Geotech Geol Eng (2018) 36:3135–3147
https://doi.org/10.1007/s10706-018-0525-8

ORIGINAL PAPER

Sustainable Improvement of Marine Clay Using Recycled Blended Tiles

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Received: 17 September 2017 / Accepted: 12 March 2018 / Published online: 17 March 2018

Abstract The usage of recycled material for improving problematic soil as a construction and pavement material has been a sustainable interest. Recycled blended tiles (RBT), a waste from ceramic tiles factories containing high amount of sodium and magnesium, was used as a soil stabilizer for marine clay improvement in this study. This research investigated the effects of sizes and percentages of RBT on the physical and strength properties, which included particle size distribution, Atterberg limits, compaction, and unconfined compressive strength (UCS) of marine clay. Microstructural characterization, including the scanning electron microscopic, energy dispersive X-ray spectroscopy, and X-ray diffraction was conducted on both untreated and treated marine clay-RBT samples to examine the mechanism of strength development. The addition of RBT reduced the water holding capacity, which then caused the reduction in soil plasticity (from 18 to 11%) and optimum water content (from 20 to 16%) along with the increase in peak dry density (from 1.66 to 1.74 Mg/m^3). The UCS of marine clay increased from 50 to almost 220 kPa. The optimum RBT contents, providing the highest UCS, were at 20 and 30% for 0.063 mm RBT and 0.15 mm RBT, respectively. The UCS improvement of treated marine clay is attributed to the formation of cementation compounds, mainly aluminum magnesium silicate hydrate (A–M–S–H). The outcome of this research will allow the use of RBT as a low-carbon soil stabilizer across civil engineering applications.

Keywords Soft soil · Unconfined compressive strength · Recycled blended tiles · Atterberg limits · Compaction

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1 Introduction

The rapid growth of massive construction projects in both developed and developing countries are depleting the available resources. Impelled by the shortage of

high quality materials and economic reasons, engineers and contractors are eagerly looking to improve problematic soils in the context of construction materials (Hassan et al. 2017; Tabarsa et al. 2018; Latifi et al. 2016a, 2017a; Pourakbar et al. 2015; Rashid et al. 2017). Soil can be improved mechanically by compaction (e.g. Izabel and Sangeetha 2014; Pourakbar et al. 2015; Wong et al. 2016; Yilmaz 2015), chemically by chemical stabilizers (e.g. Latifi and Meehan 2017; Anggraini et al. 2015; Fattah et al. 2015; Radhakrishnan et al. 2014; Vichan and Rachan 2013; Yi et al. 2015), biologically by bacteria (e.g. Kamaraj et al. 2016; Kim and Park 2013; Shahaji and Keshav 2015), electro-kinetically by applying a current to electrodes that are subsequently inserted into soil (e.g. Hojati 2014, 2017; Jayasekera 2006; Jayasekera and Hall 2007; Tjandra and Wulandari 2007), and hydraulically by thermal processes. Nowadays, chemical stabilization is accorded greater attention in soft soil improvements due to its rapidly enhancing engineering and physical properties. Chemical stabilizers are classified into two groups: traditional stabilizers and non-traditional additives (Latifi et al. 2017b). Against this backdrop, various traditional chemical stabilizers have been adopted in the stabilization of marine clay (e.g. Bushra and Robinson 2010; Liu et al. 2011; Miura et al. 2001; Phetchuay et al. 2016; Rajasekaran and Rao 2002a, 2004; Zillianstetra 2009). These include cement, lime, fly ash and bituminous substances. Al-Bared and Marto (2017a) reviewed the common stabilization methods of marine clay and the engineering properties of the stabilized clay and demonstrated that cement is the most common stabilizer for marine clay soils worldwide. Unfortunately, using large amounts of cement in large projects is not impervious to some shortcomings, especially in terms of environmental/sustainability. In particular, significant amounts of carbon dioxide (CO_2) and nitrogen oxide (NOx) gases are emitted during cement production, with particulate air emissions (in the form of cement dust) posing another potential environmental problem.

To circumvent the negative environmental impacts associated with cement usage, several studies have recently been devoted to develop soil improvement technologies that reduce or obviate the use of cement. The involvement of waste materials in soil stabilization is a global concern that impedes measures undertaken to reduce environmental and economic costs whilst achieving sustainability. Waste materials can be used alone or in conjunction with other chemical agents to enhance the properties of the soil while lowering their negative environmental impacts (Canakci et al. 2016a, b; Ilies et al. 2017; Hojati and Radlińska 2017). Using waste materials with a certain percentage of chemical additives in soil stabilization has caused remarkable improvement in geotechnical properties (Hambirao and Rakaraddi 2014; Ho and Chan 2010; Marto et al. 2015; Mujah et al. 2015; Pourakbar et al. 2015). The combination of waste materials, such as palm oil fuel ash (POFA), recycled tires, and plastics, with chemical binders has shown significant strength improvements. However, when these materials were used to treat soft soils, no significant improvement were found. This could be due to the insignificant cementation compounds formed between the waste materials and soil particles. Meanwhile ceramic tile factories contain high waste levels with an approximate percentage of 7–30% of their products (Al Bakri et al. 2008; Elçi 2016). The waste produced in factories is in a slurry form. This slurry gets accumulated in areas that are adjacent to the factories such as mud, and are exposed to the atmosphere. This mud contains plenty of fine contents, which gets suspended in the air, when dried fully. Consequently, the percolation of high fine contents in the atmosphere leads to several environmental problems, including air pollution. Other environmental damage caused by the disposal of tile waste to landfills. Moreover, the dumped waste affects the fertility of the soil, damages the vegetation at the accumulation area and consumes very large spaces.

Soft soils (e.g. marine clay) are widely found in coastal and offshore areas along with other parts globally. Their poor physical and engineering characteristics make them problematic for the nature (Latifi et al. 2016b) due to high moisture content and organic matter. Moreover, it is always associated with high plasticity and settlement, low shear strength and permeability, and uncertain performance (Al-Bared and Marto 2017b). Notably, the natural moisture content of soft clay is usually close to or higher than its liquid limit (Rao et al. 2009, 2011; Shahri and Chan 2015). Additionally, marine clay is known to have a high swelling potential due to the relatively high percentages of expandable clay minerals, such as vermiculite and smectite (Rajasekaran and Rao 2002b). After the chemical treatment, marine clay

can be used as a raw material for developing the pavement material (Sukmak et al. 2017). The 7-day strength of geopolymer treated marine clay met the requirements for stabilized subgrade, as specified by the Department of Highways, Thailand (> 294.2 kPa).

To the best of the authors' knowledge, no effort has been undertaken to explore the suitability of RBT in enhancing the engineering properties of marine clay as a construction material. Therefore, an analysis of improved engineering properties of treated marine clay is the focus of this study, which investigates the impact of size and percentage of RBT on index properties, compaction characteristics, and unconfined compressive strength (UCS). Microstructural and chemical tests, such as scanning electron microscopic (SEM), X-ray spectroscopy (EDS), and X-ray diffraction (XRD), were performed on both untreated and treated samples to examine the role of RBT on strength improvements. The research outcome promotes RBT as an environmental-friendly and sustainable binder for marine clay improvement.

2 Materials and Testing Program

2.1 Materials

Marine clay sample was collected from a construction site at a depth of 1 m below the original ground surface in Nusajaya, Johor state, Malaysia. Soft soil was air-dried and ground into a smaller particle size after removing plant roots. After being sieved through a 2 mm sieve, the soil was stored inside plastic containers for testing. Figure 1 illustrates the particle size distribution of marine clay. The physical and engineering characteristics are depicted in Table 1. The recycled blended ceramic tiles (RBT) were collected from different factories in Johor located in the southern part of peninsular Malaysia. Table 2 shows the RBT's physiochemical properties and chemical components. Notably, the RBT contains high amounts of sodium and magnesium.

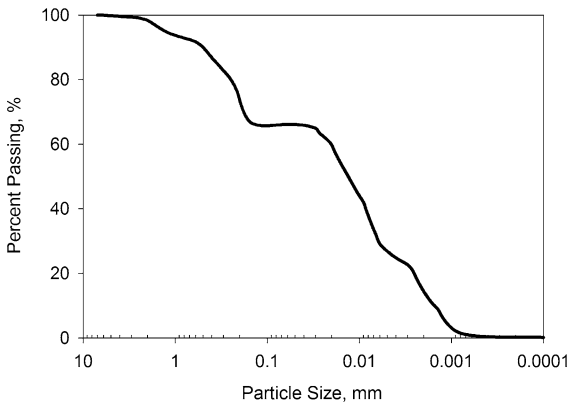

Fig. 1 Particle size distribution of marine clay

The tiles were first grouped into several sets of tiles based on their color and contents, in accordance to the guidelines of the manufacturing company. The group containing the majority of same type of tiles was used as an additive to treat marine clay. The preparation started by cleaning the tiles to remove cement, dust and other foreign materials sticking on its surface. Subsequently, tiles were crushed manually into small pieces using a hammer to make the tiles fit into the mechanical crushing machine and obtain particle sizes finer than 5 mm size. In order to produce a very fine tile powder, tiles were further crushed by being rotated inside a Los Angeles abrasion machine for 48 h. They were then fully transformed into a fine powder with particles measuring at 0.15 mm. Finally, the tiles were sieved using the mechanical shaker to attain the target RBT sizes. The sizes of the two studies RBT were 0.15 and 0.063 mm, respectively.

2.2 Testing Program

Atterberg limits tests were conducted on both untreated and treated marine clay in accordance with BSI 1377: Part 2 (1990). Marine clay samples were first air-dried and sieved through a 0.425 mm mesh to make them suitable for liquid limit and plastic limit tests. The sieved sample was then mixed with various mix designs (10, 20, 30 and 40%) of 0.063 and 0.15 mm RBT. After being mixed with water, marine clay-RBT mixtures were kept inside air-tight plastic containers for at least 24 h before testing.

Untreated and treated marine clay samples with 10, 20, 30 and 40% of 0.063 and 0.15 mm RBT underwent the standard compaction tests as per the guidelines specified by the BSI 1377: Part 4 (1990). The 2 mm mesh sieved clay was mixed by hand as well as palette knives with dry RBT at different RBT contents (before compaction) until homogeneity was observed. After being mixed with water, samples were kept for at least 24 h for proper moisture distribution. Next, the maximum dry density (MDD) and optimum moisture

Table 1 Physical, chemical and mechanical properties of the test marine clay

Marine clay property	Standard used	Values
Grain size distribution		
Sand (%)	BS 1377-2	33
Silt (%)	BS 1377-2	31.1
Clay (%)	BS 1377-2	30.9
pH	BS 1377-3	2.80
Natural moisture content (%)	BS 1377-1	59
Specific gravity, G_s	BS 1377-2	2.52
Organic contents (%)	BS 1377-3	2.74
Atterberg limits		
Liquid limit, LL (%)	BS 1377-1	41
Plastic limit, PL (%)	BS 1377-1	22
Plasticity index, PI (%)	BS 1377-1	19
Mechanical properties		
Optimum moisture content, OMC (%)	BS 1377-4	22
Maximum dry density, MDD kg m^{-3}	BS 1377-4	1590
Unconfined compressive strength, UCS kPa	BS 1377-7	50
BS classification	BS 5930 [40]	CI
Chemical elements of marine clay		
O (%)		25.45
Al (%)		6.21
Si (%)		46.09
K (%)		3.98
Fe (%)		5.94
Cu (%)		7.20
Pt (%)		5.09

Table 2 Physiochemical properties and chemical compositions of RBT

Physiochemical properties Phase	Powder
Diameter size	0.063 and 0.15 mm
Colour	White
Density (Mg/m^3)	2.06
Specific gravity	2.57
Chemical elements of RBT	
C (%)	0.82
O (%)	42.68
Al (%)	17.49
Na (%)	2.63
Si (%)	29.17
K (%)	2.61
Mg (%)	4.6

content (OMC) for both untreated marine clay and marine clay-RBT mixtures were determined.

Using the predetermined MDD and OMC for treated and untreated samples, UCS samples were

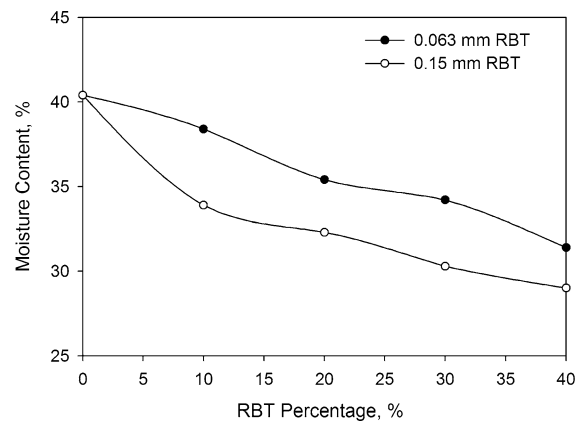

Fig. 2 Liquid limit of marine clay treated with 0.063 and 0.15 mm RBT

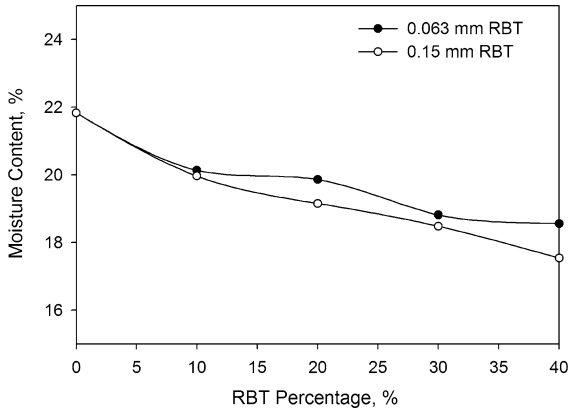

Fig. 3 Plastic limit of marine clay treated with of 0.063 and 0.15 mm RBT

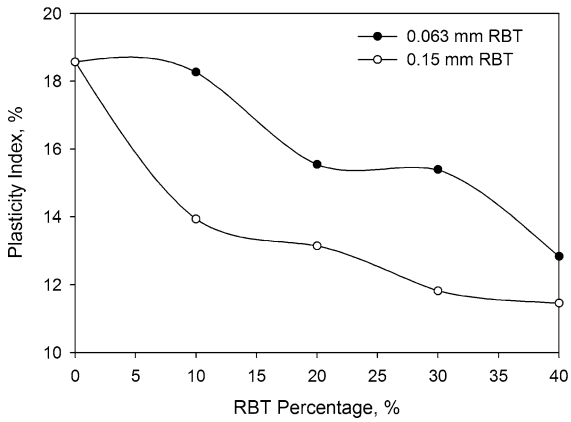

Fig. 4 The plasticity index of marine clay treated with 0.063 and 0.15 mm RBT

prepared inside a cylindrical mold of 80 mm height and 38 mm internal diameter (Latifi et al. 2015). The determined proportions of RBT were evaluated on the basis of dry mass of untreated marine clay. The soil-RBT mixtures were then placed inside the mold in three equal layers. Each layer, which was approximately 25.3 mm in diameter, was compacted 27 blows using a stainless steel tamper with a circular face diameter of 37.5 mm to attain the desired dry unit weight (Ahmed 2015; Yilmaz 2015). Upon compaction, the UCS samples were extruded using a stainless steel plunger. Next, the samples were trimmed and wrapped using several layers of cling film before being placed in air-tight plastic bottles. These samples were stored inside the humidity chamber (27 ± 2 °C and humidity of 97 ± 2%) for 7, 14 and 28 days. The reported results were the

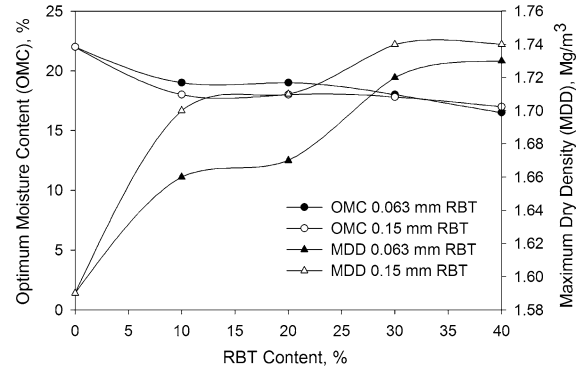

Fig. 5 MDD and OMC of marine clay treated with 0.063 and 0.15 mm RBT

average of at least three specimens in order to safeguard their reliability. Under the same testing conditions, most cases were reproducible with a low standard deviation, SD ($SD/\bar{x} < 10\%$, where $\bar{x}$ denotes the mean strength value). The axial deformation and applied load were recorded automatically using a data acquisition unit (DAU). The maximum axial strain was set at 20%, and the UCS was obtained with reference to its peak axial stress at failure (BSI 1377: Part 7, 1990). If each test sample's difference in UCS was found to be greater than 10%, the test was repeated. Subsequently, the average UCS value of three samples was reported.

Microstructural tests included X-ray diffraction (XRD), energy dispersive X-ray spectroscopy (EDS) and scanning electron microscopic (SEM). They were carried out to assess the mineralogical changes at the surface of treated samples as a result of adding RBT and investigate the formation of new crystalline

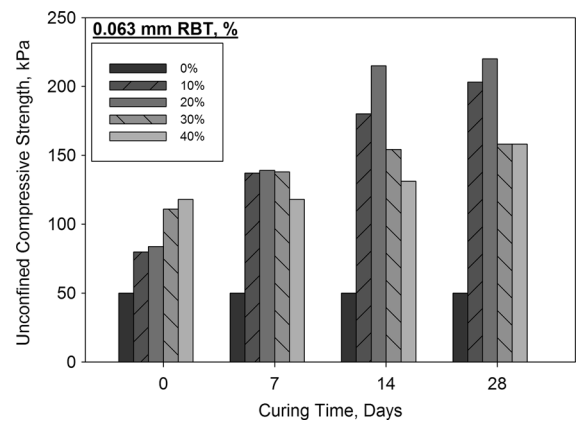

Fig. 6 UCS results for 0.063 mm RBT treated marine clay

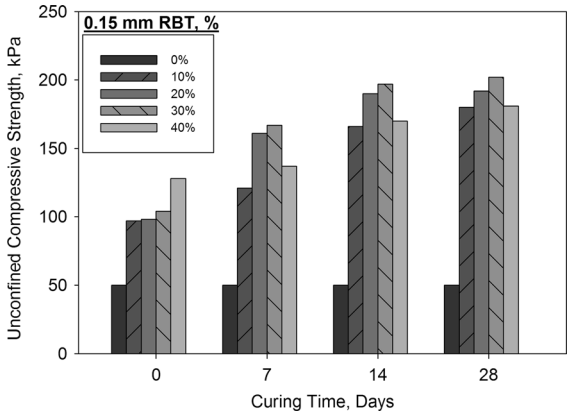

Fig. 7 UCS results for 0.15 mm RBT treated marine clay

products. Preparation for these tests began by oven drying the samples for 24 h to stop the reactions occurring between the marine clay particles and the RBT additive (Ahmed 2015). Dried samples were then pulverized to powder and mounted in an aluminum holder. Each sample was sputtered with platinum for 120 s under high vacuum with specified electrical current (30 mA) until it was completely ready for the analysis (Eisazadeh et al. 2011). Samples were installed inside A JEOL Model JSM 6380LA scanning electron microscope (SEM) operating with 15 kV. The SEM technique is generally used to qualitatively evaluate the morphological changes of the soil fabrics. It provides critical data about its shape, size and orientation (Latifi et al. 2016c). When imaging the samples, an energy-dispersive X-ray spectrometry (EDS) was used to investigate the elemental compositions at the surface of the analyzed samples.

Thereafter, XRD tests were performed to investigate the mineralogical changes in marine clay-RBT cured samples. Performing the XRD tests makes it possible to determine whether marine clay particles and RBT took place by observing the changes of diffraction peaks. Then, the samples were ground and passed through a 0.063 mm sieve; about 10 g was used for the test. XRD samples were scanned using Rigaku Smart LabX-ray diffractometer. Finally, the Cu–Ka radiation was used to scan the samples, with the data being collected from an angle (2θ) of 6°–90° at 0.002° per step.

3 Results and Discussion

3.1 Atterberg Limits

The Atterberg limits of marine clay treated with 0.063 and 0.15 mm RBT, including liquid limit, plastic limit and plasticity index, are presented in Figs. 2, 3 and 4. Figure 2 illustrates the liquid limit for marine clay treated with two sizes of RBT. A significant improvement was observed when 0.063 and 0.15 mm RBTs were added at 40%. This reduction in liquid limit led to better physical properties of marine clay. A higher percentage of RBT resulted in a lower liquid limit. The 0.15 mm resulted in a greater improvement than the 0.063 mm RBT. Similarly, Fig. 3 depicts a steady reduction in the plastic limit of marine clay upon the addition of 10–40% RBT (Rani et al. 2014). The pattern of reduction was nearly the same for both sizes of RBT, but 0.15 mm RBT provided a slightly lower plastic limit than 0.063 mm RBT. The plasticity index of marine clay was reduced using higher increments of RBT for both sizes of RBT (Fig. 4). The larger size of RBT resulted in a lower plasticity index. The reduction of plasticity index for RBT-treated samples is attributed to the agglomeration and coagulation of marine clay minerals with the addition of RBT. Consequently, the RBT treatment led to the reduction of marine clay's plasticity from intermediate to low. Significant improvements in the Atterberg limits of marine clay, through the addition of RBT, would facilitate the utilization of the ceramic tiles' waste content in soil improvement applications.

3.2 Compaction

Standard compaction tests were conducted on untreated and treated clay with various contents (10, 20, 30 and 40%) of 0.063 and 0.15 mm RBT. Figure 5 shows the relationships between OMC and MDD versus the percentage of RBT. The increment of both 0.063 and 0.15 mm RBT contents led to the increase in MDD but the decrease in OMC. The decrease in OMC is attributed to the reduction in the clay's water holding capacity by adding coarse particles (Rani et al. 2014; Sabat 2012). Evidently, the larger size of RBT led to a higher maximum MDD (Ameta et al. 2013). In other words, the larger size significantly improves the compactibility of marine clay.

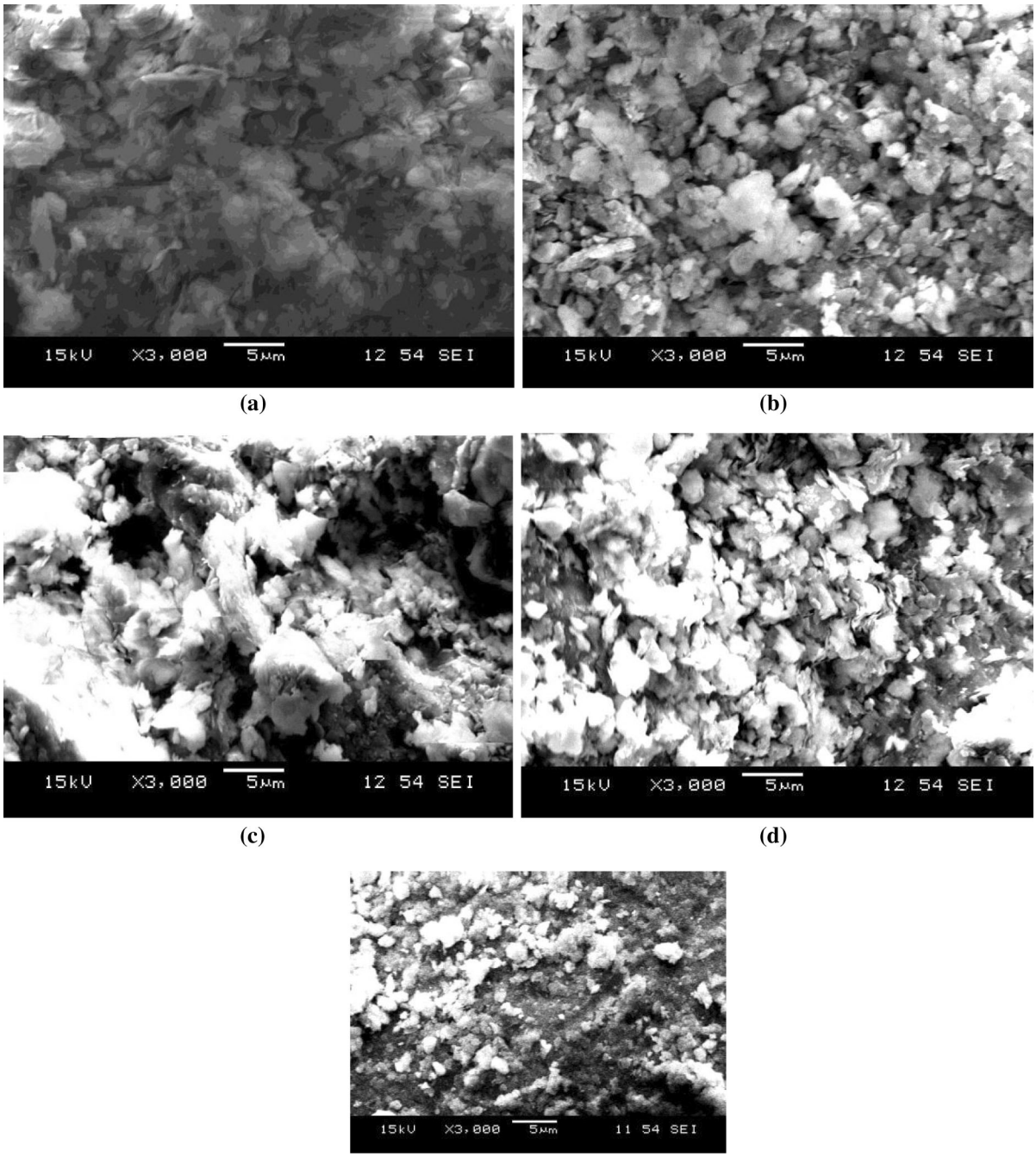

Fig. 8 SEM micrographs for **a** untreated marine clay, **b** treated marine clay with 20% 0.063 mm RBT cured 14 days, **c** treated marine clay with 20% 0.063 mm RBT cured 28 days, **d** treated marine clay with 30% 0.15 mm RBT cured 14 days, and **e** treated marine clay with 30% 0.15 mm RBT cured 28 days

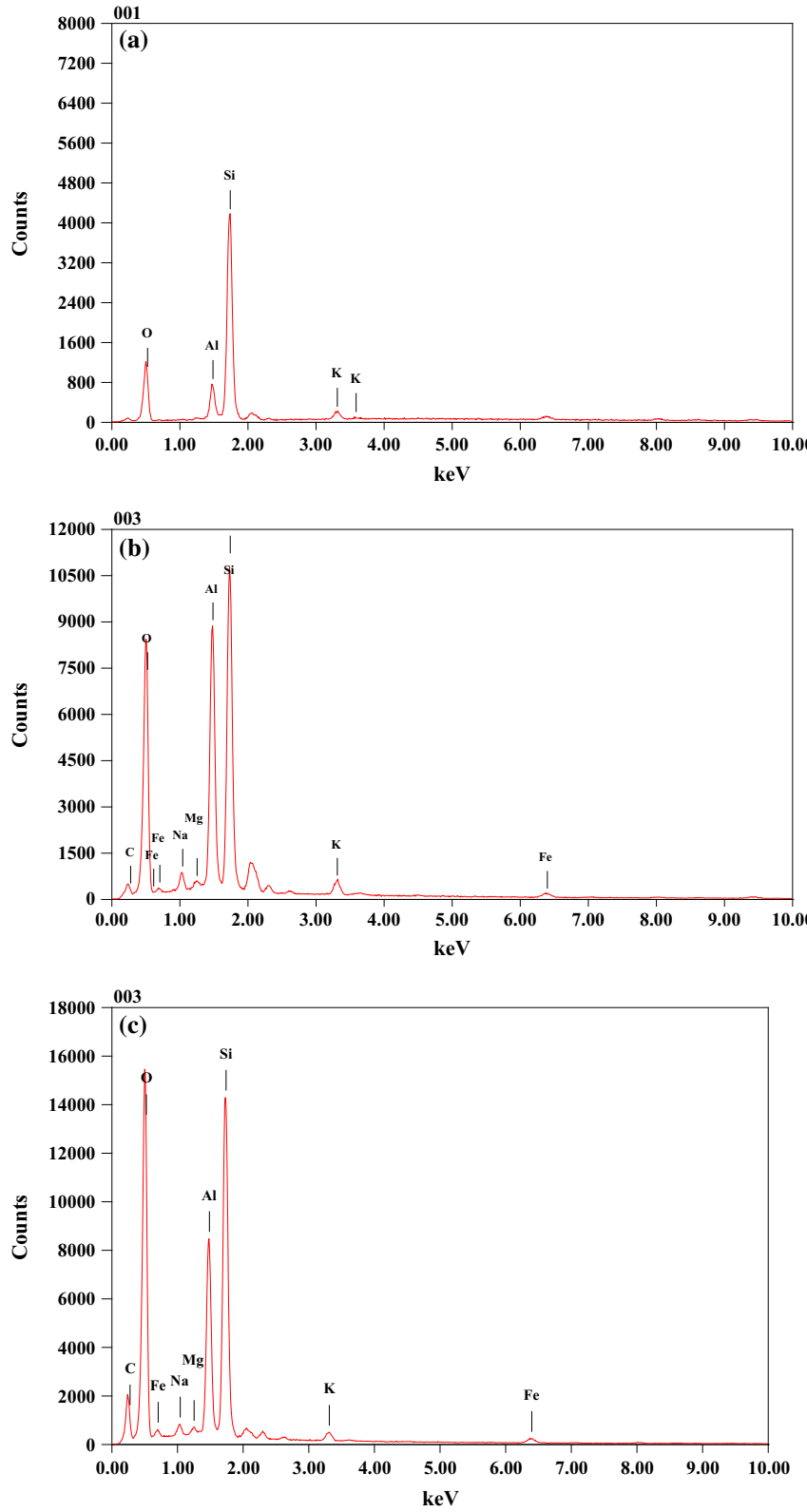

Fig. 9 EDS spectra for **a** untreated marine clay, **b** treated marine clay with 20% 0.063 mm RBT cured 28 days, and **c** treated marine clay with 30% 0.15 mm RBT cured 28 days

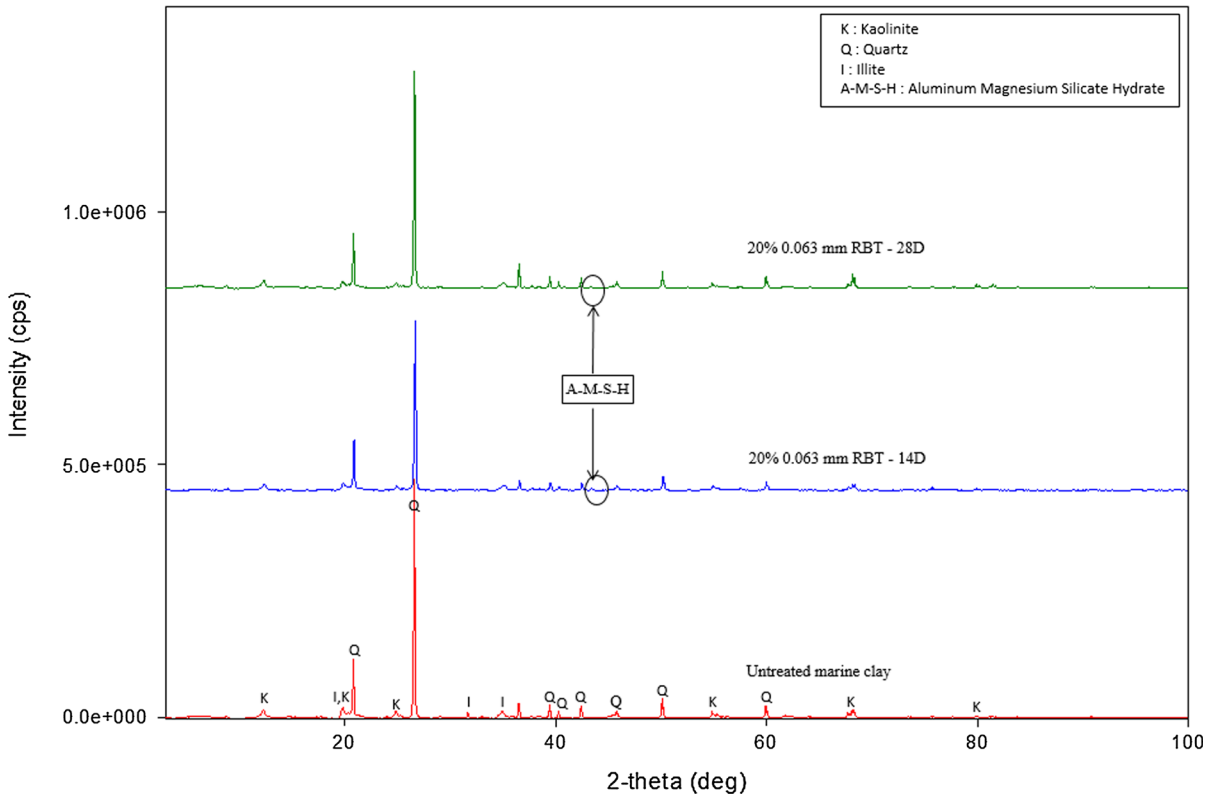

Fig. 10 XRD patterns for untreated and treated marine clay with 20% 0.063 mm RBT at different curing times

3.3 Unconfined Compressive Strength (UCS)

The unconfined compressive strength (UCS) test is an indicator of strength of marine clay treated using two different sizes of RBT. Figures 6 and 7 illustrate the UCS versus the RBT content of treated marine clay samples with 0.063 mm RBT and 0.15 mm RBT at different curing times, respectively. The UCS of treated samples was increased by almost 4 times that of untreated samples at 20% of 0.063 mm RBT. For all treated marine clay samples, the 0.063 mm RBT was observed to improve the UCS values at all curing times. However, the difference in UCS at 14 and 28 days is insignificant. The optimum RBT content, which yielded the maximum UCS at various curing times, was 20% for 0.063 mm RBT (Fig. 6) while it stood at 30% for 0.15 mm RBT (Fig. 7). The maximum 28-day UCS was 220 and 202 kPa for 0.063 mm BRT and 0.15 mm RBT treated clay, respectively. Meanwhile the RBT treated clay can find application in engineering fill material Malaysia's Johor state and the southern region of Thailand, where soft clay is found in abundance.

The significant increment in UCS of RBT-treated samples can be attributed to the exchange of the cations and the formation of cementation compounds, which lowers the porosity of the treated soil. Notably, the UCS of treated samples dropped beyond the optimum RBT content. The UCS increased with a surge in RBT due to the presence of magnesium and sodium which catalyzed the formation of some cementation compounds. The reduction of the UCS could be caused by the alkalinity of RBT (pH = 9), which exceeded the requirement of chemical reactions with the soil particles.

3.4 SEM and EDS Analyses

Microstructural analysis for untreated and treated marine clay samples was performed using SEM and EDS analysis, respectively. Figure 8a–e shows the surface morphology of untreated and treated marine clay at optimum RBT contents (20% for 0.063 mm

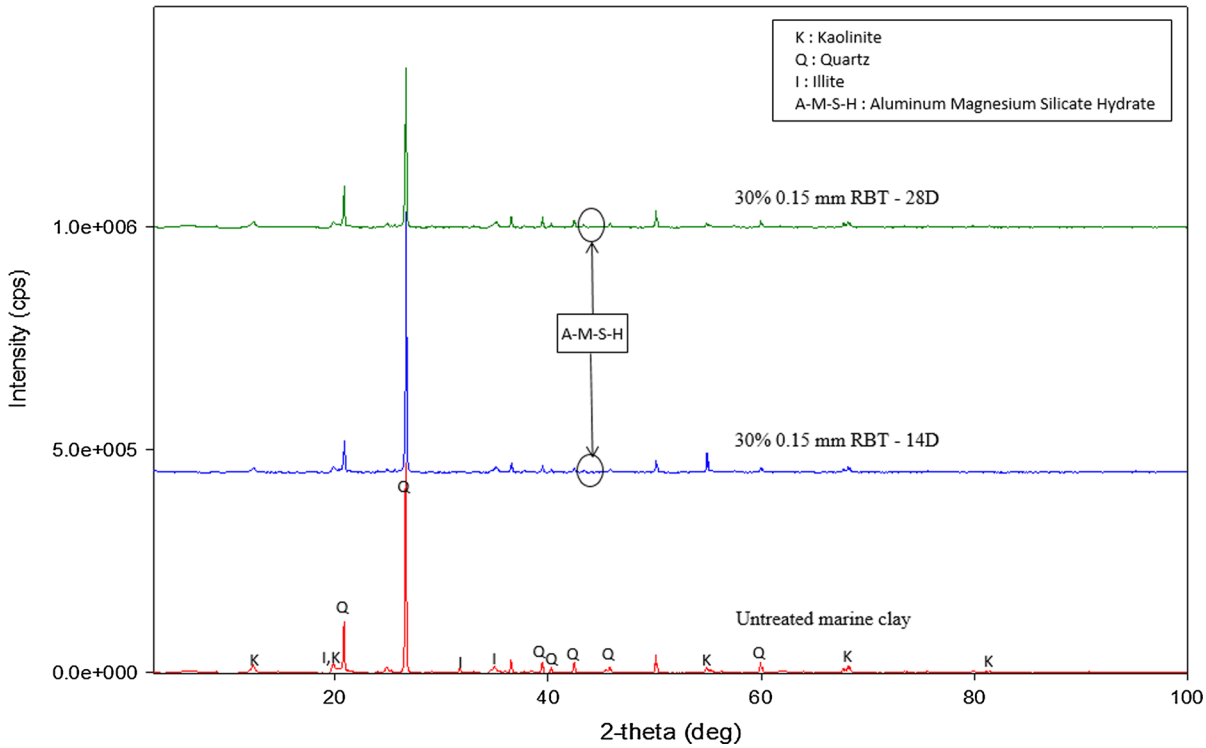

Fig. 11 XRD patterns for untreated and treated marine clay with 30% 0.15 mm RBT at different curing times

RBT and 30% for 0.15 mm RBT) at 14 and 28 days of curing, respectively. The untreated marine clay sample entails a discontinuous and porous surface structure marked by an absence of hydration compounds. In contrast, crystalline white lumps were observed on the surface of treated samples that were responsible for denser and less porous surface structure. The crystalline lumps coated the marine clay particles, which led to a heightened interlocking within the soil particles and caused the strength improvement. For a better understanding of the compositions on their sample surface, EDS analysis was conducted on both untreated and treated marine clay samples. Figure 9a–c depicts the results of the EDS analysis for untreated and treated marine clay at the optimum content for both RBT sizes at 28 days of curing. The dominant elements of natural marine clay were Si, Al, O, and K, whereas the treated samples (with both sizes of RBT) had high concentrations of Na, Mg, Fe, and C. The addition of RBT increased the amount of Si and Al in treated samples due to the high levels of Si and Al in RBT. As per the analysis, aluminum magnesium silicate hydrate was the new compound that was responsible for the changes on the surface of treated marine clay samples (A–M–S–H) (Ganesh et al. 2001; Jayaseelan et al. 2007; Latifi et al. 2016c; Pal et al. 2010a, b).

3.5 XRD Analysis

The results of XRD analysis for untreated and treated marine clay are shown in Figs. 10 and 11, respectively. The dominant minerals existing in natural marine clay were quartz, kaolinite and illite. Although the XRD patterns of untreated and RBT-treated samples were similar, the intensity of both kaolinite and illite was lowered for the treated samples. The latter indicated the stabilization process and weathering effect of RBT on the marine clay matrix. As detected by EDS, new reflections observed in the treated samples confirmed the formation of aluminum magnesium silicate hydrate (A–M–S–H).

4 Conclusion

Experimental tests were conducted on untreated and treated marine clay with 0.063 and 0.15 mm of recycled blended tiles (RBT), respectively to explore their suitability in improving plasticity, compactability and compressive strength of marine clay. The experimental program included Atterberg limits, specific gravity, standard proctor, unconfined compressive strength, XRD, EDS and SEM tests. The following conclusions can be drawn based on the study:

1. The RBT treatment reduced the water holding capacity of marine clay. The bigger RBT particle size resulted in a lower water holding capacity, which in turn led to the drop in soil plasticity and optimum water content. However, it did cause a surge in peak dry density. This reduction in water holding capacity could also be attained by the treatment of carbon-binders such as cement and lime.
2. The unconfined compressive strength of RBT treated clay was improved by almost 4 times that of its untreated counterpart. The optimum RBT content, which imparts the highest strength, was observed to be 20% for 0.063 mm RBT and 30% for 0.15 mm RBT. There was a reduction in UCS when the RBT contents were greater than the optimum content because the excessive positive charges triggered the repulsive forces between clay particles.
3. The SEM and XRD analysis of the treated marine clay confirmed the formation of aluminum magnesium silicate hydrate (A–M–S–H), resulting from the reaction between RBT and clay. Since this A–M–S–H product improved the UCS of marine clay, the utility of RBT as a low-carbon soil stabilizer alternative to Portland cement can be established.

Acknowledgements This paper was premised on the research conducted using the Research University Grant Scheme (Q.J. 130000.2522.13H85) from Universiti Teknologi Malaysia (UTM). The authors would like to express their sincere gratitude to UTM for its generous support. The last author acknowledges the financial support provided by the Thailand Research Fund under the TRF Senior Research Scholar program Grant No. RTA5980005, and the Suranaree University of Technology.

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