Engineering Properties of Silty Soil Stabilized with Lime and Rice Husk Ash and Reinforced with Waste Plastic Fiber

Agus Setyo Muntohar[1]; Anita Widianti[2]; Edi Hartono[3]; and Wilis Diana[4]

Abstract: Although abundant plastic waste contaminating the environment may be utilized as reinforcing materials, a potential pozzolanic material (rice husk ash blended with lime) possesses superior properties in stabilizing soils. Engineering behavior of the stabilized clayey/silty soil reinforced with randomly distributed discrete plastic waste fibers is investigated in this paper. The results indicate that the proposed method is very effective to improve the engineering properties of the clayey/silt soil in terms of compressive, tensile, and shear strength, which further enhanced the stability and durability of the soil. Based on the compressive strength, California bearing ratio (CBR), shear strength, and failure characteristics, the optimum amount of fiber mixed in soil/lime/rice husk ash mixtures ranges from 0.4–0.8% of the dry mass. **DOI: 10.1061/(ASCE)MT.1943-5533.0000659.**

CE Database subject headings: Fibers; Lime; Soil stabilization; Plastics; Waste management; Recycling; Subgrades; Fiber reinforced materials.

Author keywords: Engineering properties; Fiber; Lime; Rice husk ash; Soil stabilization; Plastic wastes; Subgrade.

Introduction

Disposal of different waste materials produced from various industries is a serious problem. The wastes pose environmental pollution problems for the surrounding disposal area because some of the wastes are not biodegradable. The utilization of industrial wastes in road construction has been of great interest in industrialized and developing countries during recent years. Such utilizations are commonly based on technical, economical, and ecological considerations. Lack of conventional materials and improvement of the environment renders it imperative to search for substitutions, including that of industrial wastes. Industrial wastes (e.g., fly ash, slag, and mine tailing) have been blended with lime and cement to improve the geotechnical properties of roadway subgrade (Balasubraniam et al. 1999; Kaniraj and Gayathri 2003; Bin-Shafique et al. 2010; Rahmat and Kinuthia 2011). Another waste that has potential for alternative materials is rice husk. Rice husk is abundant in rice-producing countries such as Indonesia, Thailand, Philippines, and many others (Hwang and Chandra 1997). It is sometimes burnt for parboiling paddy in rice mills. The partially burnt rice husk will contribute to environmental pollution. Significant efforts has been devoted not only to overcome the pollution problem but also to increase its added value by using it as substituting or secondary materials for limited-availability conventional materials.

During the last few decades, research has been carried out to investigate the utilization of rice husk ash as a stabilizing material in soil improvement (Lazaro and Moh 1970). Much research (e.g., Lazaro and Moh 1970; Rahman 1987; Ali et al. 1992a; Basha et al. 2005; Hossain 2011) has shown that rice husk ash (RHA) is a promising secondary material to improve lime or cement-stabilized soils. Addition of rice husk ash in lime or cement-stabilized soils enhanced the compressive strength significantly (Balasubramaniam et al. 1999; Muntohar and Hashim 2002; Muntohar 2002). However, the stabilized soil exhibited brittle-like behavior (Muntohar 2002; Basha et al. 2005). The brittleness of the stabilized soil may be suppressed by inclusion of discrete elements such as fibers. Stabilized and reinforced soils are composite materials that result from an optimum combination of the properties of each individual constituent material. A well-known approach in this area is the use of fibers and cemented materials in composites. Experimental verification reported by various researchers (e.g., Messas et al. 1998; Muntohar 2000; Consoli et al. 2002; Ghiassian et al. 2004; Kaniraj and Gayathri 2003; Cavey et al. 1995) has shown that the fiber-reinforced soils are potential composite materials, which can be advantageously employed in improving the structural behavior of stabilized and natural soils. Other researchers (Consoli et al. 1998; Kaniraj and Havanagi 2001; Tang et al. 2007) have successfully used fiber reinforcement in a cement-stabilized soil. Fieldwork experience suggests that it is easier to control the fiber content in comparison with its length. Longer fiber will be more difficult to uniformly distribute in the soil–fiber interface and resulting slippage plane in the soil. Thus, it was suggested to limit the fiber length to be less than 50 mm in length (Al-Refei 1991; Santoni et al. 2001; Jiang et al. 2010). Previous studies have indicated that the fiber content is the most controlling strength parameter (Consoli et al. 2002; Gaspard et al. 2003; Muntohar 2009).

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The use of composite materials from industrial by-products is beneficial to the environment. Plastic waste materials, such as polyethylene terephthalate (PET) plastic bottles, polypropylene (PP) of plastic sacks, and PP of carpet, is plentifully produced every day. They are commonly discarded in storage or disposal sites. Nevertheless, little attention has been paid for such materials for applications in roadway and geotechnical construction. The utilization of lime/rice husk ash and plastic waste to stabilize and reinforce soils needs to be further investigated. The present paper examines the influence of the plastic-waste fiber to improve the engineering properties of the lime/rice husk ash-stabilized soils. The properties being evaluated are compressive and tensile strength, shear strength, and California bearing ratio (CBR) of the soil. In addition, environmental effects on the change of soil strength and the optimum fiber content required to improve the strength and durability are also reported in this paper.

Experimental Methods

Materials

The soil samples were taken from the area of Sentolo, Yogyakarta, Indonesia. They were dried and crushed into small pieces in the laboratory and sieved by passing through a 4.75-mm sieve. Table 1 presents the properties of the soil samples. Based on the index tests, the soil sample was comprised of 76% fines particles. Thus, the soil can be classified as fine-grained, which is silt of high plasticity. The soil has the symbol MH in accordance with ASTM D2487-11 (ASTM 2011a) or grouped as A7-5 in accordance with ASTM D3282-09 (ASTM 2009a).

A powder-hydrated lime was used as a stabilizing material for the research reported in this paper. Table 2 presents the oxide elements of the lime. The lime was comprised of 95% CaO as the primary chemical constituent. To reduce the carbonation effect attributable to humidity, the lime was kept in an airtight plastic container. The other material, RHA, was obtained from the rice-husk-burning disposal area at Godean, Yogyakarta. For this research, only the grey-colored ashes were collected and sun-dried to reduce the moisture. To produce acceptable fineness, the ashes were ground in a Los Angeles abrasion machine. The steel balls were replaced with 40 steel bars to enhance the ability to grind the RHA. The steel bars were 10 and 12 mm in diameter with various lengths ranging from 200–300 mm. Five kg of the RHA was placed into the machine and ground for about 3 h. This technique produced a suitable fineness and proper surface area of 25 mm^2/g. The fineness of the RHA sample was tested by a Blaine fineness apparatus as recommended in ASTM C204-11 (ASTM 2011d). The ground RHA was then transferred into a plastic bag and stored in an airtight container at room temperature (about 25°C) to prevent atmospheric humidity absorption. Chemical composition of the RHA and lime was examined using the X-ray fluorescence method (Table 2). The RHA was comprised of 89.08% SiO_2, 1.75% Al_2O_3, 0.78% Fe_2O_3, and 1.29% CaO. In accordance with the chemical composition as specified by ASTM C618-12 (ASTM 2012), the RHA could be classified as Class N pozzolana because the sum of the SiO_2, Al_2O_3, and Fe_2O_3 was 91.61% with a SO_3 of 0.01% and a Na_2O of 0.85%.

Polyproylene plastic waste was used as the fiber reinforcement. The plastic bag waste was collected from the local municipal disposal area in Yogyakarta. The quality of the fibers was examined by hand-tension. If the fibers were easily fracturing, the plastic wastes were discarded. Discrete fibers were obtained by cutting the available plastic bag wastes to a length range from 20–30 mm. The width of a single fiber was approximately 2–2.5 mm (Fig. 1). Tensile strength tests were performed on the plastic bag sheet of

Table 1. Properties of the Soil Samples

Parameters	Values
Specific gravity, G_s	2.62
Water content at air dry (weight %)	18.3
Consistency limits	
Liquid limit, LL (%)	63
Plastic limit, PL (%)	37
Plasticity index, PI (%)	26
Soil fraction	
Clay size (%)	16.0
Silt size (%)	60
Sand (%)	24
Proctor standard compaction	
Maximum dry density, MDD (kN/m^3)	12.1
Optimum moisture content, OMC (%)	37.5
Unconfined compressive strength, q_u (kPa)	2.34
Soaked-California bearing ratio, CBR (%)	6.22
Soil classification	
Unified soil classification system	MH
AASHTO	A-7-5

Table 2. Chemical Composition of the Additives

Constituents	Lime (%)	RHA (%)
SiO_2	0.00	89.18
Al_2O_3	0.13	1.75
Fe_2O_3	0.08	0.78
CaO	95.03	1.29
MgO	0.25	0.64
Na_2O	0.05	0.85
K_2O	0.03	1.38
MnO	0.04	0.14
SO_3	0.02	0.01
P_2O_5	0.00	0.60
H_2O	0.04	1.33
Loss on ignition	4.33	2.05

Fig. 1. Sample of the fibers used in the research reported in this paper

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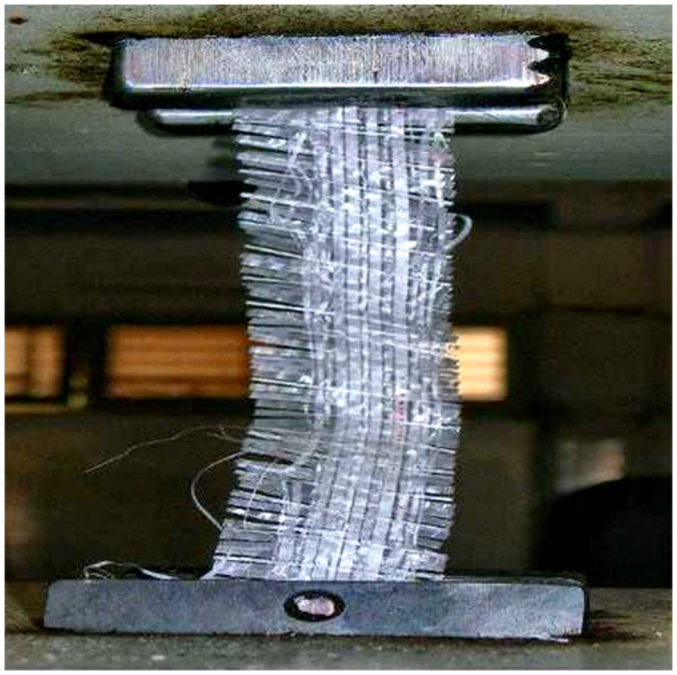

Fig. 2. Illustration of the tensile test of a plastic bag sheet

100 × 200-mm sizes (Fig. 2). The tensile strength of the plastic fiber specimens was 63 kN/m on average and the strain at rupture was 15.3% on average.

Specimen Preparation and Testing Procedures: Overview

An amount of soil was mixed with lime and rice husk ash to yield stabilized soil specimens. The ratio of the lime to rice husk ash was designed as 1:2 by their weight as provided by previous investigations (Muntohar 2002, 2009; Ali et al. 1992b; Sharma et al. 2008). The lime required for stabilization (LRS) was determined in accordance with the method suggested by Eades and Grim (1966). The LRS was determined at a pH of the soil/lime solution reaching 12.40. In the research reported in this paper, the amount of LRS was about 12%. To reinforce the stabilized soil, the fiber content was designed in various contents that are 0.1, 0.2, 0.4, 0.8, and 1.2% of the dry weight of the soil. Table 3 presents the mixture design and tests. All the specimens were prepared to the maximum dry density (MDD) and optimum moisture content (OMC), and tested after a 14-day moist-curing period.

Specimen Preparation and Testing Procedures: Mixing Procedure

Fiber-reinforced specimens were mixed to the OMC in accordance with a two-stage procedure. In the first stage, the dry soil and admixture (lime and RHA) was mixed with approximately 50% of the total amount of water needed to bring the sample to the desired moisture content. In the second stage, the reinforcing fibers were distributed within the hydrated soil samples in three approximately equal amounts. The soil/admixtures/fiber sample was mixed manually and the remaining water was added. As the fibers tended to lump together, it required considerable care and time to separate them to obtain an even distribution of the fibers in the mixture. All of the mixing was done manually and proper care was taken to prepare homogeneous mixtures at each stage of mixing. After mixing and production of the desired specimen sizes, they were cured and stored at room temperature (about 25°C) to prevent moisture loss.

Specimen Preparation and Testing Procedures: Unconfined Compression and Split-Tensile Tests

The unconfined compressive strength (UCS) test apparatus was employed in the tests. Samples were shaped in a mold with a length of 100 mm and an inner diameter of 50 mm. The specimens were prepared at the state of MDD and OMC. To ensure uniform compaction, the required quantity of the material was placed inside the mold in three layers and compacted statically by applying compressive pressure from a hydraulic jack. Two identical specimens were used to determine the unconfined compressive strength and split-tensile strength. To control the variation of the test results, especially for the UCS and split-tensile tests, the difference of the two values should not be greater than 10%. If the difference of the values between the specimens was greater than 10%, other specimens were prepared and tested.

The unconfined compression tests and the split-tensile tests were carried out in accordance with ASTM D5102-09 (ASTM 2009b) and ASTM C496-11 (ASTM 2011b), respectively. After the curing period and before testing, the mass and dimension of specimen were recorded. The tests were performed on a 50-kN universal testing machine. A force was applied until the specimens reach a failure. The loading rate was approximate 1 mm/min. The split tensile strength was calculated as

$$T = \frac{2P_{\max}}{\pi \cdot L \cdot D} \tag{1}$$

where T = split tensile strength; $P_{\max}$ = maximum applied load; and L and D = length and diameter of the specimen, respectively.

Table 3. Mix Design and Type of Tests Conducted in the Experimental Program

Mixture number	Description	UCS	STS	UU	CBR	DUR
N1	Unstabilized soil, e.g., with neither lime, RHA, nor fiber	X	X	X	X	X
S1	Soil + 12% lime			X	X	X
S2	Soil + 12% lime + 12% RHA			X	X	X
SR3	Soil + 12% lime + 12% RHA + 0.1% fibers			X	X	X
SR4	Soil + 12% lime + 12% RHA + 0.2% fibers	X	X	X	X	X
SR5	Soil + 12% lime + 12% RHA + 0.4% fibers			X	X	X
SR6	Soil + 12% lime + 12% RHA + 0.8% fibers	X	X	X	X	X
SR7	Soil + 12% lime + 12% RHA + 1.2% fibers	X	X	X	X	X

Note: UCS = unconfined compressive strength test; STS = split-tensile strength test; UU = triaxial unconsolidated-undrained test; CBR = California bearing ratio test (soaked condition); DUR = wetting/drying durability test; RHA = rice husk ash. An "X" indicates that the test was performed at 14 days; all of the other tests were performed at 1, 7, 14, 28, and 56 days of curing.

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Specimen Preparation and Testing Procedures: Unconsolidated/Undrained Triaxial Tests

Three samples were formed at the state of MDD and OMC in a mold with a length of 76 mm and an inner diameter of 38 mm. Each mold contained the same volume of mixture such that the density of all tested samples was approximately the same. The soil samples were extracted from the molds after compaction. The specimens were placed in the triaxial chamber under unconsolidated/undrained (UU) conditions. In the research reported in this paper, the specimens were tested at unsaturated conditions. The testing procedure of triaxial UU followed that laid out in accordance with ASTM D2850-11 (ASTM 2011c). The cell pressures were applied at 98.1, 196.2, and 294.3 kPa. The specimens were sheared at a rate of 0.8 mm/min.

Specimen Preparation and Testing Procedures: California Bearing Ratio Test

The California bearing ratio tests were conducted on specimens prepared in a cylindrical mold of 150 mm-diameter and 175-mm height. The specimens were prepared by compacting samples in five layers at its MDD and OMC based on the standard Proctor compaction. The tests were conducted in accordance with ASTM D1883-07 (ASTM 2007). The specimens were immersed in water for 3 days before crushing by applying compressive pressures. This condition produced a soaked CBR value. During the soaking process, vertical deformation was measured to determine the swelling.

Specimen Preparation and Testing Procedures: Durability Test

Durability test was conducted by repeating wetting and drying of the specimens in accordance with ASTM D559-03 (ASTM 2003). The specimens are compacted statically in a mold of 50-mm diameter by 100-mm length to the MDD and OMC values. The specimens were subject to a cycle comprised of 1-day submersion in water and 1-day air-drying. In the research reported in this paper, the specimens were subjected to 1–10 cycles of wetting/drying. The unconfined compressive test was then employed after each cycle was completed.

Results and Discussion

Unconfined Compressive Strength and Split-Tensile Strength

Table 4 presents the average unconfined compressive strength and split tensile strength of the specimens. Lime-stabilized soil increased both the compressive strength (q_u) and tensile strength (T_u). The q_u of the lime-stabilized soil was about 4× that of the unstabilized soil. The q_u increases from 23.4 to 98.4 kPa, whereas the T_u increases 2× from 2.4 to 4.8 kPa. The strength ratio, i.e., of the unconfined compressive strength to split tensile strength (T_u/q_u), of the lime-stabilized soil is about 0.05, which is smaller than the unstabilized soil (N1 specimen). Addition of the RHA in the lime/soil mixture slightly increased the compressive strength about 14% from 98.4 to 112.9 kPa, whereas the split tensile strength increased about 106% from 4.8 to 9.9 kPa. The strength ratio of the RHA-added lime/soil stabilization is about 0.09, which is slightly smaller than the unstabilized soil (N1 specimen) but higher than the lime-stabilized soil (S1 specimen), indicating that RHA did increase the tensile resistance of the lime-stabilized soil.

Table 4. Unconfined Compressive Strength, Split Tensile Strength, Secant Modulus, Shear Strength Parameters (c and ϕ), and Soaked-CBR of the Specimens

Mixture number	q_u (kPa)	T_u (kPa)	T_u/q_u	E_{50} (MPa)	Shear strength parameters: ϕ (degrees)[a]	Shear strength parameters: c (kPa)[a]	CBR (%)
N1	23.4	2.4	0.10	0.8	21.3	11	6.2
S1	98.4	4.8	0.05	2.15	22.4	106	18.6
S2	112.9	9.9	0.09	5.08	24.2	317.3	22.54
SR3	152.7	19.0	0.12	5.78	21.9	326.0	29.53
SR4	166.0	18.6	0.11	6.19	22.3	376.5	41.19
SR5	161.3	20.4	0.13	7.05	21.7	501.6	40.93
SR6	190.3	20.8	0.11	7.39	21.1	244.3	53.88
SR7	165.0	18.7	0.11	6.86	21.4	233.2	37.04

Note: q_u = unconfined compressive strength; T_u = split tensile strength; CBR = California bearing ratio; E_{50} = secant modulus of elasticity; ϕ = friction angle; and c = intercept cohesion.
[a]Obtained from triaxial UU test.

The test results show that fiber-reinforced lime/RHA/soil mixtures enhanced both the unconfined compressive strength and split tensile strength of the soil. Table 4 indicates that adding fiber to the stabilized soil slightly increased the strength ratio from about 0.11 to 0.13 by increasing the fiber content from 0.1 to 1.2%. The highest strength gain is obtained at 0.8% fiber content, and further addition of fibers tends to reduce both the unconfined compressive and tensile strengths, but the strength is still higher than the stabilized (specimen S2) and unstabilized (specimen N1) soils. The increase in the compressive and tensile strengths of the fiber-reinforced stabilized soil can be attributed to the increasing total contact area between the fibers and soil particles. The increase in fiber content consequently increased the friction between the soil particles, which contributes to increasing resistance to the forces applied. This phenomenon was also observed by Cai et al. (2006).

The increase of the both compressive and split-tensile strengths is beneficial for fiber reinforcement in soil/lime/rice husk mixtures. Increases in unconfined compressive strength and split tensile strength specimens were affected by the amount of fibers. Fig. 3

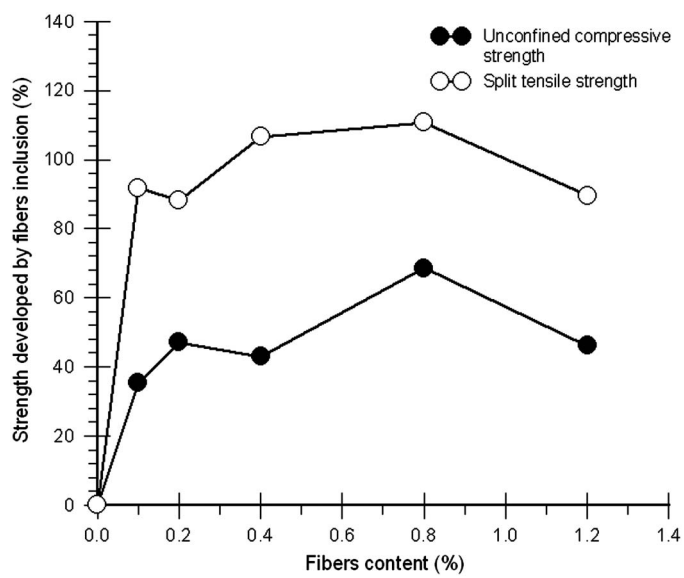

Fig. 3. Effect of fiber inclusion on the unconfined compressive strength and split-tensile strength of the stabilized soil

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Table 5. Values of q_u and T_u with Various Curing Times for Selected Samples

Age (days)	q_u (kPa) for specimen				T_u (kPa) for specimen				q_u/T_u for specimen			
	S1	S2	SR3	SR5	S1	S2	SR3	SR5	S1	S2	SR3	SR5
1	51	53	54	52	3.1	5.7	6.6	6.2	0.06	0.11	0.12	0.12
7	76	65	86	90	3.8	7.0	10.5	11.2	0.05	0.11	0.12	0.12
14	98.4	113	153	161	4.8	9.9	19.0	20.4	0.05	0.09	0.12	0.13
28	108	145	186	218	5.1	11.9	25.7	33.0	0.05	0.08	0.14	0.15
56	112	153	198	228	5.3	12.3	29.5	35.2	0.05	0.08	0.15	0.15

illustrates that the inclusion of fibers in the stabilized soil contributed about 35–68% and 88–110% of the increase in the unconfined compressive and split-tensile strengths, respectively. The results demonstrate that fibers play a significant role in increasing the tensile strength of stabilized soil when comparing with its compressive strength. The increase in fiber content causes the interface between the fiber and soil particles to increase and hence the friction between the fiber and soil particles increases, which renders it difficult for soil particles that surround fibers to change in position from one point to another and thereby improves the bonding force between soil particles, i.e., cohesion of the soil. Moreover, when local cracks appear in the soil, fibers across the cracks will take on the tension in the soil with fiber/soil friction, which effectively impedes further development of cracks and improves the resistance of soil to the force applied. Tang et al. (2007) noted the ability of the fibers to prevent further cracks as a bridge effect of fiber inclusion.

Table 5 presents the effect of curing on the q_u and T_u of the selected samples, showing that the strength increased as the curing period increased. Because of the time-dependent pozzolanic reactions, the stabilization of lime soil is a long-term process (Rao and Rajasekaran 1996). Thus, the strength of the stabilized soil increases and the curing duration increases. In general, the compressive strength increased with time, as did the tensile strength. For the unreinforced specimens (S1 and S2), the strength ratio decreased marginally, about 17–27%, whereas the compressive and tensile strength increased with the increase in curing time. In contrast with the fiber-reinforced specimens, the strengths were higher than the unreinforced specimen. The strength ratio of the fiber-reinforced specimens increases slightly, from about 0.12 to 0.15, with respect to the curing time. This finding is probably attributable to the cementitious product of the lime-RHA binds soil particles together and imparts a more compact matrix structure, and thus greatly restricts the rearrangement of particles on the interface and increases the interfacial effective contact area. The hydrated cement-like products of lime/RHA, which covers around the fiber surface, might improve the interfacial bond characteristics and increase the interlock force and friction coefficient between the fiber/soil. The cement-like product from lime and RHA mixtures was also shown by James and Rao (1986).

Unconsolidated/Undrained Triaxial Tests: Effect of Fiber on Shear Strength

The UU triaxial test was conducted to evaluate the total stress shear strength parameter and failure behavior under different confining stresses. Normally, in saturated or near-saturated conditions, the failure envelope is usually in a horizontal straight line. Thus, the friction angle is almost zero or relatively very small. In this experiment, the degree of saturation was calculated, ranging from 0.51–0.53. For unsaturated or partially saturated conditions, consolidation may occur when a confining pressure is applied and affects the undrained shear strength. The shear strength parameter measured from the research described in this paper will definitely not be the true friction angle and intercept cohesion. Therefore, it will just be an artifact of testing, and thus the parameter will only be used for comparison purposes between the unreinforced and reinforced soil samples. For determination of total stress shear-strength parameters c and ϕ, the failure deviatoric stress $(\sigma_1 - \sigma_3)_f$ was taken as the peak deviator stress for unreinforced specimens and reinforced specimens. The total stress shear-strength parameters c and ϕ were determined by drawing the $p - q$ plots (Fig. 4). Table 4 summarizes the values of c and ϕ. The lime-stabilized (S1) and RHA/mixed lime (S2) soils showed a higher shearing resistance by improving the cohesion intercept, but the effect on the friction angle was marginal. A similar result was indicated by Thompson (1965) for lime-stabilized fine-grained soils that yields a substantial increase in cohesion and minor improvement in the internal friction angle. A nonmonotonic trend was observed from Fig. 4 for S2–SR7 specimens. The nonmonotonic trend is probably attributable to the distribution of fiber in the stabilized soil. As noted in the paper, it is difficult to mix and prepare a specimen with a higher fiber content. Hence, for the SR6 and SR7 specimens, the peak stress differs slightly. The results show that the friction angle of the soil was not affected by the addition of fiber. Addition of a large amount of the fiber will cause a slippage and decrease the friction between soil and fiber. The inclusion of fibers in the lime/RHA specimen resulted in a slight decrease in the friction angle from 24° to 21°. The cohesion of fiber-reinforced lime/RHA/soil mixture tend to increase initially as the fiber increased to 0.4%, and then decreased with increasing fiber content up to 1.2%. The maximum cohesion value was observed at a fiber content of 0.4% (SR5 specimen). The characteristic indicates that the addition of fiber has a significant influence on the development of cohesion of the stabilized soil.

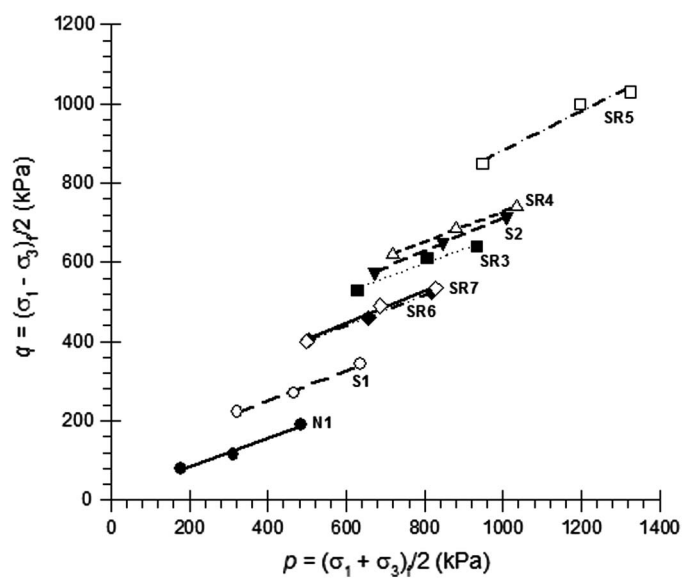

Fig. 4. Failure envelopes (p-q plot) for the UU triaxial test

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A possible explanation for the decrease in friction angle can be explain that in the UU triaxial test; i.e., because of the small percentage of plastic fibers and the small size of the reinforcing fiber. Theoretically, the moisture content at the fiber/soil interface will be higher because the excess pore water pressure could not dissipate from the soil during shearing. The moisture therefore potentially softened the soil/fiber interface and decreased the shearing resistance. As the result, this mechanism will decrease the friction angle. A similar result was measured by Fabian and Fourie (1986). The increasing cohesion with fiber content can be attributed to the cementation effect caused by the lime/RHA reaction with available moisture. The process will produce an increasing in the bonding between soil and fibers in addition to the cohesive portion of shear resistance. Second, during the shearing, the soil particles surrounding the fibers cannot easily change their position, thereby improving the bonding force between soil particles, i.e., cohesion of the soil. The addition of fiber caused the appearance of friction between the fiber and soil particles, which enhances the bonding action between particles and improves cohesion of the soils. Increasing the cohesion with the addition of fibers was also found by Cai et al. (2006) for fiber and lime mixed-clayey soils. However, if the amount of fiber admixed into soil is abundant the fibers will adhere to each other to form lumps, which leads to an uneven distribution of fiber in the soil and deficient contact of the fiber with the soil particles. This consequently reduces the shear strength parameters, especially the cohesion.

Unconsolidated/Undrained Triaxial Tests: Failure Behavior

Figs. 5(a–c) show the stress–strain relationship of the treated and reinforced soil/lime/RHA mixtures for various cell pressures, i.e., 98.1, 196.2, and 294.3 kPa. In general, the peak stress difference at failure ($\Delta\sigma_f$) increases with the increase in applied cell pressure. The stabilized soil has a higher peak stress than the unstabilized soil (N1). Figs. 5(a–c) show that the RHA-stabilized lime/soil mixture (S2) had a higher peak stress response than the lime-stabilized soil (S1). Lime/RHA will react and produce

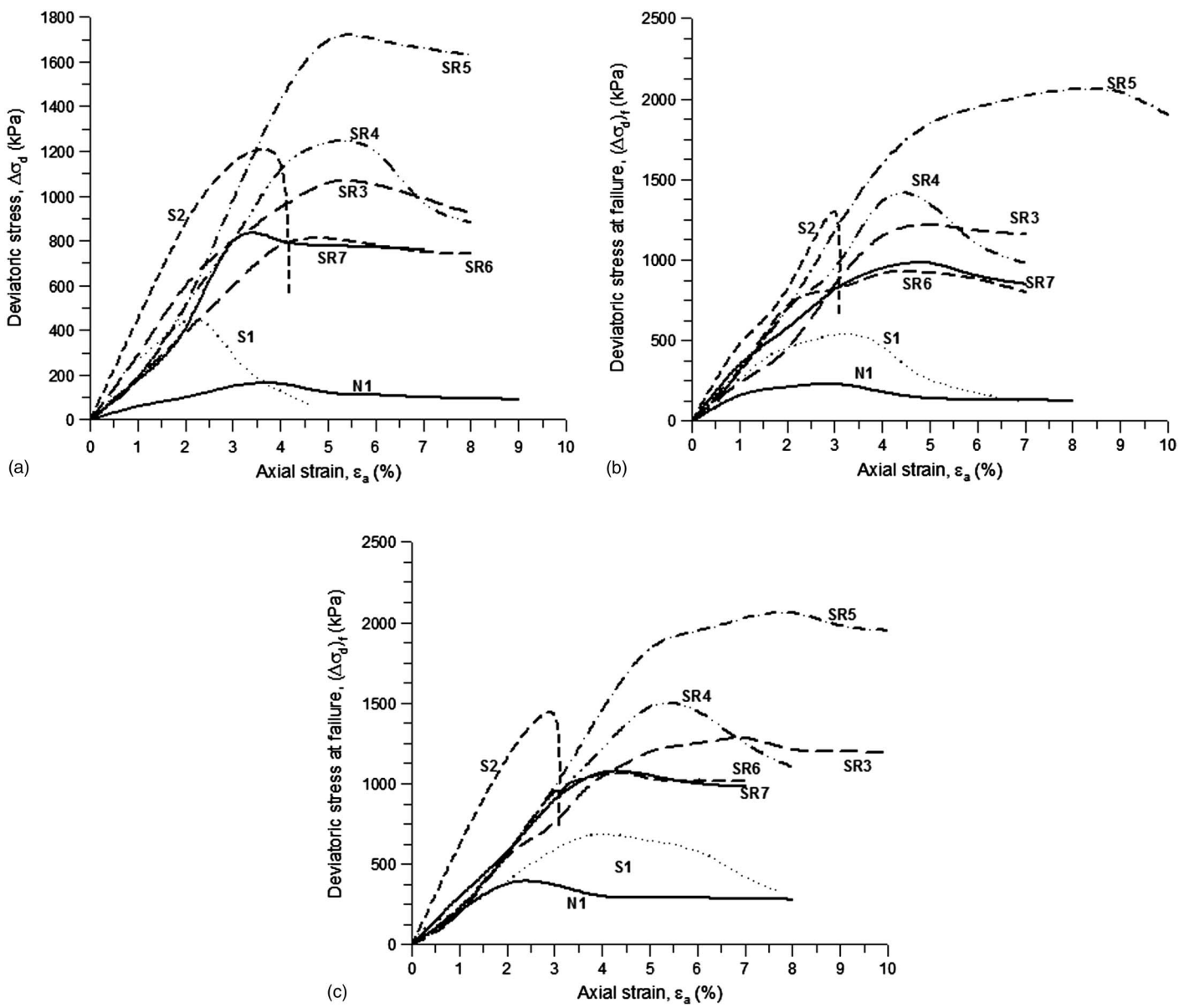

Fig. 5. Stress/strain relationship obtained from the UU triaxial test with various cell pressures: (a) 98.1 kPa; (b) 196.2 kPa; (c) 294.3 kPa

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a cemented material that increases the strength of the mixture. However, the stabilized soil failed at a relatively smaller strain, about 3–5%, depending on the cell pressure. Inclusion of the fibers in the stabilized soil leads to increasing the failure strain up to 10% (SR5 specimen), which depends on the fiber content. This behavior may be attributable to strong interfacial adherence and frictional interaction between the fiber and soil particles. Consoli et al. (2002) noted that the failure of the fiber-reinforced cemented specimen occurred because of slippage between the soil particles and fibers.

The stress-strain relationship in Fig. 5 can be used to interpret whether the failure behavior is brittle or ductile. The failure behavior is expressed as the brittleness index. Consoli et al. (2002) and Li (2005) proposed the brittleness index (I_B) as the ratio of the peak principal stress to the residual stress that quantifies the differences in the stress-strain curves of the soil. The brittleness index is given in Eq. (2):

$$I_B = \frac{(\Delta\sigma_d)_f}{(\Delta\sigma_d)_{\text{ult}}} - 1 \tag{2}$$

where I_B = brittleness index; and $(\Delta\sigma_d)_f$ and $(\Delta\sigma_d)_{\text{ult}}$ = peak deviatoric and residual stress, respectively. The value of I_B ranges from 0–1, where 0 represents perfectly ductile behavior.

Fig. 6 illustrates the change of the brittleness index of the treated and untreated soil with respect to fiber content. The best-fit line and 95% confidence interval band in Fig. 6 shows that the I_B value declines with addition of fiber. The term confidence interval band refers to the region of uncertainties in the predicted values over a range of values for the independent variable. Fig. 6 shows that the stabilized soil with a lime/RHA mixture (specimen S2) exhibits brittle behavior because the I_B value is 1 for all of the applied cell pressures. Fiber-reinforced stabilized soil is able to reduce the brittle behavior. Fig. 6 shows that the addition 0.1% fiber in the stabilized soil reduced the brittleness index from 1 to 0.4 on average. Addition of fiber up to 0.4% reduced the brittleness index up to 0.08 on average, and increasing the fiber up to 1.2% slightly decreased the brittleness index. The relationship in Fig. 6 suggests that inclusion of 0.1% fiber was enough to decrease the brittleness behavior of the stabilized soil.

Effect of Fibers on the California Bearing Ratio

The bearing capacity of subgrade candidate is an important factor for designing road construction. The CBR value is commonly used to evaluate the quality of road materials. Fig. 7 shows the CBR value in relation to unstabilized, stabilized, and reinforced specimens. The unstabilized soil had the smallest CBR value at 6.2%, and the specimens experienced swelling by 1.12% when subjected to 3 days of water immersion. The CBR value of the unstabilized soil (N1) was slight greater than the requirement for subgrade as required in Indonesian standard SNI 03-1732-1989F (National Standardization Agency of Indonesia 2002). The lime/RHA mixture enhanced the bearing of soil in which the CBR increased from 6.2 to 22.5%. The Indonesian standard SNI 03-1732-1989F requires a CBR value of 20 and 50% for subbase and base course, respectively. Based on SNI 03-1732-1989F, the stabilized and reinforced soil can be used either as subgrade and subbase materials in roadway construction. As in the unconfined compressive strength characteristics, the reason for the CBR improvement was because of the pozzolanic reaction between the soil and lime/RHA material. The chemical hydration during the reaction, regarded as the primary reaction, formed additional cementitious material that bound particles together and enhanced the strength of the soil.

The CBR values increased with an increase in the amount of fiber up to 0.8%, and thereafter the CBR decreased slightly with the further addition of fibers (Fig. 7). In general, fiber-reinforced stabilized soil meets the requirement of SNI 03-1732-1989F as subbase materials and base course materials, especially for the SR6 specimen. As discussed in the previous section, the increasing CBR value was attributable to the fact that fibers contributed significantly to enhance the bearing of the stabilized soil. The highest CBR value is 53.8%, which is obtained at an inclusion of 0.8% fibers into the stabilized soil, but further additional fiber tends to decrease the CBR value. This behavior may be attributed to the compaction resistance of the fibers and the fact that the fibers had a lower specific gravity than soils. Nataraj and McManis (1997) noted that the interaction between the soil and the fiber reinforcement controlled the response of the soil/fiber mixture to compaction.

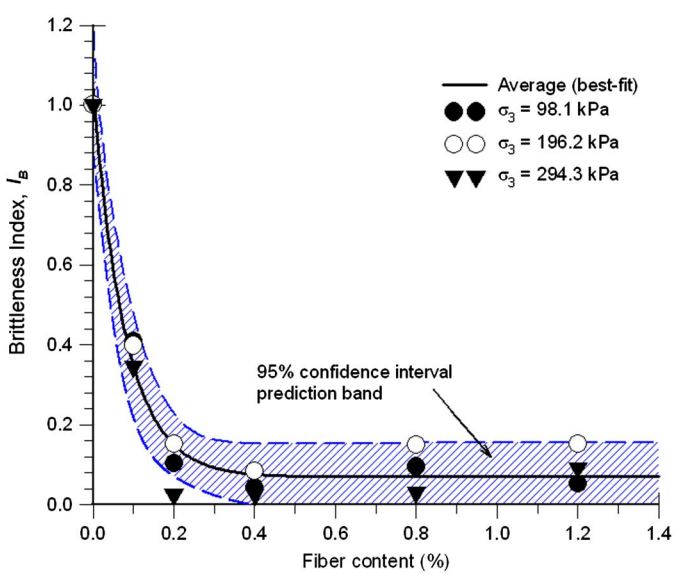

Fig. 6. Relationship between the brittleness index and fiber content

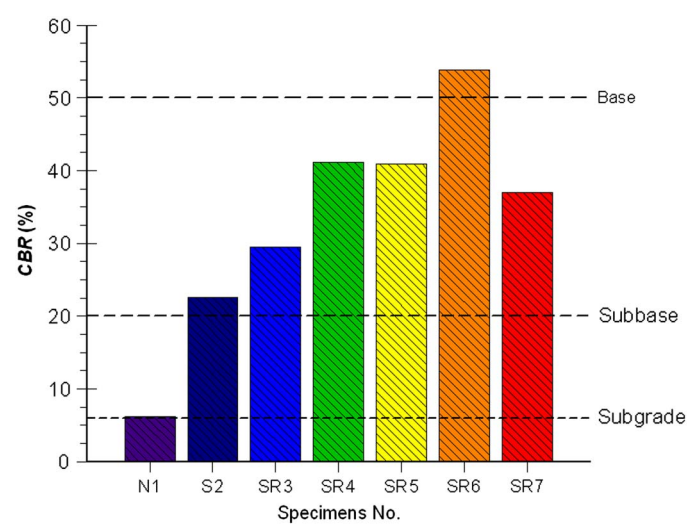

Fig. 7. Variation of the soaked CBR of the unstabilized, stabilized, and reinforced specimens

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Table 6. Unconfined Compressive Strength after Wetting/Drying

Number of cycles	UCS (kPa) for specimens						
	S1	S2	SR3	SR4	SR5	SR6	SR7
0	98.4	113	152	166	161	190	165
1	50.2	65	137	128	125	143	140
2	28.7	55	123	108	100	138	134
3	11.4	50	101	99	97	124	120
4	Ruin	76	137	149	136	145	152
5		90	170	142	140	153	160
6		88	154	125	126	120	147
7		108	160	141	143	133	167
8		114	170	185	130	140	145
9		138	155	200	175	152	179
10		153	156	225	198	207	220

Effect of Wetting/Drying on Compressive Strength

Table 6 presents the unconfined compressive strength of the stabilized and reinforced specimens after wetting/drying cycles. The compressive strength varies with the wetting/drying cycles. The change of compressive strength after the wetting/drying cycles can be expressed as the residual strength index, R, which is the ratio between the compressive strength after the wetting/drying cycles, $q_{u(\mathrm{wet/dry})}$, and prior to the cycle, $q_{u(0)}$:

$$R = \frac{q_{u(\mathrm{wet/dry})}}{q_{u(0)}} \tag{3}$$

Fig. 8 plots the relationship between the residual strength index and the number of the wetting/drying cycles for the lime/RHA stabilized soil and fiber-reinforced stabilized soil. Generally, the best-fit and 95% confidence interval prediction band line show that the compressive strength decreased up to three cycles, and then a slight increase of strength was noticed for all specimens subjected to further wet/dry cycles. Increasing the wetting/drying cycles indicates that the age of the specimen increased and the strength of the stabilized specimens would increase as the time increased (Table 5). The absorbed water during wetting will produce a softer soil mixture but the moisture causes an increase in strength with increasing length of the curing period. Although the exact reasons for that slightly enhanced unconfined compressive strength were not investigated in detail in this paper, this is attributed to the following: (1) expansion may take place to cause a reduction on particle interlocking within the stabilized soil (Oti et al. 2009; Staridavakis 2005) and create a change in the structure of the stabilized soil; subsequently, the compressive strength decreases because of wet/dry cycles (Ahmed et al. 2011; Ahmed and Ugai 2011); and (2) during wet/dry cycles, the stabilized soil can gain extended curing time; consequently, the durability of stabilized soil improved (Bin-Shafique et al. 2010). The strength of air-cured cemented soil can be increased by the number of wettings because the wetting can supply sufficient water for hydration in soil stabilization mechanisms that cause complete hydration. This is also an important factor for strength development (Naeini and Ghorbanalizadeh 2010; Park 2010).

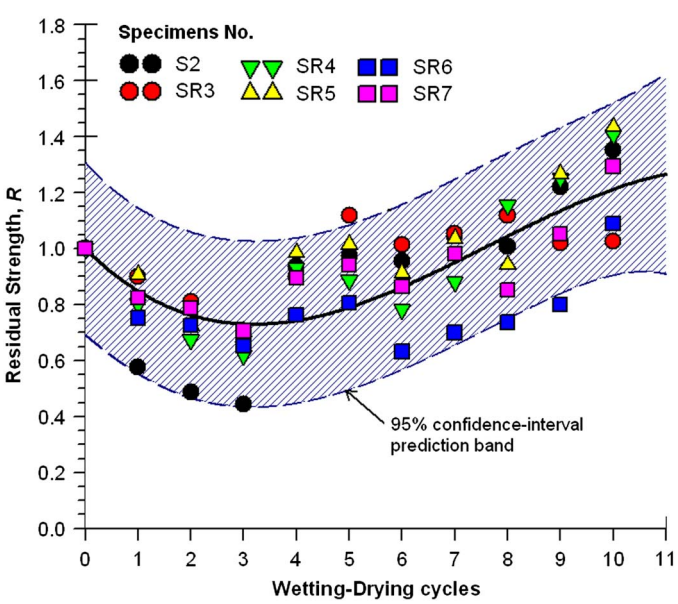

Fig. 8. Effect of wetting/drying cycles on the compressive strength of the stabilized and fiber-reinforced stabilized clay

Wetting/drying cycles significantly reduced the compressive strength of the lime-stabilized soil specimen (S1). The wetting/drying cycles caused the specimens to fail after three cycles. The result indicated that lime-stabilized soil was not resistant to the wetting/drying effect. The RHA/mixed lime/soil mixture (S2) shows more resistance to wetting/drying than the lime/soil specimen (S1). The lime/RHA mixed soil specimen loses its strength after three cycles of wetting/drying. During the wetting process, the cementitious materials such as CaO could be leached away or washed out, and this resulted in a weak cementation process. Park (2010) found a similar behavior for cement stabilization after three cycles of wetting/drying. In contrast, wetting will result in a higher water content as necessary for the pozzolanic reaction. Under this circumstance, the pozzolanic reaction will produce a cemented material that will coat the soil particles and increase the strength with an increase in the age of the mixture. Addition of 0.1–1.2% fibers in the stabilized soil (specimens SR3–SR7) enhanced the strength resistance attributable to wet/dry cycles. As presented in Table 5, the compressive strength of fiber-reinforced stabilized soil is generally higher that the stabilized soil specimens (S2). Fibers contributed significantly to enhance the compressive strength and improve the durability of stabilized soil. When local cracks appear in soil because of drying, fibers will act in tension in the soil with fiber-stabilized soil friction and cohesion, which effectively impedes further development of cracks and improves the resistance of the soil to the force applied. General results suggest that that the strength reduction occurred immediately after wetting. This characteristic should be considered when stabilized soils are constructed in the field.

Effect of Fiber on Secant Modulus of Elasticity

The modulus of elasticity is one of the parameters used to characterize stiffness or elasticity of soil. The value is commonly expressed as the secant modulus, E_{50}. The secant modulus is the slope of a straight line drawn from the origin to a specified stress on the stress-strain curve. The value of E_{50} is expressed as $E_{50} = q_{50}/\varepsilon_{50}$, where q_{50} is half of the peak compressive strength, and ε_{50} is the strain, which corresponds with q_{50}. In the research described in this paper, the secant modulus is determined from the axial stress and strain of the UCS test. Table 4 presents the secant modulus of the specimens. The results show that the unstabilized soil specimen (specimen N1) had the smallest secant modulus among other mixture specimens. Addition of lime increased the E_{50} of the soil from 0.8–2.15 MPa. The mixing of the RHA in lime/soil mixture increased, and doubled the E_{50} from 2.15 to 5.08 MPa. Increasing the secant modulus was higher when the lime/rice husk ash and soil mixtures were added with the fibers.

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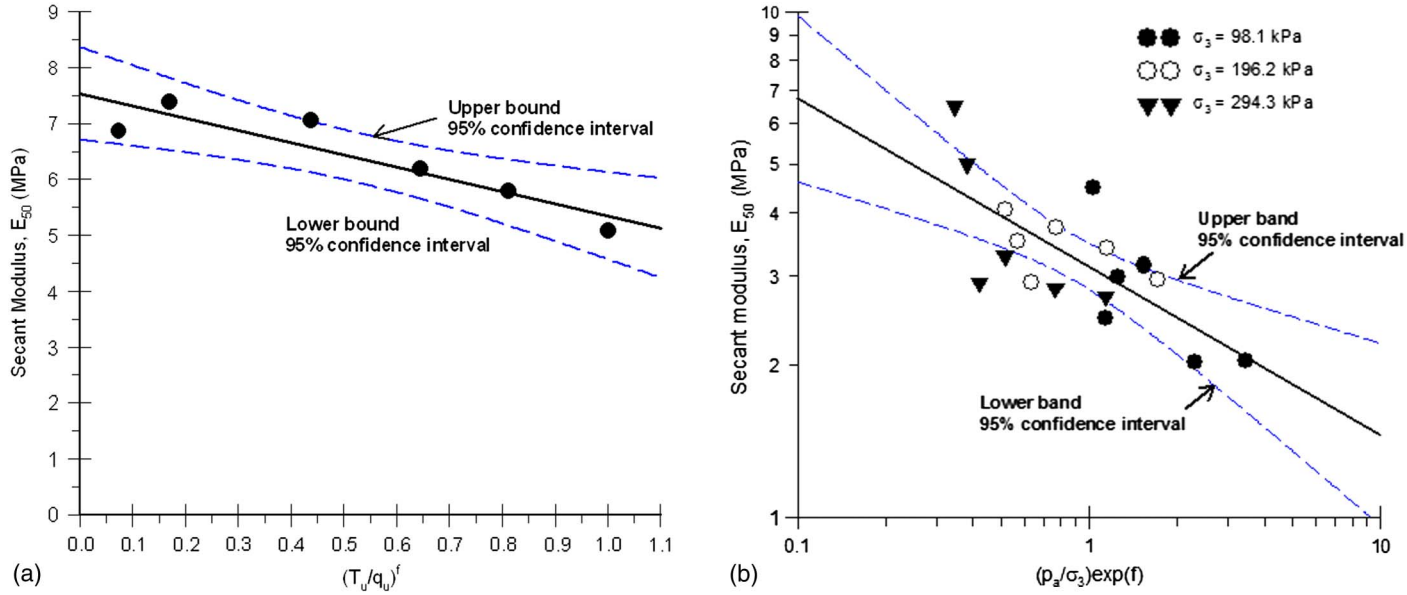

Fig. 9. Relationship of the secant modulus with the following: (a) strength ratio (T_u/q_u) and fiber content; (b) stress ratio (p_a/σ_3) and fiber content

The largest secant modulus was obtained at 0.8% fiber mixture (specimen SR6).

Much research has been done to estimate the E_{50} from the correlation equation between E_{50} and unconfined compressive strength (Kim et al. 2008; Tang et al. 1996; Ahmed et al. 2011). Tang et al. (1996) reported that E_{50} was in the range of 40–260× the value of q_u, and tends to decrease as the total confining pressure increases. Regarding the previous discussion, the fiber content has a significant influence on the tensile strength of the stabilized soil, and the T_u was correlated with q_u as the strength ratio. Therefore, an empirical model of the secant modulus was developed as a function of the strength ratio (T_u/q_u) and fiber content (f). Fig. 9(a) shows the correlation. According to this correlation, the modulus proportional to a power law of the strength ratio and fiber content. The power exponent in Fig. 9(a) is the fiber content. Eq. (4) shows the secant modulus of the fiber-reinforced lime/RHA/soil mixture. The correlation indicates that the secant modulus decreases with increasing the strength ratio and fiber content in the stabilized soil

$$E_{50} = a + b\left(\frac{T_u}{q_u}\right)^f \tag{4}$$

where E_{50} = secant modulus (MPa); a and b are constants ($a = 7.5$, $b = -2.2$); T_u and q_u = split-tensile (kPa) and unconfined compressive (kPa) strengths, respectively; and f = fiber content (%).

The mean stresses have a significant influence on the soil modulus. This is also termed the confinement effect. Fig. 9(b) shows the secant modulus as a function of different confinement levels and fiber content. The correlation shows that the secant modulus decreases with increasing the confinement pressure and fiber content in the stabilized soil. This result is in agreement with Tang et al. (1996). Eq. (5) gives the correlation to estimate E_{50}:

$$E_{50} = a + b\left(\frac{p_a}{\sigma_3}\right)\exp(f) \tag{5}$$

where E_{50} = secant modulus (MPa); a and b are constants ($a = 0.5$, $b = -0.33$); and p_a and σ_3 = atmospheric (kPa) and confined (kPa) pressure, respectively.

For pavement design purposes, the CBR value is commonly correlated with the modulus of elasticity of the soil. Fig. 10 shows the relationship of the CBR and secant modulus of elasticity obtained from the unconfined compressive strength test. In Fig. 10, the CBR value is normalized with the fiber content using a power law because the CBR changed with the addition of fiber content in the stabilized soil. The correlation can be approached by using a bilinear equation

$$E_s = 1.1435\log[\mathrm{CBR}^{(f)}] + 5.2453 \quad \text{for } f \le 0.4\%$$
$$E_s = 0.0856\log[\mathrm{CBR}^{(f)}] + 6.8433 \quad \text{for } f > 0.4\% \tag{6}$$

where E_s = secant modulus of elasticity (MPa); and CBR = soaked California bearing ratio (%). There is a linear relationship between the CBR and modulus of elasticity, although this applies strictly to the soils examined.

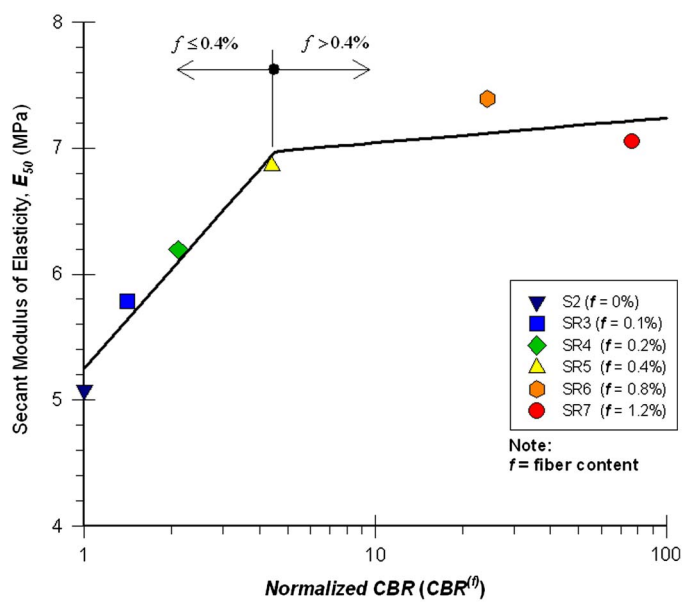

Fig. 10. Correlation between CBR, fiber content, and secant modulus of elasticity

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Conclusions

A series of tests have been performed to study the effects of randomly distributed plastic-waste fiber reinforcement on the strength of stabilized soil with lime/RHA mixtures. The effects of fiber inclusions in the soil and lime/RHA mixtures on the engineering properties were examined. It was observed from testing that these engineering properties of fiber/lime/RHA soil vary and depend on the fiber content. New empirical equations to estimate the secant modulus of elasticity have been developed as a function of fiber content, CBR, unconfined strength, tensile strength, and confining pressure in the triaxial test. The effect of the plastic waste fiber on the failure behavior was interpreted by the brittleness index. Environmental effects were simulated as wet/dry cycles in this paper. Based on the strength, CBR, shear strength, and failure characteristics, the optimum amount of fiber mixed in soil/lime/RHA mixtures range from 0.4–0.8%. Thorough this paper, the technique of a fiber-reinforced lime/RHA soil system is a very effective method of soil improvement, which improves the compressive strength, tensile strength, shear strength, and bearing of the soil; consequently, this improvement enhances the stability and durability of infrastructures such as foundations and roadbeds. Furthermore, the following conclusions can be drawn from this paper:

- Lime and rice husk ash mixtures enhanced the compressive and tensile strength of the soil up to 4× and 5×, respectively. Inclusion of the plastic waste fibers played a significant role in increasing the tensile strength and strength ratio of stabilized soil. The compressive strength increased as the curing age increased.
- The shear strength of the soil increase by addition of the lime/rice husk ash mixture. The inclusion of fibers resulted in a decrease in the friction angle. The cohesion of fiber-reinforced lime/RHA/soil mixtures increased initially and then decreased with increasing fiber content, and the maximum value was observed at a fiber content of 0.4%. Plastic fibers in the soil/lime/RHA mixtures had a significant influence in development of the cohesion rather than friction angle of the soil.
- Inclusion of the plastic-waste fiber reduced the brittleness behavior of the stabilized soil. Addition of 0.1% fiber was enough to decrease the brittleness of the stabilized soil. In general, inclusion of the plastic-waste fiber increased the secant modulus E_{50} of the stabilized soil specimen.
- Regarding the strength behavior, the plastic-waste fiber-reinforced stabilized soil meet the requirements as subbase and base course materials in term of its CBR values. The CBR value of the soil increased up to 3.6× by mixing of lime/RHA. However, the CBR value increased considerably up to 8.7× by adding plastic-waste fibers.
- The compressive strength of stabilized and reinforced soil/lime/RHA/plastic-waste fiber was reduced by three cycles of wetting/drying, and then a slight increase of strength was noticed when subjected to further wet/dry cycles. Adding plastic-waste fiber enhanced the residual strength of the stabilized soil.

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References

Ahmed, A., and Ugai, K. (2011). "Environmental effects on durability of soil stabilized with recycled gypsum." *Cold Regions Sci. Technol.*, 66(2), 84–92.

Ahmed, A., Ugai, K., and Kamei, T. (2011). "Investigation of recycled gypsum in conjunction with waste plastic trays for ground improvement." *Constr. Build. Mater.*, 25(1), 208–217.

Al-Refeai, T. (1991). "Behavior of granular soils reinforced with discrete randomly oriented inclusions." *Geotext. Geomembranes*, 10(4), 319–333.

Ali, F. H., Adnan, A., and Choy, C. K. (1992a). "Geotechnical properties of a chemically stabilized soil from Malaysia with rice husk ash as an additive." *Geotech. Geol. Eng.*, 10(2), 117–134.

Ali, F. H., Adnan, A., and Choy, C. K. (1992b). "Use of rice husk ash to enhance lime treatment of soil." *Can. Geotech. J.*, 29(5), 843–852.

ASTM. (2009a). "Standard practice for classification of soils and soil-aggregate mixtures for highway construction purposes." *D3282-09*, West Conshohocken, PA.

ASTM. (2011a). "Standard practice for classification of soils for engineering purposes." *D2487-11*, West Conshohocken, PA.

ASTM. (2012). "Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete." *C618-12*, West Conshohocken, PA.

ASTM. (2007). "Standard test method for CBR (California bearing ratio) of laboratory-compacted soil." *D1883-07*, West Conshohocken, PA.

ASTM. (2011b). "Standard test method for splitting tensile strength of cylindrical concrete specimens." *C496-11*, West Conshohocken, PA.

ASTM. (2009b). "Standard test method for unconfined compressive strength of compacted soil-lime mixtures." *D5102-09*, West Conshohocken, PA.

ASTM. (2011c). "Standard test method for unconsolidated undrained triaxial compression test on cohesive soils." *D2850-11*, West Conshohocken, PA.

ASTM. (2011d). "Standard test methods for fineness of hydraulic cement by air-permeability apparatus." *C204-11*, West Conshohocken, PA.

ASTM. (2003). "Standard test methods for wetting and drying compacted soil-cement mixtures." *D559-03*, West Conshohocken, PA.

Balasubramaniam, A. S., Lin, D. G., Acharya, S. S. S., Kamruzzaman, A. H. M., Uddin, K., and Bergado, D. T. (1999). "Behavior of soft Bangkok clay treated with additives." *Proc., Asian Regional Conf. on Soil Mechanics and Geotechnical Engineering*, Balkema, Rotterdam, Netherlands, 11–14.

Basha, E. A., Hashim, R., Mahmud, H. B., and Muntohar, A. S. (2005). "Stabilization of clay and residual soils using cement-rice husk ash mixtures." *Constr. Build. Mater.*, 19(6), 448–453.

Bin-Shafique, S., Rahman, K., Yaykiran, M., and Azfar, I. (2010). "The long-term performance of two fly ash stabilized fine-grained soil subbases." *Resour. Conserv. Recy.*, 54(10), 666–672.

Cai, Y., Shi, B., Ng, C. W. W., and Tang, C. S. (2006). "Effect of polypropylene fibre and lime admixture on engineering properties of clayey soil." *Eng. Geol.*, 87(3), 230–240.

Cavey, J. K., Krizek, R. J., Sobhan, K., and Baker, W. H. (1995). "Waste fibers in cement-stabilized recycled aggregate base course material." *Transportation Research Record 1486*, Transportation Research Board, Washington, DC, 97–106.

Consoli, N. C., Montardo, J. P., Prietto, P. D. M., and Pasa, G. S. (2002). "Engineering behavior of sand reinforced with plastic waste." *J. Geotech. Geoenviron. Eng.*, 128(6), 462–472.

Consoli, N. C., Prietto, P. D. M., and Ulbrich, L. A. (1998). "Influence of fiber and cement addition on behavior of sandy soil." *J. Geotech. Geoenviron. Eng.*, 124(12), 1211–1214.

Eades, J. L., and Grim, R. E. (1966). "A quick test to determine lime requirements for lime stabilization." *Highway Research Record 139*, Transportation Research Board, Washington, DC, 61–72.

Fabian, K., and Fourie, A. (1986). "Performance of geotextile-reinforced clay samples in undrained triaxial tests." *Geotext. Geomembranes*, 4(1), 53–63.

J. Mater. Civ. Eng. 2013.25:1260-1270.

Gaspard, K., Mohammad, L., and Wu, Z. (2003). "Laboratory mechanistic evaluation of soil-cement mixtures with fibrillated polypropylene fibers." *Transportation Research Board Annual Meeting* (CD-ROM), Washington, DC.

Ghiassian, H., Poorebrahim, G., and Gray, D. H. (2004). "Soil reinforcement with recycled carpet wastes." *Waste Manage. Res.*, 22(2), 108–114.

Hossain, K. M. A. (2011). "Stabilized soils incorporating combinations of rice husk ash and cement kiln dust." *J. Mater. Civ. Eng.*, 23(9), 1320–1327.

Hwang, C. L., and Chandra, S. (1997). "The use of rice husk ash in concrete." *Waste materials used in concrete manufacturing*, S. Chandra, ed., William Andrew Publishing/Noyes, Norwich, NY, 184–234.

James, J., and Rao, M. S. (1986). "Reaction product of lime and silica from rice husk ash." *Cement Concrete Res.*, 16(1), 67–73.

Jiang, H. T., Cai, Y., and Liu, J. (2010). "Engineering properties of soils reinforced by short discrete polypropylene fiber." *J. Mater. Civ. Eng.*, 22(12), 1315–1322.

Kaniraj, S. R., and Gayathri, V. (2003). "Geotechnical behavior of fly ash mixed with randomly oriented fiber inclusions." *Geotext. Geomembranes*, 21(3), 123–149.

Kaniraj, S. R., and Havanagi, V. G. (2001). "Behavior of cement-stabilized fiber-reinforced fly ash–soil mixtures." *J. Geotech. Geoenviron. Eng.*, 127(7), 574–584.

Kim, Y. T., Kim, H. J., and Lee, G. H. (2008). "Mechanical behavior of lightweight soil reinforced with waste fishing net." *Geotext. Geomembranes*, 26(6), 512–518.

Lazaro, R. C., and Moh, Z. C. (1970). "Stabilisation of deltaic clays with lime-rice husk ash admixtures." *Proc., 2nd Southeast Asian Conf. on Soil Engineering*, Southeast Asian Geotechnical Society, Singapore, 215–223.

Li, C. (2005). "Mechanical response of fiber-reinforced soil." Ph.D. dissertation, Univ. Of Texas, Austin, TX.

Messas, T., Azzouz, R., Coulet, C., and Taki, M. (1998). "Improvement of the bearing of the soils by using plastic-rubbish matters." *Geotechnical hazards*, L. Maric and S. Noddan, eds., Balkema, Rotterdam, Netherlands, 573–579.

Muntohar, A. S. (2000). "Evaluation of the usage of plastic sack rubbish as fabric in expansive embankment stabilization." *J. Semesta Teknika*, 3(2), 85–95.

Muntohar, A. S. (2002). "Utilization of uncontrolled-burnt of rice husk ash in soil improvement." *J. Civ. Eng. Dimension*, 4(2), 100–105.

Muntohar, A. S. (2009). "Influence of Plastic Waste Fibers on the Strength of Lime-Rice Husk Ash Stabilized Clay Soil." *J. Civ. Eng. Dimension*, 11(1), 32–40.

Muntohar, A. S., and Hashim, R. (2002). "Silica waste utilization in ground improvement: A study of expansive soil treated with LRHA." *Proc., Int. Congress on Environmental Geotechnics*, Int. Society of Soil Mechanics and Geotechnical Engineering, London, 515–519.

Naeini, S. A., and Ghorbanalizadeh, M. (2010). "Effect of wet and dry conditions on strength of silty sand soils stabilized with epoxy resin polymer." *J. Appl. Sci.*, 10(22), 2839–2846.

Nataraj, M. S., and McManis, K. L. (1997). "Strength and deformation properties of soils reinforced with fibrillated fibers." *Geosynth. Int.*, 4(1), 65–79.

National Standardization Agency of Indonesia. (2002). "Code of practice for thickness of flexible hardening of highways by component analysis method." *SNI 03-1732-1989F*, Jakarta, Indonesia.

Oti, J., Kinuthia, J., and Bai, J. (2009). "Engineering properties of unfired clay masonry bricks." *Eng. Geol.*, 107(3), 130–139.

Park, S. S. (2010). "Effect of wetting on unconfined compressive strength of cemented sands." *J. Geotech. Geoenviron. Eng.*, 136(12), 1713–1720.

Rahman, M. A. (1987). "Effect of cement-rice husk ash mixtures on geotechnical properties of lateritic soils." *Soils Found.*, 27(2), 61–65.

Rahmat, M. N., and Kinuthia, J. M. (2011). "Effects of mellowing sulfate-bearing clay soil stabilized with wastepaper sludge ash for road construction." *Eng. Geol.*, 117(3), 170–179.

Rao, N. S., and Rajasekaran, G. (1996). "Reaction products formed in lime-stabilized marine clays." *J. Geotech. Eng.*, 122(5), 329–336.

Santoni, R. L., Tingle, J. S., and Webster, S. L. (2001). "Engineering properties of sand-fiber mixtures for road construction." *J. Geotech. Geoenviron. Eng.*, 127(3), 258–268.

Sharma, R. S., Phanikumar, B. R., and Rao, B. V. (2008). "Engineering behavior of a remolded expansive clay blended with lime, calcium chloride, and rice-husk ash." *J. Mater. Civ. Eng.*, 20(8), 509–515.

Stavridakis, E. I. (2005). "Evaluation of engineering and cement-stabilization parameters of clayey-sand mixtures under soaked conditions." *Geotech. Geol. Eng.*, 23(6), 635–655.

Tang, C. S., Shi, B., Gao, W., Chen, F. J., and Cai, Y. (2007). "Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil." *Geotext. Geomembranes*, 25(3), 194–202.

Tang, Y. X., Tsuchida, T., Shirai, A., Ogata, H., and Shiozaki, K. (1996). "Triaxial compression characteristics of super geo-material cured underwater." *Proc., Japan National Conf. on Geotechnical Engineering*, Japanese Geotechnical Society, Tokyo, 2493–2494.

Thompson, M. R. (1965). "Shear strength and elastic properties of lime-soil mixtures." *Rep. Prepared for the Bureau of Public Roads*, Washington, DC, 1–14.

J. Mater. Civ. Eng. 2013.25:1260-1270.