compression strength; scanning electron microscope.

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Introduction

Ground improvement is a fundamental step in geotechnical engineering to improve the strength of naturally occurring soils. The application of such improved soils is in the rise in areas like the subgrade layers (Crockford, 1993), fill material (Festugato *et al*., 2013), and stability for shallow foundations (Mitchell, 1981; Ibraim *et al*., 2013). Major parameters such as strength, modulus of deformations, failure planes, permeability, and the soil microstructure interaction must be examined to support engineering structures. Several methods have been proposed to produce high-strength soils for engineering construction purposes within the last decade. Soil improvement can be made by modifying the existing properties or by stabilisation (Fattah, 2013). Stabilisation methods include densification techniques using cement-rich mixtures, pozzolans to stabilise the soil chemically, and reinforcement techniques using different types of fibres. The use of densification practices by cement has been more and more considered worldwide, but this has led to a tremendous increase in construction costs and environmental impacts associated with cement manufacture (Alhassan, 2008). This encounter has led to the sustainable use of industrial wastes like rice husk ash (RHA) and fibres as potential replacements or reduction aggregates to conventional cement densification techniques, as described in the next section.

The pozzolanic stabilisation technique

One of the predominant pozzolanic materials in engineering use today is RHA. Rice husk is a by-product of the rice grain production process. Upon the controlled and open burning of rice husks, we obtain RHA, which is extensively used to improve soils' geotechnical properties due to its abundance and is superiorly inexpensive compared to other conventional stabilising agents such as cement and lime (Aprianti, 2015). Pozzolans are those materials that are rich in siliceous and aluminous compounds and which in themselves have very minimal cementitious properties until chemically reacted with calcium hydroxide from materials such as cement (Malhotra and Mehta, 2004; Basha *et al*., 2005). Therefore, using RHA in soil stabilisation is advantageous for improving soil strength and durability. In addition, environmental impacts related to the uncontrolled disposal of agricultural waste and excess carbon dioxide emissions from uncontrolled burning of these wastes in the fields (Ali, 1992) can be diminished.

Rahman (1986), in his research on the effects of rice husk ash alone on the unconfined compressive strength (UCS) of stabilised soils, showed that an increase of RHA to 20% increased the UCS of lateritic soils, after which they started to decrease. Noor (1993) also examined the RHA-cement ratios and how they positively influenced the proposed mix ratios, UCS, and durability. Muntohar's (2004) results showed that mixing RHA with 6% lime significantly reduced swelling and increased durability on such improved soils. The literature also showed that RHA had an optimum percentage above which the UCS of improved soils decreased. Alhassan (2008) showed that adding RHA percentages between 0 to 4% to clay soils and lime specimens significantly increased the UCS value at specified lime contents. On the other hand, from the same research, increasing rice husk ash percentages from 6 to 8% decreased the UCS value considering the curing period in both cases.

Soil stabilisation by RHA involves a pozzolanic reaction between the Ca $(OH)_2$ rich cement or lime and the SiO_2 rich RHA ash in an alkaline environment leading to the formation of calcium silicate hydrate (CSH) gel (Rogers and Glendinning, 2000). James and Rao (1986) investigated the setting process for a lime-excess and a lime-deficient mixture. The reaction product showed the CSH gel by a combination of thermal analysis, XRD, and electron microscopy. In a nutshell, the formation of CSH gel accounted for the strength of lime-RHA and cement, as shown in Eq. (1).

$$Ca\ (OH)_2 + SiO_2 = CaO_{0.8\text{-}1.5}SiO_2\ (H_2O)_{1.0\text{-}2.5} + CaO_{1.5\text{-}2.0}SiO_2.2(H_2O) \quad (1)$$

Fibre stabilisation techniques

Fibre inclusion in a soil matrix has proved to add more intensification in the compressive abilities of soils due to the reinforcing technique between the soil particles. Therefore, several pieces of research have been investigated considering different fibres and their applicability in enhancing soil strength from literature. For example, Kumar (2006) studied the UCS gain on the soil by mixing polyester fibres and soft clay and observed that the compaction degree affected fibre reinforcement. Also, the unconfined compressive strength of clay increased with the addition of fibres, and it further increased when fibres were mixed in the clay-sand mixture.

Hossain (2011) also examined the structural improvement on cement-based matrices using varied carbon fibre lengths, improving durability and compressive strength. With the diversity in the fibre available for soil stabilisation, polypropylene and recycled carpet have also been used before. Where bender element tests on 126 cylindrical specimens of cement-treated clay with various cement and fibre contents were analysed to distinguish the relationships between fibre and cement content and the small-strain mechanical properties (Fatahi *et al*., 2013). Park (2009) further showed that compacting polyvinyl alcohol (PVA) fibre in different layers inside a cylindrical river sand specimen improved the compressive strength as the number of fibre layers increased. With fibres evenly distributed throughout the five layers a reinforced model was twice as strong as a non-fibre-reinforced specimen. A more comparable study to this research was done by Cristelo *et al*. (2015). In their study, the influence of discrete fibre reinforcement on the uniaxial compression response found that sandy clay reinforced with polypropylene fibres and cement increased the stiffness, modulus of deformation, and compression strength of the mixtures for every cement content. Similar results were also determined by Maher and Gray (1990) and Consoli *et al*. (1998).

Therefore, the present study focuses on stabilisation by pozzolanic reactivity of RHA and reinforcement technique by randomly distributed basalt fibre in the proposed hybrid fibre composite. Compressive tests and permeability tests on soil composites with basalt fibres (lengths 3 mm, 6 mm, and 12 mm), cement (3% of the dry weight of soil), and rice husk ash (5%, 10%, and 15% of the dry weight of soil) were carried out. The influence of these stabilisation aggregates was demonstrated by stress-strain curves and associated geotechnical properties presented in graphical form to aid future designs and relevant construction applications.

Research significance

Using fibres and chemical stabilising agents in weak soils can be very effective in arresting cracks on such soils when used in engineering construction applications. The problem associated with the soil failure phenomenon and the bearing capacity factors has been studied in the past. Literature quotes various techniques used to curb the engineering challenges when dealing with low-strength soils. Despite such data, little to no technical literature is available on the dimensional influence of basalt fibres on the unconfined compressive strength and permeability of such chemically stabilised soils. Therefore, investigations can be conducted to examine the optimal stress-strain response of the hybrid fibre composites at micro and macro levels, using different basalt fibre dimensions. This study explores the impacts of these different basalt fibre lengths on the engineering properties of hybrid fibre composites for ground improvement if present.

Materials and methods

Material properties

The materials used in this research included soil, RHA, cement, and basalt fibre (BF). Figure 1 is a pictorial representation of the engineering materials. A detailed explanation of the properties of the materials is as discussed below.

Soil

The soil used in this research was collected from Handa Area, Mie Prefecture, Japan. The soil was air-dried for 3 weeks then sieved through the 2mm sieve, after which sieve analysis and hydrometer analysis were conducted on a 500 grams specimen to

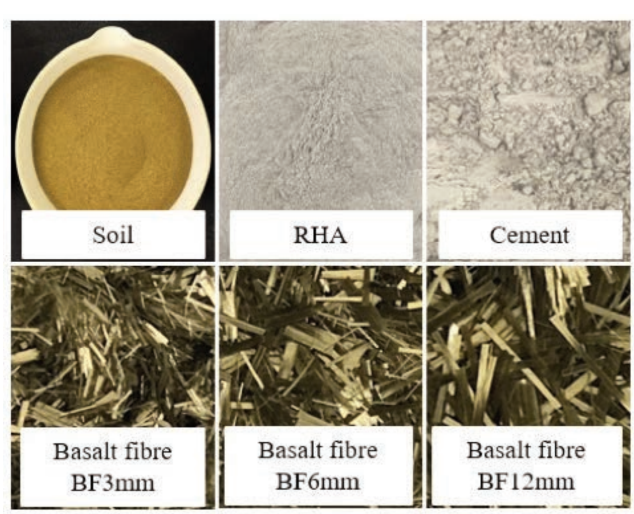

Figure 1. Experimental materials. RHA, rice husk ash.

classify the soil. According to the American Association of State Highway and Transportation Officials (AASHTO), the soil was classified as A-7-5(2) clayey soils with 6.2% coarse sand, 54.58% medium sand, 39.2% clay, and 2.215 group index. More detailed properties are shown in Table 1.

Rice husk ash properties

RHA was obtained from Make Integrated Technology Co., Ltd, Osaka, Japan. The RHA was controlled-burned ash at 650-700°C with a high silica content of 91.10%. In this research, unground ash was used, keeping it in its natural particle size distribution of 0.07 to 0.3 mm. As a result, the most dominant particles were between 0.07 and 0.106 mm. Table 1 shows the rice husk ash's detailed physical and chemical properties.

The particle distribution curves developed from sieve analysis and hydrometer analysis for soil and sieve analysis only for RHA are shown in Figure 2A.

Basalt fibre properties

Basalt fibre is (BF) made from basalt rock. The basalt rock is washed and melted, then extruded through small nozzles to produce the continuous filaments called basalt fibres (Lopresto *et al*., 2011). Its application in engineering construction reinforcement works is derived from the high tensile strength of between 4100-4840 MPa, high elastic modulus ranging from 93.1-110 GPa (Berozashvili, 2001), durability, alkali resistance, and thermal stability compared to other fibres (Sim and Park, 2005). Table 1 illustrates the fundamental properties related to this study.

Ordinary Portland cement

Ordinary Portland cement (OPC) cement was chosen for this study due to its availability in the market.

Table 1. Properties of the experimental materials.

Materials	Parameters	Values
Soil properties	Specific gravity, (g/cm^3)	2.75
	Maximum dry density, (g/cm^3)	1.64
	Optimum water content, %	24.00
	Sand (75 µm - 2 mm), %	6.20
	Silt (5-75 µm), %	54.58
	Clay <5 µm, %	39.22
	Liquid limit, LL, %	58.20
	Plastic limit, PL, %	31.05
	Plasticity Index, PI, %	27.15
	AASHTO classification	A-7-5(2)
RHA Properties	Average particle size, mm	0.001 to 0.3
	Loss of ignition, %	4-6
	Specific gravity, g/cm^3	2.12
	Burning temperature, °C	650-700
	Burning time, hour	27
	Silica (SiO_2), %	91.10
	Carbon dioxide (CO_2), %	4.35
	Potassium oxide (K_2O), %	2.40
	Calcium oxide (CaO), %	0.57
	Iron oxide (Fe_2O_3), %	0.05
	Alumina (Al_2O_3), %	0.03
	Others, %	1.50
Basalt fibre properties	Fibre diameter, (µm)	6～30
	Density, (g/cm^3)	2.63～2.8
	Tensile strength, (MPa)	4100～4840
	Elastic modulus, (GPa)	93.1～110
	Fibre lengths, (mm)	3, 6 and 12
	Fracture elongation rate, (%)	3.1

Testing methods

Standard proctor compaction test

A standard proctor test was done following the JIS A 1210 (2010) standards to evaluate the specimens' maximum dry unit weight (MDD) and the optimum moisture content (OMC). The soil specimen (herein, specimen refers to a mixture of soil, RHA, cement, and basalt fibre in varied ratios) were compacted in three layers inside the compaction mould measuring 10cm diameter and 12.68 cm height, using a 2.5 kg rammer at a falling height of 30 cm. A record of 25 blows was registered for each layer. A representative specimen was taken and tested for moisture content, and the process was repeated for all water increments. The codes for the specimen under study are explained in Table 2.

Unconfined compressive strength test

Unconfined compressive strength (UCS) test was done on a cylindrical specimen with dimensions 5cm diameter and 12.5 cm height to examine the compressibility behaviour of the mix ratios above. The specimens were prepared using a cylindrical mould and a rammer weighing 1 kg at a falling height of 30 cm. All specimens were set at the optimum moisture content obtained from compaction tests and wet cured for 1 day, 7 days, and 28 days at a constant temperature of 25 degrees Celsius before testing. The data sets obtained from each specimen were then analysed in the stress-

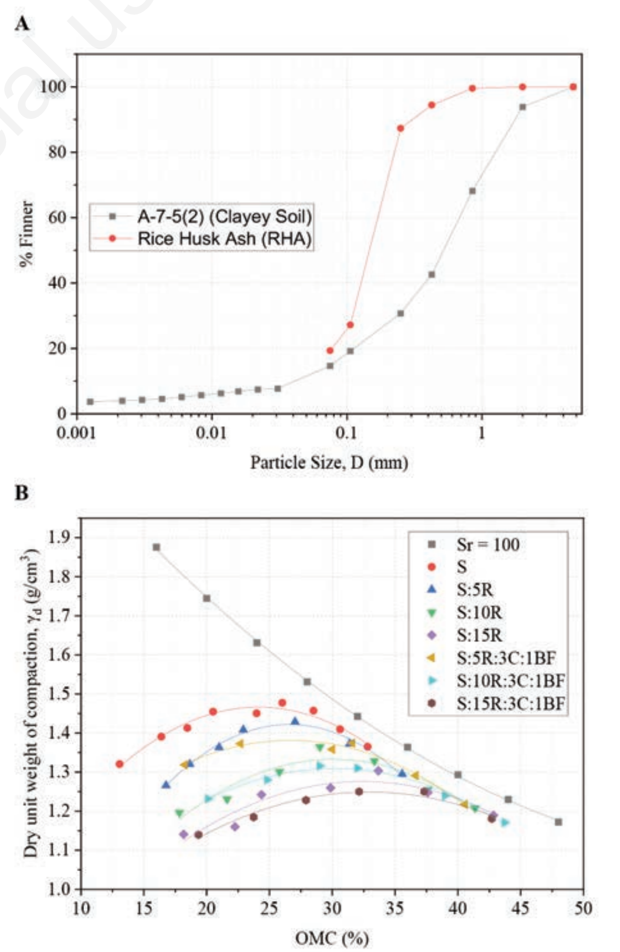

Figure 2. A) Particle size distribution for soil and of rice husk ash (RHA). B) Compaction curves for the mixing ratios. OMC, optimum moisture content.

strain curve plots to evaluate the compressive stress (q_u) and axial strain ($\mathcal{E}$) relationship and the modulus of deformation, E_{50}. The testing procedures followed the Japan standards, JIS A 1216 (2010).

Permeability test

In this study, a constant head permeability test was carried out to examine the coefficient of permeability, k, for all the specimens considering curing periods 1 day, 7 days, and 28 days. Each specimen was compacted in three layers in the compaction mould (10.4 cm diameter and 6.3 cm height) at 20 blows per layer to maintain constant compaction energy. The specimens were wet cured while retaining the water content at OMC, which allowed for enough hydration and pozzolanic activity. The constant water head was maintained at 45 m, simulated by the air pressure of 0.45 MPa in the water chamber on top of the specimen. Water flowed through the specimen until it was saturated before the first reading. Then, four readings were taken by measuring the volume of percolated water and the corresponding time for flow. Afterward, the average k of each flow was used to evaluate the final permeability coefficient (k). The experimental procedures followed Japan standards, JIS A 1218 (2010).

Scanning electron microscope

Microscopic examination was necessary to understand the macro and microstructure interaction of the proposed hybrid composite. Therefore, a scanning electron microscope was used on a specimen with dimensions 3 mm by 3 mm by 0.5 mm collected from the centre of the cylindrical specimen used during the UCS test. Soil-RHA microstructure was examined at a magnification of ×500. At the same time, the soil-RHA-cement-basalt fibre

Table 2. Specimen codes and mixing ratios.

Specimen code	Description of the mixing ratios
S	Soil only (control specimen)
S:5R	Soil+5%RHA
S:10R	Soil+10%RHA
S:15R	Soil+15%RHA
S:5R:3C:1BF3	Soil+5%RHA+3%cement+1%basalt fibre 3 mm
S:10R:3C:1BF3	Soil+10%RHA+3%cement+1%basalt fibre 3 mm
S:15R:3C:1BF3	Soil+15%RHA+3%cement+1%basalt fibre 3 mm
S:5R:3C:1BF6	Soil+5%RHA+3%cement+1%basalt fibre 6 mm
S:10R:3C:1BF6	Soil+10%RHA+3%cement+1%basalt fibre 6 mm
S:15R:3C:1BF6	Soil+15%RHA+3%cement+1%basalt fibre 6 mm
S:5R:3C:1BF12	Soil+5%RHA+3%cement+1%basalt fibre 12 mm
S:10R:3C:1BF12	Soil+10%RHA+3%cement+1%basalt fibre 12 mm
S:15R:3C:1BF12	Soil+15%RHA+3%cement+1%basalt fibre 12 mm

RHA, rice husk ash.

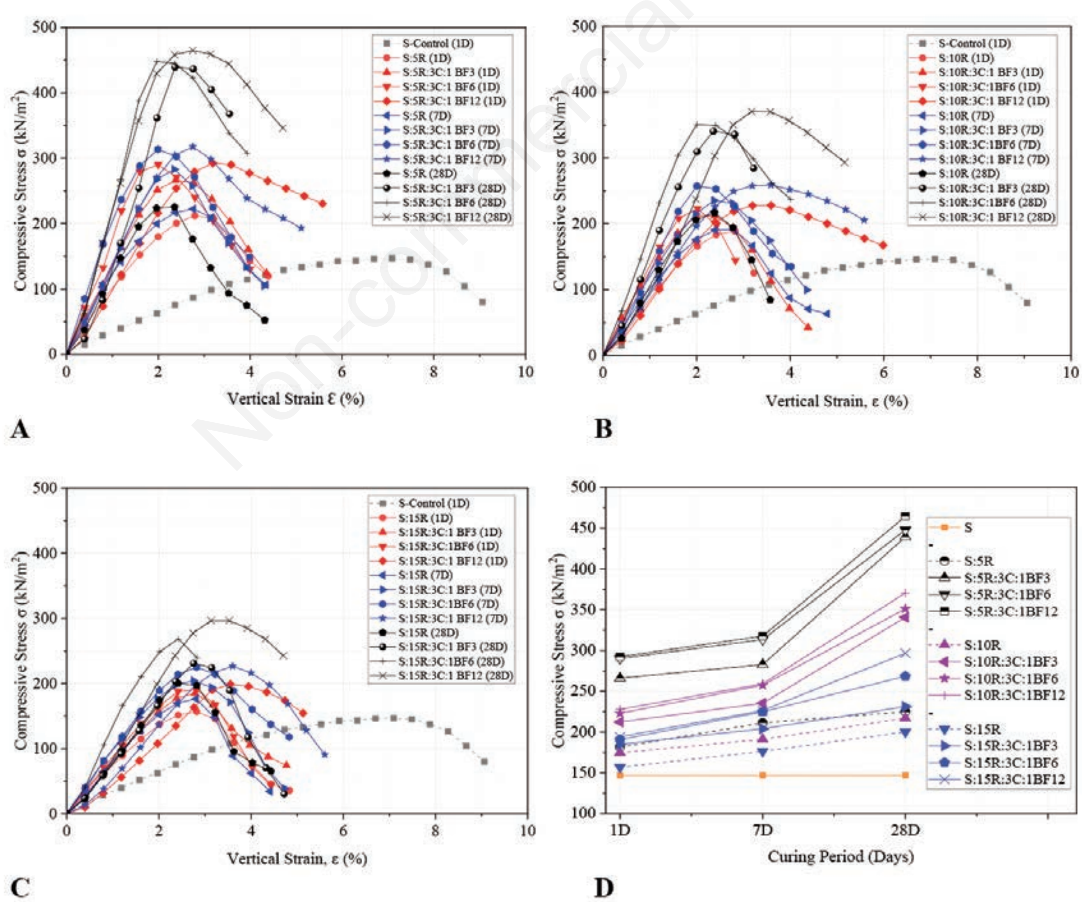

Figure 3. A) Stress-strain relationships for 5% of rice husk ash (RHA) and basalt fibre. B) Stress-strain relationships for 10% RHA and basalt fibre. C) Stress-Strain relationships for 15% RHA and basalt fibre. D) Variation of compressive stress with curing period.

macrostructure was observed at a magnification of ×150 to provide a wider area for spotting the basalt fibres' random distribution in the soil composite matrix.

Results and discussion

Standard Proctor compaction test results

Compaction test refers to soil densification by removing air and rearranging the soil particles through mechanical energy. The degree of compaction is measured in terms of the maximum dry density, γ_{dmax}, and the optimum moisture content, OMC (Robert, 2008). Figure 2B shows a plot of the compaction curves and the saturation line Sr, emphasising the maximum values for the OMC and the dry unit weight γ_{dmax} for all the specimen mix ratios. In this study, compaction curves did not pass the saturation line, showing the correctness of the relationships between OMC and γ_{dmax}. The optimum water content increased with an increased percentage of RHA. Similarly, upon adding cement into the mix ratios, there was a further increase in the OMC.

The dry unit weight decreased with the addition of RHA and cement. The increase in OMC was due to the high-water affinity by the increasing percentage of RHA and the hydration effect with cement mixtures (Anupam, 2012). Furthermore, the decrease in dry density was attributed to flocculation and cementitious compounds in the new composite soil mixtures.

Unconfined compressive strength test results

This section shows the relationship between compressive stress, q_u, and axial strain, ε for RHA percentages (5%, 10%, and 15%), and basalt fibre lengths (3 mm, 6 mm, and 12 mm). In Figure 3A, the maximum compressive stresses, q_u, were achieved with 5% RHA specimen at lower axial strains, ε compared to control. In Figure 3B and C, adding RHA to 10% and 15%, respectively, reduced the compressive stresses with a slight increase in the axial strain for all basalt fibre lengths. A similar trend on axial strain versus RHA was also observed by Basha (2005) and Rao *et al*. (2011). Compressive stress reduction can be attributed to the reduced cementitious properties due to excess RHA, hence less bonding of soil particles and basalt fibres, leading to increased axial displacements. Nevertheless, all 10% RHA and 15% RHA specimens produced significantly more stress-bearing than the control specimen.

Correspondingly, the curing period was considered for 1 day, 7 days, and 28 days as shown in Figure 3D. A slight improvement in q_u was observed from the graph for all the specimens after 7 days of curing. For example, specimen S:5R:3C:1BF12 had an unconfined compressive strength (UCS) of 292 kN/m^2 after one day, and the value increased to 318 kN/m^2 at 7 days of curing. After 28 days of curing, there was a significant increase in the UCS value for S:5R:3C:1BF3, S:5R:3C:1BF6 and S:5R:3C:1BF12 specimen with values 438 kN/m^2, 453 kN/m^2 and 463 kN/m^2 respectively.

The soil matrix also gained strength with an increase in the length of basalt fibres which enhanced the bonding of soil particles by anchoring them together. The highest compressive strengths

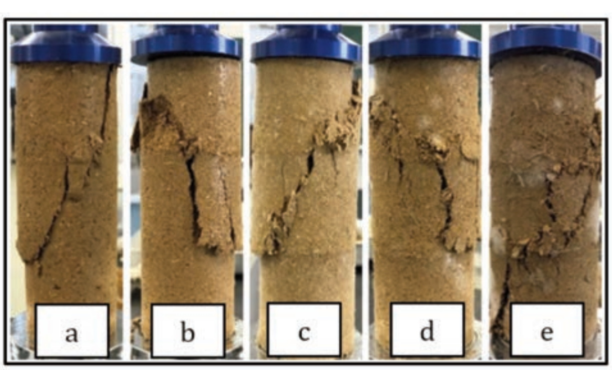

Figure 4. Failure patterns (a) S, (b) S:5R, (c) S:5R:3C:1BF3, (d) S:5R:3C:1BF6, (e) S:5R:3C:1BF12.

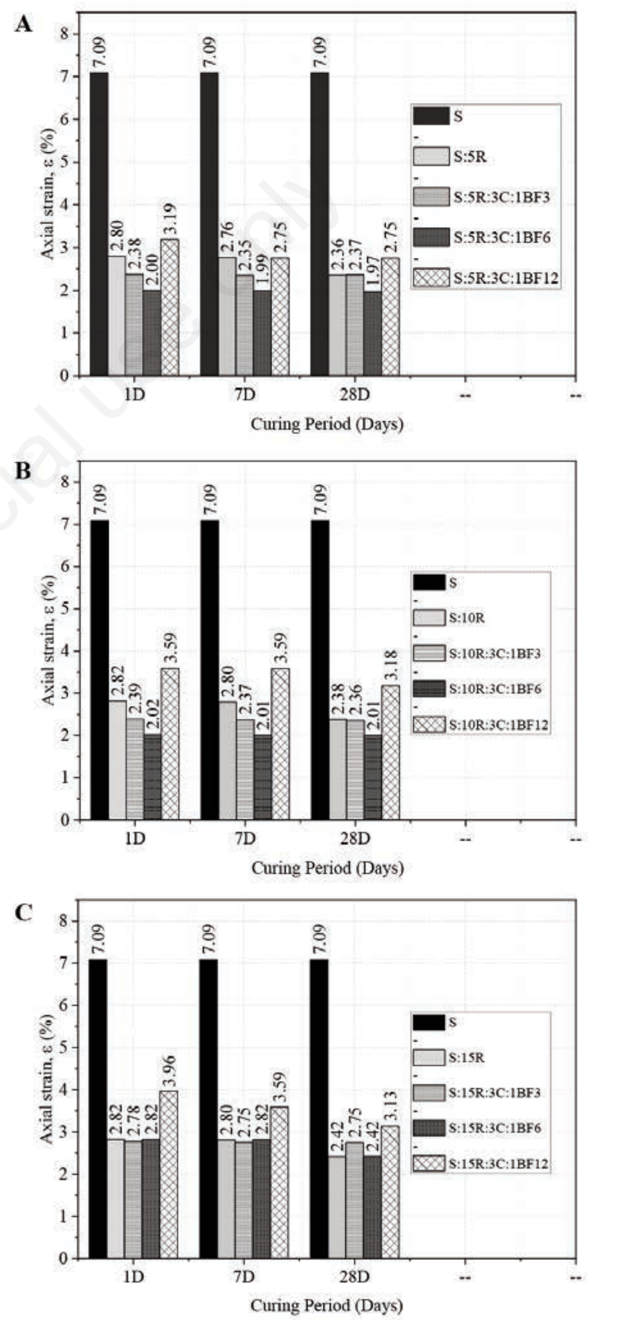

Figure 5. A) Strain *vs* curing periods for 5% of rice husk ash (RHA) and basalt fibre. B) Strain *vs* curing periods for 10% RHA and basalt fibre. C) Strain *vs* curing periods for 15% RHA and basalt fibre.

considering basalt fibre length were obtained from S:5R:3C:1BF12 (463 kN/m^2), S:10R:3C:1BF12 (362 kN/m^2), S:15R:3C:1BF12 (297 kN/m^2) compared to the control specimens' 147 kN/m^2. The UCS increased due to the basalt fibre reinforcements as seen in this study and chemical reaction in the soil matrix, leading to silica gel formation (Kumar *et al*., 2006). Das (1994) classified the quality of subgrade based on UCS value with hard sub-base having UCS values greater than 380 kN/m^2. From this study, S:5R:3C:1BF12 produced a compressive strength of 463 kN/m^2 and can be used as subgrade material for construction works

Figure 4 summarises the failure planes for control specimen, S and the 5% RHA specimen (S:5R, S:5R:3C:1BF3, S:5R:3C:1BF6, and S:5R:3C:1BF12). The first three *specimens*, *a*, *b* and *c*, experienced a simple shear failure with a diagonal failure plane on the upper layers upon maximum compression load. The higher strength mix ratios S:5R:3C:1BF6 and S:5R:3C:1BF12 showed a tension failure with an almost vertical failure plane cutting across all three layers.

It was observed that cracks occurred in the vertical plane for *specimen a* at a strain of 7%, and this strain value reduced considerably to less than 3% for *specimens b*, *c*, and *d* after adding basalt fibres. This reduction in axial strain is shown in Figure 5 for 5%, 10%, and 15% RHA, respectively. Amongst the basalt fibre specimen, 12 mm long fibres had a 1% increase in axial strain compared to BF 3 mm and BF 6 mm. The increase was due to the slight extra deformations during compression, required to tension the randomly placed 12mm long basalt fibres in the specimen structure before the reinforcing benefits were realised. Lawton *et al*. (1993) reported a relatable increase in strain value using multi-oriented geosynthetics. The axial strains reduced slightly after 28 days of curing, signifying shear strength and stiffness development in the soil specimen.

For better clarification on the field use of the results, Figure 6A shows the relationship between the modulus of deformation, E_{50}, and curing period. Adding RHA, cement, and basalt fibre had a tremendous influence on E_{50}. A significant increase was observed after 28 days of curing with 5% mix ratios giving the highest E_{50}. For mix ratios, 5R, S:5R:3C:1BF3, S:5R:3C:1BF6, S:5R:3C:1BF12 the modulus of deformations were 16 MPa, 20 Mpa, 26 MPa, and 29 MPa, respectively, which were much higher compared to control specimen (3 MPa). Specimen S:5R:3C:1BF12 gave the maximum E_{50} due to the high compressive stress of 463 kN/m^2 and additional reinforcing effect after the tensioning of the longer fibres compared to the fibre lengths 3 mm and 6 mm. The dimensional configurations of the basalt fibres and the random dis-

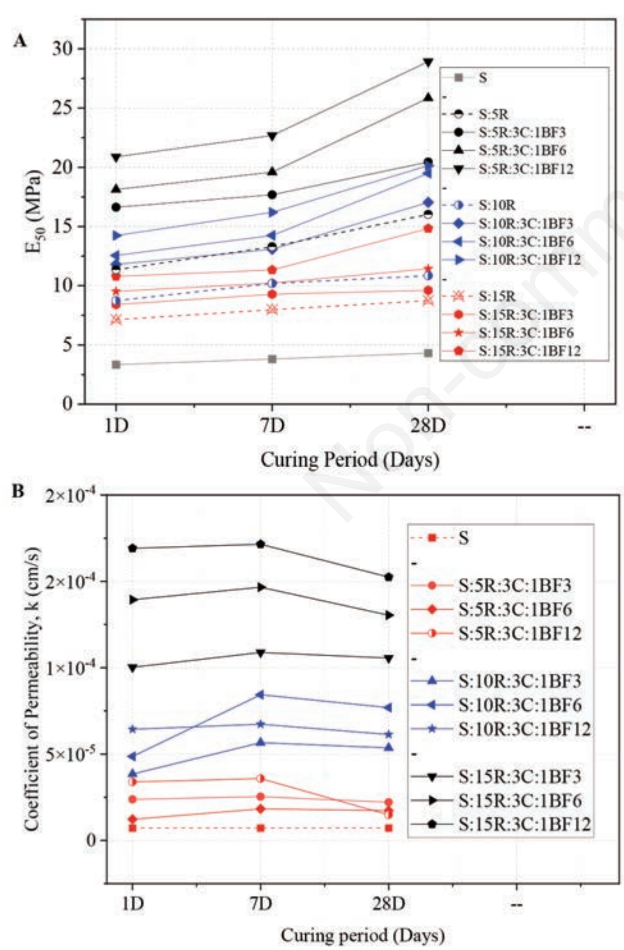

Figure 6. A) Relationship between E_{50} and curing period. B) Coefficient of permeability, k *vs* curing periods.

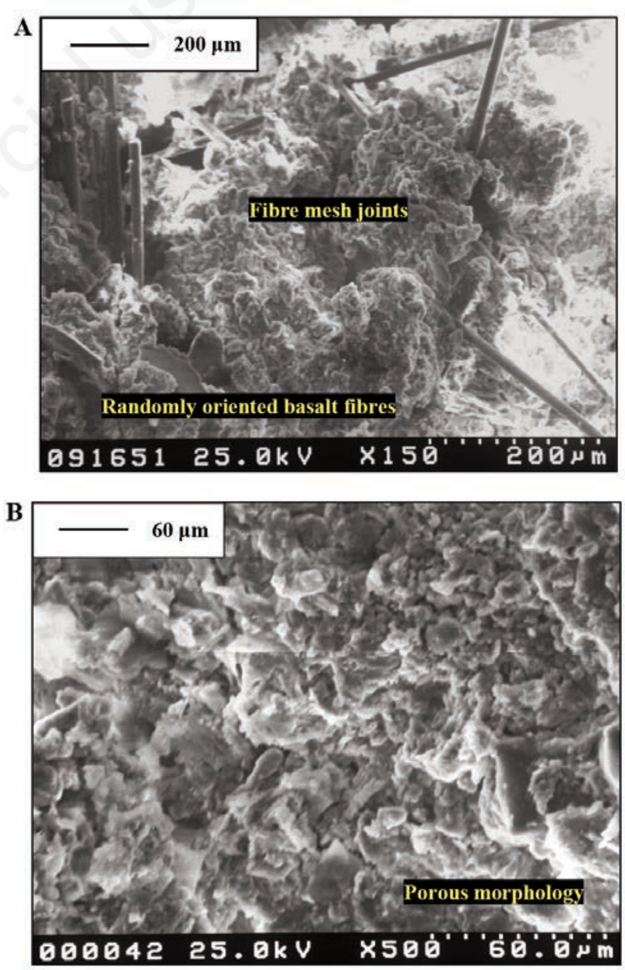

Figure 7. A) Scanning electron microscope (SEM) of magnification ×150. B) SEM of magnification ×500.

tribution of the 12 mm fibres reinforced a larger area in the soil composite structure than the shorter 3 mm and 6 mm upon full tensioning during compression.

Permeability test results

Permeability test examines the water flow rate through a soil medium and is expressed as the coefficient of permeability, k. This water flow rate significantly impacts soils' physical properties when it comes to drainage of subgrade material. In this study, the soil had a very low permeability of 7.1×10^{-6} cm/s, which was not considered suitable for subgrade or shallow foundation use - adding basalt fibres into the soil increased k to 10^{-5} cm/s for all 5% to 10%RHA specimen and 10^{-4} cm/s for 15% RHA specimen, as shown in Figure 6B. From 1 day to 7 days of curing, k increased due to the rapid flocculation of particles in the specimens (Hossain and Sakai, 2008; Wong, 2008) that led to the formation of larger voids in addition to the gaps created by basalt fibres. It was also evident that k declined at 28 days of curing due to the cementation effect that enhanced the binding of the particles in the specimen (Wong *et al*., 2008). This study found out that adding basalt fibres to RHA treated soil increased the value of k, thus improving the drainage potential of the stabilised expansive soil.

Scanning electron microscope

The bonding phenomenon can be validated using SEM images with different magnifications to examine the specimen at both macro-level (Figure 7A) and micro-level (Figure 7B). Figure 7 shows a representative high strength specimen sample with the combinations S:5R:3C:1BF12. The macro-level examination of the specimens (×150) showed the anchoring effect of the basalt fibres, while the micro-level (×500) exhibited the porous morphology in the soil composite structure. This anchoring effect confirmed the increase in compressive strength within the specimens compared to the control. Furthermore, the chemical reaction between soil, RHA, and cement combined with the reinforcing behaviour of basalt fibres form the porous morphology that increased permeability substantially.

Conclusions

The effects of basalt fibre as a potential reinforcing material to RHA-treated soils for ground stabilisation were investigated in this paper. From the results and discussions above, the following conclusions can be drawn. Unconfined compressive strength of compressible clay having 5% rice husk ash increased with the addition of basalt fibres from BF 3 mm to BF 6 mm to BF 12 mm. An increase in UCS value was also evident for 10% and 15% RHA which had UCS values higher than the control specimen but lower than the 5% RHA specimen. Basalt fibres (BF) and the cementitious soil mass improved compressibility and permeability. Notably, the dimensional considerations of the basalt fibre had a significant influence on the compressive strength, with the 12 mm fibres specimen, S:5R:3C:1BF12, showing the top q_u of 463 (kN/m^2) and E_{50} of 29(MN/m^2) after 28 days of curing at 25°C.

In general, the inclusions of randomly oriented Basalt fibre into the soil, combined with the rapidly hardening CSH gel, improved the geotechnical engineering behaviour of the new material and can be proposed for use as a subgrade material for farm roads, pavements, and as fill material in shallow foundations.

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