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Geomechanical Behaviour of Clay Stabilised with Fly-Ash-Based Geopolymer for Deep Mixing

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Abstract: Geopolymer has recently become an attractive alternative to traditional binders (e.g., cement and lime) used for chemical soil improvement, with several environmental benefits including lower toxic emissions and energy consumption. This paper presents an evaluation of the geomechanical behaviour of soft clay treated with fly-ash-based geopolymer incorporating slag for deep soil mixing (DSM) applications. The geomechanical properties of stabilised clay were evaluated using unconfined compressive strength (UCS) tests and durability against wetting–drying. Thermal conductivity and pH tests along with microstructural analysis using scanning electron microscopy (SEM) were also performed to provide insights into the effect of geopolymer on treated clay. The results indicate that the inclusion of geopolymer with the increase in curing time and activator content considerably improves the geomechanical performance of geopolymer-treated soft clay in terms of stress–strain response and attainable peak compressive strength. Although it was found that a small percentage of geopolymer can enhance the initial compressive response, a larger dosage of geopolymer up to 30% was necessary to maintain stable durability performance over successive wetting–drying cycles. Such improved durability performance is related to the enhanced soil structure due to the cementation development and overall reduction in thermal conductivity. The reduction in thermal conductivity of treated clay was found to be activator-dependent and was suppressed steadily with the increase in activator concentration. Overall, geopolymer-treated clay showed promising potential for DSM applications due to its enhanced strength and durability responses.

Keywords: fly-ash geopolymer; soil stabilisation; ground improvement; deep soil mixing

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1. Introduction

Chemical stabilisation has been extensively utilised as an economical option in the geotechnical industry to improve the inherent properties of problematic soils, including inadequate bearing capacity and excessive compressibility [1]. The technique generally involves soil mixing with traditional chemical binders (e.g., lime or cement) that interact, in the presence of water, through hydration and pozzolanic reactions to develop enhanced soil structure and improved engineering properties. The in situ mixing of soil with a binder can be either surface or deep mixing [2]. Deep soil mixing, denoted as DSM, has grown in popularity with improved technology since the early 1970s to enhance the engineering properties of soft soils [1–3]. DSM has been developed to offer two types of soil mixing, including mass mixing (up to 6 m depth) and column mixing (up to 30 m depth) with the binder applied using either a dry method (powder form) or wet method (slurry form). However, the heavy reliance of DSM on traditional binders possesses key environmental issues due to the increased carbon footprint associated with their production; the manufacture of Ordinary Portland Cement (OPC) and lime is responsible for about 10% of the global artificial CO_2 emissions per year [4–7]. The reported percentage of CO_2 emissions associated with using non-renewable materials and the degradation of landscapes [6,8] is significant and has prompted research to identify more sustainable alternatives in DSM applications without compromising soil stabilisation capabilities.

Geopolymer, as an alkali-activated type of cement, has been developed in response to the demand for sustainable binders, making use of the alkaline activation of low-calcium-aluminosilicate waste material, such as fly-ash [4,9,10]. When fly-ash comes in contact with an alkaline activator (usually sodium-based) added to the soil, an immediate reaction called geopolymerisation begins. This reaction is responsible for the formation of an artificial cementitious product within the soil particles, thereby stabilising soil and enhancing its geomechanical properties [11–16], including unconfined compressive strength [14,17,18] and undrained shear behaviour [19]. The addition of geopolymer increases the peak strength and decreases the corresponding axial failure strain of geopolymer-treated specimens, both of which contribute to a stiff response similar to that of OPC-treated soils [20]. Geopolymer products synthesised from geopolymerisation within treated soil can be represented by the chemical structure Sodium Aluminium Silicate Hydrate (N-A-S-H), which differs from C-A-H and C-S-H products from hydration and pozzolanic reactions for OPC and lime–soil mixtures [21]. However, the formation of the N-A-S-H product is favoured only at elevated temperatures and in high-alkalinity media [22–25]. This has been found to form a significant limitation in the practical utilisation of geopolymers for soil stabilisation since aggressive synthesised conditions are not practical for soil treatment application due to the negative impacts of heavy metals and high pH, usually >12 (the neutral value is 7 for drinking water). In an attempt to promote effective treatment at ambient curing and low-alkalinity conditions, recent research efforts have focused on enhancing the reactivity of fly-ash-based geopolymer by including calcium-based components such as ground granulated blast furnace slag (GGBFS) e.g., [26] due to its wide availability as a waste material produced from the steel industry. The availability of calcium ions within geopolymer assists the formation of secondary cementation products, i.e., Calcium Aluminate Silicate Hydrate (C-A-S-H) within the N-A-S-H geopolymer framework [27–29], thereby enhancing geopolymer performance for soil stabilisation. However, to promote geopolymer for DSM applications, there is an urgent need to characterise an efficient and practical geopolymer mixture that can outperform traditional binders in all aspects, especially strength and durability performance.

The present study aims to characterise the geomechanical behaviour of soft clay treated with fly-ash-based geopolymer incorporating slag for DSM. This subject is relatively new, especially considering a synthesised recipe of geopolymer suggested for surface mixing [26]. In this study, commercially available kaolin clay was used, and unconfined compressive strength (UCS) tests were conducted to investigate the strength development of geopolymer-treated clay under uniaxial loading conditions. Wetting–drying tests were also carried out to evaluate the durability performance of the treated clay. The mechanical and durability performance was further assessed against pH and geothermal responses. Images captured using Scanning Electron Microscopy (SEM) were also analysed for a typically treated clay mixture to improve the understanding of how the structure of the geopolymer–clay mixture contributes to enhanced strength characteristics. Furthermore, the effects of geopolymer dosage, activator content and curing time on the geomechanical behaviour of geopolymer-treated clay were investigated.

2. Materials and Methodology

2.1. Clay

The clay used in the current study was white-coloured kaolin commercially available in Western Australia. Detailed characteristics of the kaolin clay used are listed in Table 1. All tests were performed following the Australian Standards requirements including the Atterberg limits [30,31], particle size distribution [32] and pH value [33]. According to the Unified Soil Classification System (USCS), the kaolin clay used is classified as high-plasticity (CH) clay.

Table 1. Characteristics and classification of kaolin clay used.

Property	Value/Designation
Liquid limit, *LL* (%)	53
Plastic limit, *PL* (%)	27
Plasticity index, *PI* (%)	26
Passing sieve 75 µm (%)	99
Clay fraction < 2 µm (%)	79.4
Soil pH	7.8
Activity index, *A*	0.33
Soil classification (USCS)	CH

2.2. Geopolymer Ingredients

The geopolymer used in this study comprises a mixture of fly-ash, ground granulated blast furnace slag (GGBFS) and a sodium-based activator. Low-calcium fly-ash (Class F, Australian Standard AS 3582.1, 1998), produced by Cement Australian Limited from Gladstone Power Station, was used. This type of fly-ash is rich in aluminosilicate material and commonly used for geopolymers [4,34]. GGBFS, supplied by Independent Cement & Lime Limited, was used to enhance the performance of the fly-ash-based geopolymer after activation at ambient temperature [27,28]. The particle size distribution and chemical compositions of the fly-ash and GGBFS used are provided in Figure 1 and Table 2, respectively.

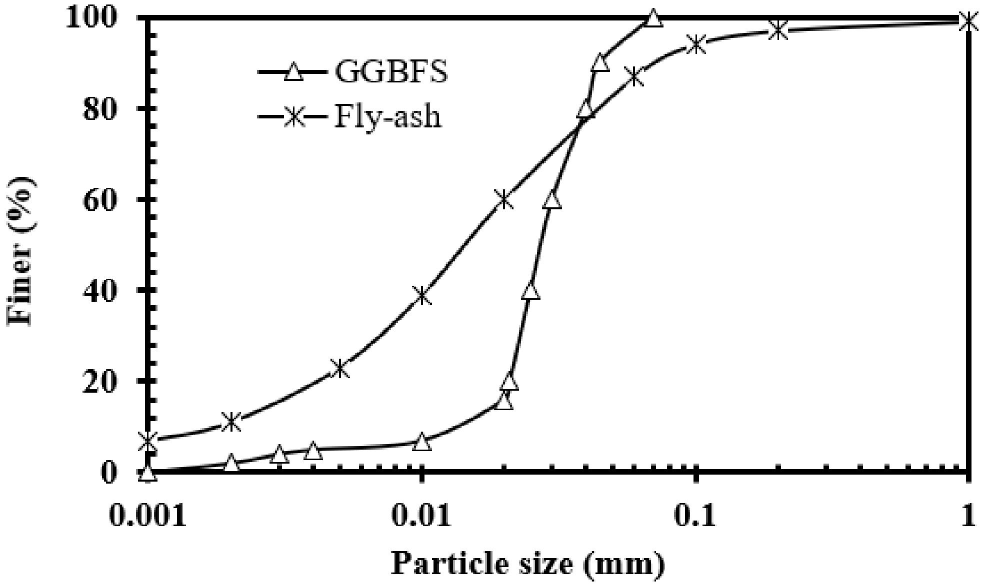


Figure 1. Particle size distribution of fly-ash and GGBFS.

Table 2. Chemical compositions of materials used, as provided by suppliers.

Material	Chemical Composition (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
Fly-ash	51.11	25.56	12.48	4.30	1.45	0.70	0.77	0.24	0.57
GGBFS	29.96	12.25	0.52	45.45	5.99	0.38	0.31	3.62	2.39

In this study, an alkaline activator comprising sodium silicate (Na2SiO3) and sodium hydroxide (NaOH) was used, as suggested by many researchers e.g., [13,14,20,35,36]. The sodium silicate was supplied by PQ Australia and contained 14.7% Na2O with a mass ratio (SiO_2/Na_2O) of 2. The sodium hydroxide, originally in pellet form, was dissolved in deionised water to a concentration of 14 molars for at least 24 h before mixing with the sodium silicate. The weight ratio of the sodium silicate to sodium hydroxide was 2.33, which was required to maximise the reaction phase of the geopolymer, as recommended by Hardjito [34].

2.3. Soil–Geopolymer Admixtures

The mixing procedure in this study aimed to simulate the in situ wet mixing method used for DSM applications. The dry clay was first mixed with water to achieve a liquid limit state and then left to cure in tide containers for at least 24 h before further mixing with the previously prepared geopolymer mixture. The geopolymer was selected to be synthesised to a specific weight ratio of slag/fly-ash of 20%; this ratio was recommended by Abdullah et al. [26] to develop improved short-term geopolymer hardening in stabilised clay in ambient curing conditions. The concentration of the liquid activator was varied within the geopolymer mixture to allow for the investigation of a practical combination; the ratio of activator/(fly-ash + slag), coded as A/B, was equal to 0.5, 0.75 and 1.0. Geopolymer was added to the clay to achieve different combinations equal to 10%, 20% and 30%, as shown in Table 3, which summarises the details of all mixtures used. Additional mixtures were prepared and stabilised by adding 10%, 20% and 30% OPC and fixed water to cement ratio = 0.4, as shown in Table 3. These samples were tested to provide a baseline and compare them with the other binders of geopolymer stabilised mixtures. It should be noted that the percentage of geopolymer in Table 3 represents the ratio of dry additive to the total weight of dry clay before activation.

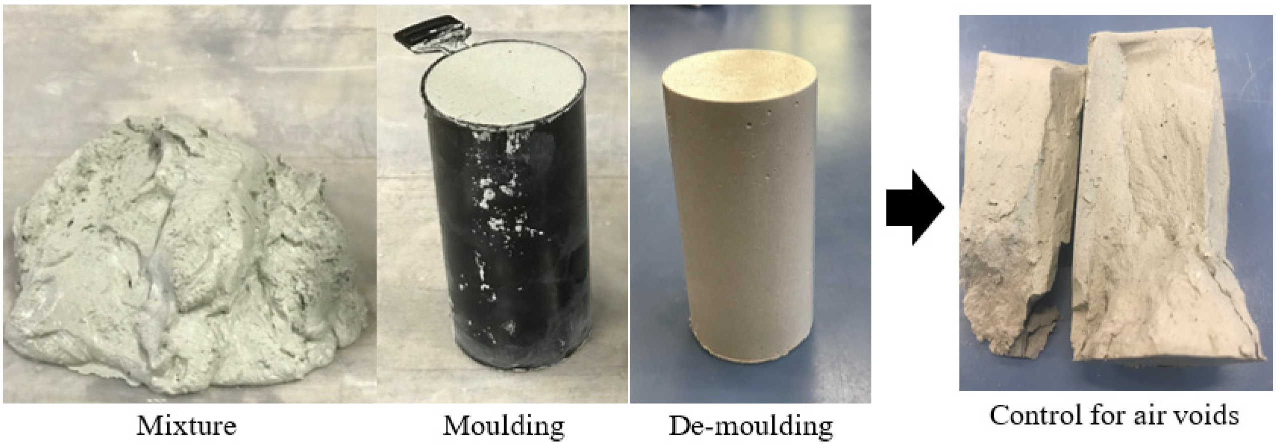
Table 3. Geopolymer and OPC–clay mixtures.

Binder %	Activator/Binder (A/B)	Water/Binder (W/B)
10% Geopolymer	0.50	-
	0.75	-
	1.00	-
20% Geopolymer	0.50	-
	0.75	-
	1.00	-
30% Geopolymer	0.50	-
	0.75	-
	1.00	-
10% OPC	-	0.4
20% OPC	-	0.4
30% OPC	-	0.4

2.4. Specimen Preparation and Tests

Following mixing, the treated clay was remoulded in a split cylindrical polyvinyl chloride (PVC) mould (50 mm diameter and 100 mm height) to attain an aspect ratio of diameter-to-height of 1:2 (Figure 2). It should be noted that the workability and viscosity of different mixtures varied depending on the amount of activator used; therefore, care was taken to minimise the air entrapped during remoulding. For mixtures with low viscosity, entrapped air was controlled by direct tapping to the sides of the mould. For other mixtures of high viscosity, air entrapped was minimised by performing static compaction in two layers, as directly tapping on the mould was inefficient. To avoid any interaction due to stabiliser hardening, extreme care was taken to complete the sampling within 30 min after mixing. Specimens were left to initially cure for 24 h and then removed from the split moulds, wrapped in cling film and left to cure at 60% humidity and 18–22 °C temperature.

To investigate the strength of treated clay, unconfined compressive strength (UCS) tests were conducted on different specimens following the Australian Standards AS 5101.4 [37] and using a strain rate of 1% per minute. Specimens were tested at 7 and 28 days of curing. Two specimens for each curing period were tested, and the average result was considered. When the variation between the UCS values of the two specimens was significant (>20%), a third specimen was tested to establish the accuracy with the outlier discarded.



Mixture Moulding De-moulding Control for air voids

Figure 2. Geopolymer-treated clay specimen.

Durability testing considering wetting–drying cycles was also conducted on treated specimens following ASTM D559-03 [38]. After 28 days of curing, specimens were immersed in water for 5 h to commence the first wetting phase and then oven-dried at 70 °C for 43 h. Specimen dimensions were determined after each wetting–drying cycle to determine the corresponding volumetric change; a durable specimen is defined as one that experiences less than 10% volumetric change over the test period [39]. This 48 h process, representing one wetting–drying cycle, was repeated 12 times. To assess the residual strength of treated clay, additional UCS tests were then performed on soil specimens that survived the wetting–drying cycles. It should be noted that UCS testing is not a typical procedure for durability evaluation; however, it provides a parameter to quantify the degradation experienced by the treated specimens [40]. UCS testing directly on oven-dry specimens would give an unrealistic indication of specimen strength because such a moisture content is not representative of the in situ conditions. Therefore, the specimens were submerged in water for 1 h and allowed to air dry for 15 min before UCS testing.

To enable the investigation of the effect of alkalinity on treatment, a series of pH tests were conducted on treated specimens according to the Australian Standards AS 1289.4.3.1 [33]. The tests were conducted using fragment materials collected from UCS specimens after testing. At the designated curing time, a 30 g sample of the material (i.e., treated soil) was ground to powder, sieved through a 2.36 mm sieve and stirred with 75 mL of distilled water to form a slurry. After 1 h of curing, the pH was then determined using an electronic pH meter.

The rate of change in temperature within the treated specimen during the wetting and drying phases of a durability test is expected to impact the volumetric response of treated soil; a sudden thermal difference (cooling or heating) between the surface and the core of the specimen might develop internal stresses which cause a non-uniform volumetric response. Such thermal response is partially controlled by the thermal conductivity (i.e., a measure of the soil's ability to conduct heat); thus, it was investigated in this paper. The thermal conductivity of untreated and geopolymer-treated clay was evaluated using a TSL-100 m equipped with a single needle probe of 2 mm diameter and 100 mm length complying with ASTMD5334-14 standards (Figure 3). At 28 days of curing, different specimens were tested for thermal conductivity by inserting the TSL probe and applying a sequence of heating/cooling within the specimen. For treated specimens with low geopolymer content, the specimens were soft enough to allow the insertion of the probe. For specimens with high geopolymer content, the use of a drill was necessary. For all cases, care was taken to apply a layer of thermal grease to the TSL probe before the test to minimise any effects of contact resistance with the traded clay.

Figure 3. Thermal conductivity test.

Scanning electron microscopy (SEM) was employed before treatment to examine the soil fabric and after treatment to detect the changes caused by the binder. This was performed using fully PC-controlled MIRA3 XMU equipment at the John de Laeter Centre, Curtin University. It should be noted that the SEM study only allowed a small, localised area of the untreated and treated specimen to be examined (unlike engineering laboratory specimens). However, it was assumed to be representative of the reaction process of treated specimens [41].

3. Results and Discussions

3.1. Strength Performance

The effect of geopolymer addition on the strength enhancement of geopolymer-treated clay, as determined by UCS, was investigated as shown in Figure 4. The UCS behaviour of each mixture was considered for different geopolymer contents (i.e., 10%, 20% and 30%), activator-to-dry binder ratios (i.e., A/B = 0.5, 0.75 and 1.0) and two curing periods (i.e., 7 and 28 days). Generally speaking, UCS tests indicated that the addition of geopolymer considerably increased the yield (peak) stress of treated clay, showing a high dependency on geopolymer content. For samples treated with 10% geopolymer at a typical A/B ratio of 0.5 and curing time of 7 days (Figure 2a), an increase of 28 kPa in the peak UCS value compared to zero strength for untreated clay was observed. Further, an increase in geopolymer contents to 20% and 30% at the same A/B ratio and curing time resulted in total strength increases of 155 kPa and 378 kPa, respectively, compared with untreated clay. Such a dependence of UCS on geopolymer content was found to be similar to those reported in the geopolymer soil literature for surface mixing applications e.g., [13,35], which are mainly related to the formation of the N-A-S-H and C-A-S-H artificial cementitious products resulted from fly-ash and slag activation, and ultimately, the formation of a relatively solid structure. As the geopolymer content is increased, more artificial cementitious products are formed within the modified structure of treated clay; thus, the specimens showed a greater increase in UCS.

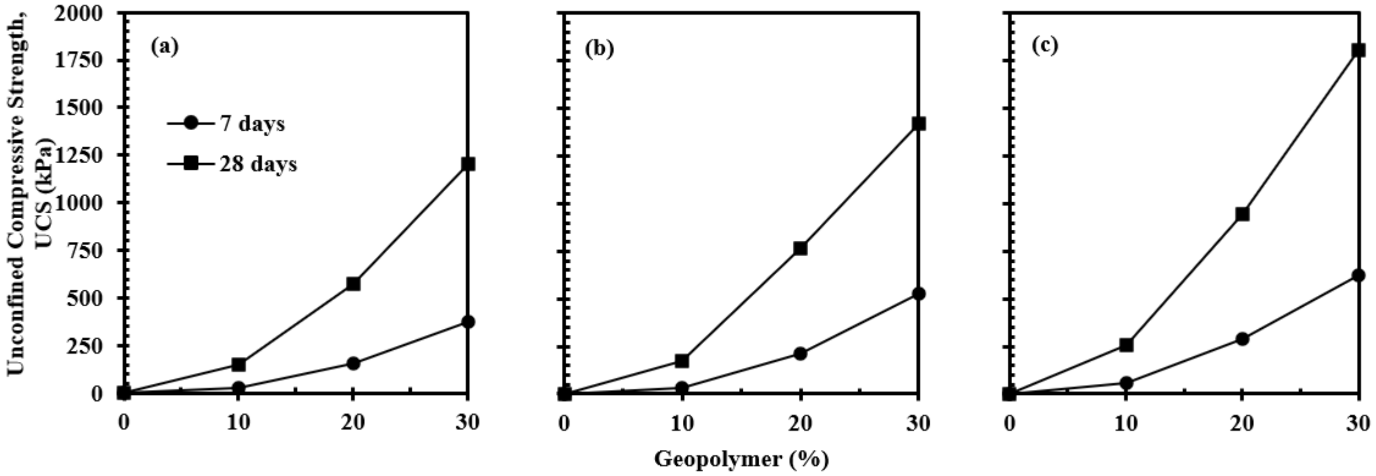


Figure 4. Effect of geopolymer content on peak strength of treated clay at 7 and 28 curing days for different activator-to-binder (A/B) ratios: (**a**) A/B = 0.5; (**b**) A/B = 0.75; and (**c**) A/B = 1.0.

The results presented in Figure 4 also indicate that the curing time is a key factor in the enhanced strength response of geopolymer-treated clay. For mixtures with an A/B ratio of 0.5 (Figure 4a), increasing the curing time from 7 to 28 days further increases the UCS values for 10%, 20% and 30% geopolymer contents from 28, 155 and 378 kPa to 152, 574 and 1250 kPa, respectively. The progressive development of artificial cementitious products with the increase in curing time may justify the obtained increases in the UCS peak values, as explained by many researchers [14,17,18]. The influence of curing time on the strength performance of treated clay was persistent over the selected geopolymer content range and A/B different ratios, as depicted in Figure 4b,c with a maximum UCS value of 1800 kPa achieved for the mixture synthesised with 30% geopolymer content and A/B ratio of 1.0.

Although the ultimate achievable UCS increase is influenced by the geopolymer content and curing time, the enhanced strength can be affected principally by the activator content represented by the activator to dry binder ratio, A/B. To further investigate this point, Figure 5 is presented. As can be seen from Figure 5a, the increase in the A/B ratio from 0.5 to 1.0 for 7 days of curing time suggests an additional increase in strength response by 100%, 85% and 65% for 10%, 20% and 30% geopolymer contents, respectively. At 28 days of curing time (Figure 5b), these additional increases were 71%, 64% and 49% for 10%, 20% and 30% geopolymer contents, respectively. As explained by Phummiphan et al. [14], this can be attributed to the increase in leaching of the silica and alumina of the aluminosilicate material (i.e., fly-ash and GGBFS) due to the increase in alkalinity, which in turn increases the formation of cementitious products, i.e., N-A-S-H and C-A-S-H between the clay particles, thereby strengthening the soil. To highlight the correlation between the A/B ratio and pH of treated clay, Figure 6 is shown. Generally speaking, the addition of an activator increases the pH value of treated clay considerably. For 10% geopolymer content and A/B ratio = 0.5, the pH value increased from 7.2 (untreated clay) to 11.75. A further increase in A/B ratio up to 0.75 and 1.0 caused further increases in the pH value to 11.99 and 12.12, respectively. For 20% and 30% geopolymer contents, the range of increasing pH was 11.97–12.37 and 12.18–12.48, respectively.

Figure 7 shows the initial stiffness for each treated specimen at 28 days of curing time; the initial stiffness is represented quantitatively as the secant modulus of elasticity, E_{50}, for each specimen. In general, treated specimens with 30% geopolymer content exhibited the highest stiffness, with this trend being persistent over the selected range of A/B ratios. Specimens treated with 10% and 20% geopolymer contents also exhibited progressive stiffness increases for all A/B ratios, yet to a lesser extent than 30% geopolymer content. This observation was further supported by examining the failure modes of treated specimens (Figure 8). The difference in the initial stiffness between the different geopolymer-treated specimens may relate to the interactions between associated contents and differences in alkalinity (pH value). These factors seem to influence the geopolymerisation process and characteristics of bonded clusters that formed along the shear plane.

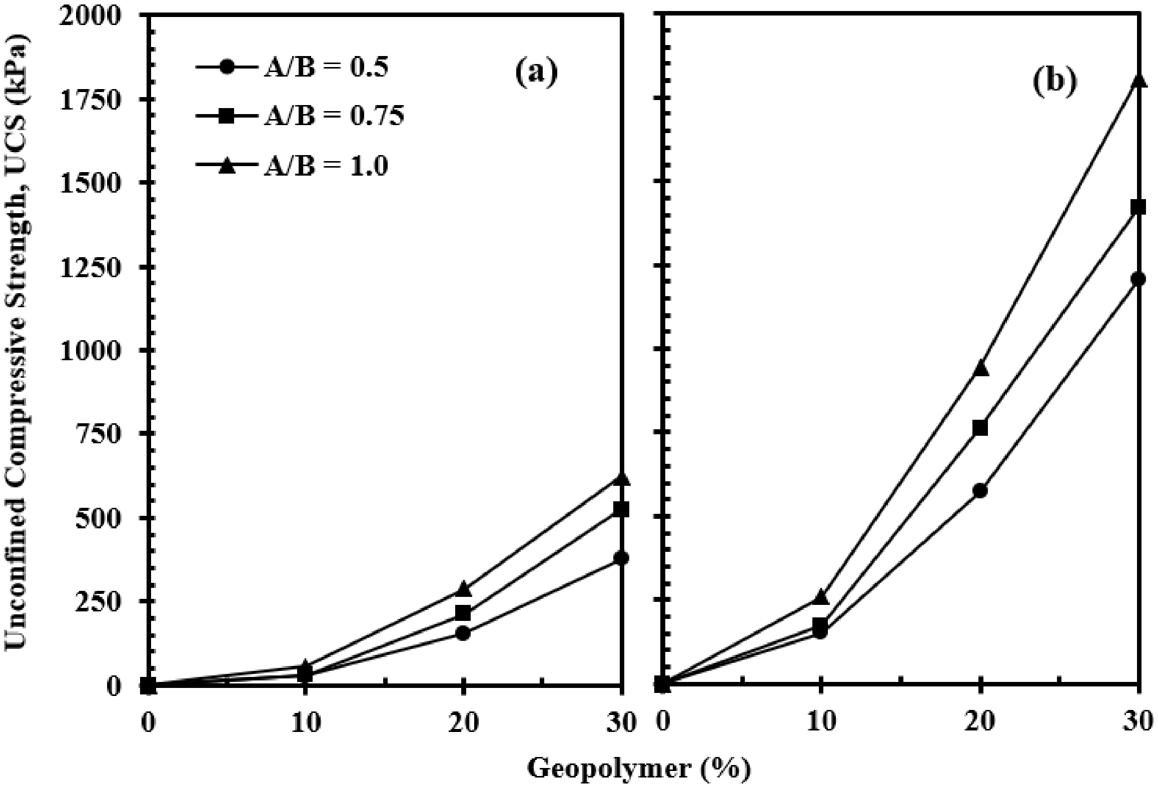


Figure 5. Effect of activator to binder ratio (A/B) on peak strength of clay at different curing periods: (**a**) 7 days and (**b**) 28 days.

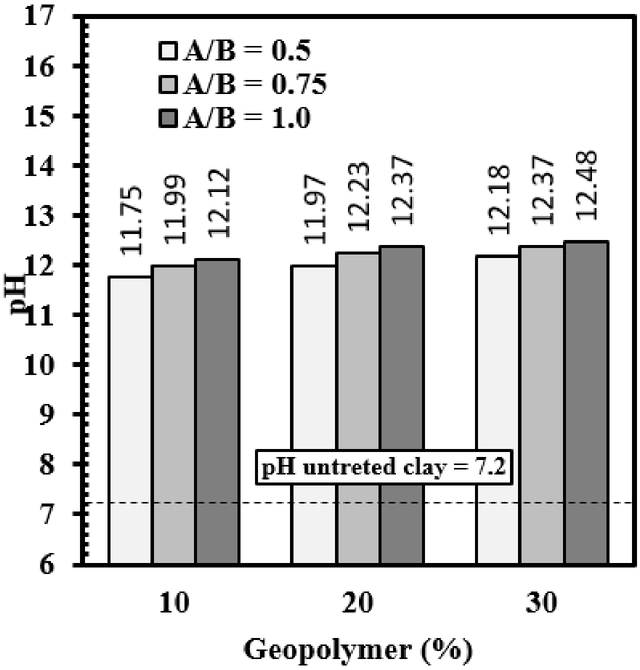


Figure 6. pH performance of clay treated with different geopolymer contents and various activator to binder (A/B) ratios.

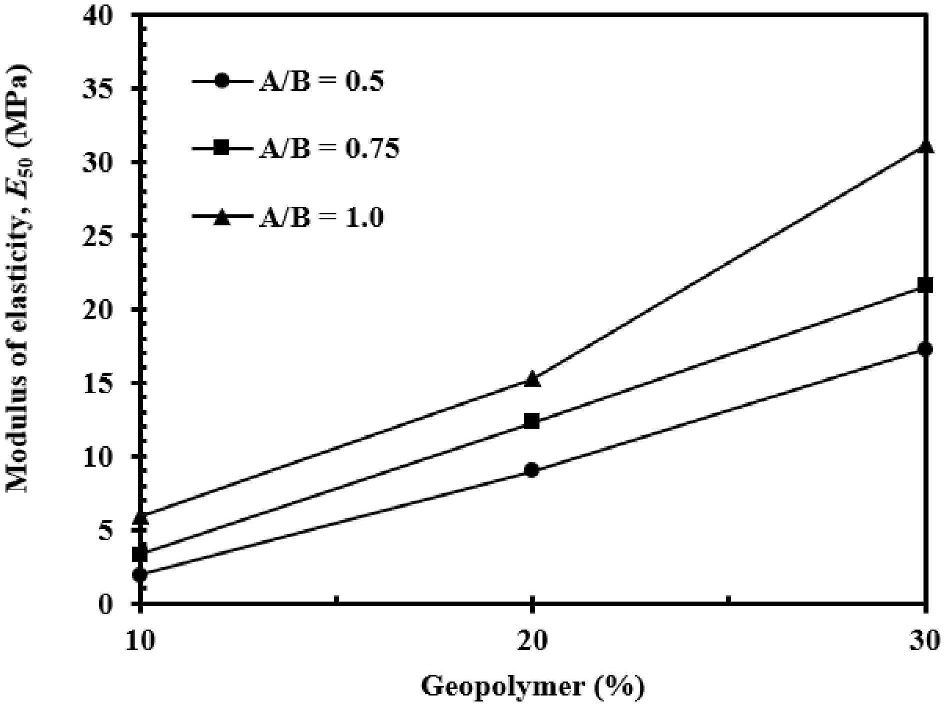


Figure 7. Effects of geopolymer content and A/B ratios on the modulus of elasticity (E_{50}) for kaolin clay at 28 days of curing time.

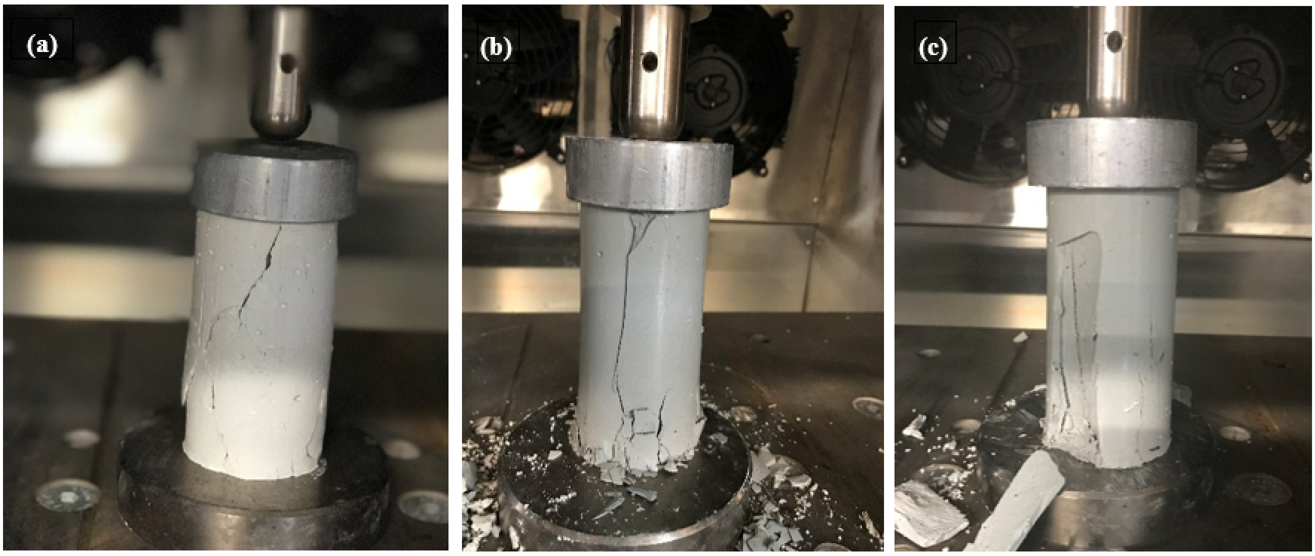


Figure 8. Typical influence of geopolymer addition on UCS failure mode of treated clay: (**a**) 10% geopolymer; (**b**) 20% geopolymer; and (**c**) 30% geopolymer.

Three mixtures investigated in the current study containing 30% geopolymer content and activator-to-binder ratios of 0.5, 0.75 and 1.0 were found to give a strength range between 1200 and 1800 kPa in a typical curing period of 28 days. The strength performance of these three mixtures may fulfil the minimum requirements of most DSM applications, i.e., 1000 kPa [42], and thus are compared with the strength performance of traditional OPC-treated soil at 28 days. Figure 9 shows the results of such a comparison in terms of the stress–strain relationship. Both the geopolymer- and OPC-treated clay mixtures show similar qualitative strength responses (i.e., brittle stress–strain behaviour) in the 28-day curing period. However, the quantitative differences in their response (i.e., values of peak strength and stiffness) were detected within the treated clay. Generally, 30% OPC mixtures showed superior peak strength improvement over soil treated with geopolymer; treated clay with 30% geopolymer content and A/B = 1.0 was only equivalent to that of 20% OPC content with an approximate UCS of 1800 kPa. Such quantitative differences may be attributed to the differences in the rate of geopolymerisation in the geopolymer-treated clay compared to the hydration reaction in the OPC-treated clay. In other words, the rate of formation of cementitious products in the fly-ash-based, geopolymer-treated clay incorporating GGBFS was lower than that of the OPC-treated clay for the same binder percentage.

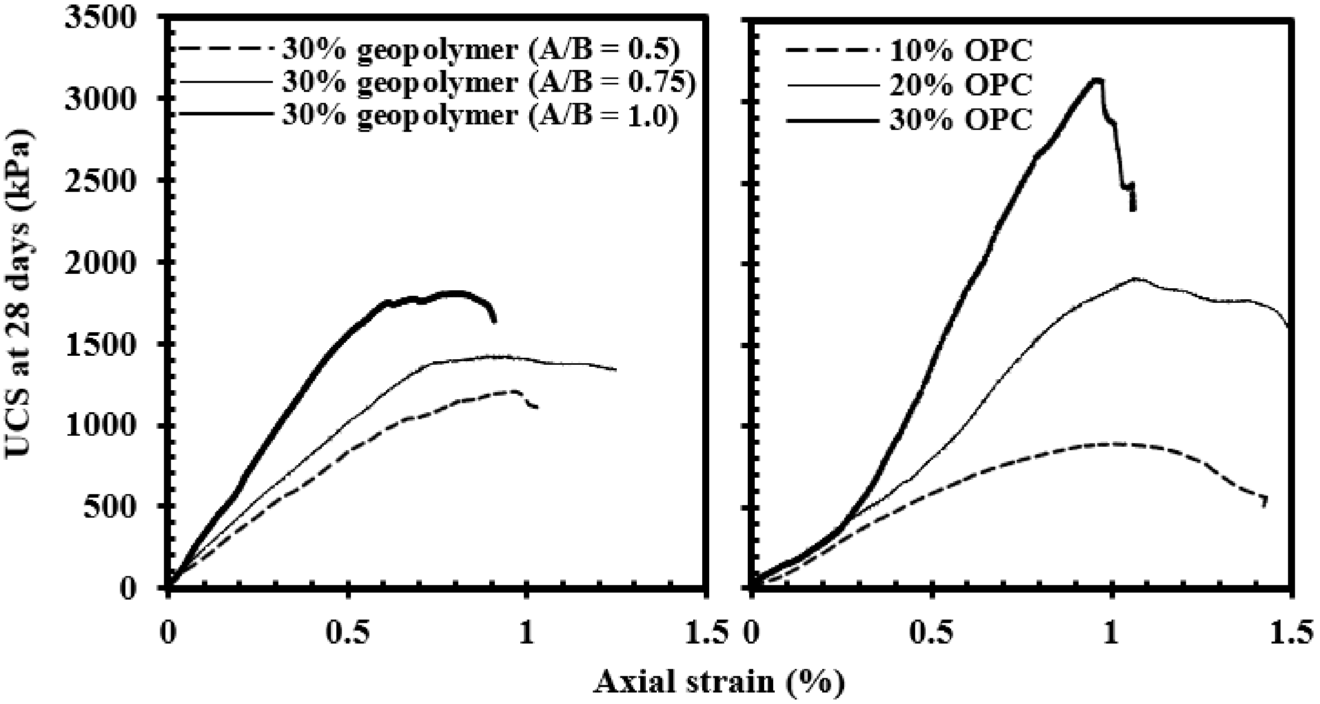


Figure 9. Typical stress–strain curves of geopolymer-stabilised clay and OPC-treated clay.

3.2. Durability Performance

The effect of geopolymer addition on the durability performance of geopolymer-treated clay, as determined by the wetting–drying cycle test, was investigated in simulated weathering conditions (i.e., wetting–drying). Clay was treated with 10%, 20% and 30% geopolymer contents and different activator-to-binder (A/B) ratios and then cured for 28 days. After curing, various mixtures were tested in successive wetting–drying cycles; successfully treated samples were generally characterised by attaining the 12 wetting–drying cycles and volume changes <10% [39] with some residual strength.

Figure 10 shows a pictorial representation of different treated specimens undergoing wetting–drying durability cycles. It can be seen that at least 30% geopolymer content was necessary for the treated clay to attain the targeted 12 durability cycles (Figure 10c). The durability performance of this mixture can be attributed to the sufficient formation of the stabilised matrix around the soil particles after hardening, which resists the stresses generated during the successive wetting–drying cycles. For the lower geopolymer contents (i.e., 10% and 20%), the level of treatment is shown to be inadequate with premature failure at earlier cycles in Figure 10a,b. It is noteworthy that for 10% and 20% geopolymer contents, the increased A/B ratio increased the number of cycles attained before failure; this confirms the impact of alkalinity on the treatment effectiveness of the clay specimens.

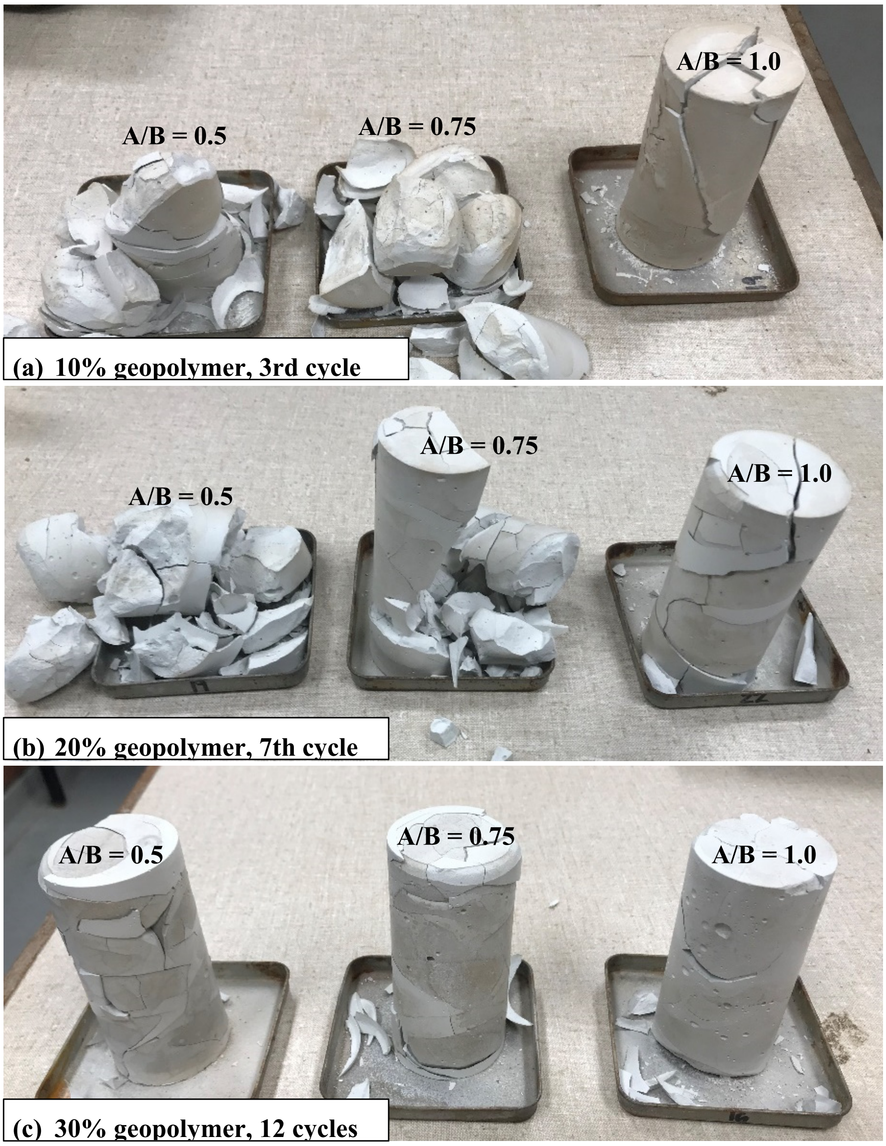


Figure 10. Wetting–drying durability performance of different geopolymer-treated clay mixtures: (**a**) 10% geopolymer; (**b**) 20% geopolymer; and (**c**) 30% geopolymer.

In terms of volumetric changes, the 30% geopolymer surviving samples showed variable performance throughout the 12 wetting–drying durability cycles controlled mainly by the amount of alkalinity (A/B ratio). For the A/B ratio = 0.5, the overall volumetric change value after 12 cycles was 8.3%. Further increases in the A/B ratio to 0.75 and 1.0 caused suppression in volumetric change to 6.7% and 4.1%, respectively. The detected range of volumetric change (i.e., 4.1% to 8.3%) was lower than the 10% volumetric stability threshold, as mentioned by Pedarla et al. [39]. However, such a successful performance was adversely identified with significant surface cracks and material loss due to exfoliation (Figure 10). The degradation in the structure of the specimens coincided with a reduction in the residual strength down to 30%, 41% and 55% for A/B = 0.5, 0.75 and 1.0, respectively, compared to the strength at cycle zero.

3.3. Thermal Conductivity Performance

The results of the thermal conductivity performance, as indicated in Figure 11, were for the testing of different mixtures with various binder concentrations of 10%, 20% and 30%, and A/B ratios of 0.0, 0.5, 0.75 and 1.0. For untreated clay (i.e., 0% geopolymer content), the thermal conductivity (k) was approximately 1.438 W/(m·K). Such a value was found to be located between two orders of magnitude of 0.56 and 3.0 W/(m·K), representing *k* responses to water and pure mineral particles, respectively [43]. For 10% geopolymer content addition and an A/B ratio of 0.5, it can be seen that the thermal conductivity of geopolymer-treated clay increased slightly to 1.583 W/(m·K); this was a 10% total increase compared to that of untreated clay. With the increase in geopolymer content, the thermal conductivity was undergoing a reduction trend; however, the values were still higher than untreated clay by 6.8% and 5.9% at 20% and 30% geopolymer content, respectively. Such an increasing–decreasing trend for the thermal conductivity of treated clay with the increase in geopolymer content was persistent for all A/B ratios but with prominent reduction at high ratios; for 30% geopolymer contents at A/B = 1.0, for instance, the thermal conductivity was 91.3% of that of untreated clay. The initial increase in thermal conductivity at 10% geopolymer content can be attributed to the fact that fly-ash and slag within activated geopolymer possess higher thermal conductivity than kaolin clay minerals. At higher geopolymer contents (>10%), the amount of N-A-S-H product developed due to geopolymerisation within treated clay increased due to increased alkalinity and seemed to pose lower thermal conductivity than clay due to a possible increase in porosity. Consequently, the higher the amount of N-A-S-H product, the lower the thermal conductivity with lesser interior stresses generated within treated samples subjected to wetting–drying cycles. This would partially explain why 30% of geopolymer-treated samples had a higher wetting–drying response at a high A/B ratio of 1.0 than treated samples at a low A/B ratio of 0.5.

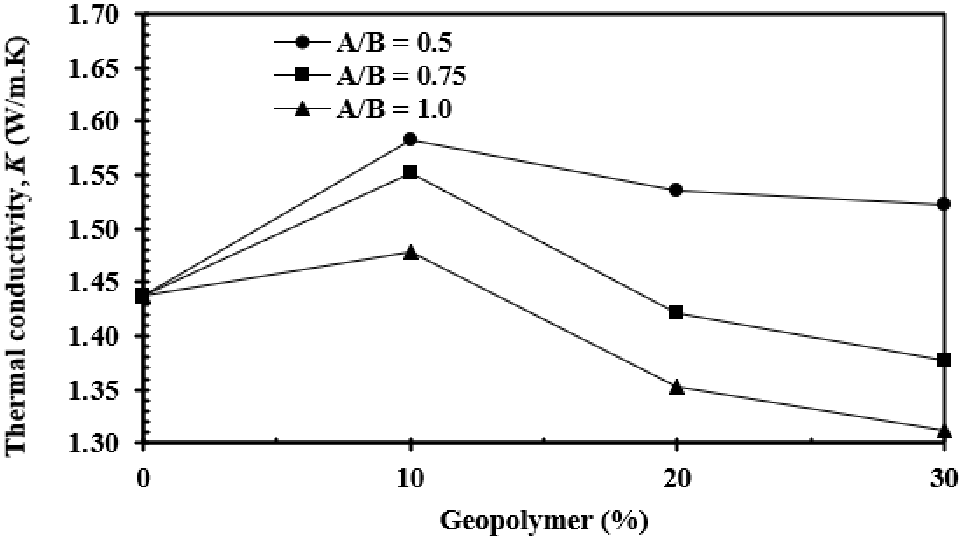


Figure 11. Typical variation of thermal conductivity versus pH at 10% geopolymer content and various A/B ratios.

3.4. Microstructure Characteristics

To further understand the mechanism of strength and durability improvement in geopolymer-treated clay, the microstructure fabric of untreated and geopolymer-treated clay was examined using scanning electron microscopy (SEM). Figure 12 shows the microstructure of untreated clay and clay treated with typical geopolymer content of 30% synthesised at an A/B ratio of 1.0 and cured for 28 days. The SEM image of the fracture surface of untreated kaolin clay, as shown in Figure 12a, clearly indicates the plate-like shape of the clay particles with a significant number of voids developed between soil particles. In comparison, the fragment surface of geopolymer-treated clay, as shown in Figure 12b, indicates a more homogeneous clay fabric. This is due to the formation of the N-A-S-H geopolymer gel that links the clay particles together in an enhanced structure. This is evident in Figure 12b, as a substance was captured on the smooth spherical surface of the partially reacted fly-ash particle as an indication of leaching the metals and the formation of cementitious product. It is speculated that the partially reacted fly-ash particle with cementitious products on its surface serves as a nucleation site that bonds clay plates into clusters. Such an enhancement in the clay fabric is believed to produce a higher strength clay structure evident from the results of the UCS and wetting–drying durability tests presented earlier, and this finding agrees well with those observed by other researchers in earlier geopolymer–soil studies [17,18,44]. However, Figure 12b shows the presence of microvoids within the formed geopolymer gel. Such microvoids are highly dependent on the concentration of alkaline content within the geopolymer mixture, as previously confirmed in the literature [45,46]. The increase in the microvoids due to the increase in the alkalinity of geopolymer-treated clay may explain the reduction in thermal conductivity with the increase in geopolymer content, as detected earlier in Figure 11.

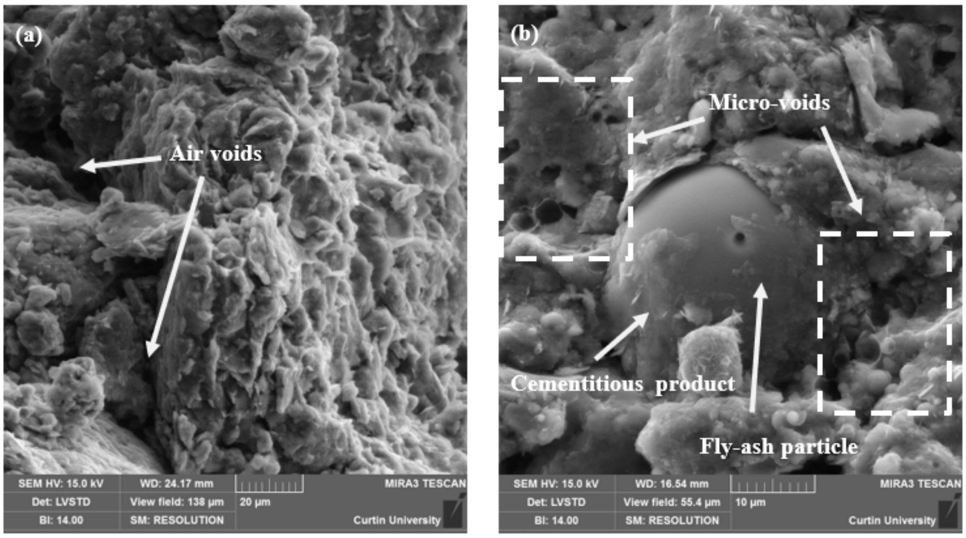


Figure 12. SEM of clay samples: (**a**) untreated clay; and (**b**) geopolymer-treated clay cured at 28 days.

4. Conclusions

The influence of geopolymer addition on the mechanical performance of treated clay for a deep soil mixing application was investigated through a series of laboratory tests. The addition of geopolymer showed great potential for upgrading the strength and durability of treated clay, with geopolymer content and curing time as the main determinant factors for enhancement. It was found that increasing geopolymer content generally increased compressive strength, and this impact became more prominent with the increase in curing time. It was also found that insufficient geopolymer content within treated clay may result in problems related to durability performance under wetting–drying conditions. Both strength and durability performance were also found to be highly driven by the amount of activator incorporated in the geopolymer mixture. For specific geopolymer content, a mixture with high activator content showed increased strength gain and durable performance compared to mixtures with low activator content. The improved durability performance with the increase in geopolymer content was related to the enhanced soil structure, due to the cementation development, and the overall reduction in thermal conductivity detected for geopolymer-treated clay. It was postulated that the role of increased porosity in the geopolymer product in increasing the overall microvoids within the mixture dominated the effect of cementation in linking clay particles and causing degradation in the thermal conductivity of treated clay.

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