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Article

Strength and Equivalent Modulus of Cement Stabilized Lateritic with Partial Replacement by Fly Ash and Rice Husk Ash

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Abstract. The effect of industrial/agricultural waste materials including fly ash (FA) and rice husk ash (RHA) as Portland cement replacement on properties of stabilized lateritic soil as a road construction material is investigated. The compacted lateritic soil samples treated with Portland cement at 1%, 2% and 3% by weight of the dry soil and three different amounts (10%, 20% and 30%) of FA and RHA for replacing cement are prepared and the unconfined compression and cyclic loading tests are conducted on 28 days curing samples. The equivalent modulus (E_{eq}) defined as the average linear portion from the unloading/reloading cycles, is used to quantify the effects of stress level on the cyclic resistance of the treated lateritic. Based on the compressive strength results, both replacement materials have demonstrated potential applications in lateritic soil stabilization. Overall, the RHA shows a better efficiency than FA for replacement particularly at 2% cement content. Based on cyclic loading tests, the E_{eq} values increase as the stress level increases for all samples. The FA and RHA notably enhance the E_{eq} values of cement treated lateritic.

Keywords: Lateritic, fly ash, rice husk ash, strength, equivalent modulus.

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1. Introduction

The unbound granular materials (i.e., crushed rock, sand and lateritic soil) are generally used in construction of base and subbase layers for flexible pavements. The performances of the pavement are thus affected by the stiffness and strength of the pavement layers. The fundamental requirements to a general pavement design are the Californian Bearing Ratio (CBR) or in the best case, the Young's modulus as well as the unconfined compressive strength [1]. The CBR value is used to evaluate the subgrade strength, which provides the penetration resistance of unbound granular materials. The CBR method has been first introduced to estimate the thickness of pavement based on the empirical method [2]. To simulate the pavement behavior realistically, the complex elasto-plastic behaviors are required for the pavement analysis when the materials are subjected to cyclic loading generated by moving traffic [3]. Since the pavement structures undergo repeated traffic loading, the deformation of pavement layers experiences both resilient deformation and permanent deformation [4, 5]. At present, the resilient response with respect to geotechnical and pavement materials is typically expressed by the resilient modulus (M_r) [3]. Therefore, the inelastic behavior under traffic loading becomes necessary to reliably analyze the deformation response of the unbound materials during service of any roads.

Lateritic is residual soils resulting from the in-situ weathering and decomposition of common silicate rocks under humid tropical climate conditions [6]. Lateritic consists mainly of precipitation of iron hydroxide, aluminum and other oxides of metals, particularly Titanium and Manganese oxides [7]. Lateritic soils are commonly found with red, brown to chocolate colors. Lateritic has been successfully used in civil engineering construction materials for instance construction of highways, earthen dams, airfields, foundations and slopes. Because of their availability, lateritic soils are used in pavement engineering, mainly in the base, sub-base or the subgrade layers of road [8, 9]. Compacted lateritic soil for the road base material is practical aspects of the use of lateritics in Thailand.

It has also been recognized that the properties of lateritic soils are very different from place to place due to the difference of geological settings, prevailing weathering regimes and rock-forming minerals [6]. Lateritic soils with fine content is often vulnerable, particularly when the fines represent the non-plastic nature. Poor engineering properties (i.e., high compressibility, high creep rate, low strength) of natural lateritics are commonly found, when they come with high fine content [10]. Several approaches have been used to modify or improve the engineering properties of lateritic soils. Traditionally, cement stabilization with chemical admixtures has been widely used to improve the properties of poor lateritic soils in many aspects [11]. Technical literature provides evidence on beneficial of soil cement stabilization for instance, improving shear and compressive strength, reducing soil compressibility and permeability [12].

The soil stabilizing agent or binders include a broad range of materials for instance, Ordinary Portland cement, lime and industrial by-product [12]. Among of these customary stabilizing agents, Portland cement and lime are widely used to stabilize the soil that do not meet the design specification [13, 14]. However, these stabilization agents own disadvantages that are its raised financial and environmental concerns [15]. In an offer to diminish a sharp addition in the cost, high silica and alumina material like pozzolanic material has taken instead some of cement in concrete works and assisted in reaction with hydroxide when it has high fineness [16].

Several investigations have demonstrated that the use of pozzolanic materials is effective in soils mixed with waste materials as a partial replacement of cement [15-17]. Several researches have been conducted previously on new uses and application of locally available wastes, which can be broadly obtained from 2 main sources. First, industrial waste materials, by-product of coal combustion in power plants (generate large volume of coal ash) like fly ash (FA) and bottom ash (BA) (mainly cons isted of SiO_2, Al_2O_3, Fe_2O_3 and CaO) have been widely studied in several applications, such as replacement for pavement applications [18-25], cement-admixed clay [26-28] and soil improvement in road embankment [29-32]. Second, the agricultural waste materials, for instance rice husk ash (RHA) from burning rice husks, with their high Silica content, has been also utilized as a replacement of Portland cement [17, 33]. Lateritic soils stabilized with different agricultural waste materials i.e., rice husk ash [7], rice straw ash (RSA) [34], nut husk ash (NHA) [36] and coconut waste ashes [37] were reported in the literatures. Despite the several studies regarding the effect of partial use of industrial/agricultural waste materials on the lateritic soils stabilized in pavement structures [7, 20-22, 34-35], the investigations are mainly focused on the typical geotechnical soil properties (i.e., compaction, California bearing ratio and unconfined compressive strength). The comprehensive study on the cyclic behavior has received limited attention.

The aim of this study is to study the effect of industrial/agricultural waste materials (including fly ash and rice husk ash) partially admixed with Portland cement on the strength and cyclic properties of lateritic soil for use as pavement layer. The objectives were to determine the changes in the strength and cyclic properties of mixtures with varying cement content (1%, 2%, and 3% by dry weight of soil) and partial replacement by fly ash and rice husk ash (10%, 20% and 30% of cement) using the 50 kN displacement-controlled compression loading apparatus. The test samples were prepared using the modified Proctor method and then subjected to the unconfined compression and cyclic loading tests. For more accurate evaluation of the deformation response, the Local Deformation Transducer (LDT) and the Linear Variable Differential Transformer (LVDT) are used to measure the specimen deformation, comparatively. The equivalent modulus (E_{eq}), defined as the average linear portion from the unloading/reloading cycles, is used to quantify the effects of stress level on the cyclic resistance of cement treated lateritic.

2. Materials and Methods

2.1. Materials

Lateritic Soil: bulk sample of the lateritic soil used for this study was taken from Ratchaburi Province, which is about 100 km from Bangkok, Thailand. This sample presented a reddish-brown color. The lateritic soil between the depths of depth 1-3 m below the ground surface from a trial pit of approximate size 1.5 m was collected. After collection, the material was oven-dried, ground and sieved to obtain particles less than 9.8 mm. The specific gravity (G_s) was determined following the procedures as stipulated in ASTM D854 [37]. The Atterberg's limit tests were performed according to ASTM D-4318 [38]. The sample was then subjected to the modified Proctor test, ASTM D-1557 [39]. The physical properties of the lateritic soil were summarized in Table 1.

Table 1. Engineering properties of lateritic soil in this study.

Property	Quantity
Specific gravity	2.69
Percent passing #200 sieve (%)	22
Liquid limit (%)	19
Plastic index (%)	5
Classification USCS	SM-SC
Classification AASHTO	A-2-4
Maximum dry density (kN/m^3)	20.6
Optimum moisture content (%)	9

Cement: the selected cement in this research was the Portland cement type I that was available commercially from the TPI Polene Public Company Limited. The cement was kept in an airtight container and was used from a single bag throughout this study. The specific gravity of cement was 3.14.

Fly ash and Rice husk ash: Two pozzolanic materials including fly ash (FA) and rice husk ash (RHA) were used in this study. Fly ash is widely known as a fine powder that is a by-product material produced in the combustion process of coal used in power stations. In Thailand, fly ash is typically utilized in aggregates and cement blends as a pozzolanic material. In this study, fly ash was obtained from Mae Moh power plant, which is the Thailand's largest lignite-fired power plant located in Mae Moh district, Lampang province, Thailand. The fly ash was ground and sieved through a sieve number 325 with sieve opening 45 micrometers to obtain a fine ash that can be categorized as Class F. In addition, the size and gradation of both ashes are carefully controlled to be comparatively the same. Rice husk ash is considered as waste material that is an abundantly available agriculture by-product from rice processing plant. Black rice husk ash waste was used in current study, which was taken from Global Scales and Solution Company Limited, Nakorn Rachasima province. RHA was burnt at a temperature, ranging from 400-800 °C. The pozzolanic aggregates were broken down by using the Los Angles Abrasion Machine and were controlled following similar gradation with FA. The rice husk ash can be classified as Class N. The particle gradation of all materials used are illustrated in Fig. 1 and the chemical compositions are presented in Table 2. It can be seen that both pozzolanic materials are composed mainly of SiO_2, Al_2O_3 and Fe_2O_3. With these chemical compositions, FA and RHA present their existing pozzolanic nature that can be used in supplementary cementitious materials.

Table 2. Chemical composition of Fly ash, Rice husk ash and Portland cement.

Chemical Composition	Cement Type I	Rice Husk Ash	Fly Ash
SiO_2 (%)	20.20	92.99	48
Al_2O_3 (%)	5.40	0.17	26
Fe_2O_3 (%)	2.90	0.35	10
SiO_2 + Al_2O_3 + Fe_2O_3 (%)	28.50	93.51	84
SO_3 (%)	2.30	0.11	0.7
CaO (%)	63.80	0.91	5
MgO (%)	1.50	0.42	2
Na_2O (%)	2.72	0.63	0-2
K_2O (%)	0.30	2.82	0-5
Other (%)	-	-	-
LOI. (%)	2	4.7	3

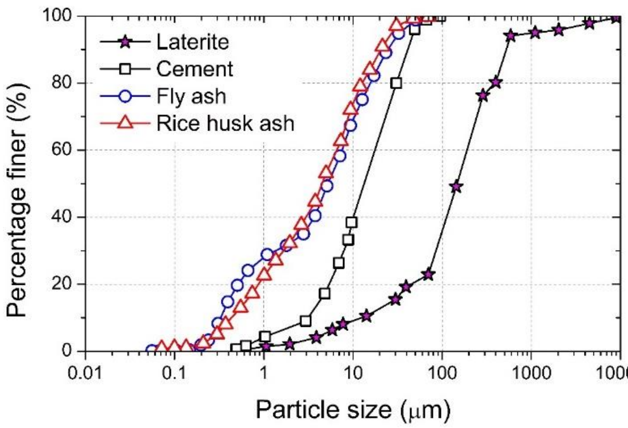

Fig. 1. Grain size distribution of tested materials.

2.2. Mixture Proportion

For compacted sample preparation, specimens (5 cm in diameter and 10 cm in height) of the lateritic were statically compacted in the mold according to the modified Proctor method, ASTM D-1557 [39], to obtain the good compaction. The optimum moisture content (OMC) for mixing was found at 9%. Table 3 presents the mixing design for both UC and CL tests. A total of 30 mixtures were prepared considering the range of cement content of 1%-3% according to the general amount used for soil

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improvement projects in Thailand [24]. The amount of cement was replaced with FA and RHA at 10, 20 and 30%, respectively. The letter 'C' denotes cement content, 'FA' fly ash and 'RHA' rice husk ash. For replacement specimens, the different cement dosages were considered by the dry weight of the C:FA or C:RHA blends. For instance, at 1% cement with 10% ashes replacement, the rations of C:FA or C:RHA were 90:10.

Table 3. Summarizes design mixing ratio of the samples for unconfined compression and cyclic loading tests.

Water Content (%)	Cement content (%)	FA replaced (%)	RHA replaced (%)
9	1, 2, 3		
	1	10, 20, 30	10, 20, 30
	2	10, 20, 30	10, 20, 30
	3	10, 20, 30	10, 20, 30

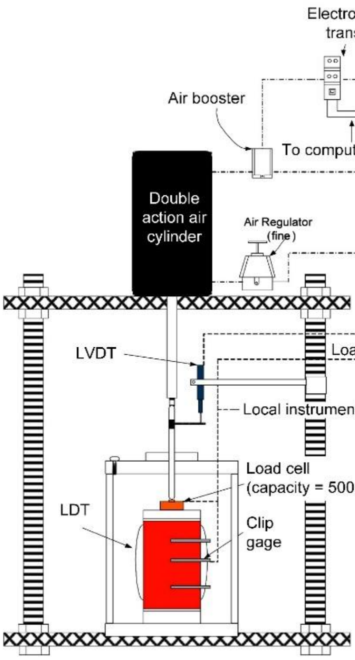

Fig. 2. Schematic of the monotonic/cyclic loading system.

All materials were batched by weight and mixed according to the design mixing ratio until a homogenous mixture was obtained with water at OMC. Then, the compaction was performed according to the modified Proctor method. The blows were uniformly distributed over the surface of each layer according to the modified proctor effort (2,700 kJ/m^3) to achieve the target unit weight at 20.6 kN/m^3 within 5 layers. After compaction, specimens were weighed and recorded. Then, the specimens were extruded from the mold and covered with a plastic cling wrap for further moisture equalization. Three specimens were conducted for each mix as a quality controlled and the unit weight was measured for consistency. To ensure that sufficient pozzolanic reaction can cooperate with hydration one [17, 26-27], the specimens were cured at room temperature (25 ^{o}C) until the testing age of 28 days as mostly done in several past studies.

Figure 2 shows the layout and components of the testing system. Figure 3 depicts a photograph of the testing set up used in this study. The testing system used in current study can perform both static and cyclic tests, which is able to accurately measuring the reacting force and displacement. After the curing period, the specimens were placed on the lower platen of a compression testing machine. The axial force applied on the specimen was measured using a load cell. The setup of the measurement equipment reduces the equipment compliance errors. All of measuring devices were performed on specimen for measurement thoroughly the end of test, except for LDTs. The LDTs devices were removed before failure of specimen to avoid the damage of the devices. The LDTs measurements were removed when the axial stress reached about 60-80% of the ultimate strength. Compression and extension are provided by means of changes in the air pressure in the upper room of double-action air-cylinder arranged at the top of reaction frame. The air pressure in the upper room of the air cylinder was controlled by a personal computer through an electro-pneumatic (EP) transducer while the one in the lower room by a fine regulator. To achieve as fast as possible the response during changes in the load rate and direction, the volume of air flow from the electro-pneumatic transducer was amplified by using an air booster. By using this loading apparatus, cyclic loading tests with specified load amplitude (S_{amp}) at a specified frequency can be performed, without any intermission at the start of respective cyclic loading, during otherwise loading at a constant load rate.

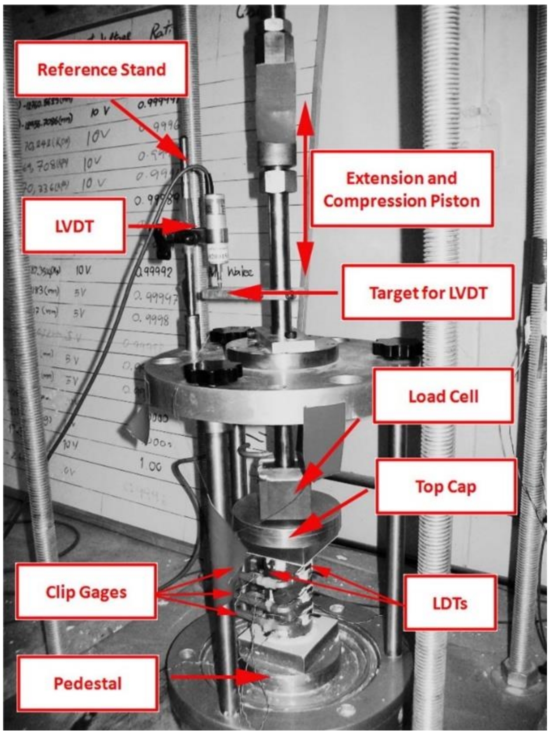

Fig. 3. Sample after preparation and locations of measuring devices.

Table 4. Loading sequence for cyclic loading test

Sample	q_u (kPa)	L_s (kPa)	S_{amp} (kPa)
C1	1,962	200-1,400	60
C1FA10	2,053	200-1,400	60
C1FA20	2,043	200-1,400	60
C1FA30	1,976	200-1,400	60
C1RHA10	2,043	200-1,400	60
C1RHA20	2,042	200-1,400	60
C1RHA30	1,905	200-1,400	60
C2	2,872	290-2,030	85
C2FA10	2,437	290-2,030	85
C2FA20	2,329	290-2,030	85
C2FA30	2,200	290-2,030	85
C2RHA10	2,743	230-1,610	70
C2RHA20	2,751	230-1,610	70
C2RHA30	2,865	230-1,610	70
C3	3,924	390-1,950	115
C3FA10	3,369	340-2,040	100
C3FA20	3,398	340-2,040	100
C3FA30	3,302	340-2,040	100
C3RHA10	3,491	340-2,040	100
C3RHA20	3,085	340-2,040	100
C3RHA30	3,463	310-1,860	90

2.3. Experimental Program

The unconfined compression test was carried out following ASTM D2166 standard [40]. The unconfined compression machine with the displacement-controlled compression loading type having a capacity of 50 kN was employed. The unconfined compression test was carried out on the specimen with a 1-mm/min (1%/min) rate of displacement until the failure of specimen to obtain the maximum vertical stress value. Record was taken simultaneously of the axial deformation and the axial force at regular interval until failure. Compression is provided by moving up the bottom plate of loading frame at a constant rate which can be selected at the speed control panel in front of the apparatus.

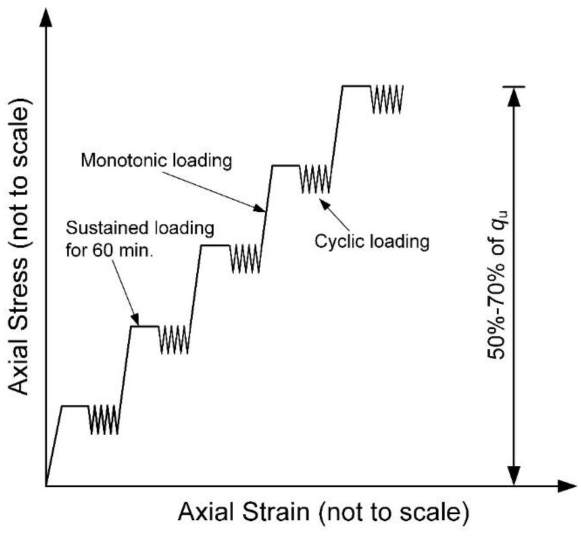

Fig. 4. Loading sequence for axial stress-axial strain of the cyclic loading tests.

Figure 4 presents a cyclic loading sequence. Monotonic loading was applied at constant vertical stress rate of 15 kPa/min. After sample conditioning (increasing vertical stress), a repeated axial cyclic stress of fixed 5 magnitude (stress amplitude about 3% of ultimate stress) was applied to the test specimens with the stress rate of 15 kPa per minute. Then, vertical stress was sustained for 60 minutes at any stress levels. Then, the stress level (L_s) was continuedly increased until the vertical stress becomes about 50%-70% of ultimate stress obtained from conventional unconfined compression test. Table 4 presents the sequence of cyclic loading tests.

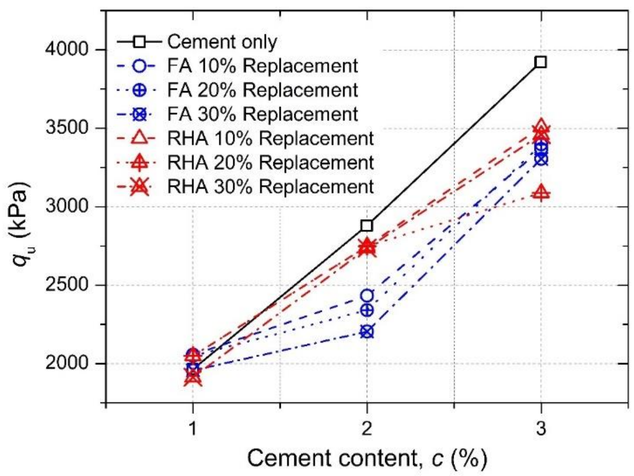

Fig. 5. The relationship of cement content and unconfined compression strength in the role of FA and RHA replacement.

3. Results and Discussion

3.1. Strength Characteristics and Stress-Strain Relation

A comparison of cement content and ash replacement effects on the unconfined compressive strength (q_u) of the test specimens is illustrated in Fig. 5. It is seen firstly that the q_u for all specimens was considerably increased with cement content. For cement only samples, the q_u values increase linearly with cement content. At 1% cement content, no significant difference between cement only and both ashes replacement specimens is observed. The cement only samples show higher values of q_u than all ash replacement samples for 2% and 3% cement contents. The smaller value of q_u in ash replacement samples would be attributed to the fact that a replacement of both ashes in the treated soil contributed to the less degree of hydration reaction, resulting in reduction in q_u value. At 2% cement content, the stabilized C/RHA samples were slightly less than cement only sample about 2.5%. At 3% cement content, the only cement sample shows a greater q_u value than those of stabilized C/RHA samples for 15% approximately. From these results, it is indicated that pozzolanic materials affect strength development, especially for high cement content condition. However, both materials have demonstrated potential applications in

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partial use on lateritic soil stabilization. The strength development during the curing of the ash replacement samples might be connected with the combination effects of pozzolanic activity and filler effect of ash and hydration reaction of ordinary Portland cement. Based on overall results, the RHA shows a better efficiency than FA for replacement particularly at 2% cement content. The high performance is due to the high content of SiO_2 as illustrated in Table 2 causing relatively high pozzolanic reaction in RHA cement mixed lateritic. This phenomenon has also been discussed in the literatures [7, 41].

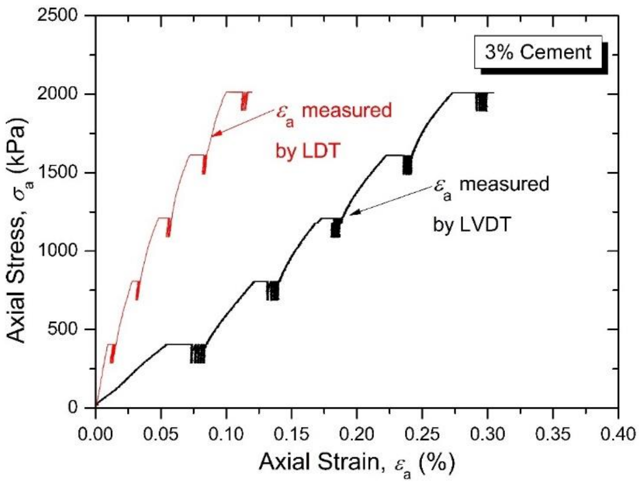


Fig. 6. Relationship between axial stress and axial strain obtained from cyclic loading test on cement mixed lateritic with 3% cement.

Figure 6 illustrates the relationship between axial stress (σ_a) and axial strain (ε_a) measured by LDT and LVDT, under monotonic loading and unloading/reloading on C3 sample. From the figure, the axial strain measured by LVDT is greater than that measured by a pair of LDTs, which is due to the measuring errors consisting of system compliances and bedding errors. As a result, from the stress-strain response, it is indicated that the modulus properties of geomaterials were notably affected by the specimen's instrumentation [4]. The axial strains measured by using a pair of LDTs were found to give a sound basis for axial strain measured with small strains. Note that creep and residual strains caused by minute-amplitude cycles performed after creep are noticeable. Therefore, the rate effect on the development of residual strain is not negligible.

3.2. Equivalent Modulus

For the dynamic properties, Resilient modulus (M_r) is evaluated by cyclic loading with a rapid haversine-shaped load pulsed form. This form of load pulse is a way of simulating traffic loading. However, because the resilient modulus is a modulus value determined after many cyclic loadings have been applied until only small recoverable strain is experienced, the response can be treated as purely elastic. Indeed, M_r and Young's modulus (E) are very similar. The former refers to E with a specific cyclic loading load pulse form, whereas the latter is for general meaning. Many past studies showed that E of geomaterials can be evaluated by applying small strain-amplitude cyclic loadings, by which the sample's response is recoverable (e.g., [42]). The E value obtained with such a technique is called the Equivalent modulus (E_{eq}).

In this study, dynamic properties of each sample, E_{eq} was determined by defining the slope of the apparently linear portion from the unloading/reloading cycles as depicted in Fig. 7. According to the definition, E_{eq} is the modulus at a given stress level. Like other stiffness and shear properties, E_{eq} for unbound granular materials (i.e., sand and gravel) is mainly influenced by the representative stress state [43-45]. The unloading/reloading of axial or deviator stress generally provides greater stiffness value than those from initial virgin loading for fine grained soils [46-47], silty soils [49] and lateritic soil [45].

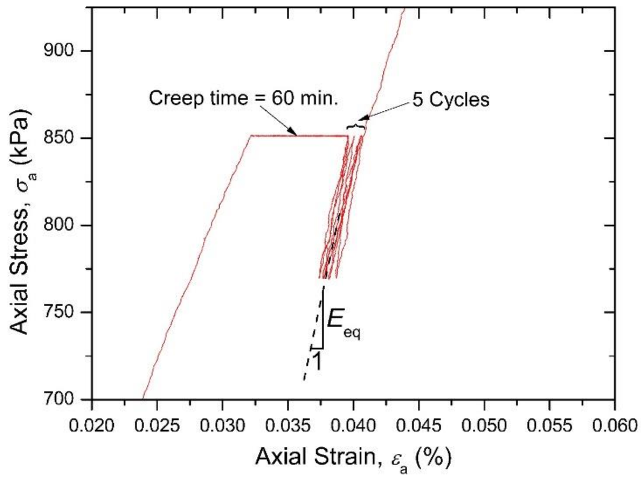


Fig. 7. Definition of Equivalent elastic modulus (E_{eq}).

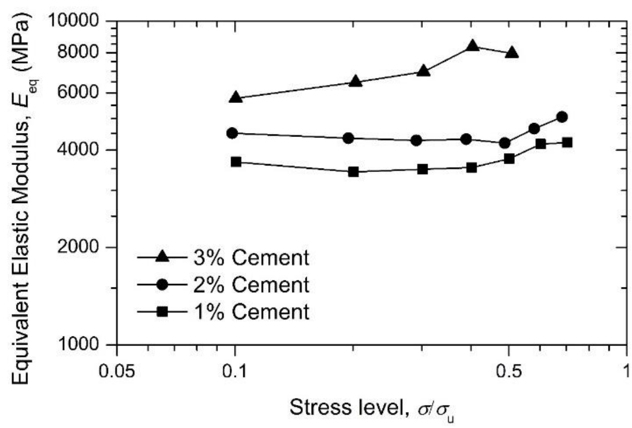


Fig. 8. Relationships between E_{eq} and stress level for lateritic mixed with cement only at 1%-3%.

In current study, the E_{eq} value were evaluated from stress-strain relation obtained from LDTs during five minute-amplitude unloading/reloading cycles after sustained loading for 60 minutes. The E_{eq} values were obtained from the average of a set of 5 cyclic loading as seen from Fig. 7. From observation it is implied that, at small strain level near the origin, the stress-strain behaviors are significantly elastic for all specimens prepared at different mixes. All the cases investigated in the current study were listed in Table 5. Figure 8 presents the E_{eq} values obtained from the cement treated lateritic samples with cement content 1%-3% plotted against the normalizing stress that equals to the ratio of applied stress and unconfined compressive stress. It is evident that the E_{eq} values mostly increase as the stress level increases. For C1 and C2 samples, the decrease occurs slightly at the early stage (stress level equals to 0.1-0.3, approximately). C3 sample exhibits the highest E_{eq} values with about 2 times greater than other samples. As increase stabilizing agent for lateritic soil, increase of q_u was observed, resulting to withstand increased the stiffness.

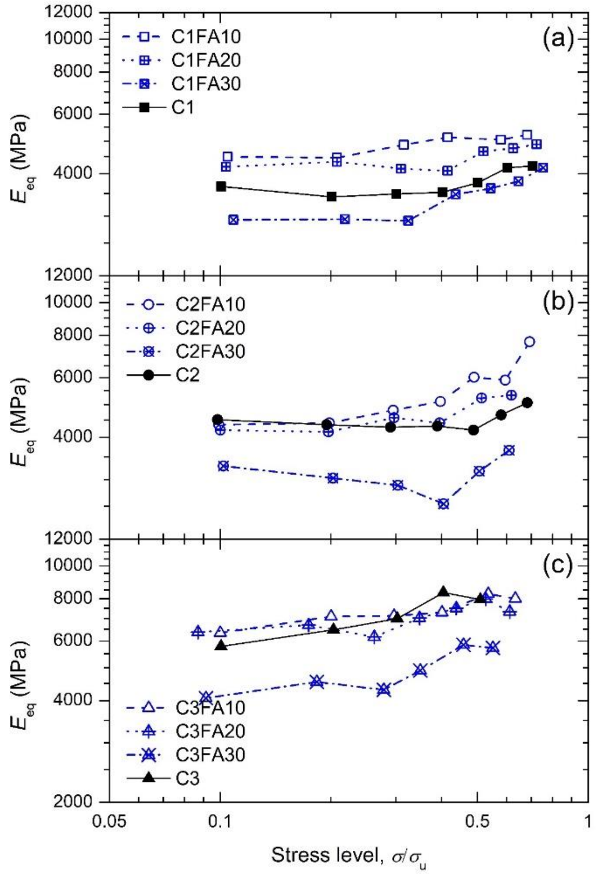


Fig. 9. Relationships between E_{eq} and stress level for lateritic mixed cement and FA replacement.

Figures 9(a)-(c) show the variation in E_{eq} values with the effect of FA replacement. It is observed that E_{eq} generally increases with an increasing of stress level, except for some samples replaced with high fly ash content (i.e., C2FA30, C3FA30) at low stress level. For 1% cement content, the E_{eq} values of the samples with 10-20% FA replacement are higher than those of the samples without ash replacement as shown in Fig. 9(a). A similar trend is observed in Fig. 9(b) for the treated soils with 2% cement content. The addition of pozzolanic materials to the mixture is notably enhances the modulus of cement treated lateritic. The underlying reason for this significant improvement can be explained that the pozzolan materials are able to clog the pore spaces of the matrix. Then, the microstructure of treated lateritic with cement is closely packed, reinforced and strengthened as the hydration and pozzolanic products are developed during cement hydrolysis. For 3% cement content (see Fig. 9(c)), the E_{eq} values obtained from C3FA10 and C3FA20 samples showed similar trend compared to the C3 sample. By increasing the replacement ratio to 30%, the values of E_{eq} of the mixtures for 2%-3% cement content are notably lower than the others as seen from Figs. 9(b)-(c). According to the results obtained, this decrease in E_{eq} can be possibly explained that the high amount of ash replacement significantly decreased in hydration rate and a consequent decrease in strength development. It is seen that the FA replacement is less efficient in the samples with cement content of 2%-3% and replacement ratio of 30%.

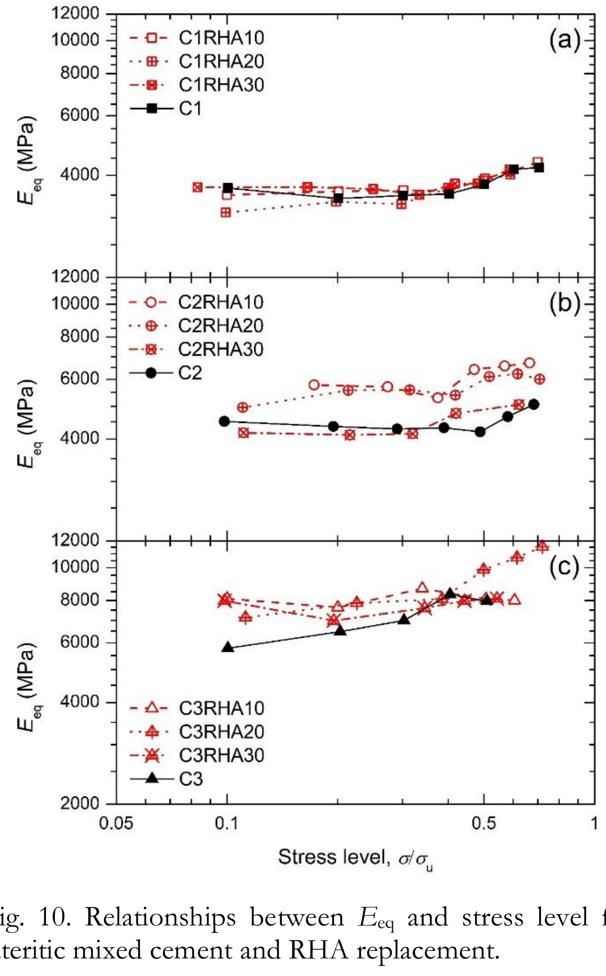
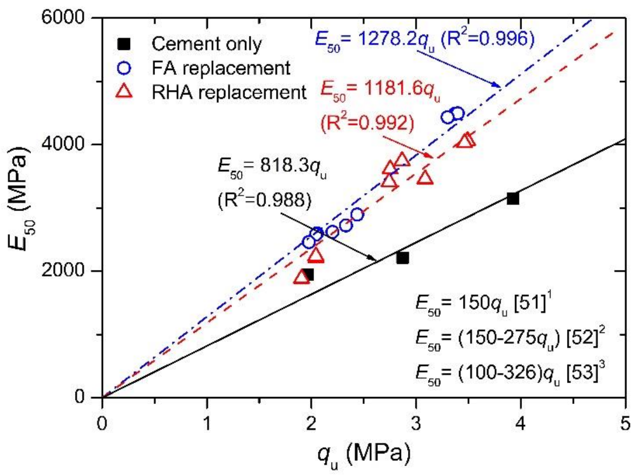


Fig. 10. Relationships between E_{eq} and stress level for lateritic mixed cement and RHA replacement.

Figures 10(a)-(c) show that when cement content and RHA replacement decrease, the E_{eq} values increase as the stress level or axial stress increase. For all equivalent modulus trend of lateritic soil cement mixed was harmonized with the trend of unbound materials (i.e., sands and gravels) that increases with an increase in the axial stress [43, 48, 50]. At 1% cement content, the E_{eq} values are remarkably the same for these RHA replacement and on-replacement samples (see Fig. 10(a)). The E_{eq} values grow about 20% when the stress level increases from the beginning to the end of test. For 2%

cement content, by replacing the cement with 10-20% RHA, E_{eq} of those samples are higher than the sample without ash replacement as can be seen from Fig. 10(b). In the same figure, the variation of E_{eq} obtained from C2RHA30 sample is very closed to C2 sample. It is observed that a decrease in the E_{eq} at low stress level was followed by a consequent increase at higher stress level. At highest cement content (see Fig. 10(c)), in accordance with the expectation, all RHA replacement samples shows the higher in E_{eq} than the non-replacement sample. The maximum E_{eq} was found for the C3RHA20 sample with the modulus value up to 11,535 MPa. The results show that it would be desirable for cement treated lateritic with RHA replacement when cement content was 1%-3% and replacement ratio was 10%-30%.



Noted that: [1] Cement-admixed (5–20%) Bangkok clay in Thailand [51], [2] Cement-admixed (10–20%) marine clay in China [52], [3] Cement-treated (7–13%) silt, silty clay, and laterite in Malaysia [53].

Fig. 11. Relationship between Modulus of elasticity (E_{50}) - unconfined compressive strength (q_u).

3.3. Evaluation of Unconfined Compressive Strength and Equivalent Stiffness

Based on a summary of values of the stabilized lateritic samples examined in this study, the secant modulus at 50% (E_{50}) has been related with q_u as provided in Fig. 11. The E_{50} values increase linearly with increasing q_u. According to Fig. 11, the relation of E_{50}-q_u for each material can be determined by using Eqs. (1)-(3) for cement only, FA and RHA samples, respectively.

$$E_{50,cement} = 813.3q_u \quad (1)$$

$$E_{50,FA} = 1278.2q_u \quad (2)$$

$$E_{50,RHA} = 1181.6q_u \quad (3)$$

It can be seen that the observed E_{50} values from cement mixed with both FA and RHA replacement are higher than those of only cement samples. The obtained correlations are useful for estimating the modulus from strength when required for instance in numerical modeling. It can be seen that the E_{50} values obtained from the current study are much higher than those obtained from previous studies. This is because they are measured from different instrumentations as discussed in section 3.1. The modulus obtained from LDTs is typically higher than LVDT. However, by using LVDT, E_{50} values can be determined by the relations of $E_{50,cement}$ = 196.5q_u, $E_{50,FA}$ = 329.5q_u and $E_{50,RHA}$ = 311.3 q_u, which are within the range of previous studies.

From Table 5, summary of modulus values of the stabilized lateritic samples of all samples are presented. It can be found that the E_{eq} value is typically higher than E_{50} value for all testing. Depending on the stress level, the E_{eq} value at 0.4 level stress is defined. This remarkable point of increasing trend of equivalent modulus, namely the reference modulus ($E_{0.4\sigma}$). In other word, the equivalent modulus trend increased from the stress level 0.1 to 0.4 with one slope and increased with higher slope when the stress level is greater than 0.4. The $E_{0.4\sigma}$ was therefore identified as the normalizing parameter for the equivalent modulus value, which was selected at level stress = 0.4. The data points for all samples were plotted in terms of $E_{0.4\sigma}$-E_{50} in Fig. 12. The $E_{0.4\sigma}$ values increase with E_{50} and the linear relationship can be used to fit the data, which can be estimated as 1.945E_{50}, 1.579E_{50} and 1.810E_{50} for only cement, FA and RHA replacement samples, respectively. When compared with the relation M_r-E_{50} obtained from the stabilization of organic soils with fly ash [54]. The obtained relations of $E_{0.4\sigma}$-E_{50} from this study falls within the lower bound of previous study. It can be found that both M_r and $E_{0.4\sigma}$ are higher than E_{50}.

Table 5. Summary of test results.

Sample	E_{50} (MPa)	E_{eq} (MPa)	$E_{0.4\sigma}$ (MPa)
C1	1,945	3,423 – 4,235	3,575
C1FA10	2,597	4,432 – 5,203	5,020
C1FA20	2,577	4,087 – 4,873	4,383
C1FA30	2,460	2,886 – 4,164	3,283
C1RHA10	2,212	3,506 – 4,374	3,607
C1RHA20	2,239	3,115 – 4,023	3,678
C1RHA30	1,886	3,512 – 4,159	3,609
C2	2,212	4,231 – 5,058	4,312
C2FA10	2,896	5,148 – 7,760	5,493
C2FA20	2,721	5,015 – 5,978	5,333
C2FA30	2,620	3,550 – 4,583	3,569
C2RHA10	3,411	5,309 – 6,691	5,789
C2RHA20	3,614	4,999 – 6,230	5,383
C2RHA30	3,744	4,104 – 5,093	4,738
C3	3,142	5,786 – 7,940	6,239
C3FA10	4,485	6,344 – 8,226	7,247
C3FA20	4,494	6,167 – 7,972	7,294
C3FA30	4,432	4,084 – 5,841	5,338
C3RHA10	4,063	7,660 – 8,758	8,542
C3RHA20	3,455	7,174 – 11,535	8,345
C3RHA30	4,027	6,992 – 8,188	7,898

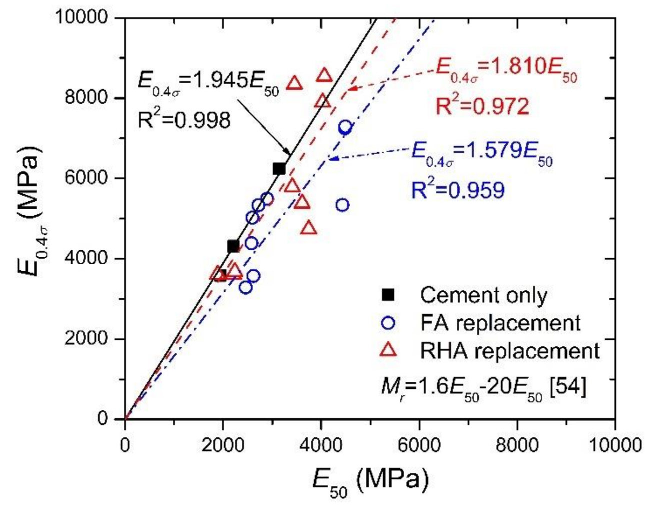


Fig. 12. Relationships between Reference modulus ($E_{0.4\sigma}$) and Modulus of elasticity (E_{50}).

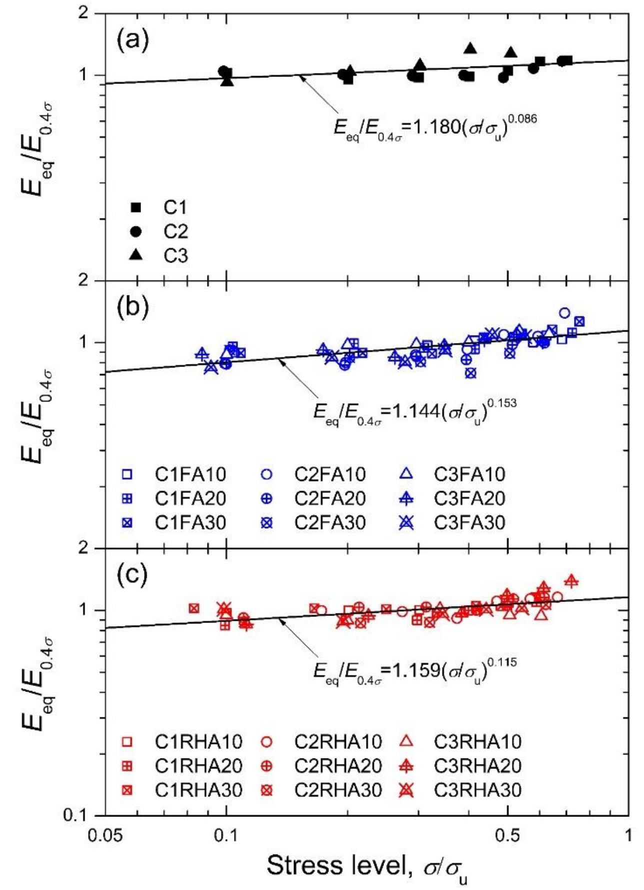


Fig. 13. Relationships between normalized equivalent modulus and level of stress level.

Figs. 13(a)-(c) show the normalized relationships between $E_{eq}/E_{0.4\sigma}$ and stress level. After normalization, the value of Eeq becomes rather unique against the stress level. The trend of $E_{eq}/E_{0.4\sigma}$ increase with an increase in the stress level. The functions which could fit the results more reasonably have been chosen as Eqs. (4)-(6).

$$\frac{E_{eq}}{E_{0.4\sigma}} = 1.180\left(\frac{\sigma}{\sigma_u}\right)^{0.086} \quad ;For\ cement\ only \tag{4}$$

$$\frac{E_{eq}}{E_{0.4\sigma}} = 1.144\left(\frac{\sigma}{\sigma_u}\right)^{0.153} \quad ;For\ FA\ replacement \tag{5}$$

$$\frac{E_{eq}}{E_{0.4\sigma}} = 1.159\left(\frac{\sigma}{\sigma_u}\right)^{0.115} \quad ;For\ RHA\ replacement \tag{6}$$

The term of σ and E_{eq} were defined to axial stress value and elastic modulus from the applied cyclic loading. The value of σ_u or q_u can be determined from the conventional unconfined compression test. It can be seen that the dependency of E_{eq} on the FA and RHA replacements are larger than that of the cement only. This behavior may also be affected by the different of the properties of pozzolan replacement materials. From this result, the performance of RHA replacement is slightly better than that of FA replacement. Under the controlled gradations of both ashes to be the same (see Fig. 1), it can be interpreted that the role of both ashes in terms of packing should be relatively the same. Considering the SiO_2 content as depicted in Table 2, the difference in improvement can be attributed to pozzolanic reaction.

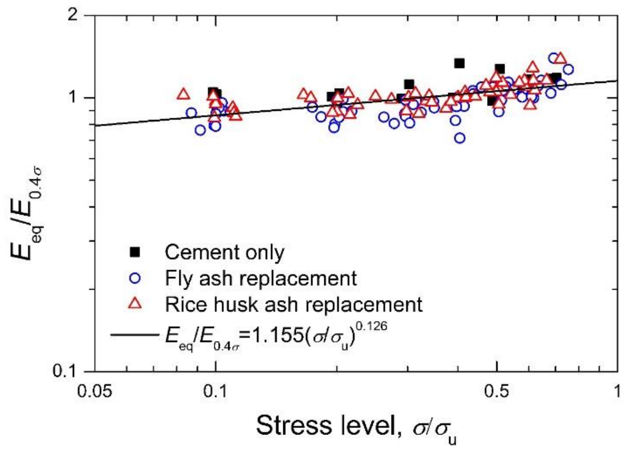


Fig. 14. Relationships between normalized equivalent modulus and level of stress level for all samples.

Based on the experimental presented, several factors affect the E_{eq}. However, the modulus values obtained from both materials were found to have the same characteristics. The trend and magnitude for cyclic modulus are consistent for FA and RHA. To accomplish this purpose, a power function was performed on the data set of all testing. The E_{eq} for cement treated lateritic with 1%-3% cement content, and FA and RHA replacement with 10%-30% can be determined by the following Eq. (7):

$$\frac{E_{eq}}{E_{0.4\sigma}} = 1.155\left(\frac{\sigma}{\sigma_u}\right)^{0.126} \tag{7}$$

Although, some data points would appear as scatter plot as provided in Fig. 14, they seem to indicate that the presented correlation between $E_{eq}/E_{0.4\sigma}$ and stress level for all testing cases can be established. By substituting the obtained parameters into Eq. (7), the E_{eq} of cement-ashes treated lateritic can be obtained. The relationship between calculated equivalent modulus ($E_{eq,cal}$) and measured equivalent modulus ($E_{eq,mea}$) is shown in Fig. 15. It can be seen that the equation proposed is reasonable to predict the cyclic modulus of cement-ash treated lateritic and they also showed insignificant difference between $E_{eq,cal}$ and $E_{eq,mea}$.

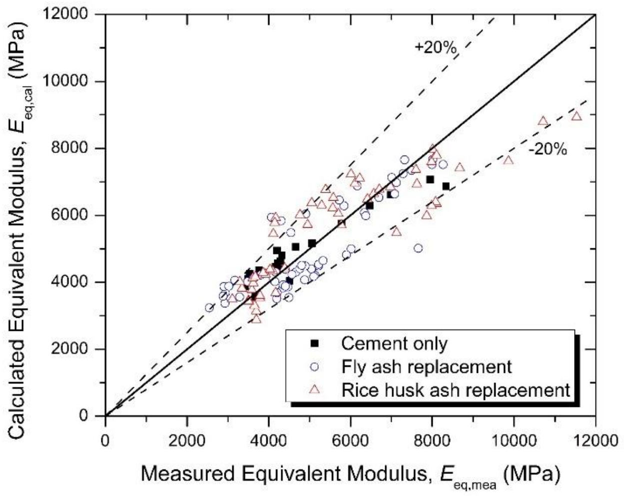


Fig. 15. Correlation of calculated and measured equivalent modulus ($E_{eq,cal}$- $E_{eq,mea}$) at 28 days of curing time for all samples.

4. Conclusions

A series of conventional unconfined and cyclic loading tests on the cement treated lateritic with 1%-3% cement content is carried out. Fly ash and Rice husk ash for replacing the Portland cement by 10%-30% are considered in order to assess the performance of pozzolan replacement materials which are increasingly used in cement treated lateritic soil application. The following obtained results are particularly noteworthy:

1. Based on the conventional unconfined compression test, the amount of Rice Husk Ash at 10-30% can be replaced effectively to the 1-2% cement mixed lateritic soil without reduction of the mixing strength.

2. Considering the q_u values, the RHA shows a better efficiency than FA for replacement particularly at 2% cement content. The high performance is due to the high content of SiO_2.

3. Under applied cyclic loading, the E_{eq} values increase as the stress level increases for all samples.

4. The addition of pozzolanic materials to the mixture notably enhances the modulus of cement treated lateritic. It is seen that the FA replacement is less efficient in the samples with cement content of 2%-3% and replacement ratio of 30%. Whereas, it would be desirable for cement treated lateritic with RHA replacement when cement content was 1%-3% and replacement ratio was 10%-30%.

5. The E_{eq} value is typically higher than E50 value for all testing. The ratio of $E_{eq}/E_{0.4\sigma}$ and stress level obtained from FA replacement is generally similar to that of RHA replacement. The presented correlation between $E_{eq}/E_{0.4\sigma}$ and stress level provided satisfactory results for all testing cases. Based on overall results, both FA and RHA materials have demonstrated potential applications in partially used on lateritic soil stabilization.

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