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Undrained shear strength and microstructural characterization of treated soft soil with recycled materials

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Abstract. Waste materials are being produced in huge quantities globally, and the usual practice is to dump them into legal or illegal landfills. Recycled tiles (RT) are being used in soil stabilisation which is considered as sustainable solution to reduce the amount of waste and solve the geotechnical problems. Although the stabilisation of soil using RT improved the soil properties, it could not achieve the standard values required for construction. Thus, this study uses 20% RT together with low cement content (2%) to stabilise soft soil. Series of consolidated undrained triaxial compression tests were conducted on untreated and RT-cement treated samples. Each test was performed at 7, 14, and 28 days curing period and 50, 100, and 200 kPa confining pressures. The results revealed an improvement in the undrained shear strength parameters (cohesion and internal frication angle) of treated specimens compared to the untreated ones. The cohesion and friction angle of the treated samples were increased with the increase in curing time and confining pressure. The peak deviator stress of treated samples increases with the increment of either the effective confining pressures or the curing period. Microstructural and chemical tests were performed on both untreated and RT-cement treated samples, which included field emission scanning electron microscopic (FESEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and energy dispersive X-ray spectrometer (EDX). The results indicated the formation of cementation compounds such as calcium aluminium hydrate (C-A-H) within the treated samples. Consequently, the newly formed compounds were responsible for the improvement observed in the results of the triaxial tests. This research promotes the utilisation of RT to reduce the amount of cement used in soil stabilisation for cleaner planet and sustainable environment.

Keywords: soft soil; consolidated undrained triaxial test; RT-cement; soil stabilisation; shear strength; curing time

1. Introduction

Untreated soft soils often reveal low shear strength and permeability that make it unsuitable foundation material for engineering structures (Al-Bared and Marto 2017). The existence of high water content and large void ratio induce different types of settlement within soft soils (Kwon *et al.* 2019). Recent studies emphasis on improving and enhancing the characteristics of problematic soils in order to meet the engineering design requirements (Al-bared and Marto 2019, Chang and Cho 2019, Chang *et al.* 2014). Chemical based stabilisers such as Portland cement are the most effective additives in improving the properties of soft soils. It has been used in the improvement of soft soils for various geotechnical applications since 1960's (Makusa 2013). The addition of cement in soft soil enhances the engineering properties and reduces the compressibility and settlement of soft soil. When soft soil is treated with the minimum (optimum) amount of cement, it exhibits similar behaviour as stiff soils with planar failure surface under triaxial testing (Pillai *et al.* 2013). The behaviour of cement treated soils in terms of strength and failure envelopes was extensively studied by several researchers (e.g., Farzana *et al.* 2016, Jitsangiam *et al.* 2016, Kang *et al.* 2015, Nusit *et al.* 2016a, Nusit *et al.* 2016b, Nusit *et al.* 2015, Sasanian and Newson 2014). Moreover, the shear strength under both undrained and drained triaxial compression tests of cement treated soils was examined and evaluated in several studies (e.g., Al-zoubi, 2008, Damoerin *et al.* 2015, Kasama *et al.*, 2006). However, the usage of high amount of cement in soil improvement has some adverse environmental impacts such as the pollution of underground water (Zainuddin *et al.* 2019). In addition, during the production processes of cement, massive amounts of carbon dioxide are produced and released into the air resulting in air pollution (Andrew 2018, Zhang *et al.* 2014). Nowadays, researchers aim to reduce the amount of cement used in soil improvement by

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introducing the utilisation of waste materials that contribute in the development of sustainability (Chang *et al.* 2018). Modern geotechnical engineering aims to provide soil additives that are environmental-friendly and have the ability to improve the soil properties (Lee *et al.* 2017, Qureshi *et al.* 2017). Solid waste materials could be mixed in a powder form with minimal amount of cement to stabilise soft soils (Al-bared and Marto 2018a).

The massive amounts of solid waste produced worldwide is considered an environmental threat that need to be dealt with (Al-bared *et al.* 2018b). Utilising waste materials in stabilisation of problematic soils have been a concern of various studies (Saltan and Findik 2008, Shahbazi *et al.* 2017). Recycled ceramic tiles are considered as one of the construction materials with higher percentage of waste during production. It is estimated that approximately 7-30% is the total wastage during the production stage of the ceramic tiles only (Al Bakri *et al.* 2008, Elçi 2016). This waste is usually dumped in legal or illegal landfills which will accumulate resulting in consuming large spaces and affecting the fertility of the soil in the surrounding areas (Al-Bared *et al.* 2018c).

The shear strength of treated and untreated soils can be investigated using either the unconfined compressive strength test (UCS) or triaxial controlled tests (Al-bared *et al.* 2018d, Lee *et al.* 2019). The shear strength obtained from the UCS test is considered unreliable as compared to that obtained from the triaxial tests. The failure criterion assessment of the treated soft clay under effective confining pressures can only be revealed using triaxial tests during which all the stress acting on and around the specimen are well controlled (Namikawa *et al.* 2017). The results obtained from the triaxial compression tests could be used to define the failure criterion of treated soft soils (e.g., Cetin and Gökoglu 2013, Ismail *et al.* 2002, Wang *et al.* 2008). For instance, drained and undrained triaxial compression tests were performed to assess the mechanical properties of cement-treated sand. Lime, Portland cement, and gypsum were used in a similar percentage (1.5-4.5%) to treat the gravely sand. The findings stated a decrease in the axial strain under the peak deviator stress with an increase in the cementation. The effect of the stabiliser type on shear strength was more profound in the drained compression tests as compared to the undrained ones (Haeri *et al.* 2006, 2005). Amini and Hamidi (2014) also conducted undrained and drained triaxial tests on cement treated sand. The authors noted a smaller amount of strain at the maximum shear strength during drained conditions as compared to that obtained during undrained conditions. Moreover, the undrained shear strength of kaolinite clay improved by cement columns was studied by Damoerin *et al.* (2015). The results indicated an improvement in the shear strength of the cement-kaolinite samples. The cohesion of the treated samples increased, and the friction angle descended as compared to the untreated kaolinite clay. Bushra and Robinson (2012) reported that the undrained shear strength of cement treated marine clay could be cured under 0 to 200 kPa stress. Samples of marine clay were mixed with 10, 15, and 20% of cement and cured for 28 days. The results showed better strength for cement treated samples cured under stress, whereas, those cured under drained condition showed higher strength. The higher the cement content, the better the critical stress path of the samples. The peak and residual shear strength of cement treated soil were also investigated by Suzuki *et al.* (2014). It was found that the undrained shear strength of the treated soil increased by either increasing the curing time or the confining pressure. Pillai *et al.* (2013) conducted a series of undrained triaxial tests to examine the effect of a low amount of cement treated marine clay. The marine clay was mixed with 5% cement which created cementation bonding between the clay particles. The cement treated clay exhibited behaviour like that of over consolidated clay. The results revealed a high pre-consolidation pressure on the cement treated clay.

To the authors' best knowledge, the behaviour of cement-recycled tiles stabilised soft soil under triaxial testing had never been explored or investigated earlier. No efforts have been taken to study the mixture of cement-RT and its suitability as an effective additive to stabilise soft soils. Hence, this study examines the undrained shear strength of both untreated soft soil and RT-cement stabilised soft soil. Several consolidated undrained compression triaxial tests with variable confining pressures were conducted in order to assess the behaviour of both untreated and RT-cement treated soft soils at different curing periods. Microstructural and chemical tests were also carried out in order to observe the formation of cementation compounds within the stabilised samples. The tests included field emission scanning electron microscopy (FESEM), Fourier transform infrared spectroscopy (FTIR), energy dispersive X-ray spectrometer, and X-ray diffraction (XRD). The recycled tiles (RT) is utilized in this research and mixed with cement in order to reduce the amount of cement used in soil stabilisation. This would help to minimize the emission of carbon dioxide (CO_2) produced during the production of cement and achieve the concept of green technology and cleaner planet.

2. Testing procedure

2.1 Soil sample and cementing additives

The soil used in this study was a problematic soft soil collected from Gelang Patah at the state of Johor, Malaysia. The soil samples were collected from a depth of 1.5 meters below the ground surface using an excavator. Then, the soil was air dried and all the debris and plant roots were removed. The soil was sieved and only those passing 2 mm diameter sieve were stored and used for the experiments. The soil had a pH value of 2.8 which shows that the soil is acidic and soil with low pH value exhibits low shear strength. The reason is due to the removal of the soil cations as a result of the high intensity and the corresponding infiltration of rainfall in Malaysia. When the water-soluble cations such as Ca^{2+}, Na^{+}, K^{+}, and Mg^{2+} are removed from the top layer of the soil, the concentration of Al and Fe oxides will increase resulting in acidic soil (Zainuddin *et al.* 2019). The maximum dry density (MDD) and the optimum moisture content (OMC) of the untreated soil were 1590 Kgm^{-3} and 22%, respectively. In addition, the MDD and OMC for RT-cement treated soil were 1670 Kgm^{-3} and 20%, respectively. The MDD of the RT-cement treated soil was increased and the OMC was decreased, and this shows that the treatment successfully enhanced the mechanical

Table 1 Physical properties of the soil specimen

Index property	W_0 (%)	G_s (%)	W_L (%)	PL (%)	I_p (%)	MDD Kgm^{-3}	OMC (%)	Clay (%)	Silt (%)	Soil classification	pH
Value	59	2.52	41	22	19	1590	22	30.9	31.1	Silty clay	2.80

Table 2 Detailed results obtained from the consolidated undrained triaxial tests for untreated and RT-cement treated samples

Test No.	Cement content (%)	RT (%)	Initial moisture content, (%)	Bulk density (Mg/m^3)	Void ratio, e (%)	Curing time (days)	Isotropic consolidation Pressure (kPa)	Initial pore water pressure (kPa)	Final pore water pressure (kPa)	Coefficient of consolidation, C_v (m^2/Yr)	Peak Strength, q_{max} (kPa)	Axial strain at peak (%)	Effective Cohesion, C' (kPa)	Effective Friction Angle, ϕ'	Moisture Content after shearing (%)
1-a	0	0	23		0.51	0	50	327	350	-	48.5	17			23
1-b	0	0	23		0.50	0	100	327	362	-	93.86	10.75	2.6	13	23
1-c	0	0	23		0.50	0	200	330	389	-	214.7	11			23
2-a	2	20	19	1.97	0.56	7	50	490	526	13.13	242	16.02			21
2-b	2	20	19	1.96	0.57	7	100	490	570	30.00	327	15.53	3	30	22
2-c	2	20	19	1.96	0.56	7	200	490	573	30.00	357	16.08			22
3-a	2	20	19	1.97	0.62	14	50	490	530	1.90	177.40	11.26			26
3-b	2	20	19	1.97	0.62	14	100	490	578	46.9	269.79	12.53	26	30	25
3-c	2	20	18	1.97	0.61	14	200	490	669	61.2	303.13	6.03			25
4-a	2	20	22	1.96	0.67	28	50	490	520	0.6	184.40	1.26			24
4-b	2	20	22	1.98	0.66	28	100	490	568	7.5	420.14	15.04	66	23	24
4-c	2	20	21	1.98	0.64	28	200	490	667	4.8	578.94	13.31			23

properties of the soil. Table 1 shows all the physical properties of the soft soil specimen.

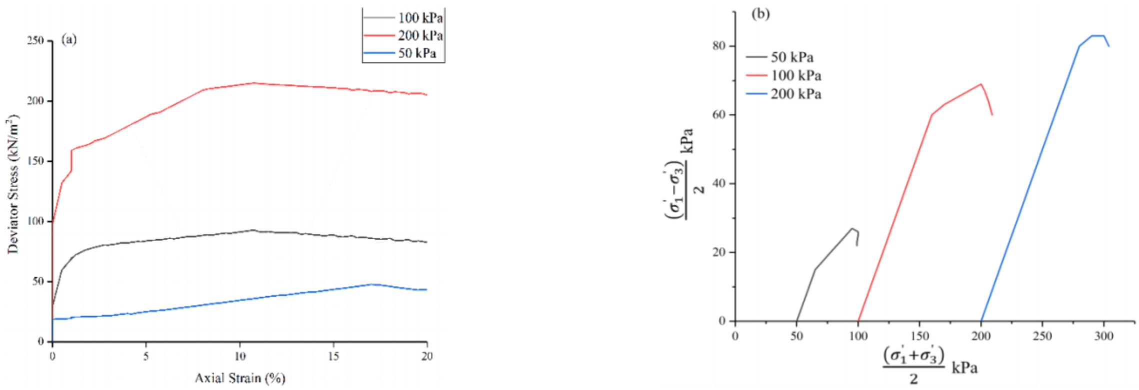
Ordinary Portland cement was the cementing agent used in this study with recycled tiles (RT). Two percent of cement was chosen in this study to increase the reaction between the RT and the soft clay. Although, the optimum amount of cement used in soft soil treatment is usually more than 10%, low amount of cement was used in order to reduce the environmental pollution created by using high amount of cement in soil stabilisation. The tiles were collected from construction sites in the state of Johor, Malaysia. The optimum percentage and size of recycled tiles to be used to treat soft soils was determined by Al-Bared *et al.* (2018e). The optimum size and percentage of recycled tiles used in this study were 0.063 mm and 20%, respectively. Portland cement and recycled tiles were mixed in a dry form until homogeneity was observed. Then, the optimum distilled water was added to the mixture and stirred for a few minutes before it was added to the soft soil.

2.2 Consolidated undrained (CU) triaxial test

The samples of the consolidated undrained triaxial tests were prepared inside a cylindrical mold of 38 mm diameter and 80 mm height using the predetermined maximum dry density and optimum moisture contents (Latifi *et al.* 2015). The proportion of recycled tiles (RT) and cement were determined based on the dry weight of the soil. The mixtures of RT, cement, and soft clay were placed inside the triaxial mold in three equal layers and compacted 27 blows each (Ahmed, 2015, Yilmaz 2015). The compacted samples were extruded, trimmed, and wrapped with several layers of cling film in order to preserve the moisture contents. Then, the samples were placed inside air-tight plastic bottles and stored inside a controlled humidity chamber (27 ± 2 °C and humidity of 97 ± 2%) for the required curing period. Prior to testing, the cured sample was placed inside a latex rubber membrane and installed on the pedestal inside the triaxial cell and subsequently, the triaxial chamber was assembled. The machine used for the testing was a traditional triaxial compression apparatus equipped with a hydraulic control system that was compiled with the methods of the triaxial consolidated undrained testing for soils (Suzuki *et al.*, 2014). The testing procedures and methods used to conduct the CU tests followed BS 1377: part 8 (British Standard Institution, 1990). The test started with the saturation process where the back pressure was limited to 40 kPa in order to reduce the time prior to consolidation. After achieving the required saturation (B=0.98), the cell pressure and back pressure were set to achieve the specified effective confining pressure. Three different effective confining pressures were used for; 50, 100 and 200 kPa as shown in Table 2 with all the testing parameters. After the completion of the consolidation process, the sample was sheared under a shearing rate of 0.01 mm/min in the undrained state. An external strain gauge attached to the machine was used to measure the axial strain.

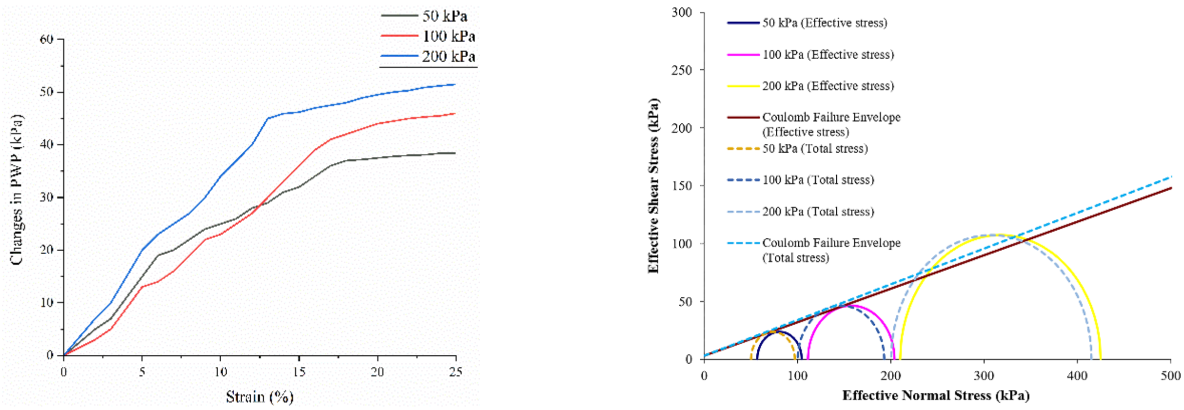
2.3 Microstructural and chemical tests

X-ray diffraction (XRD) test was used to examine the new crystalline compounds formed due to the addition of RT and cement at the soil surface. The specimen was scanned using Panalytical X-ray diffraction spectrometer.



(a) Stress-strain relationship (b) Stress path of soil

Fig. 1 Undrained behaviour of the untreated soil



(a) Changes of pore water pressure (b) Mohr's circles for untreated soil

Fig. 2 Changes of pore pressure and Mohr's total and effective stress circles

Treated samples used in the triaxial undrained tests were oven-dried, grinded into powder, and used for the XRD test. The powdered specimens were tested using a CuKα radiation at an angle between 6° and 90° with a 0.02° step (Latifi *et al.* 2017).

Field emission scanning electron microscopic (FESEM) was employed to observe the microstructural changes occurring at the surface of the untreated and RT-cement treated soil specimens. The FESEM was prepared with an energy-dispersive X-ray spectrometer (EDX) used to determine the micro-levels of the soil fabrics (Latifi *et al.* 2016a). For the powdered specimens to be ready for microscopic analysis, they were sputtered with gold for 120s under the high vacuum until the samples were fully covered. For the determination of major elemental compositions of untreated and RT-cement treated soil, the EDX spectrometer was used (Latifi *et al.* 2015).

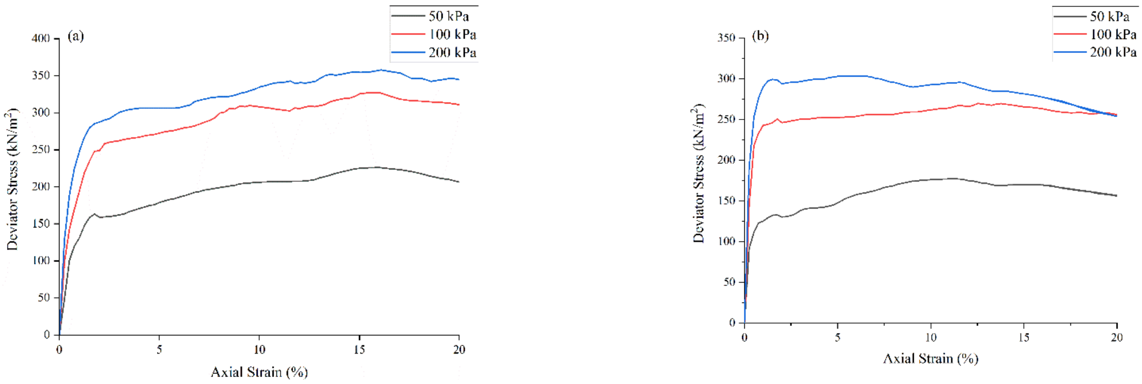
Fourier transform infrared spectroscopy (FTIR) was performed to determine the molecular structure of the untreated and RT-cement treated soil. This test is able to show the molecular changes that occur due to the stabilisation process (Latifi *et al.* 2016b). The Zeiss Supra 55 VP FTIR device was used to scan the specimens at 400 to 4000 cm^{-1} infrared spectrum range. The measurement of the absorption bands of the KBr disc was made by mixing about 2 mg dried powder of the untreated and RT-cement treated samples with 200 mg KBr.

3. Results and discussion

3.1 Undrained shear strength characteristics

The monotonic consolidated undrained triaxial tests were conducted on both untreated soil and RT-cement treated soil, cured for 7, 14 and 28 days. Fig. 1 (a) and (b) shows the deviator stress (q) versus the axial strain (ε_a) and the stress path in q'-p' plane for untreated soil at 50, 100 and 200 kPa confining pressures. As per the illustrative figures, the deviator stress increases with an increase in the axial stress for all the confining pressures while the stress path of the untreated soil has a dilative behaviour. The deviator stress reached the peak value at approximately 10 to 15% axial strain and then slightly dropped with an increase in axial strain. The maximum deviator stress for 50, 100, and 200 kPa confining pressures were 47.7, 182.1, and 213.4 kPa, respectively.

The results of the excess pore water pressure versus the axial strain and the Mohr's total and effective stress circles for the untreated soft soil tested under 50, 100, and 200 kPa confining pressures are shown in Fig. 2. The pore water pressure of the untreated soil was increased with the increase of the confining pressure and axial strain. The development of pore water pressure was quick at the beginning of the shearing stage and then slowly stabilized at later stages. On the other hand, the cohesion of the



(a) 7 days curing time (b) 14 days curing time

Fig. 3 Treated soil with 20 % RT and 2% cement

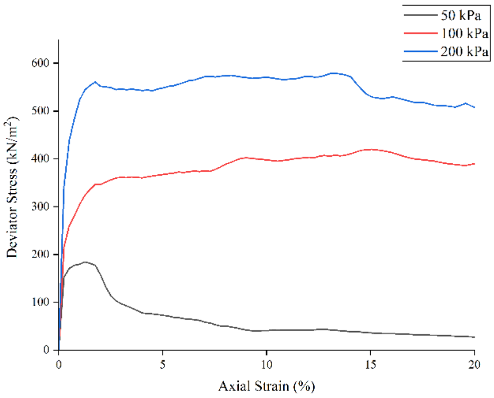


Fig. 4 Treated soil with 20 % RT and 2% cement cured for 28 days

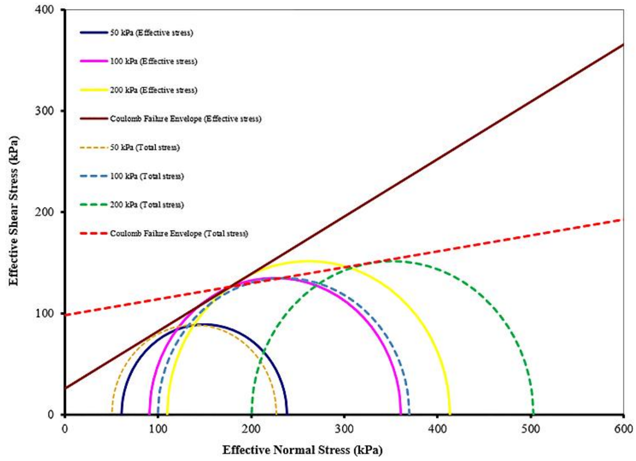


Fig. 6 Mohr's total and effective stress circles at failure for treated soil cured for 14 days

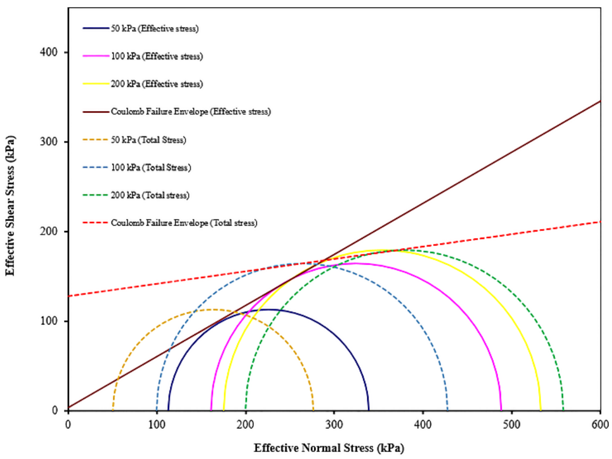


Fig. 5 Mohr's total and effective stress circles at failure for treated soil cured for 7 days

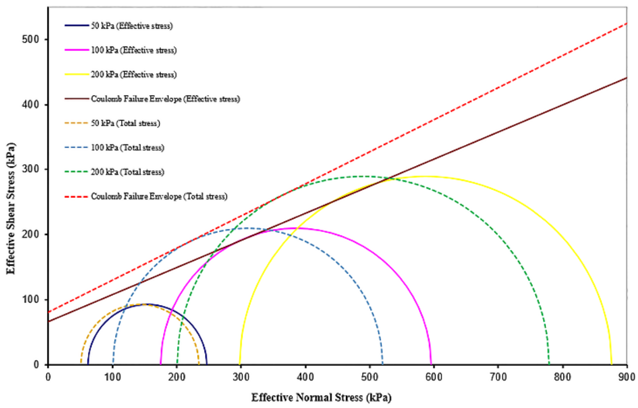
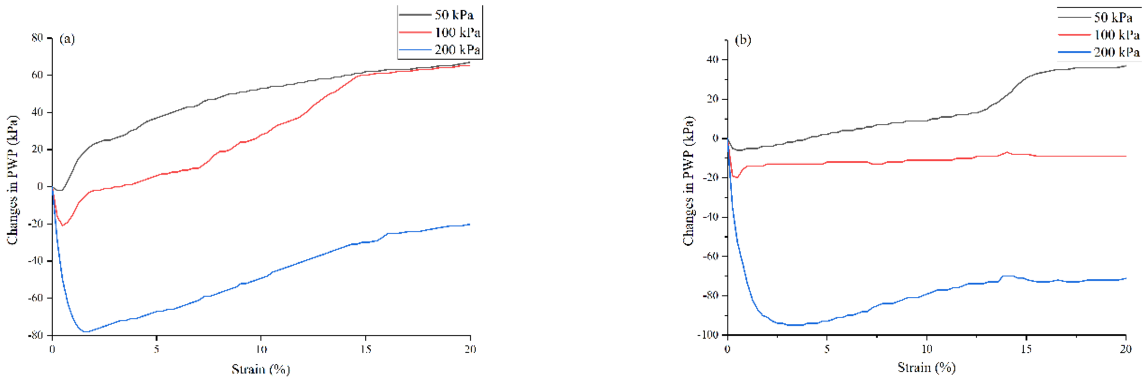


Fig. 7 Mohr's total and effective stress circles at failure for treated soil cured for 28 days

untreated soil was 2.6 kPa, while the internal friction angle was 13°as shown in Fig. 2(b).

The relationship between the deviator stress and axial strain for RT-cement treated soils under different curing periods are shown in Figs. 3(a) and 3(b) and Fig. 4. Softening behaviour was clearly seen in all treated samples cured for 7 and 14 days (Gu *et al.* 2016, Wang *et al.* 2013). The deviator stress increased with the increase in axial strain until reaching the peak value and then dropped slightly (Bushra and Robinson, 2012). Samples cured for 28 days also exhibited a softening behaviour except the one under 50 kPa confining pressure and this could be due to the formation of cementation compounds as soil treatment using cement is a time-dependent process (Bushra and Robinson, 2012). For those samples cured for 7 days, the peak deviator stress was 177.14, 269.79, and 303.2 kPa for confining pressures of 50, 100, and 200 kPa, respectively. Besides, samples cured for 14 days had deviator stress of 225.98, 327.3, and 357.65 kPa for a confining pressure of 50, 100, and 200 kPa, respectively. While, the samples



(a) 7 days curing time (b) 14 days curing time

Fig. 8 Changes in pore water pressure during shearing stage for treated soil

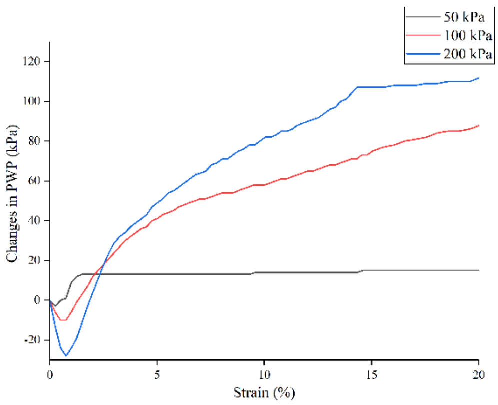
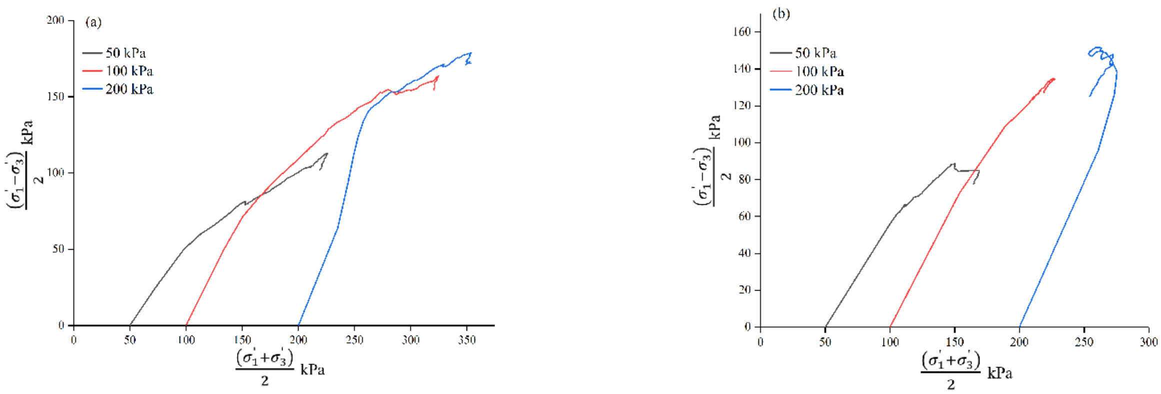


Fig. 9 Changes in pore water pressure during shearing stage for treated soil cured for 28 days



(a) 7 days curing time (b) 14 days curing time

Fig.10 Stress path relationships of treated soil

cured for 28 days had a peak deviator stress of 184.29, 420.14, and 577.23 kPa for confining pressures of 50, 100, and 200 kPa, respectively. It is clearly seen that the deviator stress increased with the curing period and those samples cured for a longer period were stronger than the ones cured for a shorter time (Frikha *et al.* 2015, Suzuki *et al.* 2014). This is also attributed to the soil improvement and the longer the curing time, the higher the possibility for cementing compounds to be formed. In addition, when comparing the untreated and RT-cement treated samples, enhancement of strength for treated samples is well-established and better performance is obtained due to the hydration process as a result of the addition of the cementing agents.

The Mohr's total and effective stress circles for RT-cement treated samples, cured for 7, 14, and 28 days, are shown in Figs. 5-7. The effective principle stresses of the peak stresses in the triaxial compression tests are used to determine those circles. Shear strength parameters (C' and ϕ') are improved by the treatment of RT-cement and the pozzolanic reaction resulted in the increase in soil cohesion (C') and reduction in the internal friction angle (ϕ'). The cohesion of RT-cement treated soil increased from 3 kN/m² at 7 days curing time to 26 kN/m² and 66 kN/m² at 14 and 28 days curing periods, respectively as shown in Table 2. While the internal friction angle reduced from 30° at 7 days

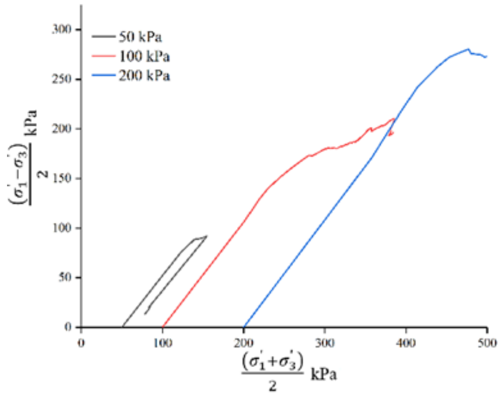


Fig. 11 Stress path relationships of treated soil cured for 28 days

curing time to 30° and 23° at 14 and 28 days curing time, respectively. The increment in the cohesion of treated soil is due to the filling of soil voids by the addition of RT particles and the strong bond between particles resulting from the pozzolanic reaction created by cement. On the other hand, the reduction in the value of the internal angle of friction is due to a reduction of the intergranular friction between the soil particles due to the addition of RT fine particles. This causes slippage of particles rearranged during compaction (Ikeagwuani *et al.* 2017).

The excess pore water pressure (Δu) and axial strain relationships for RT-cement treated soil at different curing periods are shown in Fig. 8(a) and 8(b) and Fig. 9. In general, the pore water pressure increased negatively with an increase in confining pressure and axial strain. Treated samples, cured for 7 and 14 days, had an alternating trend (negative and positive) of pore pressure development. The pore water pressure behaviour depends on the effective confining pressure. Samples with higher effective confining pressure completely exhibited a negative built-up of the pore water pressure. On the other hand, a completely different trend of pore water pressure was observed for treated samples cured at 28 days. The changes of pore water pressures were initially negative and then continued to increase at a positive phase depending on the value of their effective confining pressures as shown in Fig. 9. It is due to the stabilisation process that increases the bonding between the soil particles and the cementing agents over time. Samples at high effective confining pressures bulged in the vicinity of the maximum confining pressure resulting in creating complex systems due to strain localization (Alshibli *et al.* 2003, Gupta 2017). The soil samples used in this study are considered over consolidated due to the compaction during sample preparation and formation of cementation compounds during the stabilisation process. The behaviour of negative pore water pressure in the compacted over consolidated soils in triaxial undrained tests was observed by Harsha and Issac (2017) and Araei *et al.* (2012). Over consolidated soils have a low capacity for volume reduction during undrained compression triaxial tests which results in the build-up of negative pore water pressure.

The effective stress path in the q'-p' plane (q' is the effective deviator stress and p' is the mean effective stress at

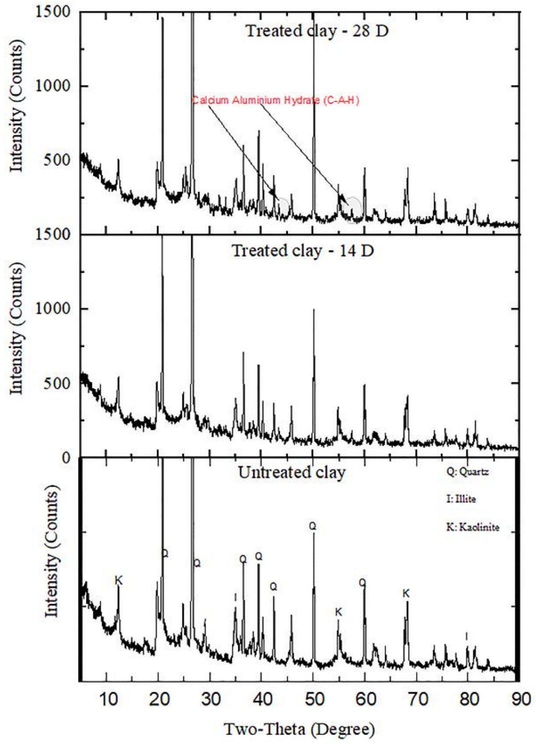


Fig. 12 XRD spectrum of untreated soil and RT-cement treated soil at 14 and 28 days curing times

the stress-strain curve) of the treated soils, cured for 7, 14, and 28 days, is expressed in Fig. 10 (a) and 10(b) and Fig. 11. Dilative behaviour can be seen from the stress paths of all the treated samples moving towards the right side. The deviator stress increases with an increase in the effective pressure. The deviator stress also increases with the curing time. Treated samples which were cured for 28 days had the highest deviator stress. Besides, the treatment improved the over consolidation of treated samples and noted an increase with the curing time. The increase of the deviator stress and the over consolidation with time is due to the pozzolanic reaction between the soil particles and the cementing agent. Similar behaviour of low cement (2.5-10%) treated soft clay was reported by Subramaniam *et al.* (2015).

3.2 Microstructural and chemical tests

3.2.1 XRD

The measurement of the XRD diffractometer was performed on both soils: on the untreated soil to examine the clay minerals; and on the RT-cement admixed soil to analyse the cementation products that were newly formed. All specimens were scanned with 2-theta ranging from 2° to 90°. The XRD results as shown in Fig. 12 for the untreated soil demonstrates two reflections of clay minerals which involves the detection of kaolinite and illite and one non-clay mineral (quarts). Whereas, the XRD analysis on RT-cement treated samples, cured at 14 and 28 days, as shown in Fig. 12 demonstrates the reflection of newly formed cementation compounds such as calcium aluminium hydrate (C-A-H) in the XRD patterns post 14 days of treatment of RT-cement. The XRD patterns at 28 days curing period indicate an increase in the formation of the calcium aluminium hydrate. This result is agreeable to the results obtained from the consolidated undrained triaxial compression tests. The results obtained from the XRD analysis for treated specimens are in agreement with the ones obtained by Yoobanpot *et al.* (2017) who used cement with fly ash to stabilise soft clay. Similar results for the XRD peaks in stabilised soft soil with cement were found by Kamruzzaman (2006).

3.2.2 FTIR

The FTIR analysis was conducted in the current study for the evaluation of minerals available in the soil and the functional groups that exist in the untreated and the RT-cement treated soft soil. FTIR analysis is used to measure the absorption bands at a characteristic wavelength. Fig. 13 illustrates the features remarked in the FTIR spectrum of the untreated and RT-cement treated soil cured for 14 and 28 days. The FTIR spectra of the untreated soil involved bands at 1031 and 1095 cm^{-1} that were assigned to the Si-O stretching. Other bands observed at 3623 and 3697 cm^{-1} are assigned to the OH stretching which corresponds to the inner hydroxyl groups (Latifi *et al.* 2017, 2016b, Madejov and Komadel 2001). Bands detected at 915, 794, 535, and 473 cm^{-1} indicated the presence of quartz and kaolinite. The results of the FTIR on the RT-cement treated samples, cured for 14 and 28 days, confirmed the ability of RT-cement to enhance and make amendments in soil particles and their functional groups. A band of considerable intensity was observed at approximately 1626 cm^{-1} corresponding to the formation of the Ca-OH bond as a result of the RT-cement treatment (Bobet *et al.* 2011, Lodeiro *et al.* 2009).

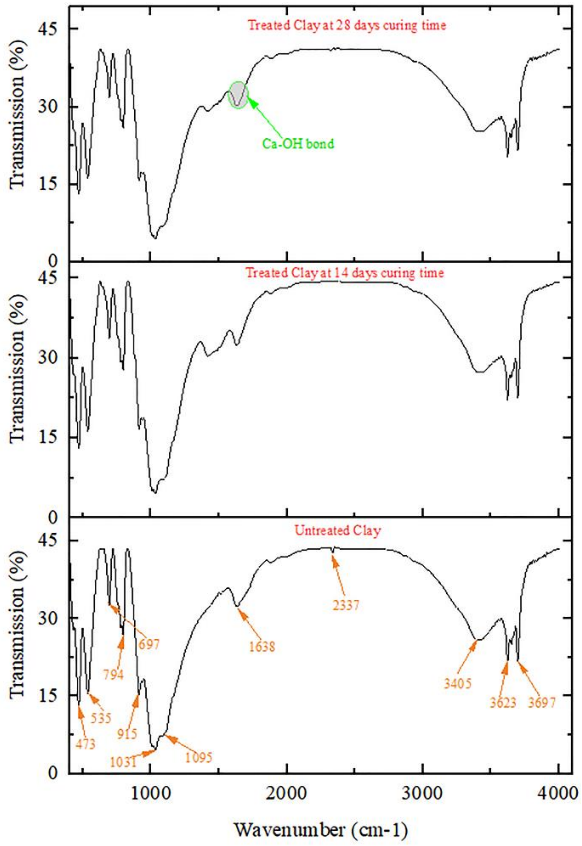


Fig. 13 FTIR spectrum of untreated soil and RT-cement treated soil at 14 and 28 days curing period

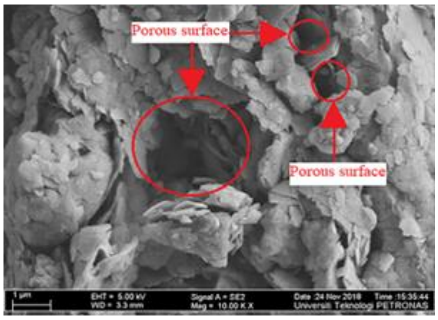


Fig. 14 FESEM morphology of the untreated soil

Fig. 15 FESEM morphology of RT-cement treated soil at 14 days curing period

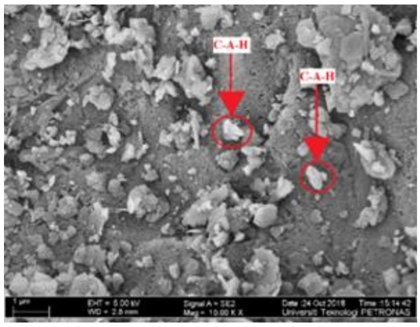


Fig. 16 FESEM morphology of RT-cement treated soil at 28 days curing period

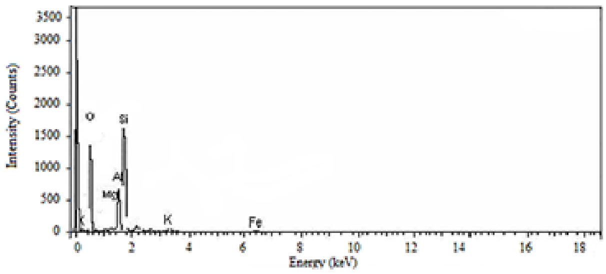
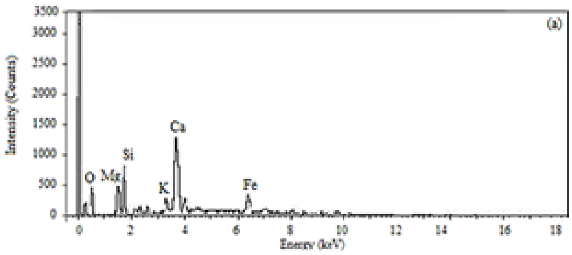


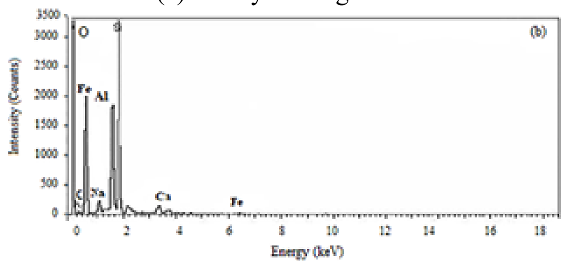
Fig. 17 EDX spectrum for the untreated soil

3.2.3 FESEM

The FESEM microanalysis was performed in this study in order to further investigate the morphology and structure of the untreated and the RT-cement treated soft soil. Fig. 14 demonstrates the morphology of the untreated soft soil. The diagnosis of the untreated soil showed a discontinuous,



(a) 14 days curing time



(b) 28 days curing time

Fig. 18 EDX spectrum for RT-cement treated soil

porous, and dispersed structure with visible voids due to the absence of hydration compounds (Latifi *et al.* 2016c). The morphology of RT-cement treated soils cured for 14 and 28 days are expressed in Figs. 15 and 16, respectively. After the 14 days curing period, most of the voids in the treated samples were filled and the texture was slightly smooth. It is observed that new hydration compounds in the form of gel formed within the stabilized soil. The gel formation increases with the increase in curing time and covers most of the soil particles as shown in Fig. 16. The formation of those new products is the reason behind the improvement of the undrained shear strength of treated samples (Rahman *et al.* 2010, Zhao *et al.* 2015).

3.2.4 EDX

The Edx analysis was performed for a better understanding of the surface composition of the untreated and RT-cement treated soil as shown in Figs. 17 and 18 (a) and (b). The surface of the untreated soil consisted of major peaks of silicon (Si), oxygen (O) and aluminium (Al) as shown in Fig. 17. For the RT-cement treated samples, the Edx analysis is demonstrated in Fig. 18(a) and 18(b) for 14 and 28 days curing periods, respectively. The results demonstrated a decline in the calcium peaks with an increase in curing time. This is due to the consumption of calcium in the pozzolanic reaction during the formation of the new cementation compounds (Latifi *et al.* 2017). The presence of the calcium and water ions together with aluminium in the surface of the soil results in a chemical reaction between the particles (Eisazadeh *et al.* 2011, Latifi *et al.* 2016a).

4. Conclusions

The study investigates the ability of the optimum amount of RT as a waste material together with minimal amount of cement to enhance and treat the properties of the soft soil. Furthermore, it examines how lesser cement content could be utilised to stabilise and enhance the geotechnical properties of soft clay. The results of the consolidated undrained triaxial tests revealed an improvement in the RT-cement treated samples as compared to the untreated soft soil. For the RT-cement treated samples cured at 7, 14, and 28 days, the shear strength parameters were increased with the increase of both, the curing time and the effective confining pressure. During the shearing process, treated samples exhibited softening behaviour at which the deviator stress increases with the increment in axial strain; whilst the stress path showed dilative behaviour and the curves moved to the right side. The over consolidation state of the treated samples increased with the curing period due to the higher formation of cementitious compounds within time. The XRD results revealed the formation of new cementation minerals such as calcium aluminium hydrate (C-A-H). Moreover, the microstructural analysis using FESEM and EDX confirmed the formation of the cementing products within the RT-cement treated samples. The micrographs showed the formation of new crystalline material within the surface of the treated samples. The FTIR analysis indicated the presence of new absorption bands at 1626 cm^{-1} that could be attributed to Ca-OH bond within the treated specimens.

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