



Stabilization of soft clay using short fibers and poly vinyl alcohol

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ABSTRACT

In this study, the effect of the combined addition of fibers and a nontraditional polymer on the mechanical behavior of a clay was investigated. Poly vinyl alcohol, PVA, used as a solution with concentrations of 0.1%, 0.3%, 0.5%, 1.0% and 1.5% and 1,2,3,4 Butane Tetra Carboxylic Acid, BTCA was added as a crosslinking agent at concentration rates of 0.1%, 0.3% and 0.5%, respectively. Short polypropylene fibers were added to the clay at proportionate quantities of 0.25% and 0.50% of the dry weight of the soil. Clay samples were prepared for unconfined compressive strength (UCS) tests at two different initial void ratio values, denoting relatively stiff and markedly soft states. UCS tests were conducted on both 1-day and 14-day cured samples. The results confirmed significant UCS improvements with combined fiber reinforcement and PVA-BTCA stabilization when samples were cured for 14 days. It was also observed that fiber reinforcement outperformed PVA-BTCA stabilization for clays with the lower initial void ratio. PVA-BTCA stabilization was however found to be superior to fiber reinforcement in clays with a relatively higher initial void ratio. The effect of fiber reinforcement and PVA-BTCA stabilization on the stability of soils subjected to excessive wetting was also evaluated using soaking tests. Stabilization with PVA and BTCA was found to enhance the stability of soaked samples significantly. The results of soaking tests proved that BTCA made PVA-stabilized samples more durable when exposed to soaking.

1. Introduction

The design and construction of roads and other geostructures, often require incorporating poor quality soil materials with low bearing capacity and high moisture susceptibility into the construction. The Australian railway network is mainly responsible for transporting bulk commodities and freight to and from ports around the nation as well as conveying passengers along major corridors. Some of the railway networks in Australia traverse coastal areas including soft clays with very low bearing capacity and excessive settlement characteristics, which are prone to flooding. This may affect the overlying rail tracks, leading to a possible derailment. The geoenvironmental solutions for counteracting the adverse effects of soft and problematic soils in construction, such as pavement subgrades, include attempting to dewater and compact the subgrade soil (Pujades et al., 2014; Koerner et al., 2016; Estabragh et al., 2018), stabilization with chemical binders such as lime, cement, polymers and geopolymers (Mirzababaei et al., 2009; Saucedo et al., 2014; Puppala, 2016; Kua et al., 2017; Hoy et al., 2017),

reinforcement with geosynthetics and short fibers (Viswanadham et al., 2009; Saad et al., 2012; Jamsawang et al., 2015; Mirzababaei et al., 2017a, 2017b; 2018; Soltani et al., 2018a), or other available amendment alternatives based on the project condition.

Chemical stabilization incorporates the use of chemical binders for improving the shear strength, compressibility, permeability and durability of weak soils, especially soils subjected to harsh environmental impacts (Harichane et al., 2011; Correia et al., 2015; Mohammadinia et al., 2017). Traditional chemical binders include lime, cement, fly-ash, and bituminous materials. The chemical stabilization technique often requires a curing period to enhance the strength improvement process. Research into the use of traditional binders and their stabilization mechanisms has been well documented in the literature (Sherwood, 1993; Celauro et al., 2012; Nagaraj et al., 2014; Soltani et al., 2017a). Lime has been found to successfully modify fine-grained soils by reducing the plasticity and increasing the workability and strength (Little, 1995). The strength gain mechanism in lime-stabilized soils involves an immediate change in the soil texture (i.e. flocculation),

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and long-term pozzolanic and carbonation reactions (Lin et al., 2007). The addition of cement to fine-grained soils also contributes to the pozzolanic reaction, resulting in a strength gain. Unlike lime stabilization, stabilization with cement is quicker and independent from the soil type (EuroSoilStab, 2002; Yong and Ouhadi, 2007).

Non-traditional binders, on the other hand, have become increasingly available for soil improvement projects. A number of non-traditional binders have been developed for soil stabilization applications, which include polymer-based additives, sulphonated oils, lignin derivatives, enzymes, resins, silicates, and calcium/sodium chloride geopolymers (Santoni et al., 2002; Alazigha et al., 2016; Kua et al., 2017; Hoy et al., 2017; Soltani et al., 2017b; Latifi et al., 2018). Although the performance of traditional binders in combination with other reinforcing agents, such as fibers has been well demonstrated in geotechnical engineering applications (Cai et al., 2006; Estabragh et al., 2012; Anggraini et al., 2015; Kumar and Gupta, 2016; Festugato et al., 2017), limited research has been undertaken to evaluate the effect of non-traditional binders such as polymers and their combination with reinforcing elements such as fibers on the mechanical behavior of soft clays (Masoumi et al., 2013; Ayeldeen and Kitazume, 2017; Soltani et al., 2018b). There are many commercially available chemical binders that have been proved to be effective for soil stabilization and dust control purposes. However, such products often lack documentation of measured engineering properties, and more importantly, the manufacturers merely detail the involved stabilization mechanisms (Onyejekwe and Ghataora, 2015).

Polymers with hydrocarbon chains act as potential particle binders by entwining within the soil particles and thus stabilizing the weak soil into a relatively firm mass (Brown et al., 2004). Mirzababaei et al. (2009) reported a significant reduction in the swelling pressure of highly expansive clays stabilized with poly (methyl methacrylate) and poly (vinyl acetate), owing to the formation of aggregated clay particles.

Poly vinyl alcohol (PVA) is recognized as an eco-friendly, odorless, water-soluble, non-ionic and hydrophilic polymer with an excellent film forming potential, which can potentially be used to aggregate clay particles (Carr and Greenland, 1975). PVA is the only water-soluble biodegradable polymer with carbon atom chains that can be degraded in the environment by microorganisms and is capable of establishing hydrogen bonds with water. Some major applications of PVA include paint industry, paper coating, adhesives, water-soluble packaging films for detergents and short fiber production for soil and concrete reinforcement (Ojeda, 2013). PVA has also been reported as a well-accepted safe component for humans and environment in the pharmaceutical, cosmetic, food industry, and agricultural products (Luadthong et al., 2008).

As a non-toxic polymer with high flexibility and tensile strength (in dry form), PVA is an uncharged molecule which can simply diffuse into the soil pores (Greenland, 1963). Therefore, once PVA has entered the pore-spaces of the host soil, it can stabilize the soil by filling the pores and entwining within soil particles. PVA has also been reported to improve the chemical resistance of the concrete against environmental impacts such as corrosion (Viswanath and Thachil, 2007). The PVA-cement gel can effectively fill the pores in the concrete, preventing absorption of water, and thus improving the flexural strength of the concrete (Allahverdi et al., 2010; Yaowarat et al., 2017).

Soil aggregates coated with a PVA film are still vulnerable to an increase in the moisture content of the soil in that, aggregates may tend to disperse upon an exposure to the excessive free water within soil pores due to environmental impacts such as excessive rainfall. Çay et al. (2014) suggested using a crosslinking technique such as freezing/thawing, methanol treatment, chemical crosslinking, or irradiation to ensure the stability of PVA film against excessive moisture contents. 1,2,3,4-butane tetra carboxylic acid (BTCA) has been reported for crosslinking PVA to form three-dimensional hydrophilic hydrogel structures, capable of absorbing large amounts of water. The results of

their research indicated that crosslinking with BTCA improved the water stability of PVA membranes and made the PVA membranes water resistant.

Mirzababaei et al. (2017a) originally investigated the effect of fiber reinforcement using short fibers on the shear strength of soft to stiff clays. It was concluded from this earlier study that short fibers did not perform well in soft clays with a high initial void ratio. Therefore, in this study, it was decided to combine the fibers with a non-traditional additive to enhance the improving effect of fibers for increasing the strength of soft clays with a high initial void ratio/moisture content. Therefore, this research on the stabilizing soft clay with PVA and studying the combined effects of PVA and short propylene fibers on the soft clay's mechanical response is novel. In this study, to investigate the combined effects of fibers and polymers on the mechanical behavior of stiff and soft clays, a series of unconfined compressive strength (UCS) tests were carried out on fiber-reinforced and polymer-stabilized clay samples compacted to relatively low (i.e. stiff clay) and high (i.e. soft clay) initial void ratio values. In order to study the behavior of stabilized samples subjected to extended curing times, a number of samples were also cured for 14 days and further were subjected to UCS tests. To investigate the durability of the stabilized samples subjected to excessive wetting, stabilized/reinforced samples with optimum PVA and/or BTCA concentrations and fiber were also subjected to soaking tests.

2. Materials

The soil used in this study was collected from Sarina Township located in Central Queensland, Australia. The soil is classified as a clay with high plasticity (CH) in accordance with the Unified Soil Classification System (USCS). The activity ratio and the specific gravity of the soil were measured as 0.50 and 2.71, respectively. The grain-size distribution of the soil indicated a 93.30% clay fraction ($< 2 \mu\text{m}$). The consistency limits included a liquid limit of 74% and a plastic limit of 27%. Mechanical properties of the soil, determined as per relevant Australian standards, are provided in Table 1. Short monofilament propylene fibers with a length of 19 mm and a thickness of 32 μm , supplied by Texo (www.Texo.net.au), were used as the reinforcements. PVA and BTCA in dry form, supplied by Sigma-Aldrich (www.SigmaAldrich.com), were used as the chemical binders. Basic properties of the fibers and the chemical binders used in this study are summarized in Table 2.

3. Experimental program

Modified Proctor compaction tests were carried out on unreinforced and 0.50% fiber-reinforced soils, and the results are provided in Fig. 1. The highest fiber content used in this study, i.e., 0.50%, did not

Table 1
Mechanical properties of the soil.

USCS soil classification		CH
Specific gravity, G_s		2.71
Activity		0.50
Grain size analysis	Sand (%)	3.60
	Silt (%)	3.10
	Clay (%)	93.30
Atterberg limits	Liquid limit, LL (%)	74.00
	Plastic limit, PL (%)	27.00
	Plasticity index, PI (%)	47.00
Compaction characteristics	Maximum dry unit weight, γ_{dmax} (kN/m^3)	16.20
	Optimum moisture content, ω_{opt} (%)	16.80
Swelling properties at γ_{dmax} and ω_{opt}	Swelling pressure (kPa)	218.50

Table 2
Properties of the fibers and the chemical binders.

Monofilament fibers	
Tensile strength (MPa)	600
Length (mm)	19
Thickness (μm)	32
Specific gravity, G_s	0.91
Poly vinyl alcohol ($[-CH_2CHOH-]_n$)	
Molecular weight (g/mol)	130,000
Specific gravity, G_s (at 25 °C)	1.26
Viscosity 4% in H ₂ O (20 °C) (mPa.s)	16–20
1,2,3,4-Butane tetra carboxylic acid ($C_8H_{10}O_8$)	
Molecular weight (g/mol)	234.16

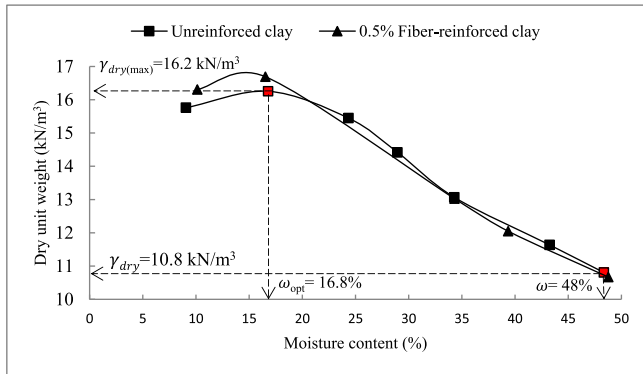


Fig. 1. Modified Proctor compaction curves of unreinforced and 0.50% fiber-reinforced clay.

significantly deviate the maximum dry unit weight and optimum moisture content of the host soil. Therefore, the compaction curve of the unreinforced soil was used for sample preparation. Fig. 1 illustrates the selected unit weight/water content pairs on the modified Proctor compaction curve of the unreinforced soil. Therefore, to investigate the

combined performance of fiber reinforcement and chemical stabilization on the mechanical behavior of stiff and soft clays, two series of UCS tests were carried out on samples prepared at two different initial void ratios of 0.64 and 1.46, respectively (see Fig. 1).

The testing program was conducted in three stages to determine the optimum PVA/BTCA concentration and the optimum fiber content, respectively. In the first series of experiments, five PVA concentrations, i.e. 0.1%, 0.3%, 0.5%, 1.0% and 1.5%, were examined. Therefore, the optimum concentration of PVA was obtained for both stiff and soft soils. In the second stage, BTCA was added at concentration rates of 0.1%, 0.3% and 0.5% to the stabilized soil with the optimum PVA concentration. In the final stage, to further enhance the UCS of the chemically stabilized soils, fibers were included at proportionate amounts of 0.25% and 0.50% (by dry weight of the soil) to the samples stabilized with optimized concentrations of PVA. UCS tests were carried out on triplicate samples, and the average of the three values was reported. The effect of curing time on the UCS development of chemically stabilized and fiber-reinforced samples was investigated through a series of UCS tests on 14-day cured samples. The stability of chemically stabilized and fiber-reinforced samples submerged in water was also visually monitored during the soaking test.

4. Sample preparation

In this study, control and stabilized soil samples with a diameter of 50 mm and a height to diameter ratio of two were prepared using static compaction method at a specified target dry unit weight and moisture content in a steel cylinder. For stabilized samples, predetermined amounts of polymer (i.e., PVA and BTCA) in powder form were mixed in distilled water (i.e., based on concentration in 1000 mL of distilled water) using a magnetic stirrer hot-plate for a minimum period of 1.5 h. The stirring was continued at 85 °C until a clear solution was achieved. The solution was stored in a glass bottle to cool down to the room temperature. As an example, 1% PVA solution was prepared by mixing 10 g PVA powder in 1000 mL of distilled water. To prepare the stabilized clay, the polymer solution was used to wet the soil to the target

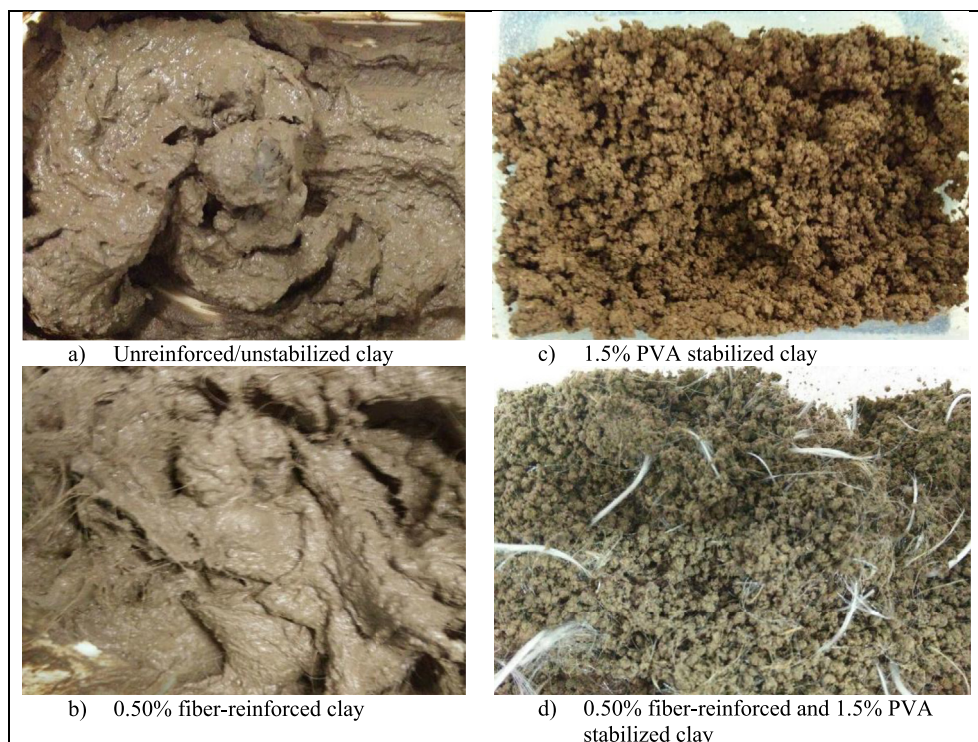


Fig. 2. Physical state of the control, stabilized and fiber-reinforced clay mixture with 48% moisture content before compaction.

moisture content and mixed thoroughly with the clay to prepare a homogenous mixture. Fiber-reinforced clay samples were prepared by mixing the dry soil and fibers first, followed by adding the water/polymer solution at a proportionate amount. Fig. 2 shows the mixture of control, stabilized and fiber-reinforced stabilized clay mixtures. For curing the stabilized and reinforced clay, prepared samples were wrapped in vinyl cling and sealed in double vinyl bags for 14 days in a sealed container at the room temperature (i.e., 21 °C). Once the curing period reached, the weight of the sample was checked to determine any possible loss of the moisture content during the curing period. However, due to use of the cling layer around the sample and double vinyl bags, no noticeable moisture loss was observed.

5. Results and discussion

To investigate the contribution of fibers and chemical binders for improving the compressive strength of relatively stiff and soft clays, a series of UCS tests were carried out on cylindrical samples (i.e. diameter of 50 mm, and height of 100 mm) prepared at predetermined initial void ratio values, i.e. $e_0 = 0.64$ for stiff samples, and $e_0 = 1.46$ for soft samples. The stress–strain and strain–energy relationships were studied, and the combined role of chemical stabilization and fiber reinforcement on the microfabric of the clay soil was analyzed using SEM micrographs. Five PVA concentrations of 0.1%, 0.3%, 0.5%, 1.0% and 1.5% were examined. Three BTCA concentrations of 0.1%, 0.3% and 0.5% were also considered. The required amounts of PVA and BTCA corresponding to the desired concentrations were determined based on the solution in a liter of distilled water. The solutions were then used to prepare soil samples with predetermined moisture contents (i.e. $\omega_{opt} = 16.8\%$ for stiff clay, and $\omega = 48\%$ for soft clay).

5.1. The effect of PVA and BTCA on the strength of stiff clay

In the first series of experiments, to obtain the optimum concentration of PVA and BTCA, a series of UCS tests were carried out on unstabilized and PVA-stabilized stiff clay samples prepared with an initial void ratio of $e_0 = 0.64$ (i.e., $\gamma_{dmax} = 16.2 \text{ kN/m}^3$, and $\omega_{opt} = 16.8\%$; see Fig. 1). Therefore, the UCS of samples stabilized with 0.1%, 0.3%, 0.5%, 1.0% and 1.5% PVA was examined. Samples were cured both for 1 and 14 days prior testing to investigate the early age and aged behavior of the stabilized stiff clay. Fig. 3a and b compare the UCS, peak strain energy and stress-strain behavior of unstabilized and PVA-stabilized stiff clay samples. In this study, the strain energy is defined as the required energy to deform the sample to a strain level equivalent to the peak stress or 10% strain for a strain hardening behavior and is calculated from the area under the stress-strain curve up to the selected strain value (Maher and Ho, 1994; Mirzababaei et al., 2013a, 2013b). A larger strain energy demonstrates a more ductile behavior of the compacted clay sample. At early age condition, the addition of 0.3% PVA resulted in 9.5% improvement in the UCS of the stiff clay. After 14 days of curing, however, the UCS of cured unstabilized clay increased with the addition of PVA and reached a maximum improvement of 13% at 1% PVA concentration. The lower efficiency of PVA at early age condition to improve the UCS of the stiff clay could be attributed to the excessive increase in lubrication effect of soil particles without necessarily forming strong bonds between the liquid polymer and soil particles. The UCS of the 1.0% PVA-stabilized sample, cured for 14 days, increased from 555.5 kPa (for unstabilized sample) to 630.2 kPa. Therefore, 1% PVA was chosen as the optimum PVA solution for stabilizing the stiff clay. In addition, Fig. 3a and b indicated that the strain energy at peak and ductility of the stabilized samples increased slightly with the addition of PVA and curing time.

In the second stage of the testing program, the concentration of PVA was maintained constant at 1%, while the concentration of BTCA was varied to determine its optimum concentration for stiff clay stabilization. Fig. 3c and d illustrate the UCS, strain energy and stress–strain

behavior of the 14-day cured samples stabilized with 1% PVA and 0.1%, 0.3% and 0.5% BTCA, respectively. The addition of 0.5% BTCA resulted in 13.1% and 36.8% improvement in the 14-day UCS and strain energy of the PVA treated stiff clay without BTCA, respectively. The addition of BTCA was mainly aimed for crosslinking the hydroxyl groups of PVA, promoting a water-insoluble property when the stabilized soil is exposed to a soaking condition.

5.2. The effect of PVA and BTCA on the strength of soft clay

The next series of experiments were carried out on unstabilized and PVA-stabilized samples prepared at an initial void ratio of 1.46 (i.e. $\gamma_d = 10.8 \text{ kN/m}^3$, and $\omega = 48\%$; see Fig. 1). Fig. 4a and b illustrate the effect of PVA on the UCS, strain energy and stress-strain behavior of the soft clay. As a result of PVA-stabilization, the UCS of both early age and 14-day cured soft clay samples exhibited a significant improvement. In optimal cases, the addition of 1.5% PVA, cured for 1 day, increased the UCS of the soft clay from 6.1 kPa (for unstabilized sample) to 44.1 kPa (i.e. over a 7-fold increase). With 14 days of curing, the UCS of the stabilized soil further increased to 52.3 kPa (i.e. over an 8-fold increase compared to the unstabilized sample). The addition of 1.5%-PVA, increased the strain energy of the unstabilized clay from 0.8 kJ/m^3 to 3.2 kJ/m^3 and 4.2 kJ/m^3 at 1-day and 14-day curing periods, respectively. Therefore, 1.5% PVA was found to be an optimum for improving the mechanical behavior of the soft clay.

In the second stage of the testing program, the concentration of PVA was maintained constant at 1.5%, while the concentration of BTCA was varied to arrive at its optimum concentration for soft clay stabilization. Fig. 4c and d illustrate the UCS, strain energy and stress–strain behavior of the 14-day cured samples stabilized with 1.5% PVA and 0.1%, 0.3% and 0.5% BTCA, respectively (i.e. the sample stabilized with 1.5% PVA alone).

Therefore, it can be inferred that the PVA-BTCA film forms with a delay in the presence of high water content clay with an initial moisture content of 48% and the free PVA-BTCA solution may act as a lubricant reducing the strength of the soil subjected to axial loading. However, for clay with the lower initial void ratio (i.e., 16.8% water content) PVA-BTCA molecules can potentially form a film around clay particles to improve the interfacial bonds with clay particles and hence to increase the UCS of the clay.

5.3. The combined effect of polymers and fibers on the strength of stiff and soft clays

In the next series of experiments, to investigate the effect of fibers on the compressive strength of stabilized clay with optimum concentration of PVA (i.e., 1% for stiff clay, and 1.5% for soft clay), UCS tests were carried out on 0.25% and 0.50% fiber-reinforced and chemically-stabilized samples prepared at both relatively low and high initial void ratio values. The results of the UCS tests carried out on 0.25% and 0.50% fiber-reinforced stiff clay samples (i.e. $e_0 = 0.64$), stabilized with 1% PVA and 0.1%, 0.3% and 0.5% BTCA, are provided in Fig. 5a and b. As a result of 0.25% fiber reinforcement and 1 day of curing, the soil exhibited a significant UCS improvement of 36.5% compared to the unreinforced soil. With 14 days of curing, 0.25% fiber-reinforced sample experienced a further improvement of 13% over that of 1-day cured fiber-reinforced sample. Although the 1-day UCS of the 0.50% fiber-reinforced sample was slightly lower than that of the 0.25% fiber-reinforced sample, with 14 days of curing, the UCS of the 0.50% fiber-reinforced sample was 6% higher than that of the 0.25% fiber-reinforced sample cured for 14 days. The ductility of the soil increased significantly with fiber reinforcement as a measure of enhanced strain energy required for deforming the sample up to 10% strain and increased axial strain at the failure. Therefore, the strain energy of the 14-day cured clay increased from 37.7 kJ/m^3 to 76 kJ/m^3 and 112.4 kJ/m^3 with 0.25% and 0.50% fiber reinforcement, respectively.

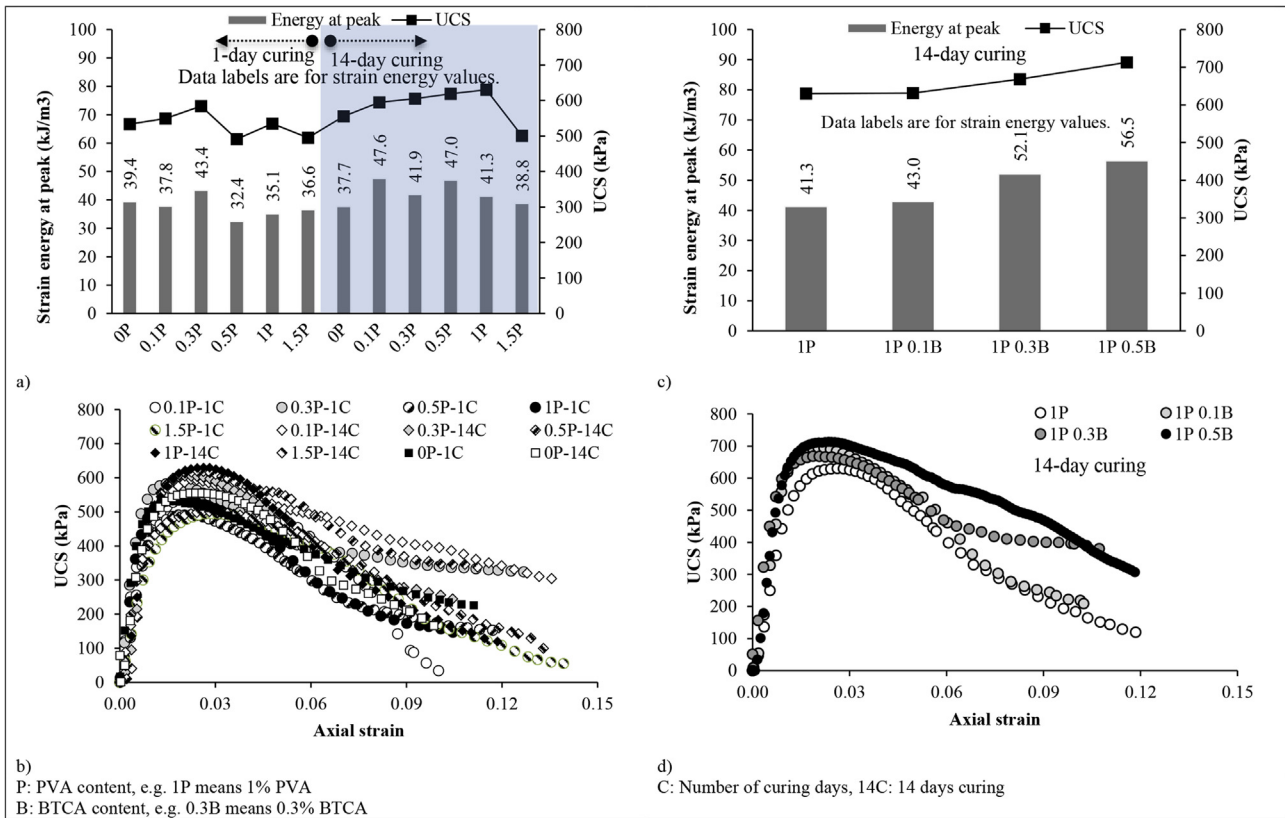


Fig. 3. UCS and strain energy of stiff clay samples ($e_0 = 0.64$): (a, b) PVA-stabilized; and (c, d) PVA + BTCA stabilized (14-day curing).

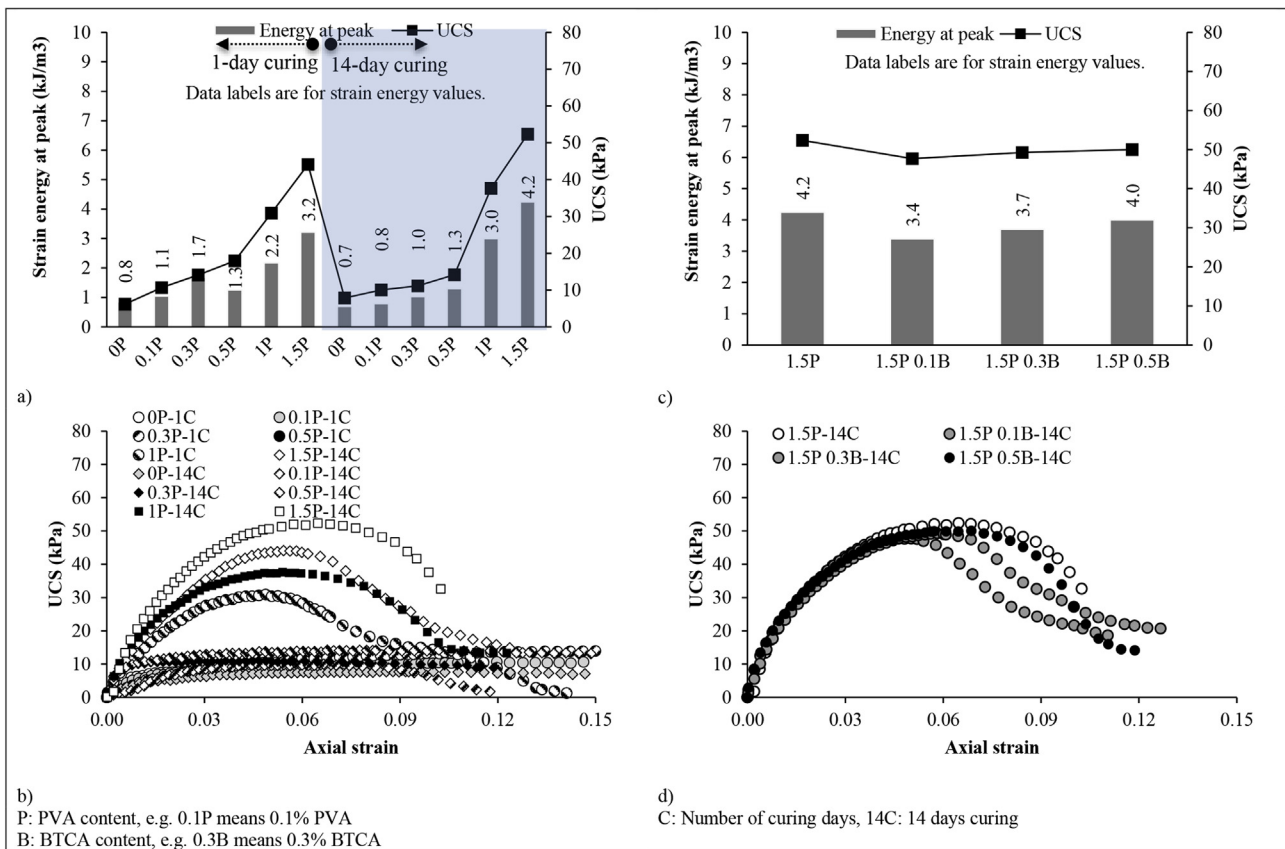


Fig. 4. UCS and strain energy of soft clay samples ($e_0 = 1.46$): (a, b) PVA-stabilized; and (c, d) PVA + BTCA-stabilized (14 days cured).

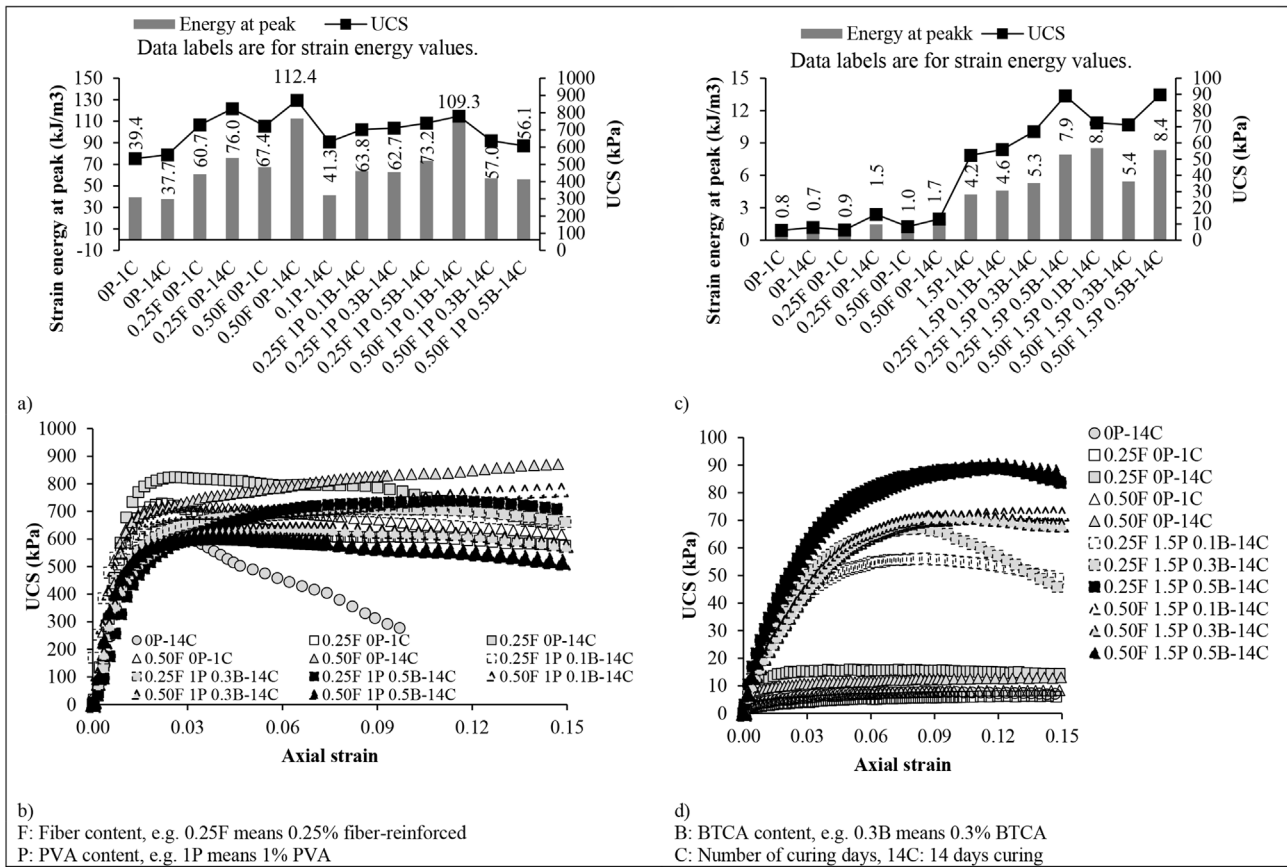


Fig. 5. UCS and strain energy of fiber-reinforced and PVA + BTCA-stabilized samples: (a, b) stiff clay ($e_0 = 0.64$); and (c, d) soft clay ($e_0 = 1.46$).

Table 3
Selected samples for the soaking test.

No.	Sample Description	Initial moisture content (%)	PVA concentration (%)	BTCA concentration (%)	Fiber content (%)	Time elapsed till onset of disintegration (dd:hh:mm:ss) (%)
$e_0 = 0.64$	1 OF OP OB	16.80	-	-	-	00:00:15:30
	2 OF 1P OB	16.80	1.00	-	-	00:00:27:15
	3 OF 1P 0.5B	16.80	1.00	0.50	-	00:04:56:45
	4 0.25F OP OB	16.80	-	-	0.25	00:05:06:15
	5 0.50F OP OB	16.80	-	-	0.50	00:06:42:30
	6 0.25F 1P 0.5B	16.80	1.00	0.50	0.25	09:00:00:00
	7 0.50F 1P 0.5B	16.80	1.00	0.50	0.50	09:00:00:00
$e_0 = 1.46$	8 OF 1.5P OB	48.00	1.50	-	-	NF
	9 OF 1.5P 0.5B	48.00	1.50	0.50	-	NF
	10 0.25F OP OB	48.00	-	-	0.25	00:00:59:00
	11 0.50F OP OB	48.00	-	-	0.50	00:00:46:40
	12 0.25F 1.5P 0.5B	48.00	1.50	0.50	0.25	NF
	13 0.50F 1.5P 0.5B	48.00	1.50	0.50	0.50	NF

F: Fiber content, e.g. 0.25F means 0.25% fiber-reinforced.
 P: PVA content, e.g. 1P means 1% PVA.
 C: Number of curing days, 14C: 14 days curing.
 B: BTCA content, e.g. 0.3B means 0.3% BTCA.
 NF: Virtually no failure was observed even after 4 months of soaking.

The combined addition of fibers and polymers resulted in moderate UCS improvement for PVA–BTCA stabilized samples (i.e., increase from 701.5 kPa for 0.25% fiber-reinforced 1%PVA-0.1%BTCA-stabilized clay to 738.7 kPa for 0.25% fiber-reinforced 1%PVA-0.5%BTCA-stabilized clay). However, the rate of improvement decreased with the addition of both PVA and BTCA compared to fiber-reinforced unstabilized clay. The UCS of the 0.25% fiber-reinforced sample stabilized with 1% PVA and 0.5% BTCA (i.e., cured for 14 days) increased by 33% compared to that of the unreinforced and unstabilized clay cured for 14 days (i.e., the UCS changed from 555.5 kPa to 738.7 kPa). For the 0.50%

fiber-reinforced soil, however, maximum UCS improvement was observed for the sample stabilized with 1% PVA and 0.1% BTCA (i.e., 40% improvement compared to that of unreinforced and unstabilized soil, see Fig. 5a).

Fig. 5c and d shows the effect of fiber reinforcement on the UCS, strain energy and stress–strain behavior of the soft clay. Fiber reinforcement alone resulted in an insignificant UCS improvement of the soft clay in that the UCS of the unreinforced soft clay increased from 7.8 kPa to 15.9 kPa and 13 kPa with the addition of 0.25% and 0.50% fiber, respectively. However, the addition of both fibers and polymers

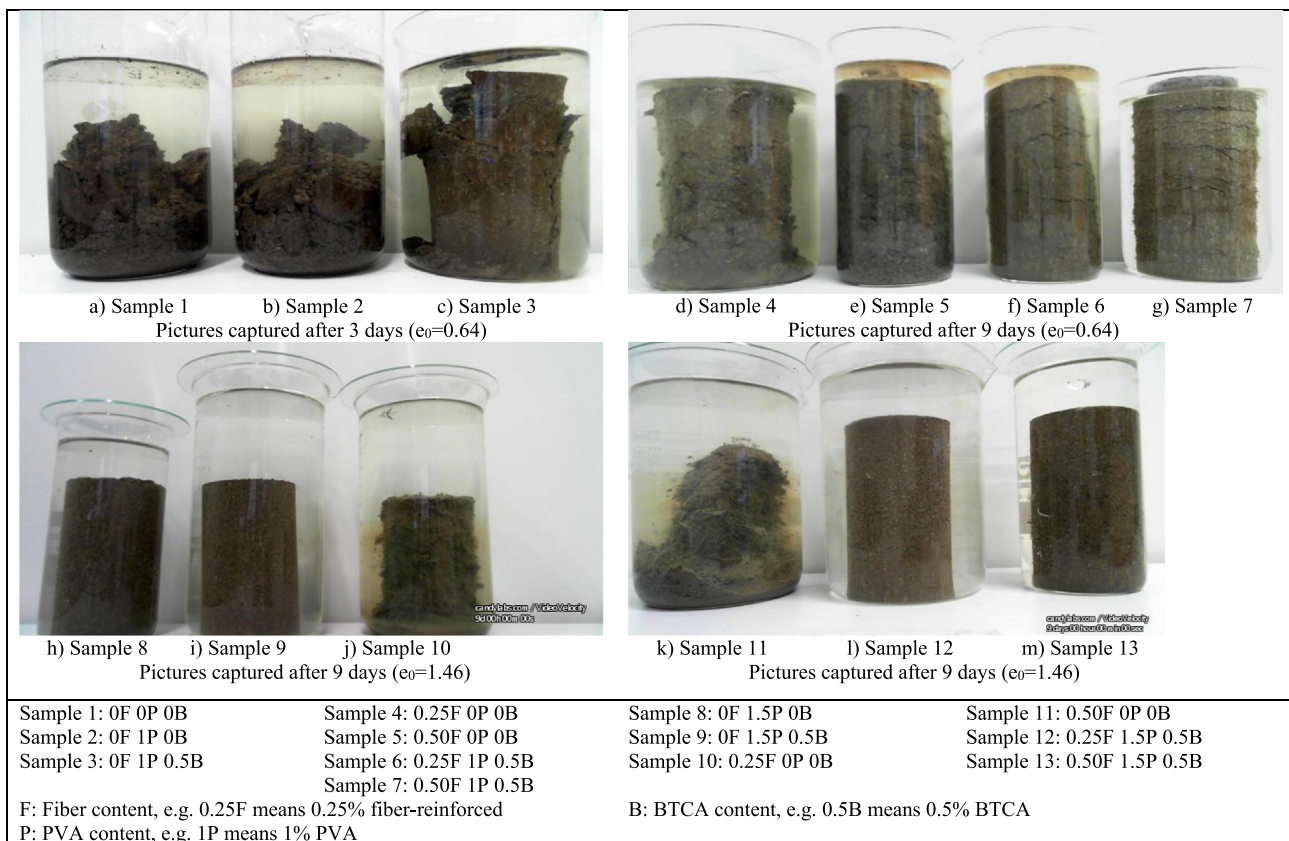


Fig. 6. Visual state of the soaked samples at the end of soaking test.

significantly improved the UCS and strain energy of the soft clay in that, the UCS of the 0.25% fiber-reinforced soft clay, cured for 14 days and stabilized with 1.5% PVA and 0.5% BTCA increased by just above 78% compared to the UCS of unreinforced 14-day cured stabilized soil with 1.5% PVA and 0.5% BTCA. The UCS of the 0.5% fiber-reinforced soft clay, cured for 14 days and stabilized with 1.5% PVA and 0.5% BTCA was almost the same as that of the same with 0.25% fibre.

5.4. Durability of the stabilized samples

Several soaking tests were carried out on 14-day cured samples to investigate the durability of the fiber-reinforced and stabilized samples at relatively stiff and soft states. Samples were soaked under the water, and their stability was visually monitored with time to a point in which samples were structurally disintegrated. Table 3 presents the selected samples for soaking tests and the elapsed time from soaking to the onset of disintegration. The onset of disintegration was visually recognized by an initial sign of sample disintegration in that, part of the cylindrical sample was detached. In addition, the visual state of the tested samples at the end of the test is shown in Fig. 6. All samples were soaked in water for 9 days except samples 1, 2 and 3 that disintegrated completely in less than 3 days. Disintegration began immediately at immersion for unreinforced-unstabilized stiff clay within the first 15 min. However, the addition of PVA slightly increased the durability of the soaked sample to 27 min. Stabilizing the clay sample with both PVA and BTCA resulted in significant increase in durability of the sample in that the initial disintegration process was delayed for 4 h and 56 min after soaking. This observation was anticipated as BTCA prevents solution of PVA in water by crosslinking PVA molecule chains. Fiber reinforcement also improved the stiff clay samples' durability and it slightly increased with an increase in fiber content (see Fig. 6d and e). Combining both fiber reinforcement and PVA/BTCA stabilization of stiff clay led to a significant extension of soaked samples' stability under water for 9 days

(see Fig. 6f and g).

Soft clay samples showed a different behavior once they soaked in the water. Addition of either PVA or both PVA and BTCA resulted in making the clay samples durable under water up to 9 days of testing (see Fig. 6h and i). However, fiber reinforcement alone could keep the samples stable just less than an hour (see Fig. 6j and k). The combination of fiber reinforcement and PVA/BTCA stabilization also resulted in an increase in the durability of the clay samples up to 9 days of soaking (see Fig. 6l & m).

5.5. SEM analysis

Fig. 7 shows the SEM micrographs of stiff clay samples prepared at an initial void ratio of $e_0 = 0.64$. Fig. 7a indicates that the microfabric of the unstabilized soil mainly included small aggregates spaced with inter pore-spaces. However, the addition of PVA and BTCA (see Fig. 7b and c) resulted in a uniform matrix of aggregated particles with less number of inter pore-spaces. Reduction in extent and number of inter pore-spaces leads to the formation of larger aggregates that contribute well to withstand the stresses at the interface of solid-void part of the soil sample skeleton. The observed changes in the microfabric of the stabilized clay samples are in line with the resulted stress-strain behavior in Fig. 3. The UCS of the unstabilized, 1% PVA-stabilized and 1% PVA-0.5% BTCA-stabilized stiff clay samples cured for 14 days were 555.5 kPa, 630.2 kPa and 712.8 kPa. The strain energy of the above samples changed significantly (i.e., 37.7 kJ/m³, 41.3 kJ/m³ and 56.5 kJ/m³, respectively). Fig. 7d shows that there was a good bond between the fiber and the individual soil aggregates. With the addition of PVA and BTCA, fibers were embedded between the matrices of the large aggregates. The combined effect of fiber embedment within large matrices of the aggregated particles of PVA stabilized sample resulted in particular strain energy and UCS improvement of the clay. The strain energy of the control 14-day cured stiff clay sample increased from

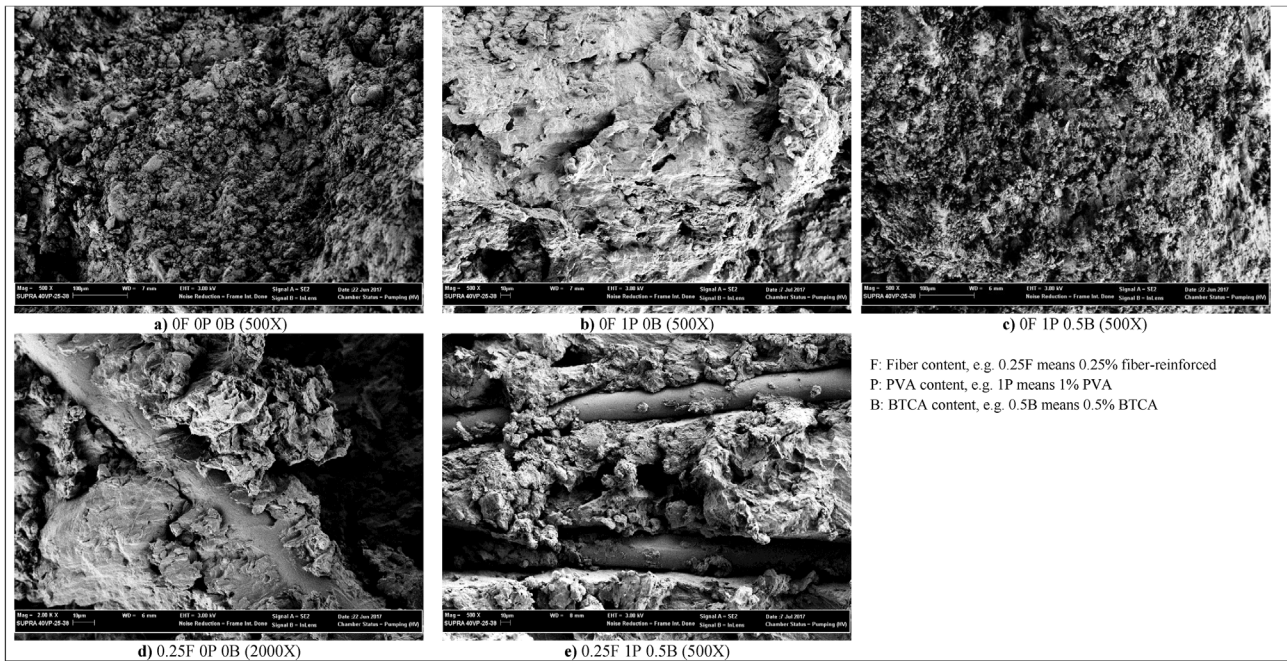


Fig. 7. SEM micrographs of clay with initial void ratio of $e_0 = 0.64$.

37.7 kJ/m³ to 73.2 kJ/m³ for a 14-day cured 0.25% fiber-reinforced and 1% PVA-0.5% BTCA stabilized sample. However, although the 14-day UCS of the control clay increased from 555.5 kPa to 823.4 kPa with 0.25% fiber reinforcement, there was a slight reduction for the 14-day UCS of the 0.25% fiber-reinforced 1%PVA-0.5%BTCA stabilized clay to 738.7 kPa (see Fig. 5a and b).

Fig. 8 shows the microfabric of soft clay samples prepared at an initial void ratio of $e_0 = 1.46$. In comparison to stiff clay where $e_0 = 0.64$, the extent of pore-spaces between aggregates increased (see Fig. 8a). Similarly, the addition of PVA and BTCA led to the formation of larger aggregates and further contribution to strength improvement (see Fig. 8b and c). Although fibers could effectively interact with the unstabilized soil particles, the formation of large matrices of aggregated

particles, owing to the treatment with PVA and BTCA, resulted in physically improved bonds between fibers and soil aggregates (see Fig. 8d). Therefore, the observed improvement in UCS and strain energy of control soft clay sample was apparent (see Fig. 5c and d).

6. Conclusions

A suite of UCS tests were conducted to explore the efficiency of poly vinyl alcohol (PVA) and 1,2,3,4 Butane Tetra Carboxylic Acid (BTCA) in combination with fiber reinforcement with short polypropylene fibers for improving the compressive strength of a clay. A systematic testing program was designed to determine the optimum binder content for improving the mechanical behavior of relatively soft and stiff clays with

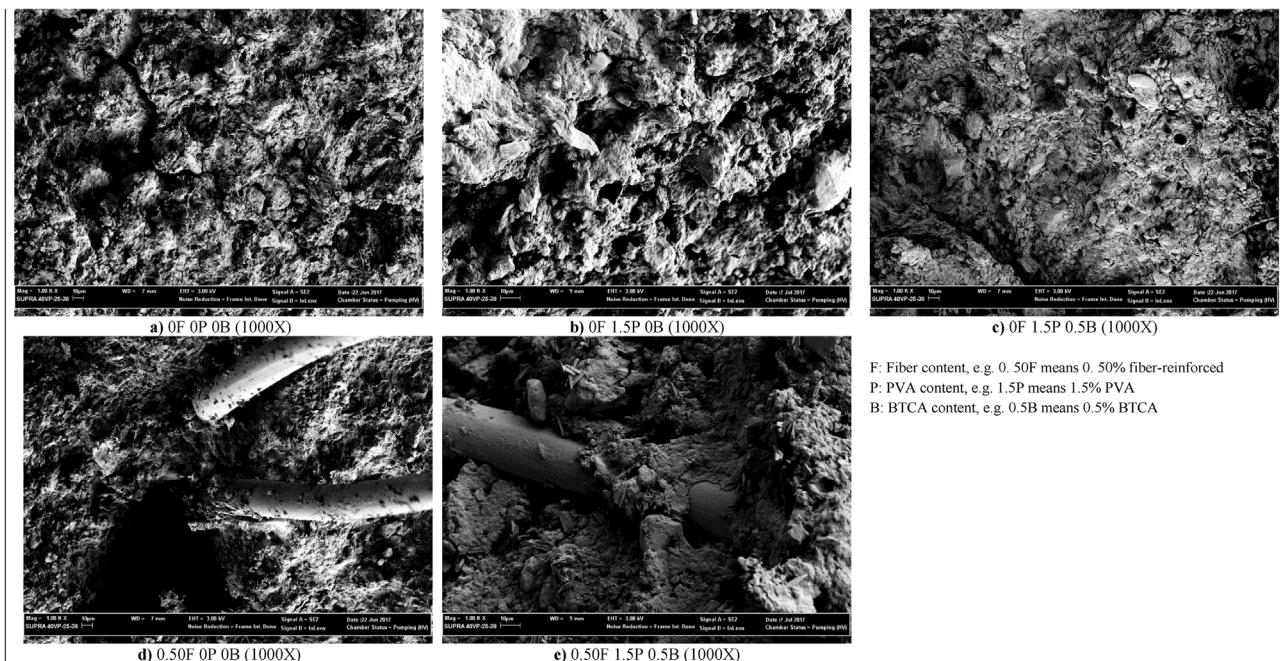


Fig. 8. SEM micrographs of clay with initial void ratio of $e_0 = 1.46$.

different initial void ratio and moisture content values including initial void ratio and moisture content pairs of (0.64, 16.8%) and (1.46, 48%), respectively. The results indicated that the combined effects of fiber reinforcement, PVA and BTCA addition improved the UCS and ductility of the clay significantly. However, the optimum content of binders and fiber content were sensitive to the initial void ratio and moisture content of the soil sample. The addition of 1% PVA resulted in a small improvement of the UCS of clay samples with the lower initial void ratio (i.e., 13% improvement). However, for soil sample with a higher initial void ratio, the addition of PVA up to 1.5% concentration significantly increased the UCS of the clay. The UCS of the 1.5% PVA stabilized soft clay increased from 6.1 kPa (i.e., for unstabilized clay) to 44.1 kPa (i.e., over a 7-fold increase). The UCS of both stiff and soft stabilized clay increased moderately with curing. The optimum PVA concentration rates for improving the UCS of stiff and soft clay samples were found to be 1% and 1.5%, respectively. The addition of fibers to PVA-stabilized clay also indicated a moderate to intense improvement in UCS of both stiff and soft clay samples. The combined effect of fiber reinforcement and PVA and BTCA stabilization on the mechanical behavior of clay was found to be dependent on the initial void ratio of the soil. Fibers were found to be more effective for strength improvement of the stiff clay while for the soft clay; fibers alone could not improve the UCS of the soil effectively. However, once fiber reinforcement and polymer stabilization were combined, the UCS of the soft clay was improved significantly.

BTCA used in this study was mainly for making PVA hydrogels insoluble in water and did not participate in a strength gaining process. The results of soaking tests indicated that stabilizing clay with PVA and BTCA potentially increased the durability of the soil when exposed to a soaking condition (e.g., flooding). The fiber-reinforced and stabilized clay lasted longer under water. SEM analysis of the PVA and BTCA stabilized clays showed the formation of uniform matrices of aggregated particles with less inter pore-spaces, resulting in a strength increase and slowing down the water intake process at micro levels after soaking in the water.

The results of this study showed that PVA, with environmentally friendly features, can be used as an organic copolymer for soil improvement. PVA is more effective for clays with higher water content and initial void ratio. The mechanism of soil improvement with the addition of PVA involves absorbing the extra water in the soil by PVA molecules to form aggregated soil particles and replacement of the pore-water with hydrogel layers between particles.

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