Geomechanics and Engineering, *Vol. 19, No. 1 (2019) 37-47*
DOI: https://doi.org/10.12989/gae.2019.19.1.037

Mechanical behaviour of waste powdered tiles and Portland cement treated soft clay

Mohammed A. M. Al-Bared*[1], Indra S. H. Harahap[1a], Aminaton Marto[2b],
Seyed Vahid Alavi Nezhad Khalil Abad[3c], Zahiraniza Mustaffa[1d] and Montasir O. A. Ali[1e]

[1]Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 32610, Malaysia
[2]Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia (UTM) Kuala Lumpur, 54100 Kulala Lumpur, Malaysia
[3]Department of Civil Engineering, Birjand University of Technology, Birjand, Iran

(Received July 25, 2019, Revised August 12, 2019, Accepted September 2, 2019)

Abstract. The main objective of this study is to evaluate and compare the efficiency of ordinary Portland cement (OPC) in enhancing the unconfined compressive strength of soft soil alone and soft soil mixed with recycled tiles. The recycled tiles have been used to treat soft soil in a previous research by Al-Bared *et al.* (2019) and the results showed significant improvement, but the improved strength value was for samples treated with low cement content (2%). Hence, OPC is added alone in this research in various proportions and together with the optimum value of recycled tiles in order to investigate the improvement in the strength. The results of the compaction tests of the soft soil treated with recycled tiles and 2, 4, and 6% OPC revealed an increment in the maximum dry density and a decrement in the optimum moisture content. The optimum value of OPC was found to be 6%, at which the strength was the highest for both samples treated with OPC alone and samples treated with OPC and 20% recycled tiles. Under similar curing time, the strength of samples treated with recycled tiles and OPC was higher than the treated soil with the same percentage of OPC alone. The stress-strain curves showed ductile plastic behaviour for the untreated soft clay and brittle behaviour for almost all treated samples with OPC alone and OPC with recycled tiles. The microstructural tests indicated the formation of new cementitious products that were responsible for the improvement of the strength, such as calcium aluminium silicate hydrate. This research promotes recycled tiles as a green stabiliser for soil stabilisation capable of reducing the amount of OPC required for ground improvement. The replacement of OPC with recycled tiles resulted in higher strength compared to the control mix and this achievement may results in reducing both OPC in soil stabilisation and the disposal of recycled tiles into landfills.

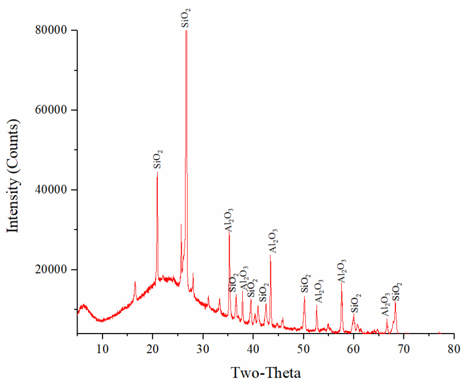
Keywords: environmental-friendly; soil stabilisation; recycled tiles; OPC replacement; chemical testing

1. Introduction

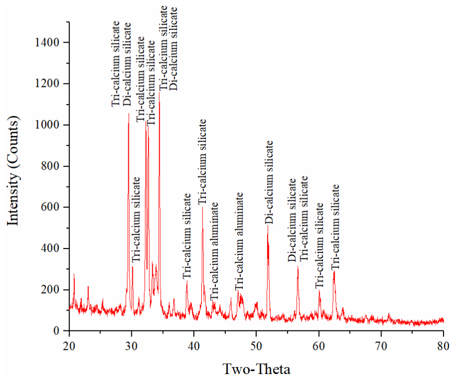
The construction of civil structures that involve light and moderate loads distributed over a large area may require high budgets for deep foundation systems to bypass the soft clay layers and be founded on strong stiff clay layers or bedrock (Rangaswamy 2016). In addition, the installation of piles in projects associated with problematic soft soil with high water contents and clay minerals might be difficult and the piles might tilt due to the very weak shear strength around the pile (Al-Bared and Marto 2017). Hence, ground improvement techniques that involve cement-based additives may provide efficient solutions to those problems by either shallow or deep mixing methods. Stabilisation techniques are mainly conducted to modify the engineering properties of soft soils to predicted or predetermined values in order to enhance their shear strength and decrease their compressibility. Soft soils can be improved traditionally using chemical additives (e.g., Damoerin *et al.* 2015, Jitsangiam *et al.* 2016, Kim *et al.* 2018, Nusit *et al.* 2016, 2015, Nusit and Jitsangiam 2016, Pourakbar *et al.* 2015, Qureshi *et al.* 2017, Wang *et al.* 2013, Wong *et al.* 2016a)), compaction (e.g., Al-Bared *et al.* 2018b, Khalid *et al.* 2016, Sabat and Moharana 2015, Wong *et al.* 2016b, Yilmaz 2015, Yilmaz and Ozaydin 2013), waste materials (e.g., Al-bared *et al.* 2018a, Chang *et al.* 2018, Singh and Vinot 2011), microbial biopolymers (e.g., Chang *et al.* 2017, 2015, Chang and Cho 2019, Ham *et al.* 2018, Kwon *et al.* 2019, Lee *et al.* 2019, 2017), biological sustainable treatments (e.g., Chang *et al.* 2016) or a combination of one or more of these techniques. Soft soil improvement using various options of stabilising additives over the years has resulted in better physical and mechanical properties. It is also used to mitigate the problems arising in civil engineering projects due to

*Corresponding author, Graduate Student
E-mail: albared2009@yahoo.com
[a]Associate Professor
E-mail: indrasati@utp.edu.my
[b]Professor
E-mail: aminaton@utm.my
[c]Assistant Professor
E-mail: svalavi@birjandut.ac.ir
[d]Associate Professor
E-mail: zahiraniza@utp.edu.my
[e]Senior Lecturer
E-mail: montasir.ahmedali@utp.edu.my

http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)



(a) Recycled ceramic tiles



(b) OPC

Fig. 1 The XRD analysis of the additives

construction work on top of soft clayey soils (Jamsawang *et al.* 2019). Various scholars have used cement to significantly improve physical and mechanical properties of soft clayey soils. Such improvements were thoroughly explained and justified by microstructural and chemical analysis (Horpibulsuk *et al.* 2011, 2010, Yoobanpot *et al.* 2017, Zhao *et al.* 2016). The strength development in cementitious materials depends on the amount of hydrating products in the cement that rises with increasing the amount of cement. Chemical stabilisation using cement is conducted by deep mixing a slurry of cement with the problematic soft soil. When soft soil is mixed with cement, the resistance to compression and shear strength increases with the curing time. The use of cement in soft soil stabilisation is due to the high compressive strength and bearing capacity exhibited in various engineering applications (Mohammadinia *et al.* 2014).

The improvement of short-term strength in cement-treated soft soils is attributed to the hydration process, while the long-term strength is produced by the pozzolanic reaction between the cementing agent and the soft soil particles (Ho *et al.* 2018). Numerous studies have explained the pozzolanic reaction taking place between the hydrating products of the cement and the soft soil or other admixtures particles resulting in the formation of calcium aluminate hydrate (C-A-H) and calcium aluminium silicate hydrates (C-A-S-H) (Chindaprasirt *et al.* 2007, 2005, Morandeau *et al.* 2015). The hydration process usually occurs in cement when it is mixed with water content in any admixture. This will be followed by a pozzolanic reaction process, where the calcium hydroxide ($Ca(OH)_2$) supplied by the cement will react with the available silica and alumina in the soil and this process will only happen in the vicinity of soil particles (Herzog and Mitchell, 1963; Sasanian and Newson, 2014). Both hydration and pozzolanic processes result in the production of gelatinous and amorphous products that crystallise and harden due to the formation of inter-aggregate bonds (Croft, 1967). The formation of the cementitious bonds between the soil minerals forms a complex matrix that encloses the unbonded particles and aggregates, resulting in apparent cohesion in the soil that makes its engineering structure very complex and strong (Kasama *et al.* 2000).

Due to the high cost and environmental concerns, such as air and underground water contamination, pozzolanic waste materials are being utilised in the stabilisation of soft soils in order to fully or partially replace OPC. During the production of OPC, thousands of tonnes of carbon dioxide are being emitted into the atmosphere, resulting in massive air pollution (Andrew 2018, Zhang *et al.* 2014). In addition, when a high amount of OPC is used for ground improvement, there is high potential for underground water contamination (Zainuddin *et al.*, 2017). The feasibility of using cheap pozzolanic waste materials to partially replace OPC in enhancing the strength of clay soil by a deep mixing technique has been investigated by Güllü *et al.* (2017). The results indicated an increment in the value of unconfined compressive strength (UCS) until the percentage of glass replacement reached 3%. Beyond this percentage, the UCS value decreased (Güllü *et al.* 2017). The pozzolanic materials are mainly the ones that contain high amounts of Al_2O_3 and SiO_2, which react with the calcium hydroxide produced by hydrating the cement (Jamsawang *et al.* 2019). The waste of materials produced in high quantities during the manufacturing process or during the construction activities at site is increasingly being considered for soil stabilisation. Waste materials, such as recycled granite tiles, waste concrete and recycled ceramic tiles, are being considered as soil stabilisers that exhibit satisfactory performance in stabilising problematic soft soils (Al-Bared *et al.* 2018a, Al-bared and Marto 2019, Ayub *et al.* 2018, Sumayya *et al.* 2016, Zainuddin *et al.* 2019). The partial replacement of OPC with 20% bagasse ash resulted in increasing the UCS value of the treated soft clay by as much as of cement alone (Jamsawang *et al.*, 2019). According to Ho *et al.* (2017), the strength of cement-treated soils depends not only on hydration and the pozzolanic reaction, but also on the water content, carbonation and suction. Marine clay was mixed with cement and metakaolin to observe the improvement in UCS value. The results indicated an improvement in the UCS of marine clay of two to three times the materials without the metakaolin admixture (Tongwei *et al.* 2014). Microstructural identification of the improvement of cemented marine clay was achieved by Kamruzzaman *et al.* (2006). The microstructural analysis showed the formation of C-A-S-H and calcium silicate hydrate, which was increased during the stabilisation with the increase of the amount of cement and curing time.

Waste materials are one of the top topics being investigated in the current research in the area of soft soil improvement. Al-Bared *et al.* (2018b) utilised the waste of ceramic tiles generated during manufacturing and in construction sites to stabilise soft marine clay. The authors used various sizes and percentages of tile waste in order to determine the optimum value for soil stabilisation. The results indicated a significant strength improvement and the increment of the strength was four times the untreated soil when using the optimum size and percentage. However, the improvement of the strength was not sufficient as it was still below the authorised value used during construction. Therefore, the aim of this study is to further investigate and compare the strength development of soft soil treated with OPC alone and OPC mixed with the pre-determined optimum percentage and size of recycled ceramic tiles. The development in strength of the cement-treated soft clay and the soft clay treated with OPC and recycled tiles was studied using compaction tests and UCS. Several conditions were considered, including four curing times, two different treatments and three different percentages of cement. Field emission scanning electron microscopy (FESEM) was performed to observe the changes in the structure of samples treated with recycled tiles and the optimum percentage of OPC cured for 7, 14, and 28 days. In addition, X-ray diffraction (XRD) was conducted in order to evaluate the new developed cementation products in the surface of samples treated with recycled tiles and the optimum value of OPC that was cured for 7, 14, and 28 days. Fourier transform infrared spectroscopy (FTIR) was used to determine the functional groups on the untreated and treated samples, while energy dispersive X-ray spectroscopy (EDAX) was used to evaluate the elemental compositions of the treated samples.

2. Materials and methods

2.1 Testing materials

The soft soil used in this study is too soft and weak due to its problematic behaviour and low shear strength and permeability, which make it a good candidate for soil stabilisation. It was collected from a depth of 1.5 m below the ground level from a construction site at Nusajaya, state of Johor, Malaysia. The physical and mechanical properties of the soil were evaluated in a previous research by Al-Bared *et al.* (2019). The recycled waste of tiles utilised as the main additive was obtained from disposal of construction sites in the state of Johor, Malaysia. The recycled tiles were cleaned, sticking materials were removed, crushed, blended to powder, and sieved to the appropriate size in the laboratory. The optimum percentage and size of recycled tiles used in this study were 20% and 0.063 mm, respectively. The cement used in this study as a stabiliser was OPC type I that conforms to the requirements specified in the ASTM standard (ASTM 2005). The physical properties and chemical compositions of the recycled tiles and OPC are compared and shown in Table 1. It is clearly shown in Table 1 and Fig. 1 that OPC contains 63.22% calcium oxide (CaO) and 21.25% silicon dioxide (SiO_2), while recycled tiles contain 65.83% SiO_2 and 24.37% aluminium oxide (Al_2O_3). The total amount of the major components of OPC was 84.47%, while the total amount of major elements in recycled tiles was 90.2%, which was higher than the limited value specified in the ASTM C 618 (2005) for pozzolanic materials. Figs. 1(a) and (b) show the results of the XRD analysis of recycled tiles and OPC. Fig. 1(a) indicates the presence of quartz and aluminium oxide as the major components of the recycled tiles, while Fig. 1(b) reveals the major components of OPC to be tricalcium silicate, dicalcium silicate and tricalcium aluminate.

Table 1 Physiochemical characteristics of recycled tiles and OPC utilised in the improvement of soft soil

Property	OPC, %	Recycled Tiles, % (Al-Bared *et al.* 2018)
Particle size, mm	< 0.063	< 0.063
Appearance	Dark powder	White powder
Specific gravity	2.9	2.56
Particle density, Mgm^{-3}	3.10	2.10
Chemical compositions		
SiO_2	21.25	65.83
CaO	63.22	1.64
Fe_2O_3	1.21	2.81
Al_2O_3	4.66	24.37
Na_2O	0.23	3.19
SO_3	3.65	-
MgO	2.20	5.84
K_2O	0.92	2.33
TiO_2	0.18	-
Loss of ignition	2.49	-

2.2 Methods implemented

Standard proctor compaction tests were conducted on untreated and treated samples with recycled tiles and OPC in order to determine the maximum dry density (MDD) and optimum moisture content (OMC). Sample preparation started by oven-drying and sieving the soil through a 2-mm mesh. Then, the deionised water was mixed with the oven-dried soil in order to attain the anticipated water content. The methods and procedures used for testing followed the BS 1924: part 4 (1990). The pre-determined results of MDD and OMC were used in the preparation of samples tested under the UCS tests. The proportions of OPC used were 2, 4, and 6% of the dry weight of the soft soil that was mixed with soil alone and with recycled tiles. The admixture of soft clay, recycled tiles and OPC were mixed in dry conditions until homogeneity was observed and then mixed thoroughly with deionised water using palette knives. The wet admixture was placed inside a cylindrical steel mould (38 mm diameter and 76 mm height) in three equal layers and compacted for 27 blows each (Ahmed, 2015). The samples were extruded from the mould using a hydraulic jack machine and wrapped with several layers of plastic sheet after being trimmed to preserve the moisture content. The trimmed samples were placed inside air-tight plastic bottles before being stored inside the humidity chamber for 7, 14, and 28 days of curing time. At the end of each curing time, samples were weighted before testing and samples that have a weight reduction of more than 0.5% were discarded.

A series of UCS tests was conducted on samples treated with OPC alone and on samples treated with recycled tiles and OPC in accordance with ASTM (2013) and British standards (1990). A compression machine was used for the testing connected to a personnel computer to store the collected data for the applied stress and the corresponding axial strain. The rate of the vertical axial displacement was set to 2% per minute and the axial strain was set to 25%. The UCS value was recorded based on the peak axial stress attained at failure. After testing, samples having more than 10% difference of peak axial stress were rejected and the test was repeated. For each test, three samples having an axial stress difference of less than 10% were averaged and taken as the UCS value (Jha and Sivapullaiah 2015).

Microstructural and chemical tests were performed on the same samples used for the UCS test after being oven-dried for 24 h. The reason for oven-drying the samples was to stop the reaction between the soil particles and the stabilising agents for better observation. The treated samples with 6% cement and 20% recycled tiles that were cured for 7, 14, and 28 days were pulverised into powder and used for XRD, FESEM, EDAX, and FTIR tests. FESEM was implemented to observe the topographical changes occurred in the surface of the treated samples and to visualise the formation of the new cementation products. Each powdered sample was mounted on the aluminium holder and a high vacuum of 30 mA was used to sputter the samples with gold for 120 s until they were completely covered. In addition, the EDAX analysis was performed for all the treated samples in order to determine the major elemental functional groups.

XRD was carried out on the treated samples in order to assess the formation of new crystalline products on the surface of analysed samples and to measure the mineralogical changes of their structure. The XRD tests were conducted using a PANalytical X-ray diffraction spectrometer. The scanning of the samples was performed using Cu-Kα radiation and the angle (2θ) of the scan was between 6° and 90°. The scanning was performed at a step size of 0.02° and a dwelling time of 1 s at each step.

FTIR analysis was conducted for a better understanding of the molecular changes in the treated samples. The test was performed using 2 mg of powdered sample that was initially mixed with 200 mg of KBr. The prepared KBr disk was scanned using a Zeiss Supra 55 VP FTIR instrument and exposed to infrared spectroscopy in order to measure the adsorption bands. The examination of the adsorption bands was performed within a range of 400 to 4000 cm^{-1}.

3. Results and discussion

3.1 Compaction tests

The standard compaction tests were performed on the treated soft clay samples with 2, 4 and 6% OPC and 20% recycled tiles. Fig. 2 shows the results obtained from the compaction tests in terms of MDD and OMC of the treated soft clay. It can be observed from the relationship of MDD and OMC that further increments of OPC from 2% up to 6% resulted in increasing the MDD and reducing the corresponding OMC. The increment of MDD value by the addition of OPC and recycled tiles was due to the replacement of the stabiliser's particles having high specific gravity with the soil particles with low specific gravity (Sabat 2012). The reduction of OMC was due to the decrease of the water holding capacity within the stabilised clay particles after the addition of OPC and recycled tiles (Rani *et al.* 2014).

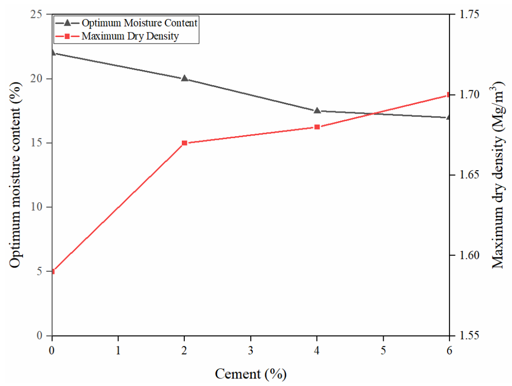


Fig. 2 OMC and MDD of treated soft clay with recycled tiles and various percentages of OPC

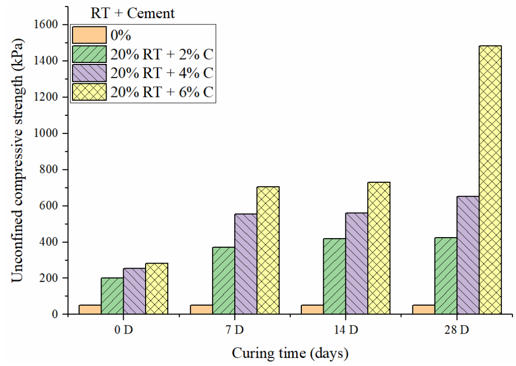


Fig. 3 UCS results of soft clay treated with recycled tiles and various percentages of OPC

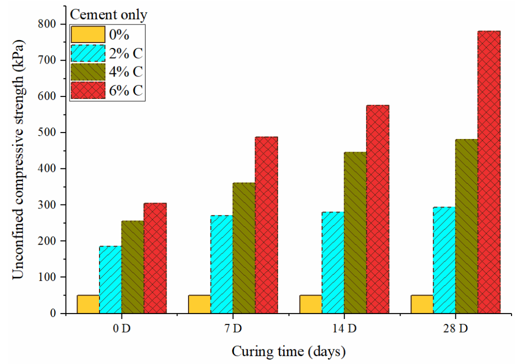
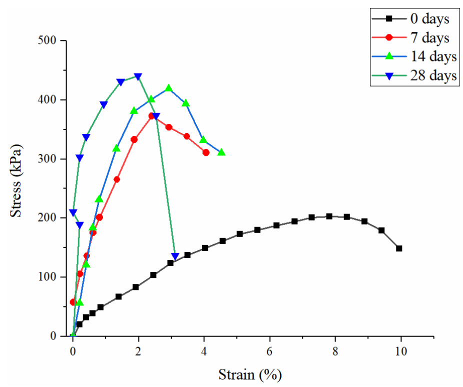


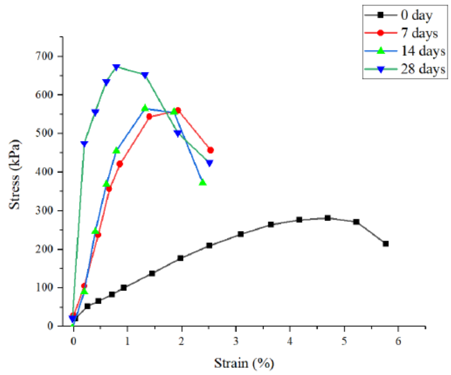
Fig. 4 UCS results of soft clay treated with various percentages of OPC only

3.2 UCS versus curing time

The UCS tests were used as an indicator to evaluate the



(a) Recycled tiles and 2% OPC



(b) Recycled tiles and 4% OPC

Fig. 5 The stress versus strain curves

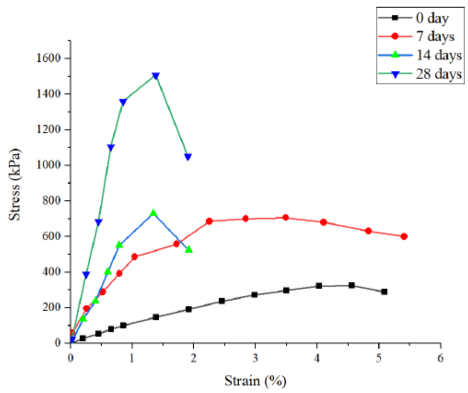
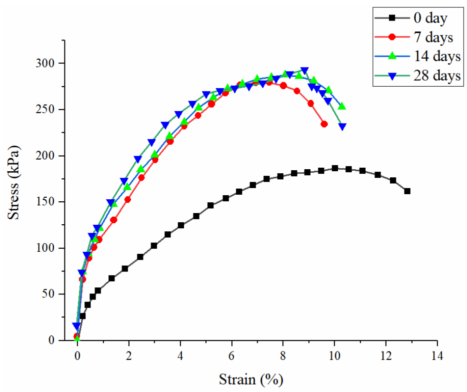
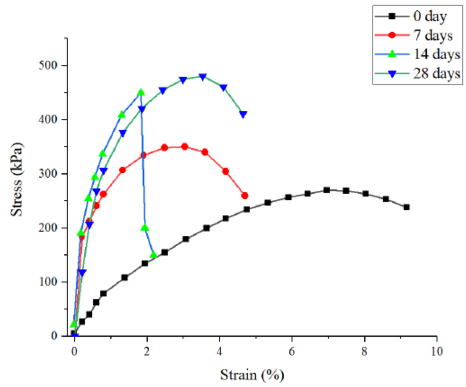


Fig. 6 The stress versus strain of samples treated with recycled tiles and 6% of OPC



(a) 2% OPC only



(b) 4% OPC only

Fig. 7 The stress versus strain curves

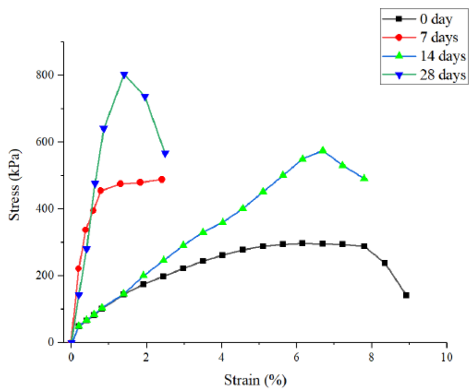


Fig. 8 The stress versus strain of samples treated with 6% of OPC only

effect of the combination of OPC and recycled tiles on the soft clay. When the OPC and recycled tiles are admixed with soft clay in the presence of water, hydration reactions occur that result in the formation of cementitious compounds, such as calcium aluminium hydrates and calcium silicate hydrates. Fig. 3 reveals the UCS results of soft clay treated with 20% recycled tiles and 2, 4, and 6% OPC at 0, 7, 14, and 28 days of curing. The results clearly indicate an increment of the UCS value with the increase of the cement content and the curing time. Thus, the development of compressive strength was dependent on the cement content and the curing time (Jamsawang *et al.*, 2019). The addition of 6% OPC and 20% recycled tiles were found to be the optimum values, at which the strength was the highest. The value of UCS at 7 days of curing was 706 kPa, which was ~14 times the untreated UCS value of the soft clay and three times the UCS value at 0 day of curing time. However, the increment of the UCS value at 14 days of curing time was not significant, but the value of UCS at 28 days of curing time was found to be 1485 kPa, which is almost twice the value achieved at 14 days of curing time. The development of the strength in the early stages of curing is due to the hydration processes, while the one achieved at 28 days of curing time is due to the pozzolanic reaction between the particles of soft clay, OPC and recycled tiles. When comparing the value of UCS obtained at 28 days of curing of soft clay, recycled tiles, and OPC with the one obtained by Al-Bared *et al.* (2018b) using only recycled tiles, the UCS value was ~ 7 times the one used recycled tiles only to treat soft soil. The addition of low amount of OPC resulted in a remarkable result that could meet the required value at site.

Fig. 4 illustrates the results of the UCS of soft clay treated with 2, 4 and 6% OPC only and cured for 0, 7, 14 and 28 days. The addition of different percentages of OPC resulted in increasing the UCS value for all samples cured for 0, 7, 14 and 28 days (Ranaivomanana *et al.*, 2018). The development of the compressive strength was found to be dependent on the percentage of cement and curing time. The optimum value of OPC was 6%, at which the strength gain was highest. The values of UCS at 0, 7, 14 and 28 days of curing were 305, 488, 575 and 781 kPa, respectively. With respect to the curing time, the development of strength was almost the same for 7, 14 and 28 days. This was in agreement with a study by Kang *et al.* (2016), who treated marine soft clay with cement and found the development of the strength to be dependent on the curing time.

The development of the compressive strength of both samples treated with OPC alone and OPC together with 20% recycled tiles depended on the cement content and curing time. When the strength of both treatment conditions is compared, it is clearly revealed that samples treated with OPC and recycled tiles exhibited two times the strength gained for samples treated with OPC alone. For instance, samples treated with 6% OPC alone and cured for 28 days had a compressive strength of 781 kPa, while samples treated with recycled tiles and a similar percentage of OPC and curing time had a compressive strength of 1485 kPa. This is due to the high amount of pozzolanic materials (Al_2O_3 and SiO_2) provided by the recycled tiles, which accelerated and enhanced the reaction with the OPC hydrating agents. The utilisation of the recycled tiles in soil improvement would help to reduce the problems arising from the accumulation of this material in the landfills and the illegal disposal areas, and also to reduce the amount of OPC used in soil treatment in order to provide a cleaner environment.

(a) Sample cured for 14 days (b) Sample cured for 28 days

Fig. 9 Modes of failure for selected samples

3.3 Stress-strain development during UCS tests

The relationships between the applied stress and the developed axial strain of treated samples with recycled tiles and OPC and treated samples with OPC alone are shown in Figs. 5-8, respectively. Figs. 5(a) and 5(b) and Fig. 6 show the stress-strain relationships for treated samples with recycled tiles and 2, 4 and 6% OPC, respectively. In addition, Figs. 7(a) and 7(b) and Fig. 8 show the relationships of the stress and axial strain for samples treated with OPC only at 2, 4 and 6%, respectively. The development of the strain was rapid for samples cured for 0 day, while the samples cured for longer times exhibited less than 4% strain before failure. The stress-strain curve for treated samples with recycled tiles and OPC had a brittle behaviour except for those cured for 7 days, which exhibited nearly plastic ductile behaviour, as shown in Figs. 5(a) and 5(b) and Fig. 6. In contrast, the samples treated with OPC only exhibited ductile plastic behaviour except for two samples cured for 28 days with OPC contents of 4% and 6%, as shown in Figs. 7(a) and 7(b) and Fig. 8. Furthermore, when the percentage of OPC was increased for samples treated with recycled tiles and samples treated with OPC only, the yield stress for all samples was increased. The difference was only that samples treated with recycled tiles and OPC had a higher maximum stress than the samples treated with OPC only. The modes of failure of the treated samples are shown in Fig. 9 for two selected samples cured 14 and 28 days. The longer curing time resulted in immediate cracking compared to bulging failure at 14 days.

3.4 Chemical and microstructural investigations

The XRD diffractograms for treated soft clay with recycled tiles and 6% OPC cured for 7, 14 and 28 days are shown in Fig. 10. The test was performed to evaluate the new reaction produced after the treatment of soft clay with

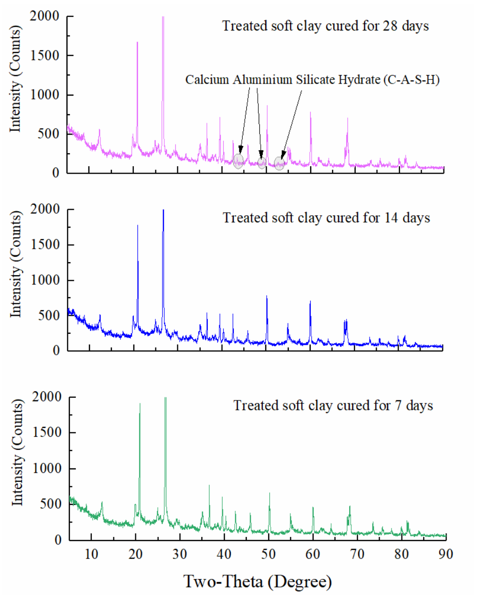


Fig. 10 XRD spectrum of treated soft clay cured at 7, 14 and 28 days

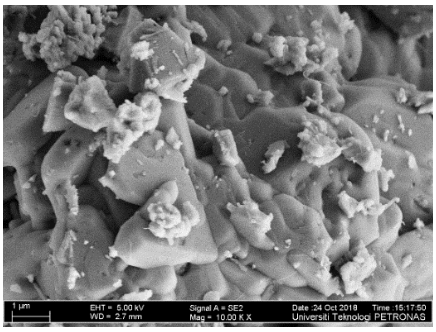


Fig. 11 The morphology of OPC

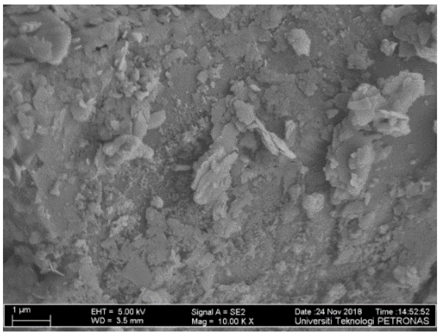


Fig. 12 The morphology of treated soft clay at 7 days curing time

recycled tiles and OPC. It is clearly seen that new peaks appeared in the treated samples, when compared with the untreated soil tested in previous study by Al-Bared *et al.* (2019). The new peaks correspond to the formation of C-A-S-H. The addition of recycled tiles provided sufficient amounts of Al_2O_3 and SiO_2 that reacted with the $Ca(OH)_2$ produced during the hydration process, forming the C-A-S-H during the pozzolanic reaction (Jamsawang *et al.* 2019)

The formation of C-A-S-H was responsible for the significant improvement of the UCS value at 28 days of curing time. In addition, the XRD patterns indicated that the

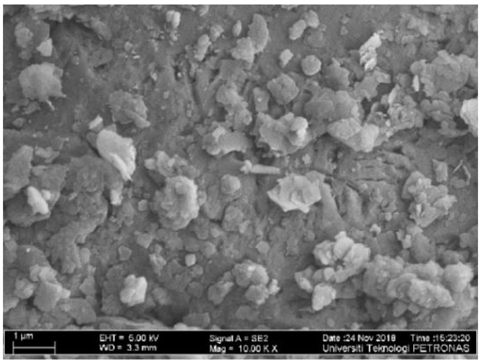


Fig. 13 The morphology of treated soft clay at 14 days curing time

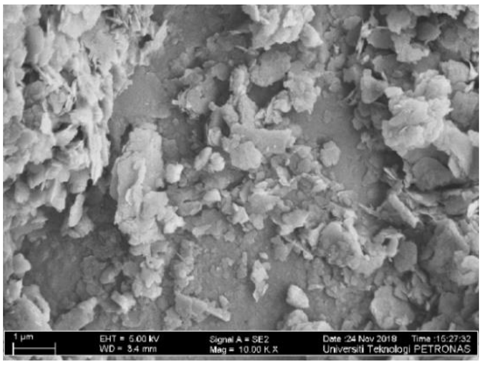


Fig. 14 The morphology of treated soft clay at 28 days curing time

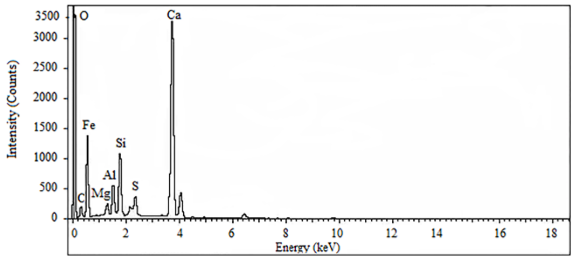


Fig. 15 The EDAX spectrum of OPC

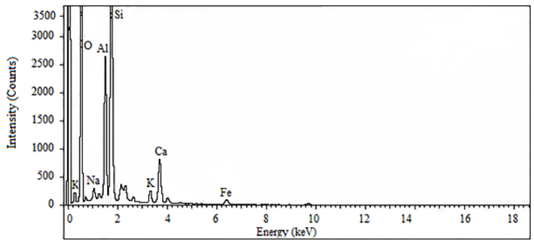


Fig. 16 EDAX spectrum of treated soft soil with recycled tiles and 6% OPC cured for 7 days

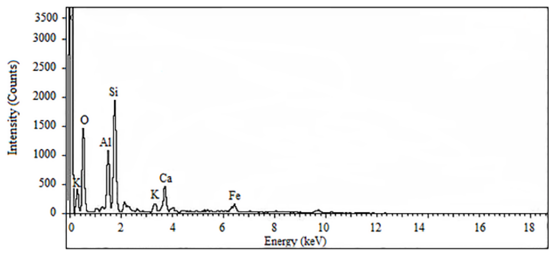


Fig. 17 EDAX spectrum of treated soft soil with recycled tiles and 6% OPC cured for 14 days

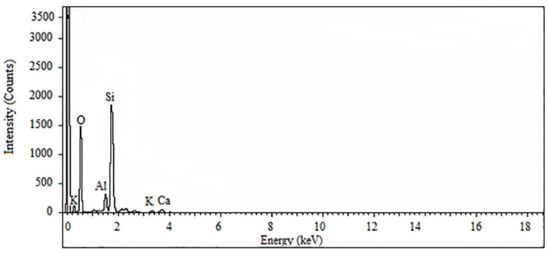


Fig. 18 EDAX spectrum of treated soft soil with recycled tiles and 6% OPC cured for 28 days

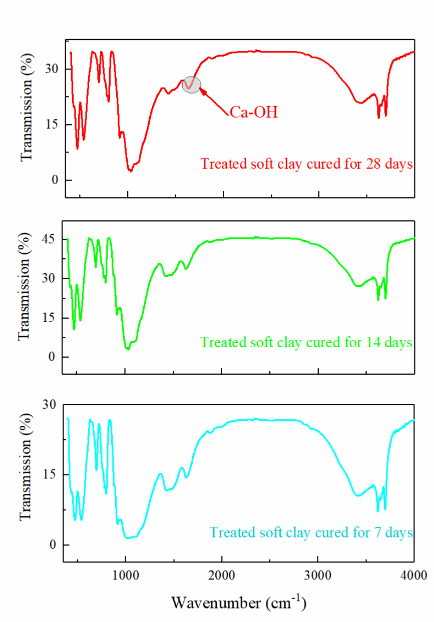


Fig. 19 FTIR spectrum of treated clay cured for 7, 14 and 28 days

intensity of C-A-S-H was increased with curing time, which is agreeable with the results obtained from the UCS tests (Yoobanpot *et al.* 2017). These results were confirmed by FESEM and EDAX tests. The ability of recycled tiles and OPC to make changes in the spectrum of the treated clay indicated that chemical reaction took place.

A series of FESEM images was taken in order to observe the microstructural changes of the treated soft soil with recycled tiles and 6% OPC. Fig. 11 show the morphological images of OPC, while Figs. 12-14 show the morphological images of the soft soil treated with recycled tiles and 6% OPC cured for 7, 14 and 28 days, respectively. For the treated samples cured for 7 days, the pores in the structure were filled with newly formed product that clearly appeared in higher intensity in the morphological image of the sample cured for 14 days. The morphological image of the sample cured for 28 days showed strong structure and formation of cementitious compounds that appeared on the surface in the form of white gelatinous material. In line with the results of the XRD tests, those newly detected cementitious products are identified as C-A-S-H (Jamsawang *et al.* 2019, Yoobanpot *et al.* 2017).

It is evident from the morphological images of the treated samples that the pores in the structure were filled, which make it denser and stronger. As a result, the particles of the treated soil aggregated, and the strength of the treated soil increased. The growth of new gelatine products filling the pore spaces of the treated soil is similar to the one reported in various studies that used cement alone or together with other additives to treat soft soils (Eisazadeh *et al.* 2011, Rahman *et al.* 2010, Zhao *et al.* 2016).

A series of EDAX analysis was performed in this study for better understanding of the chemical compositions on the surface of OPC and treated samples. Fig 15 show the EDAX spectra of the OPC used for the soft clay stabilization. It is clearly observed that the dominant elements in the OPC are silicon (Si), aluminium (Al), oxygen (O), calcium (Ca), and iron (Fe). Figs. 16 - 18 show the EDAX spectra of treated samples with recycled tiles and 6% OPC cured for 7, 14, and 28 days, respectively. The spectra of the treated samples show considerable intensities of calcium formed at their surfaces. In addition, the intensity of calcium, aluminium and silicon were reduced with curing time. This is due to the consumption of those elements during the formation of the new cementitious compounds. According to the results obtained from the XRD tests, the new formed compounds are C-A-S-H.

For the determination of the molecular functional groups of treated soft clay with recycled tiles and 6% OPC, FTIR analysis was conducted. The common features of the treated soft clay cured for 7, 14 and 28 days are shown in Fig. 19. When observing the spectra of the treated samples, a new band was detected at 1626 cm^{-1}, which could be attributed to the Ca-OH bond (Rahman *et al.*, 2010). The results of the FTIR confirmed the ability of the additives of recycled tiles and OPC to make considerable effects on the spectra of the minerals forming the soft clay and confirmed the results of the XRD and FESEM.

4. Conclusions

The current study tested the effectiveness of the mixture of recycled tiles and 2, 4 and 6% OPC to treat the physical and mechanical properties of soft soil. Furthermore, OPC was used alone with similar percentages to treat the soft soil in order to observe the difference in the strength development, when compared with the performance of recycled tiles and OPC together. The utilisation of recycled tiles to replace OPC during ground improvement was proven in this study and the observation of all the conducted tests leads to the following conclusions:

• The MDD and OMC of the soft soil treated with recycled tiles and OPC were increased and decreased with further additions of the additives, respectively.

• The UCS of the soft soil treated with recycled tiles and OPC was increased with the increases of OPC percentage and curing time. The optimum value of OPC was found to be 6%, at which the highest UCS value was obtained. For soft soil treated with OPC alone, the value of UCS also increased with the increase in the OPC percentage and curing time. The increment of the strength was due to the formation of new cementitious compounds.

• The UCS value obtained from the treatment using recycled tiles and OPC was twice the value obtained from the treatment of marine clay using OPC alone and 14 times the value obtained from treatment with recycled tiles alone in the previous study conducted by Al-Bared *et al.* (2018b). This is due to the high amount of pozzolanic materials contained within the recycled tiles and the strong bonding provided by the OPC.

• The results obtained from the XRD tests showed a reduction in the amount of the clay minerals due to the treatment with recycled tiles and OPC. In addition, new peaks were observed in the spectrum of the treated samples, which can be attributed to the formation of cementitious compounds, such as C-A-S-H.

• The microstructural tests using FESEM and EDAX confirmed the formation of the cementitious compounds that appeared in the form of white gelatinous products in the morphological images. In addition, the FTIR tests of the samples treated with recycled tiles and 6% OPC detected the formation of new adsorption bands at 1626 cm^{-1} attributed to the Ca-OH bonds.

Acknowledgments

The authors acknowledge the generous financial support provided by Universiti Teknologi PETRONAS (UTP) using the Graduate Assistantship Scheme (GA). Besides, the authors also acknowledge Universiti Teknologi Malaysia (UTM) for facilitating some of tests using their laboratory equipment.

References

Al-Bared, M.A.M. and Marto, A. (2017), "A review on the geotechnical and engineering characteristics of marine clay and the modern methods of improvements", *Malaysian J. Fundam. Appl. Sci.*, **13**(4), 825-831.

Al-Bared, M.A.M. and Marto, A. (2019), "Evaluating the compaction behaviour of soft marine clay stabilized with two sizes of recycled crushed tiles", *Proceedings of the 1st Global Civil Engineering Conference*, Kuala Lumpur, Malaysia, July.

Al-Bared, M.A.M., Ayub, A., Mohd Yunus, N.Z., Harahap, I.S.H. and Marto, A. (2018a), "Application of demolished concrete material (DCM) in civil engineering structures- a review", *Int. J. Civ. Eng. Technol.*, **9**(11), 2345-2352.

Al-Bared, M.A.M., Harahap, I.S.H., Marto, A., Abad Alavi Nezhad Khalil, S.V. and Ali, M.O.A. (2019), "Undrained shear strength and microstructural characterization of treated soft soil with recycled materials", *Geomech. Eng.*, **18**(4), 427-437. http://doi.org/10.12989/gae.2019.18.4.427.

Al-Bared, M.A.M., Marto, A. and Latifi, N. (2018a), "Utilization of recycled tiles and tyres in stabilization of soils and production of construction materials - a state-of-the-art review", *KSCE J. Civ. Eng.*, **22**(10), 3860-3874. https://doi.org/10.1007/s12205-018-1532-2.

Al-Bared, M.A.M., Marto, A., Hamonangan, I.S. and Kasim, F. (2018b), "Compaction and plasticity comparative behaviour of soft clay treated with coarse and fine sizes of ceramic tiles", *E3S Web Conf.*, **34**, 1-9. https://doi.org/10.1051/e3sconf/20183401012.

Al-Bared, M.A.M., Marto, A., Latifi, N. and Horpibulsuk, S. (2018b), "Sustainable improvement of marine clay using recycled blended tiles", *Geotech. Geol. Eng.*, **36**(5), 3135-3147. https://doi.org/10.1007/s10706-018-0525-8.

Andrew, R.M. (2018), "Global CO2 emissions cement production", *Earth Syst. Sci. Data*, **10**(1), 195-217. https://doi.org/10.5194/essd-10-195-2018.

ASTM C 150, (2005), *Specification for Portland Cement*, in *Annual Book of ASTM Standard*, Section 4 Construction, Volume 04.01 Cement, Lime, Fypsum.

ASTM C 618, (2005), *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, in *Annual Book of ASTM Standard, Section 4 Construction*, Volume 04.02 Concrete and Aggregate.

ASTM, (2013), D 2166-13, *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*, West Conshohocken, Pennsylvania, U.S.A.

Ayub, A., Mohd Yunus, N., Hezmi, M., Ali, N. and Jamaluddin, N. (2018), "Strength development of marine clay treated by demolished concrete materials with morphological identifications", *J. Phys. Conf. Ser.*, **1049**(1), 1-12. https://doi.org/10.1088/1742-6596/1049/1/012032.

British Standards Institution, (1990), *British Standard Methods of Test for Soils for Civil Engineering Purposes: Part 4, Compaction-Related Tests*, London, U.K.

BSI, (1990), *British Standard Methods of Test for Soils for Civil Engineering Purposes: Part 7, Shear Strength Tests (Total Stress)*, Milton Keynes, U.K.

Chang, I. and Cho, G.C. (2019), "Shear strength behavior and parameters of microbial gellan gum-treated soils: from sand to clay", *Acta Geotech.* **14**(2), 361-375. https://doi.org/10.1007/s11440-018-0641-x.

Chang, I., Im, J. and Cho, G.C. (2016), "Geotechnical engineering behaviors of gellan gum biopolymer treated sand", *Can. Geotech. J.*, **53**(10), 1658-1670. https://doi.org/10.1139/cgj-2015-0475.

Chang, I., Im, J., Chung, M.K. and Cho, G.C. (2018), "Bovine casein as a new soil strengthening binder from diary wastes", *Constr. Build. Mater.*, **160**, 1-9. https://doi.org/10.1016/j.conbuildmat.2017.11.009.

Chang, I., Im, J., Lee, S.W. and Cho, G.C. (2017), "Strength durability of gellan gum biopolymer-treated Korean sand with cyclic wetting and drying", *Constr. Build. Mater.*, **143**, 210-221. https://doi.org/10.1016/j.conbuildmat.2017.02.061.

Chang, I., Im, J., Prasidhi, A.K. and Cho, G.C. (2015), "Effects of Xanthan gum biopolymer on soil strengthening", *Constr. Build. Mater.*, **74**, 65-72. https://doi.org/10.1016/j.conbuildmat.2014.10.026.

Chindaprasirt, P., Jaturapitakkul, C. and Sinsiri, T. (2005), "Effect of fly ash fineness on compressive strength and pore size of blended cement paste", *Cem. Concr. Compos.*, **27**(4), 425-428. https://doi.org/10.1016/j.cemconcomp.2004.07.003.

Chindaprasirt, P., Jaturapitakkul, C. and Sinsiri, T. (2007), "Effect of fly ash fineness on microstructure of blended cement paste", *Constr. Build. Mater.*, **21**, 1534-1541. https://doi.org/10.1016/j.conbuildmat.2005.12.024.

Croft, J.B. (1967), "The influence of soil mineralogical composition on cement stabilization", *Geotechnique*, **17**(2), 119-135. https://doi.org/10.1680/geot.1967.17.2.119.

Damoerin, D., Prakoso, W.A. and Utami, Y. (2015), "Improving shear strength of clay by using cement column reinforcement under consolidated undrained test", *Int. J. Technol.*, **6**(4), 709-717. https://doi.org/10.14716/ijtech.v6i4.1206.

Eisazadeh, A., Kassim, K.A. and Nur, H. (2011), "Characterization of phosphoric acid- and lime-stabilized tropical lateritic clay", *Environ. Earth Sci.*, **63**(5), 1057-1066. https://doi.org/10.1007/s12665-010-0781-2.

Güllü, H., Canakci, H. and Al Zangana, I.F. (2017), "Use of cement based grout with glass powder for deep mixing", *Constr. Build. Mater.*, **137**, 12-20. https://doi.org/10.1016/j.conbuildmat.2017.01.070.

Ham, S.M., Chang, I., Noh, D.H., Kwon, T.H. and Muhunthan, B.

(2018), “Improvement of surface erosion resistance of sand by microbial biopolymer formation”, *J. Geotech. Geoenviron. Eng.*, **144**(7), 06018004. https://doi.org/10.1061/(asce)gt.1943-5606.0001900.

Herzog, A. and Mitchell, J.K. (1963), “Reactions accompanying stabilization of clay with cement”, *Highw. Res. Rec.*, **36**, 146-171.

Ho, L.S., Nakarai, K., Duc, M., Kouby, A. Le, Maachi, A. and Sasaki, T. (2018), “Analysis of strength development in cement-treated soils under different curing conditions through microstructure and chemical investigation”, *Constr. Build. Mater.*, **166**, 634-646. https://doi.org/10.1016/j.conbuildmat.2018.01.112.

Ho, L.S., Nakarai, K., Ogawa, Y., Sasaki, T. and Morioka, M. (2017), “Strength development of cement-treated soils: Effects of water content, carbonation, and pozzolanic reaction under drying curing condition”, *Constr. Build. Mater.*, **134**, 703-712. https://doi.org/10.1016/j.conbuildmat.2016.12.065.

Horpibulsuk, S., Rachan, R. and Suddeepong, A. (2011), “Assessment of strength development in blended cement admixed Bangkok clay”, *Constr. Build. Mater.*, **25**, 1521-1531. https://doi.org/10.1016/j.conbuildmat.2010.08.006.

Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., Raksachon, Y. and Suddeepong, A. (2010), “Analysis of strength development in cement-stabilized silty clay from microstructural considerations”, *Constr. Build. Mater.*, **24**, 2011-2021. https://doi.org/10.1016/j.conbuildmat.2010.03.011.

Jamsawang, P., Poorahong, H., Yoobanpot, N., Songpiriyakij, S. and Jongpradist, P. (2019), “Improvement of soft clay with cement and bagasse ash waste”, *Constr. Build. Mater.*, **154**, 61-71. https://doi.org/.1037//0033-2909.I26.1.78.

Jha, A.K. and Sivapullaiah, P.V. (2015), “Mechanism of improvement in the strength and volume change behavior of lime stabilized soil”, *Eng. Geol.*, **198**, 53-64. https://doi.org/10.1016/j.enggeo.2015.08.020.

Jitsangiam, P., Nusit, K., Chummuneerat, S., Chindaprasirt, P. and Pichayapan, P. (2016), “Fatigue assessment of cement-treated base for roads: an examination of beam-fatigue tests”, *J. Mater. Civ. Eng.*, **28**(10), 04016095. https://doi.org/10.1061/(asce)mt.1943-5533.0001601.

Kamruzzaman, A.H.M., Chew, S.H. and Lee, F.H. (2006), “Microstructure of cement-treated Singapore marine clay”, *Proc. Inst. Civ. Eng. Gr. Improv.*, **10**(3), 113-123. https://doi.org/10.1680/grim.2006.10.3.113.

Kang, G., Tsuchida, T. and Athapaththu, A.M.R.G. (2016), “Engineering behavior of cement-treated marine dredged clay during early and later stages of curing”, *Eng. Geol.*, **209**, 163-174. https://doi.org/10.1016/j.enggeo.2016.05.008.

Kasama, K., Ochiai, H. and Yasufuku, N. (2000), “On the stress-strain behaviour of lightly cemented clay based on an extended critical state concept”, *Soils Found.*, **40**(5), 37-47. https://doi.org/10.3208/sandf.40.5_37.

Khalid, N., Mukri, M., Awang, H., Kamarudin, F., Ghani, A.H.A. and Hashim, S. (2016), “Compaction characteristics of banting soft soil subgrade stabilized using waste paper sludge ash (WPSA)”, *Proceedings of the International Conference on Advanced Science, Engineering and Technology (ICASET)*, Penang, Malaysia, December.

Kim, A.R., Chang, I., Cho, G.C. and Shim, S.H. (2018), “Strength and dynamic properties of cement-mixed Korean marine clays”, *KSCE J. Civ. Eng.*, **22**(4), 1150-1161. https://doi.org/10.1007/s12205-017-1686-3.

Kwon, Y.M., Chang, I., Lee, M. and Cho, G.C. (2019), “Geotechnical engineering behavior of biopolymer-treated soft marine soil”, *Geomech. Eng.*, **17**(5), 453-464. https://doi.org/10.12989/gae.2019.17.5.453.

Lee, S., Chang, I., Chung, M.K., Kim, Y. and Kee, J. (2017), “Geotechnical shear behavior of xanthan gum biopolymer treated sand from direct shear testing”, *Geomech. Eng.*, **12**(5), 831-847. https://doi.org/10.12989/gae.2017.12.5.831.

Lee, S., Im, J., Cho, G.C. and Chang, I. (2019), “Laboratory triaxial test behavior of xanthan gum biopolymer-treated sands”, *Geomech. Eng.*, **17**(5), 445-452. https://doi.org/10.12989/gae.2019.17.5.445.

Mohammadinia, A., Arulrajah, A., Sanjayan, J., Disfani, M.M., Bo, M.W. and Darmawan, S. (2014), “Laboratory evaluation of the use of cement-treated construction and demolition materials in pavement base and subbase applications”, *J. Mater. Civ. Eng.*, **27**(6), 4014186. https://doi.org/10.1061/(asce)mt.1943-5533.0001148.

Morandeau, A., Thiery, M. and Dangla, P. (2015), “Impact of accelerated carbonation on OPC cement paste blended with fly ash”, *Cem. Concr. Res.*, **67**, 226-236. https://doi.org/10.1016/j.cemconres.2014.10.003.

Nusit, K. and Jitsangiam, P. (2016), “Damage behavior of cement-treated base material”, *Procedia Eng.*, **143**, 161-169. https://doi.org/10.1016/j.proeng.2016.06.021.

Nusit, K., Jitsangiam, P., Kodikara, J., Bui, H.H. and Leung, G.L.M. (2016), “Advanced characteristics of cement-treated materials with respect to strength performance and damage evolution”, *J. Mater. Civ. Eng.*, **29**(4), 04016255. https://doi.org/10.1061/(asce)mt.1943-5533.0001772.

Nusit, K., Jitsangiam, P., Kodikara, J., Bui, H.H. and Leung, G.L.M. (2015), “Dynamic modulus measurements of bound cement-treated base materials”, *Geotech. Test. J.*, **38**(3), 275-289. https://doi.org/10.1520/GTJ20140233.

Pourakbar, S., Asadi, A., Huat, B.B.K. and Fasihnikoutalab, M.H. (2015), “Stabilization of clayey soil using ultrafine palm oil fuel ash (POFA) and cement”, *Transp. Geotech.*, **3**, 24-35. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001772.

Qureshi, M.U., Chang, I. and Al-Sadarani, K. (2017), “Strength and durability characteristics of biopolymer-treated desert sand”, *Geomech. Eng.*, **12**(5), 785-801. https://doi.org/10.12989/gae.2017.12.5.785.

Rahman, M.M.R., Siddique, A.S. and Uddin, M.K. (2010), “Microstructure and chemical properties of cement treated soft Bangladesh clays”, *Soils Found.*, **50**(1), 1-7. https://doi.org/10.3208/sandf.50.1.

Ranaivomanana, H., Razakamanantsoa, A. and Amiri, O. (2018), “Effects of cement treatment on microstructural, hydraulic, and mechanical properties of compacted soils: Characterization and modeling”, *Int. J. Geomech.*, **18**(9), 1-9. https://doi.org/10.1061/(asce)gm.1943-5622.0001248.

Rangaswamy, K. (2016), “Influence of burnt ash additives on stabilization of soft clay soils”, *Innov. Infrastruct. Solut.*, **1**(25), 1-6. https://doi.org/10.1007/s41062-016-0025-8.

Rani, T.G., Shivanarayana, C., Prasad, D. and Prasada Raju, G. (2014), “Strength behaviour of expansive soil treated with tile waste”, *Int. J. Eng. Res. Dev.*, **10**(12), 52-57.

Sabat, A.K. (2012), “Stabilization of expansive soil using waste ceramic dust”, *Electron. J. Geotech. Eng.*, **17**(Z), 3915-3926.

Sabat, A.K. and Moharana, R.K. (2015), “Effect of compaction energy on engineering properties of fly ash-granite dust stabilized expansive soil”, *Int. J. Eng. Technol.*, **7**(5), 1617-1624.

Sasanian, S. and Newson, T.A. (2014), “Basic parameters governing the behaviour of cement-treated clays”, *Soils Found.*, **54**(2), 209-224. https://doi.org/10.1016/j.sandf.2014.02.011.

Singh, B. and Vinot, V. (2011), “Influence of waste tire chips on strength characteristics of soils”, *J. Civ. Eng. Architect.*, **5**(10), 819-827.

Sumayya, K., Rafeequedheen.K, M., Sameer, V., Firoz, Khais, P. and Jithin, K. (2016), “Stabilization of expansive soil treated with tile waste”, *Int. J. Civ. Eng.*, **3**(3), 67-75.

https://doi.org/10.14445/23488352/ijce-v3i3p112.

Wang, D., Abriak, N.E. and Zentar, R. (2013), "Strength and deformation properties of Dunkirk marine sediments solidified with cement, lime and fly ash", *Eng*. *Geol*., **166**, 90-99. https://doi.org/10.1016/j.enggeo.2013.09.007.

Wong, L.S., Mousavi, S., Sobhani, S., Kong, S.Y., Birima, A.H. and Mohd Pauzi, N.I. (2016a), "Comparative measurement of compaction impact of clay stabilized with cement, peat ash and silica sand", *Measurement*, **94**, 498-504. https://doi.org/10.1016/j.measurement.2016.08.029.

Yilmaz, Y. (2015), "Compaction and strength characteristics of fly ash and fiber amended clayey soil", *Eng*. *Geol*., **188**, 168-177. https://doi.org/10.1016/j.enggeo.2015.01.018.

Yilmaz, Y. and Ozaydin, V. (2013), "Compaction and shear strength characteristics of colemanite ore waste modified active belite cement stabilized high plasticity soils", *Eng*. *Geol*., **155**, 45-53. https://doi.org/10.1016/j.enggeo.2013.01.003.

Yoobanpot, N., Jamsawang, P. and Horpibulsuk, S. (2017), "Applied clay science strength behaviour and microstructural characteristics of soft clay stabilized with cement kiln dust and fly ash residue", *Appl*. *Clay Sci*., **141**, 146-156. https://doi.org/10.1016/j.clay.2017.02.028.

Zainuddin, N., Mohd Yunus, N.Z., Al-Bared, M.A.M., Marto, A., Harahap, I.S.H. and Rashid, A.S.A. (2019), "Measuring the engineering properties of marine clay treated with disposed granite waste", *Measurement*, **131**, 50-60. https://doi.org/10.1016/j.measurement.2018.08.053.

Zhang, J., Liu, G., Chen, B., Song, D., Qi, J. and Liu, X. (2014), "Analysis of CO2 emission for the cement manufacturing with alternative raw materials: A LCA-based framework", *Energy Procedia*, **61**, 2541-2545. https://doi.org/10.1016/j.egypro.2014.12.041.

Zhang, T., Yue, X., Deng, Y., Zhang, D. and Liu, S. (2014), "Mechanical behaviour and micro-structure of cement-stabilised marine clay with a metakaolin agent", *Constr*. *Build*. *Mater*., **73**, 51-57. https://doi.org/10.1016/j.conbuildmat.2014.09.041.

Zhao, H., Zhou, K., Zhao, C., Gong, B.W. and Liu, J. (2016), "A long-term investigation on microstructure of cement-stabilized handan clay", *Eur*. *J*. *Environ*. *Civ*. *Eng*., **20**(2), 199-214. https://doi.org/10.1080/19648189.2015.1030087.

IC