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Dimensional influence of basalt fiber reinforcements on the consolidation behaviour of rice husk ash stabilized soils

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A R T I C L E I N F O

A B S T R A C T

Keywords:

The development of reinforcement techniques in soils with various fibers has been a common practice since the Consolidation curves

early days *[Code a1]*. Recently, fibers and materials considered waste are being used to develop sustainable solutions in Basalt fibers *[Code a2]*

designing new soil reinforcing and stabilizing materials. In this paper, an investigation has been carried out to Expansive soil

evaluate the dimensional influence of basalt fiber on the compressibility and swelling of soils stabilized with rice Rice husk ash *[Code a3]*

Compressibility

husk ash (RHA) and cement. Incorporating a nominal dosage of basalt fibers into the soil–cement-RHA composite Swelling

produces a strong composite with smart material properties. Specimen containing expansive clay soil, basalt SEM

fibers (lengths 3 mm, 6 mm, 12 mm), RHA (5%, 10%, and 15%), and cement (3%), in their specified combi-XRD

nations, were prepared and tested. *[Code a3]* The influence of fiber length and variation of RHA-cement content was quantified using the consolidation curves (compression curves and normalized compression curves), compression index, and swelling index, which provided a detailed behavioral modification upon consolidation. Scanning Electron Microscopy (SEM) and X-ray powder diffraction (XRD) were also used to examine the reconstituted soil structure and chemical component *[Code a3]*s. It is demonstrated that a reconstituted clay soil combination of 12 mm basalt fibers, 5% RHA, and 3% cement, enhanced the ultimate yield pressures and the resistance to excessive swelling. *[Code a4]*

This paper emphasized the projected responses during the loading and unloading phases on the specimen and discussed the consolidation characteristics of the newly reconstituted soil composites *[Code a5]*.

1. Introduction

the foundation footing and subgrade [6]. Also, in literature, using RHA, lime, and gypsum as additives to expansive soil has resulted in signifi-
Construction of engineering infrastructures such as roads, embank—

cant development in the strength characteristics of weak expansive soil
ments, bridges, and buildings on clay soils is often discouraged due to

[7]. These investigations disclosed that adding cement or lime to RHA the weak structural framework. Therefore, reconstituting such soils with might accelerate the strength properties. However, cement-treated soils various stabilizing additives and reinforcements is extensively practiced are more prone to shrinkage and cracking when used as a base course

to curb this challenge. The effects of the stabilization techniques in such

[8,9].

reconstituted soils can be quantified in terms of consolidation behavior To control this shrinkage and cracking, the utilization of fibers is and bearing capacity. Upon which, the consolidation behavior helps gaining focus due to the reinforcements added to the soil mass. Fiber analyze the deformation projections of geotechnical structures built on inclusions significantly modify and improve the mechanical behavior of the reconstituted clays and model the soil behavior (for example, set-these types of soils [10-18]. Recently several pieces of research on fiber tlement, swelling, excessive shrinkage, and cracking) [1,2].

reinforced soils have been carried out to examine the compressibility In engineering practice, chemical additives such as cement and rice

responses and strength parameters. Drained triaxial compression tests husk ash (RHA) have been used to enhance the soil structure of such

have indicated increased peak strength in sandy soils stabilized with expansive clay soils because of the associated pozzolanic activity during cement and randomly oriented fiberglass [19]. In a separate study, the stabilization process [3-5]. Furthermore, stabilizing expansive soil Consoli et al. demonstrated that utilizing randomly distributed poly-using RHA and fly ash has also considerably reduced swelling between ethylene fibers obtained from plastic wastes and combined with rapid

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hardening Portland cement improved the engineering behavior of uni—

soil. Testing procedures followed Japan Industrial Standards JIS A 1204

form sand [20]. Moreover, the combined use of different types of fibers, for the sieve and hydrometer test and JIS A 1205 for the liquid and

for example, polypropylene and glass fiber, to reinforce weak soils have plastic limit tests. Additional geotechnical properties are shown in also attracted research attention [21]. Syed and Guha conducted a

Table 1.

simulation to determine the reliability index of using two kinds of fibers and found out that the amounts of fibers present in the stabilized com-2.1.2. Rice husk ash

posite are essential factors in determining the ultimate strength.

A controlled burned RHA at 650–700 ◦C with high silica content of

Regarding the consolidation response of soils, Abdi et al. [22] found 91.10% was provided by Make Integrated Technology Co., Ltd, Osaka,

out that the addition of randomly distributed polypropylene fibers Japan. The high silica content was obtained by burning the rice husks for substantially reduced the consolidation settlement of clay soil [22]. The 27 h in a computer-controlled industrial incinerator. The RHA particles literature cited a study on the consolidation settlement and swelling sizes ranged from 0.07 to 0.3 mm. Detailed particle size distribution of characteristics of clays, including 5, 10, and 15 mm polypropylene fibers soil and RHA is shown in Fig. 1. A detailed physical and chemical at the fiber content of 1, 2, 4, and 8% by weight of soil. Das and Pal [23]

property chart for rice husk ash is illustrated in Table 1.

tested the consolidation characteristics of silty-clay soil mixed with fly ash and concluded that the compression index decreased significantly 2.1.3. Basalt fiber

with increased fly ash content. Kar and Pradhan [24], in a study on Basalt fiber used in this research had a tensile strength of between strength and compressibility characteristics of local cohesive soil (CL) 4100 ~ 4840 MPa, high elastic modulus ranging from 93.1 ~ 110GPa,

with random inclusion of polypropylene and coir fibers, observed that and lengths of 3 mm, 6 mm, and 12 mm. Other physical properties compression index and the coefficient of volume change decreased with include fiber diameter; 6 ~ 30 μm, fiber density; 2.63 ~ 2.8 g/cm3, and a an increase in the fiber content. Many relatable approaches have been fracture elongation rate of 3.1%.

suggested to investigate soils with various fiber reinforcements [25-30].

Even though experimental studies have utilized fibers and cement 2.1.4. Portland cement

composites to stabilize soils and analyze the consolidation characteris- Ordinary Portland Cement (OPC) was also used as a binder element.

tics in literature, information about the dimensional effects of environ-The physical and chemical properties of OPC cement are illustrated in mentally friendly fiber such as basalt fiber is scarce.

Table 2.

Furthermore, the interaction between basalt fibers and sustainable

stabilization techniques using RHA with nominal cement dosages is also scarce. The superiority of basalt fibers over conventional fibers is 2.2. Specimen preparation and testing method

derived from the high tensile strength and the natural occurrence from basalt rocks which gives it more versatility in enhancing the compressive To prepare the specimen, 200 g of the air-dried soil passing through capabilities of expansive soil composites. Therefore, the analysis of the 0.425 mm sieve was mixed with basalt fiber, RHA, and cement in the reconstituted weak expansive soils with basalt fibers is necessary to specified combinations, as shown in Table 3. Specimen were prepared ensure its validation for vast applications due to the enhanced using soil (200 g), basalt fiber (3 mm, 6 mm, and 12 mm), RHA (5%,

geotechnical behavior. On the other hand, using RHA as a sustainable 10%, and 15% dry weight of soil), and cement (3% dry weight of soil).

means of chemically stabilizing expansive soils addresses the environ-The nominal dosage of OPC used in this study provided the necessary

mental pollution concern while maintaining sustainable geotechnical Calcium ions required to enhance the pozzolanic reactions within the applications in engineering construction works.

prepared specimen. Water was then added to an initial water content of This investigation, therefore, aims to generate information on the

approximately 45%, 50%, and 55% for 5%RHA, 10%RHA, and 15%

overall consolidation response of reconstituted expansive clay soil RHA, respectively, due to the high-water affinity for the higher per-composites reinforced with varied basalt fiber lengths and RHA-cement centages of RHA. The added water increased the water content of the dry mixtures in their specified combinations. It also evaluates the optimal soil to slightly above the liquid limit hence simulating pore water combination appropriate for engineering applications. Odometer tests pressures similar to clay in its natural state. Each soil, basalt fiber, RHA, on specimens containing basalt fibers (lengths: 3 mm, 6 mm, 12 mm),

and cement combination was then mixed for 5 min to achieve a RHA (5%, 10%, and 15%), and cement (3%), and in their specified combinations were carried out. The consolidation curves demonstrated **Table 1**

the effects of basalt fiber length, RHA content, and minimal cement Properties of Soil and RHA.

dosage. Results of consolidation yield stress (σ'), SEM, XRD, compres- Materials

Property

Value

sion index (Cc), swelling index (Cs,) and assessment of compression curves at pre-and post-yield states of the reconstituted clay soil were Soil

Specific Gravity, g/cm3

2.74

Properties

Maximum dry density, g/cm3

1.65

studied and depicted in graphical form for the sake of convenient design Saturation, %

87.14

of such soil composites during engineering applications.

Sand (75 μm − 2 mm), %

6.20

Silt (5–75 μm), %

52.56

2. Materials and methods

Clay < 5 μm, %

41.24

Liquid limit, LL, %

58.21

Plastic limit, PL, %

31.05

2.1. Materials

Plasticity Index, PI, %

27.16

AASHTO classification

A-7–5(2)

2.1.1. Soil

RHA Properties

Average Particle Size, mm

0.001 to 0.3

Loss of Ignition, %

4

The soil used in this research was collected from Handa Area, Mie

–6

Specific Gravity, g/cm3

2.12

Prefecture, Japan. The soil was air-dried for 3 weeks and then sieved
Burning Temperature, ◦C

650–700

through the 200 mm sieve, after which sieve analysis, hydrometer Burning time, hour

27

analysis, liquid limit, and plastic limit analysis were conducted to clas-
Silica (SiO2), %

91.10

sify the soil. The liquid and plastic limits were 58.21% and 31.05%, Carbon dioxide (CO2) %

4.35

Potassium Oxide (K

respectively. The soil consisted of 6.2% sand, 52.56% silt, and 41.24%

2O), %

2.40

Calcium Oxide (CaO), %

0.57

clay. Also, based on the American Association of State Highway and

Iron Oxide (Fe2O3), %

0.05

Transportation Officials (AASHTO), the soil was classified as A-7–5(2)
Alumina (Al2O3), %

0.03

clayey soils. The soil compositions above rank the soil as expansive clay
Others, %

1.50

2

3. Consolidation framework

A-7-5(2) (Clayey Soil)

100

Rice Husk Ash (RHA)

In geotechnical engineering, chemically stabilized soils possess an

Cement (C)

artificial soils structure due to the hydration effect of cement and the 80

pozzolanic reactions present [34-38]. Therefore, during the loading/

reloading phase on such artificially structured soils, the compression 60

index is low until the yield pressure (σ’) is realized due to the resistances attributed to the soil structure. An ideal illustration of the consolidation

% Finner

behavior of soils is shown in Fig. 2.

40

Beyond this yield pressure (σ’), compressibility is significantly increased due to the loss of soil structure, also known as destructuring 20

[2,39-43]. During destructuring, the additional void ratio (es) declines with the increasing effective vertical pressure(σv) due to the soil structure. Hence, with a further rise in σv, the compression curve of the 0

artificially structured clay tends to meet the compression curve of 0.0001

0.0010

0.0100

0.1000

1.0000

remolded/destructured clay, also known as the Intrinsic Compression

Particle Size, D (mm)

Line (ICL) [1,44]. This variation in the void ratio can be expressed as: e = eR + es (1).

Fig. 1. Particle size distribution for soil and RHA.

Where e: represents the void ratio of the artificially structured soil, eR: represents the void ratio of the remolded/destructured clay, and lastly, es: the additional void ratio attributed to the soil structure **Table 2**

Properties of OPC.

destruction [45]. Burland [1] suggested the ICL as a reference point for interpreting the responses of all artificially structured clays when the Materials

Property

Value

effective stresses were between 10 kPa and 4000 kPa in all testing Cement

Initial setting time, minutes

170

conditions. The ICL was plotted in terms of a void ratio e given by the Properties

Final setting time, minutes

225

Eqs. (2–3), versus the log of the effective vertical pressure, log σv.

Specific gravity, g/cm3

3.15

Specific surface area, m^2/kg

340

$e = I_v C_c^* + e^*_{100}$ (2).

28-day compressive strength, MPa

33–53

I

3

v = 2.45– 1.285log σv + 0.179 log σv (3) Where Cc* is the intrinsic
Calcium Oxide (CaO), %

63.40

compression index defined by the difference between the void ratio of
Silicon dioxide(SiO_2), %

21.60

the remolded clay at 100 kPa (e^*_{100}) and 1000 kPa (e^*_{1000}) and Iv: the
Iron Oxide (Fe_2O_3), %

5.35

intrinsic void index. It was resolved that, for normally consolidated clay,
Alumina (Al_2O_3), %

4.45

Sulfur trioxide (SO_3), %

1.92

the position of consolidation curves to the ICL line depends on the clay
Magnesium oxide (MgO), %

1.65

soil’s structural composition [1]. In addition, Hong et al. [46] found that
Sodium oxide (Na_2O), %

0.11

when the stress levels were higher than the remolded/reconstituted
Potassium oxide (K_2O), %

0.22

soils’ yield pressure, the compression curves of remolded/ reconstituted
Loss of ignition, %

< 4

clay normalized well with the ICL. The validity of this consolidation framework is illustrated in this study for the proposed reconstituted clay
Table 3

Experimental specimen codes and specified combinations.

Specimen Code

Soil, S

Basalt Fiber, BF

RHA

Cement, C

(g)

(mm)

(%)

(%)

S-Control

200

0

0

3

S:5R:3C

200

0

5

3

S:10R:3C

200

0

10

3

S:15R:3C

200

0

15

3

S:5R:3C:1BF3

200

3

5

3

S:10R:3C:1BF3

200

3

10

3

S:15R:3C:1BF3

200

3

15

3

S:5R:3C:1BF6

200

6

5

3

S:10R:3C:1BF6

200

6

10

3

S:15R:3C:1BF6

200

6

15

3

S:5R:3C:1BF12

200

12

5

3

S:10R:3C:1BF12

200

12

10

3

S:15R:3C:1BF12

200

12

15

3

homogeneous mixture. The homogeneous mix was then transferred to

the soil cutting rings (diameter 60 mm and height 20 mm) and trimmed to fit the odometer test rings of similar dimensions. After setting the specimen in the odometer testing machine, they were then subjected to incremental loads of 9.8, 19.6, 39.2, 78.5, 157, 314, 628, and 1256 kN/

m2 during the loading phase and 628, 314, 157, 78.5, 39.2, 19.6 and 9.8

kN/m2 during the unloading phase. Each load increment/reduction was

kept constant for 24 h until the primary consolidation had seized [31].

The testing procedures followed the Japan Industrial Standards [32,33].

Fig. 2. Consolidation behavior of soil. (modified from Du et al., [38]).

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soil composite, as will be discussed in the next section.

4. Results and discussion

4.1. Compression curves

The void ratio (e) versus effective vertical pressure (log σv) compression curves for the reconstituted soil specimens at RHA contents of 5, 10, and 15% are shown in Fig. 3a, Fig. 3b, and Fig. 3c, respectively.

The influence of varying the basalt fiber length from 3 mm to 6 mm to 12 mm is also shown in each RHA content. In all the figures presented in this study, the symbol S denotes soil, i R denotes a specimen with an RHA content of i%; i C denotes cement content of i%, while BF i denotes a specimen with basalt fiber length i mm. It can be seen from Figs. 3a, 3b,

and 3c that the compression curves of all S i R i CBF i reconstituted soil specimens lie above that of the corresponding soil specimen and show a typical concave shape due to the effects of soil-structure [46,47]. When the effective vertical pressure (σv) is lower than the yield pressure (σ’), slight compressibility is realized due to the resistances initiated by the **Fig. 3b.** Compression curve for basalt fiber reinforced soil at 10%RHA.

soil structure [48]. After the yield pressure, the compressibility of the reconstituted and stabilized soils increases significantly due to the gradual collapse of the soil structure at higher effective vertical pressure levels.

Meanwhile, it is noteworthy that the relationship between the void

ratios and the effective vertical pressure is highly dependent on the length of basalt fiber, RHA content, and cement content, with higher void ratios in the S:15R:3C:1BF specimens. It is noticeable that the void ratio decreases as the effective vertical pressure increases for all instances. The yield pressure (σ’) can be estimated from these plots using the Casagrande method [49].

The relationship between yield pressure (σ’) and various lengths of

basalt fiber is shown in Fig. 4. It can be observed that increasing the length of basalt fibers from 0 mm to 12 mm improves the yield pressure of the reconstituted soil composite for all the RHA-cement mix ratios.

The random fiber inclusion and the orientation of basalt fibers increase the specimen’s stiffness hence improving the yield pressure (σ’). Addi-tionally, scanning electron microscopy (SEM) shows a dense network of basalt fibers in the stabilized soil, as shown in Fig. 5a, 5b, and 5c for the high strength specimens S:5R:3C:1BF12, S:10R:3C:1BF12, and

Fig. 3c. Compression curve for basalt fiber reinforced soil at 15%RHA.

S:15R:3C:1BF12 respectively. From this phenomenon, it can be

concluded that the random inclusion of high tensile strength fibers enhances the mechanical interaction between the fibers and the sur-rounding reconstituted soil composite through an anchoring effect and is more significant as the length of basalt fibers increases from 0 mm to 12

mm.

Furthermore, the increment in yield pressure was due to the **Fig. 4.** Relationship between yield pressure (σ’) and basalt fiber length.

resistance to compression pressures initiated by the pozzolanic reaction in the soil structure [50]. For example, at low RHA contents of 5%, there was a significant improvement in reconstituted soil structure due to the complete utilization of RHA and cement during the pozzolanic reactions.

This structural development and basalt fiber reinforcements formed a **Fig. 3a.** Compression curve for basalt fiber reinforced soil at 5%RHA.

al.

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Fig. 5. Quantification of the increase in yield pressure by SEM imagery: (a) S:5R:3C:1BF12 specimen, (b) S:5R:3C:1BF12 specimen, (c) S:5R:3C:1BF12 specimen.

highly compact reconstituted soil structure with almost no visible $(SiO_2)_6$ $4(H_2O)\}$ and SiO_2, also known as CSH Gel. The presence of porous morphology, as illustrated in Fig. 5a. On the other hand, alumina in the CHS gel significantly increases the stability of the increasing the RHA content to 10% and 15% led to excess RHA within

reconstituted soil composites hence improving yield pressures of up to the reconstituted soil composite, producing a more porous soil com-110kN/m2 (for BF12mm) [51]. Correspondingly, increasing the RHA posite structure, as shown in Fig. 5b and Fig. 5c. The porous morphology contents to10% and 15% leads to the formation of CSH gel, but, with a was more susceptible to compressive pressures; thus, the noteworthy

fragile dicalcium silicate hydrate $\{Ca_2(SiO_3OH)(OH)\}$ composition due reduction in yield pressure as compared to 5% RHA content.

to the absence of alumina compounds in the reconstituted soil composite In this study, the presence of pozzolanic elements is quantified using as shown in Fig. 6b and 6c [52]. The fragility of the 10% and 15% RHA X-ray powder diffraction (XRD) analyses, as shown in Fig. 6. In Fig. 6a,

composites are quantified by the reduced maximum yield pressures of

the XRD analysis of 5%RHA reconstituted soil composites shows high

74kN/m2 and 60kN/m2, respectively. However, with the addition of peaks of Calcium Aluminohexasilicate Tetrahydrate $\{(CaO)(Al_2O_3)$ basalt fibers, the 10% and 15% RHA reconstituted soil composites **Fig. 6.** Quantification of the pozzolanic elements by XRD analyses: (a) S:5R:3C:1BF12 specimen, (b) S:10R:3C:1BF12 specimen, (c) S:15R:3C:1BF12 specimen.

showed improved characteristics than the control specimens.

4.2. Normalized compression curve

Burland [1] introduced the normalizing void index (Iv) to correlate the compression curves of various remolded clay with the initial water contents ranging between 0.6 and 4.5 times the liquid limit. This correlation reported that the compression curves normalized well with the void index of reconstituted clays at initial water contents 1.0–1.5 times the liquid limits. Therefore, a unique line named the ICL was suggested to express the normalized compression curve in terms of the void index versus effective vertical pressures. The normalized compression curves of reconstituted soil composites for S:5R:3C:1BF and S:10R:3C:1BF

specimens are shown in Fig. 7a and Fig. 7b, respectively, calculated using Eq. (3). Despite the discrepancy in basalt fiber lengths in the specimens, the compression curves of the reconstituted soil composite normalized perfectly with the ICL after the yield pressure phase, as suggested by Hong et al. [46]. The perfect normalization illustrated the **Fig. 7b.** Normalized compression curves at 10% RHA.

presence of significant bonding in the new stabilized soil composite

[53]. In addition, the higher effective vertical pressures (ranging from 100 to 1200kN/m2) accelerated the rearrangement of the soil-RHA-cement particles and the basalt fibers relative to each other, resulting in a compact reconstituted soil structure.

On the other hand, the normalized curves for S:15R:3C:BF6 and S:15R:3C:BF12 are positioned below the ICL at vertical pressures above 100kN/m2 due to high RHA content in the reconstituted clay soil, as illustrated in Fig. 7c. The inadequate pozzolanic reactions and destructuring can bring about such behavior in the soil at high loading pressures.

4.3. Compression Index, Cc

The compression index (Cc) is a fundamental parameter in determining the one-dimensional consolidation settlement of reconstituted clays. The greater the Cc value, the higher the chances of one-dimensional consolidation. The index is calculated from the normal consolidation phase (Loading phase) of the compression curves due to the elastic behavior of the soil. The compression index can be easily obtained by extending the straight-line portion of the normal consoli-Fig. 7c. Normalized compression curves at 15% RHA.

dation region of the compression curves in Fig. 3a, Fig. 3b, and Fig. 3c.

Then, taking the difference in the void ratio(e) divided by the change in reconstituted soil composite for a given soil-RHA-cement content, as effective vertical pressure (σ’) in the log scale as shown in Eq. (4).

shown in Fig. 8. The specimen without basalt fibers shows Cc values

[

]

ranging between 0.39 and 0.41 as the RHA content increases from 5% to e

15%. Adding basalt fiber into the reconstituted soil composite reduces c

a −

eb

(

c =

(4)

log σ 1 − σ 1

the compression index values by approximately 16% to values between

b

a

0.329 and 0.351; 0.33–0.345; 0.35–0.37 for basalt fiber lengths 3 mm, 6

The Cc value varies with the lengths of the basalt fiber included in the **Fig. 7a.** Normalized compression curves at 5% RHA.

Fig. 8. Compression index Cc versus length of basalt fibers.

mm, 12 mm, respectively. A comparable reduction in compression index
4.5. Assessment of compression curves

values when fibers are supplemented into a soil composite was noted by Kar and Pradhan [23]. It is also apparent from Fig. 8 that the degree of The test results in this study demonstrate that the compressibility of compression is dependent on the length of basalt fibers in the specimen.

clay soils reinforced with basalt fiber and stabilized with RHA and For example, an increase in basalt fiber length from 3 mm to 6 mm gives cement can be determined by three parameters: length of basalt fibers, an insignificant rise in compression index compared to the notable yield pressure (σ'), and RHA-cement content. It is also evident that the development at 12 mm. Moreover, it is noteworthy that compression

compressibility rate is directly related to the degree of bonding as re-index values are kept to an average value of 0.3 for the 5% RHA-3%

flected by the yield pressure (σ') [33,38]. In this study, this bonding cement specimen, and a nominal increase is achieved as the RHA con-phenomenon is attributed to the pozzolanic reactions (between soil, tent rises to 10% and 15%-3% cement. This nominal increase in the

RHA, cement) and basalt fiber reinforcements. For example, considering compression index was due to the mobilized rearrangement of the par-the S:5R:3C:1BF12 specimen, the yield stresses increase to 110kN/m2, ticles in the reconstituted soil composite due to the additional porosity reducing the compressive index from 0.392 to 0.35, as shown in formed by the excess RHA in the soil-RHA-cement composite.

Fig. 10a. Also, a reduction in compression index as yield pressure increases is observed for S:10R:3C:1BF12 and S:15R:3C:1BF12 with values 4.4. Swelling Index, Cs

of 0.354 and 0.37, respectively. The curve fitting equations illustrating the relationship between the compressive index and yield stress, based Expansive clay soils have great swelling potential due to the domion the experimental data of clay soils reinforced with different lengths of nant clay minerals that change volume when moisture changes ensue.

basalt fibers and stabilized with RHA, are therefore expressed as follows: Using fibers, methods to solve this swelling problem have recently Cc = 0.00007σ' 2 – 0.0147 σ' + 1.008; for S:5R:3C: i BF composites (5).

gained research attention [24,25,54]. In this study, the dimensional Cc = 0.00066σ' 2 – 0.0890 σ' + 3.301; for S:10R:3C: i BF composites influence of basalt fiber to curb the swelling of reconstituted clay soils is (6).

presented as shown in Fig. 9 using Eq. (4) and the unloading compres-Cc = 0.00159 σ' 2-– 0.1768 σ' + 5.245; for S:15R:3C: i BF composites sion curves in Fig. 3a, Fig. 3b, and Fig. 3c.

(7).

The reconstituted soil composite without basalt fibers depicts high

Where, Cc is the compression index and σ' is the yield pressure of the swelling indexes due to the absence of particle anchorage mechanism

reconstituted soil composite. The correlation coefficients (R2) of the brought about by the fiber reinforcements. Upon basalt fiber addition, yield pressure versus the compression index shows high reliability of the the swelling index of the 5% RHA-3% cement reconstituted soil spec-test data as illustrated in Fig. 10a, Fig. 10b and Fig. 10c with values 0.99, imen reduces from 0.0339 (for BF3mm) to 0.028 (for BF12mm), and a

0.86 and 0.94 respectively.

similar trend is observed for 10% and 15% RHA specimens as illustrated

in Fig. 9. It is evident that longer fibers (BF12mm) substantially reduce **5. Conclusions**

the swelling index. For instance, reconstituted soils composites with 3

mm basalt fibers have a swelling index of 0.0326, 0.0322, and 0.0312 for A series of oedometer tests were performed to investigate the 5%, 10%, and 15% RHA, respectively. While reconstituted soil specimen dimensional influence of basalt fibers reinforcements on the consolida-with 12 mm basalt fibers attained 0.028, 0.0265, and 0.0261 for 5%,

tion behavior of RHA-cement stabilized soils. The dimensional effects of 10%, and 15% RHA, respectively. The intensity of fiber interaction basalt fibers and the RHA-cement content on the consolidation yield

within the specimen arrests the interparticle movements hence the pressure(σ'), compression index (Cc), and swelling index (Cs) at the prereduced swelling potential during the unloading phase compared to the and post-yield state are discussed. The concept of the intrinsic specimen without fibers.

compression line is adopted to assess the compression curves of the new Furthermore, it is seen that the influence of basalt fiber re-fiber reinforced soil composite. The following conclusions can be drawn inforcements on the swell index is more significant at higher rice husk from this study:

ash content. The high RHA contents mixed with nominal cement dosages produce a low-plastic material with a high water absorption rate. Hence, 1. Increasing the length of basalt fiber in the reconstituted clay soil the decreases in swelling index with increased rice husk ash content composite improves the consolidation yield pressure (σ'). This in-

[55,56].

crease in yield pressure is also dependent on the RHA-cement content in the reconstituted soil structure. This behavior suggests that the composition of soil structure mainly governs the degree of yield **Fig. 9.** The relationship between swelling index (Cs) and length of basalt fiber.

Fig. 10a. Relationship between σ' and Cc for 5%RHA soil composites.

index of 0.0281. The improved consolidation characteristics make

the new composite suitable for use in foundation fills as it can resist excessive settlement when subjected to structural loads.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Fig. 10b. Relationship between σ' and Cc for 10%RHA soil composites.

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