

Comparative Study on the Enhancement of Soil Cement Strength Using Bentonite and Polyurethane Foam

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Abstract

The construction of buildings and infrastructure on soft ground, such as soft Bangkok clay, presents significant geotechnical challenges due to its high compressibility, high settlement potential, and low bearing capacity. Consequently, soil-cement stabilization is widely applied to improve the strength of soft ground. This study evaluated the effects of bentonite and polyurethane foam as additive admixtures to increase the strength of soil cement. The primary purpose was to investigate compressive strength. Moreover, Scanning Electron Microscopy (SEM) was employed to examine the microstructure, which supports the primary purpose. The control specimen consisted of 80% soil and 20% cement by dry weight of the total soil-cement mixture. Bentonite and polyurethane foam contents of 10%, 20%, and 30% by dry weight of the total soil-cement mixture were investigated and added as additive admixtures to the soil-cement mixture. The results showed that adding bentonite and polyurethane foam can increase the strength of soil cement. The suitable ratios of bentonite and polyurethane foam were 30% and 10% by dry weight of the total soil-cement mixture, respectively. Moreover, both bentonite and polyurethane foam can increase compressive strength. This approach offers a pathway to more efficient, sustainable soil-cement stabilization methods to improve soft soils.

Keywords: Bentonite, Ground improvement, Polyurethane foam, Soil cement, Soil stabilization.

1. Introduction

Building structures and infrastructure on soft ground, such as soft Bangkok clay, is challenging due to unstable ground conditions. Soft ground conditions often lead to long-term settlement and instability, posing serious construction challenges. Soft clay is highly compressible with a low bearing capacity. Applying a soil-cement mixture to improve soft soil is an effective ground improvement technique widely practiced in construction [1]. Soil cement is produced by blending soil with cement and water to enhance the ground's strength and stability for construction purposes. However, soil cement typically exhibits limitations, such as brittleness, shrinkage, and high density, which can reduce its effectiveness in improving soft soils, especially when a high cement content is used.

Therefore, many studies have explored ways to enhance the performance of soil-cement, emphasizing the use of alternative materials and admixtures that improve its flexibility and suitability for soft soil conditions, such as slag [2], fly ash [3–4], and asphalt waste dust [5–6]. Among these efforts, bentonite has also attracted attention for its ability to enhance both strength and water resistance. Devapriya et al. [7] reported that mixing an optimal amount of Na-bentonite into locally sourced Indian red soil at its optimum moisture content significantly reduced hydraulic conductivity, which is an essential property

for base layers that require seepage control. The best results were obtained with a mixture containing about 10–5% bentonite by dry weight of soil cement, which effectively reduced water flow and increased compressive strength while maintaining structural stability [7–8].

Moreover, various polymer materials have been investigated for ground improvement due to their ability to enhance the compressive strength of soft soils while remaining lightweight and flexible. Previous studies have reported the use of polymers, such as polyethylene glycol (PEG), polyvinyl alcohol (PVA), and polyvinylpyrrolidone (PVP) in cement-stabilized Bangkok clay [9]. Yong et al. [10] investigated the use of polyurethane (PU) columns as an alternative to cement piles for strengthening marine clay. The PU resin was injected and mixed directly with the natural marine clay, enabling the formation of PU columns without cement.

Although bentonite and polymer materials have been studied for soil improvement, most previous research has examined each admixture separately under different testing conditions. However, only a limited number of studies, such as that of Rattanapituk et al. [11], have directly compared the mechanical performance of bentonite and PU foam as replacement materials in soil-cement systems for soft Bangkok clay. Moreover, bentonite studies primarily focused on permeability control and liner applications [7–8],

whereas polyurethane research focused on lightweight fills and column reinforcement without soil-cement integration [10].

Moreover, there is limited research investigating these admixtures under identical experimental conditions. The novelty of this study lies in the direct comparison of bentonite and PU foam as additives in soil-cement mixtures under identical material proportions, mixing procedures, and curing conditions. This study evaluates their performance within the same experimental framework to address this knowledge gap, enabling a clear assessment of their individual effects on compressive strengths, specimen weight, density, and microstructural development. This approach allows the relative influences of both admixtures on compressive strengths and density to be assessed. Furthermore, the study integrates Scanning Electron Microscopy (SEM) to explicitly relate microstructural modifications to observed mechanical behaviour, thereby clarifying the distinct reinforcement mechanisms associated with each admixture. To address this gap, this study systematically compares the mechanical and microstructural performance of bentonite and polyurethane foam admixtures in soil cement for soft clay under identical cement content, mixing procedures, and curing conditions.

2. Materials and Methods

2.1 Soft clay

The soil used in this study was soft clay collected from Samut Prakan Province, Thailand, and was considered representative of Soft Bangkok Clay (SBC) from one location. The SBC specimen was obtained from the Rural Road No. SP.4002 Construction Project (junction with Highway 3344-Ban Bang Phli Yai) in Bang Phli District, Samut Prakan Province, Thailand. The SBC specimen was collected on 30 August 2024 at approximately 10 m depth below ground surface in a disturbed condition and stored in tightly sealed plastic containers, as shown in **Figure 1**. The shell fragments and other materials were eliminated from the SBC specimen before testing. The basic properties of the SBC specimen were determined in accordance with ASTM standards.

According to the Atterberg limits test (ASTM D4318-93 [12]), the liquid limit (LL) and plastic limit (PL) were determined to be 56.86% and 39.53%, respectively, with a plasticity index (PI) of 17.33%. The natural water content (ASTM D2216-98 [13]) of the specimen was 70.53%. The wet and dry unit weights (ASTM D4718-87 [14]) were found to be 16.29 kN/m³ and 10.01 kN/m³, respectively, while the specific gravity (ASTM D854-00 [15]) was determined as 2.65. The soil was classified as MH (elastic silt) based on its Atterberg limits and particle characteristics (ASTM D7928-17 [16], ASTM D6913-17 [17]).



(a)



(b)

Figure 1 Specimen of (a) Soft Bangkok Clay (SBC) specimen, (b) soil specimens stored in tightly sealed plastic containers

2.2 Hydraulic Cement

The cement used in this study was a type of hydraulic cement (**Figure 2(a)**), manufactured in accordance with Thai Industrial Standard (TIS) 2594 [18], as issued by the Ministry of Industry and referenced in ASTM C1157 (USA) [19]. This standard emphasizes performance-based specifications rather than prescriptive (chemistry-based) requirements.

In this study, the cement content was fixed at 20% by dry weight of the total soil-cement mixture (%wt) [20]. This aligns with general practice, which suggests that the typical cement content for soil-cement stabilization ranges from 10%wt to 20%wt. The cement content was fixed to isolate and directly compare the effects of bentonite and polyurethane foam under identical experimental conditions. A single cement content was selected to maintain consistent testing conditions and enable a systematic comparison between the two admixtures.

Moreover, cement was taken directly from its packaging without any filtering or sieving, and its properties complied with the SCG Cement-Building Materials standard requirements [21].

2.3 Bentonite

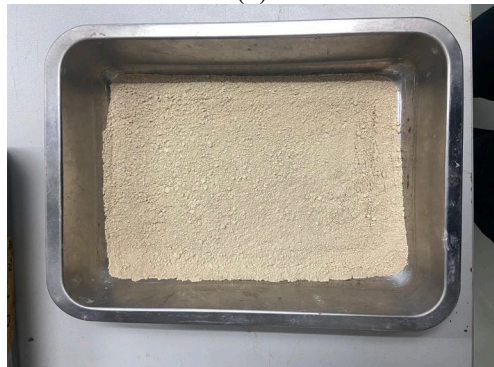
The bentonite used in this study was calcium-type bentonite (Ca-bentonite) in powder form (**Figure 2(b)**). This material was purchased from Krungthepchemi Co., Ltd., a supplier in Thailand. Physical and chemical properties [22] were provided by the supplier as follows:

1) Physical properties of Ca-bentonite

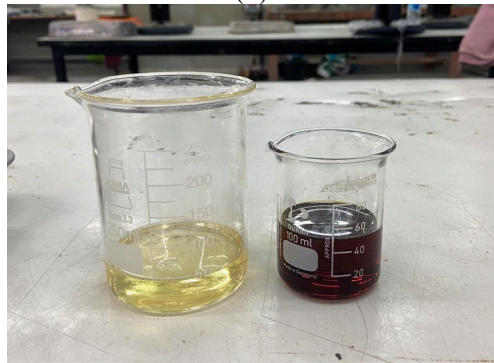
The physical properties of the Ca-bentonite include an apparent viscosity of 1.5, a Methylene Blue value of ≥ 30 g/100 g, and a colloid value of 48 ml / 15 g. The swelling value is ≥ 10 ml/g, with a pH range of 6.5–7.5. The moisture content is $\leq 10\%$, and the fineness (passing through a 200-mesh screen) is $\geq 95\%$.



(a)



(b)



(c)

Figure 2 Specimen of (a) Hydraulic cement, (b) Ca-Bentonite, and (c) Polyurethane foam (PU foam)

2) Chemical and Mineral composition of Ca-bentonite

The chemical composition of Ca-bentonite is characterized by the following oxide contents: SiO₂ (69.00–74.55%), Al₂O₃ (11.22–14.99%), and CaO (0.44–0.51%). Other components include MgO (2.53–2.70%), K₂O (1.62–1.96%), Na₂O (3.03–3.19%), Fe₂O₃ (2.50–2.70%), FeO (0.02–0.04%), MnO (0.00%), TiO₂ (0.11–0.15%), and P₂O₅ (0.05–0.08%). Meanwhile, the mineral composition comprises Quartz (SiO₂, PDF 03-0444) and

Montmorillonite (CaMg₂AlSi₄O₁₀(OH)₂·H₂O, PDF 02-0239 and Al₂O₃·4SiO₂·xH₂O, PDF 03-0016). The chemical and mineral analyses are in good agreement. The mineral characterization identified quartz and montmorillonite as the major mineral phases, while the chemical composition revealed high SiO₂ and Al₂O₃ contents characteristic of aluminosilicate clay minerals. The presence of CaO further supports the classification of the sample as calcium bentonite (Ca-bentonite).

2.4 Polyurethane foam

The polyurethane (PU) foam used in this study was closed-cell PU foam. It consists of two components: polyol and isocyanate (**Figure 2(c)**). Polyol serves as the expansion agent, while isocyanate serves as the bonding agent in the PU production process [23–24]. The mixing ratio of polyol to isocyanate is a key factor affecting the mechanical properties of PU. A higher polyol content tends to make the PU more brittle, while a higher isocyanate content increases strength but reduces expansion and final volume [24]. To achieve a good balance between strength and expansion, a 1:1 polyol-to-isocyanate mixing ratio is commonly recommended [23]. The water absorption of rigid cellular plastics was tested in accordance with ASTM D2842 [25] to determine the amount of water absorbed by the PU foam. The PU foam used in this study has a water absorption of 2.20 cm³, equivalent to 1.70% by volume.

3. Testing Conditions and Methods

3.1 Testing condition

A comparative study was conducted to investigate the strengthening of soil-cement using bentonite and PU foam solutions, with a focus on compressive strengths and SEM analysis. All testing specimens containing mixed cement were wrapped in plastic for 7 and 28 days of curing to allow hydration and strength development [26–27], respectively. The testing conditions (**Table 1**) were classified into three major conditions as follows:

- 1) To investigate the behaviour of raw materials, three conditions were studied as follows:
 - 1.1) 100% soil was designed and given a name code “S100”.
 - 1.2) 100% bentonite was designed and given a name code “B100”.
 - 1.3) 100% PU foam was designed and given a name code “PU100”.
- 2) To investigate the effect of binder-soil mixing, three experimental conditions were examined as follows:
 - 2.1) 80% soil mixed with 20% bentonite by dry weight of the total soil-cement mixture was designed and given a name code “S8B2”.
 - 2.2) 80% soil mixed with 20% PU foam by dry weight of the total soil-cement mixture was designed and given a name code “S8PU2”.
 - 2.3) 80% soil mixed with 20% cement by dry weight of the total soil-cement mixture

was designed and given a name code “S8C2”. Moreover, this condition was set as the control specimen.

- 3) To investigate the effects of binder addition (bentonite and PU foam) on soil-cement properties and to determine the optimal binder ratio, the 80% soil mixed with 20% cement by dry weight of the total soil-cement mixture was set as the soil-cement ratio. Moreover, the ratio of bentonite and PU foam varied at 10%, 20%, and 30% by dry weight of the total soil-cement mixture (%wt). Three experimental conditions were investigated as follows:

Adding bentonite content to soil cement

- 3.1) Bentonite of 10%wt mixed with soil cement was designed and given a name code “S8C2+B1”.

- 3.2) Bentonite of 20%wt mixed with soil cement was designed and given a name code “S8C2+B2”.

- 3.3) Bentonite of 30%wt mixed with soil cement was designed and given a name code “S8C2+B3”.

Adding PU foam content to soil cement

- 3.4) PU foam of 10%wt mixed with soil cement was designed and given a name code “S8C2+PU1”.

- 3.5) PU foam of 20%wt mixed with soil cement was designed and given a name code “S8C2+PU2”.

- 3.6) PU foam of 30%wt mixed with soil cement was designed and given a name code “S8C2+PU3”.

Table 1 Experimental conditions and ratios

Testing Conditions	Mixing Ratio			
	Soil (%wt)	Cement (%wt)	Bentonite (%wt)	PU foam (%wt)
Condition 1: To investigate the behaviour of raw materials				
S100	100	-	-	-
B100	-	-	100	-
PU100	-	-	-	100
Condition 2: To investigate the effect of binder-soil mixing				
S8B2	80	-	20	-
S8PU2	80	-	-	20
S8C2*	80	20	-	-
Condition 3: To investigate the effects of binder addition (bentonite and PU foam) on soil-cement properties and to determine the optimal binder ratio				
S8C2+B1	80	20	10	-
S8C2+B2	80	20	20	-
S8C2+B3	80	20	30	-
S8C2+PU1	80	20	-	10
S8C2+PU2	80	20	-	20
S8C2+PU3	80	20	-	30

3.2 Specimen Preparation

In this study, natural soil was prepared by removing shells, gravel, and other materials. To control the water content of test specimens, a portion of the soil was oven-dried to determine its natural water content. Water was then added until the soil reached twice its Liquid Limit (2LL).

A water content of 2LL was selected to provide sufficient workability and ensure homogeneity in the soil-cement mixtures. Preliminary observations indicated that mixtures prepared at lower water contents (<2LL) lacked sufficient moisture for uniform mixing, particularly in bentonite-containing mixtures due to bentonite's high-water absorption and swelling characteristics [7],[28]. Consequently, the mixtures became stiff and difficult to mix uniformly,

whereas higher water contents (>2LL) resulted in excessive fluidity and bleeding.

In addition, the 2LL water content represents a highly soft and water-saturated soil condition commonly encountered in problematic soft clay deposits and frequently adopted in laboratory stabilization studies. Although this moisture content is higher than typical field conditions, it was used to provide controlled and reproducible mixing conditions for a consistent comparative evaluation of bentonite and PU foam admixtures on soil-cement behaviour.

After achieving the target water content, the admixtures, bentonite and PU foam (1 polyol:1 isocyanate), were incorporated at the specified ratios shown in **Table 1**. For the PU foam mixture, the PU was initially prepared in a liquid state prior to expansion. The weight of the liquid PU foam was

calculated as a % by dry weight of the total soil-cement mixture (soil and cement).

The mixture proportions in this study were defined on a weight basis to maintain a consistent material-proportioning method for bentonite and PU foam admixtures. Although PU foam expands after mixing and may influence the internal volumetric distribution of the mixtures, all specimens were cast in identical molds under the same preparation and curing conditions, resulting in consistent specimen dimensions for mechanical testing. Therefore, the present study focused on comparing the mechanical behaviour of the mixtures under identical weight-based admixture conditions. The volumetric proportion of expanded PU foam may differ from its initial weight proportion, and further investigation into considering volumetric-based mixture design is recommended for future studies.

In the mixing process, all components were mixed by a mixer for 7 minutes to ensure a homogeneous mixture. To minimize variability, all specimen preparation and mixing procedures were conducted under controlled laboratory conditions at a room temperature of 30–35°C with relative humidity levels ranging from 70% to 85%, using identical mold dimensions, mixing duration, casting procedures, and curing conditions. The mixtures were cast immediately after mixing to reduce inconsistencies caused by premature hydration and PU foam expansion.

To maintain consistent initial density among specimens, the same total mass of material was placed into molds with identical dimensions using identical filling and compaction procedures for all specimens. This approach helped ensure uniform specimen density, quality, and confinement conditions during preparation and curing. In addition, five replicate specimens were prepared for each testing condition to ensure test reliability and reproducibility. The mixing details for each testing condition were as follows:

- 1) S8C2 (control specimen): the soil and water were first mixed for 4 min, then cement was added and mixed for 3 min.
- 2) S8C2+B1, S8C2+B2, S8C2+B3 (with bentonite): the soil and water were first mixed for 4 min. Then, cement was added and mixed for 1.5 min, followed by bentonite, and the mixture was mixed for an additional 1.5 min.
- 3) S8C2+PU1, S8C2+PU2, S8C2+PU3 (with PU foam solution): the soil and water were first mixed for 4 min. Cement was then added and mixed for 1.5 min, followed by isocyanate for 0.75 min, and finally polyol for an additional 0.75 min.

After mixing, the mixtures were immediately cast into cylindrical molds with a diameter of 5.50 cm and a height of 11.00 cm (volume $\approx 261.34 \text{ cm}^3$) for the compressive strength test. After 2 days of casting (starting from the mixing day), the mixing specimens

were demolded and then continuously cured with plastic wrap.

3.3 Compressive strength test

On days 7 and 28 of curing, the plastic wrapping was removed from the specimens. The specimen dimensions were measured, and the specimen weight was recorded before compressive strength testing was performed in accordance with ASTM D1633-17 [29].

The compressive testing machine was set to a displacement rate of 1 mm/min, with a load capacity of 10 kN, and continued until failure occurred (**Figure 3**). The applied load was recorded and used to calculate the compressive strength value. Laboratory specimen preparation and mechanical testing were carried out from September 2024 to August 2025 under controlled laboratory conditions. After the compressive strength tests, failed specimens from each formula were collected for Scanning Electron Microscopy (SEM) analysis to examine their microstructures after 28 days of curing, which supported the compressive strength results.



Figure 3 Testing specimen before the compressive strength test.

4. Results and Discussion

4.1 Specimens Weight and Density Change

The specimens, cast into cylindrical molds with a diameter of 5.50 cm and a height of 11.00 cm for the 28-day compressive strength test, were weighed and recorded as shown in **Table 2**. The control specimen (S8C2) at 28 days serves as a baseline for comparison with the other specimens; therefore, the weight and density of S8C2 were set as 0.00%.

From the data in **Table 2**, the changes in specimen weight and density are clearly different between bentonite and PU foam additions. For bentonite addition, the reductions in both weight and density are relatively small at low contents. Specifically, specimen S8C2+B1 (10%wt bentonite) shows decreases of 6.06% in weight and 5.66% in density. This behaviour can be explained by water loss during the curing process. During curing, cement hydration reactions in soil-cement continue to develop, and water is an essential component. Consequently, water

loss occurs, and free water not consumed by hydration is gradually removed from the system, leading to a reduction in specimen weight [30].

Table 2 Weight and density of compressive strength testing specimens at 28 days

Testing Conditions	Weight Change	Density Change
S8C2*	0.00%	0.00%
S8C2+B1	-6.06%	-5.66%
S8C2+B2	+0.37%	+2.78%
S8C2+B3	+2.23%	+0.69%
S8C2+PU1	-6.07%	-6.25%
S8C2+PU2	-8.89%	-9.03%
S8C2+PU3	-12.61%	-12.50%

Note: - is % Decreased, + is % Increased, S8C2*is control specimen

In contrast, when the bentonite content was increased to 20%wt and 30%wt (S8C2+B2 and S8C2+B3), the weights of S8C2+B2 and S8C2+B3 increased by 0.37% and 2.23%, respectively. This trend is consistent with increases in the density of S8C2+B2 and S8C2+B3 of 2.78% and 0.69%, respectively. These results indicate that bentonite helps maintain soil-cement stability in terms of weight and density by filling internal voids and retaining moisture within the matrix. Due to the small particle size and high specific surface area of bentonite, its particles can effectively fill the voids between soil grains and participate in cement hydration reactions, resulting in a more continuous and compact internal structure of the soil-cement. In addition, the water-absorbing capacity of bentonite helps regulate water movement within the system, as water adsorbed on the bentonite surface is gradually desorbed during the curing process. This mechanism reduces rapid water loss and limits drying shrinkage, resulting in relatively stable changes in the soil-cement's weight and density [31].

However, at the highest bentonite content (S8C2+B3), a reduction in density was observed compared with S8C2+B2. This can be explained by the swelling behaviour of bentonite, which is a clay mineral with a high swelling capacity. When water is absorbed, the particle volume increases significantly. In soil systems containing high bentonite contents, excessive water absorption causes initial swelling of the internal structure, and subsequent water loss at later stages leads to drying shrinkage. This repeated swelling-shrinkage process can create small voids within the matrix. Although the overall specimen weight may still increase due to water retention, the increase in internal voids reduces the material's bulk density. This mechanism indicates that, at the highest bentonite content, the soil-cement structure is increasingly influenced by the volumetric change behaviour of bentonite rather than by its void-filling role alone, leading to a decrease in density [28],[32].

At 20% bentonite, the increase in density may be associated with improved particle packing and void filling effects. In contrast, at 30% bentonite, the decrease in density could be related to increased water absorption and swelling behaviour caused by the higher proportion of fine particles and larger specific surface area of bentonite [33]. In addition, Ca-bentonite may contribute to pozzolanic interactions and microstructural changes in stabilized soil [34]. These interpretations are supported by observed trends and previous studies reported in the literature [33–34]. Further microstructural investigation may help confirm the proposed mechanisms.

In contrast, PU foam addition showed a marked weight reduction compared with the control specimen (S8C2). Specifically, specimens with PU foam contents of 10%wt, 20%wt, and 30%wt (S8C2+PU1, S8C2+PU2, and S8C2+PU3) showed weight reductions of 6.07%, 8.89%, and 12.61%, respectively. In addition, these specimens showed density reductions of 6.25%, 9.03%, and 12.50%, respectively.

The reductions in weight and density of the soil-cement specimens containing PU foam can be explained by the formation of a porous structure and microstructural changes within the material. Specifically, after PU foam is added to soil-cement, a rapid chemical reaction occurs following mixing, leading to the expansion of the PU foam. This expansion results in a volumetric increase several times the original volume. Such expansion not only increases the volume of entrapped air within the material but also facilitates the drainage and movement of water out of the matrix. Consequently, a flexible structure with many air voids forms, leading to a significant reduction in overall mass despite the addition of new material to the soil matrix. This type of structure can reduce the material's self-weight and modify the load-transfer mechanism from a rigid to a more energy-absorbing, deformable structure [10],[24]. Furthermore, the material's bulk density decreases with increasing air content in the porous structure. PU foam typically has a much lower density than the solid matrix. When such foam is distributed within the soil-cement matrix, the composite material's average density is markedly reduced, decreasing with increasing PU foam content [34–35].

4.2 Compressive Strength

Compressive strength is an important parameter that indicates the strength of cementitious materials [36]. The stress-strain curves obtained from the compressive strength test of all soil-cement mixtures at 7 days (**Figure 4**) and 28 days (**Figure 5**) are presented. Due to the increase in curing period from 7 to 28 days, the stress-strain curves tend to increase because the cement hydration process continues, resulting in a progressively stronger and denser internal structure over time [30],[37].

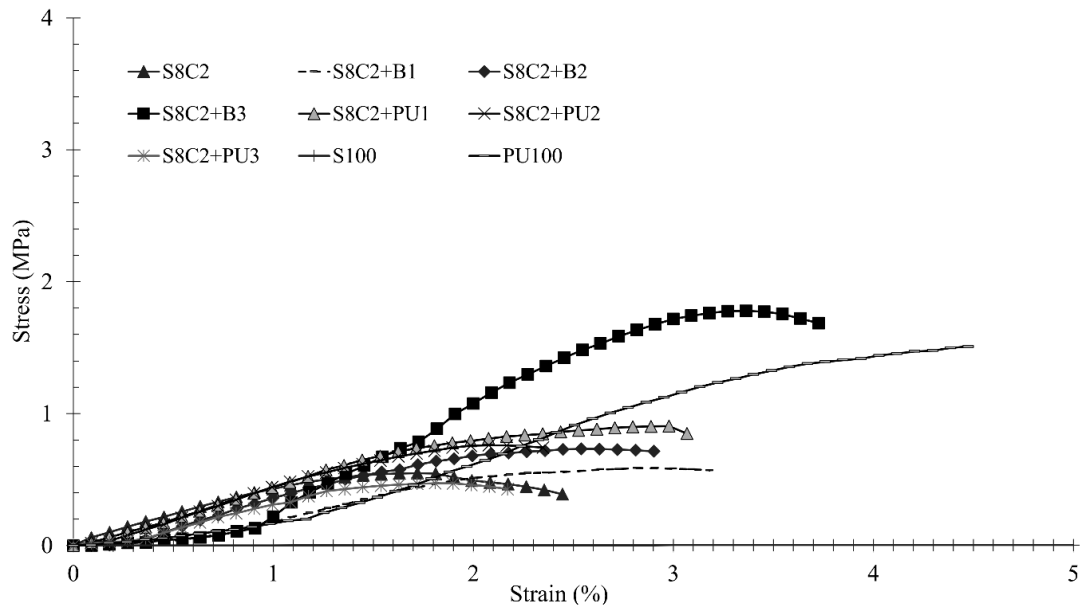


Figure 4 Stress-strain curves of soil-cement specimens at 7 days

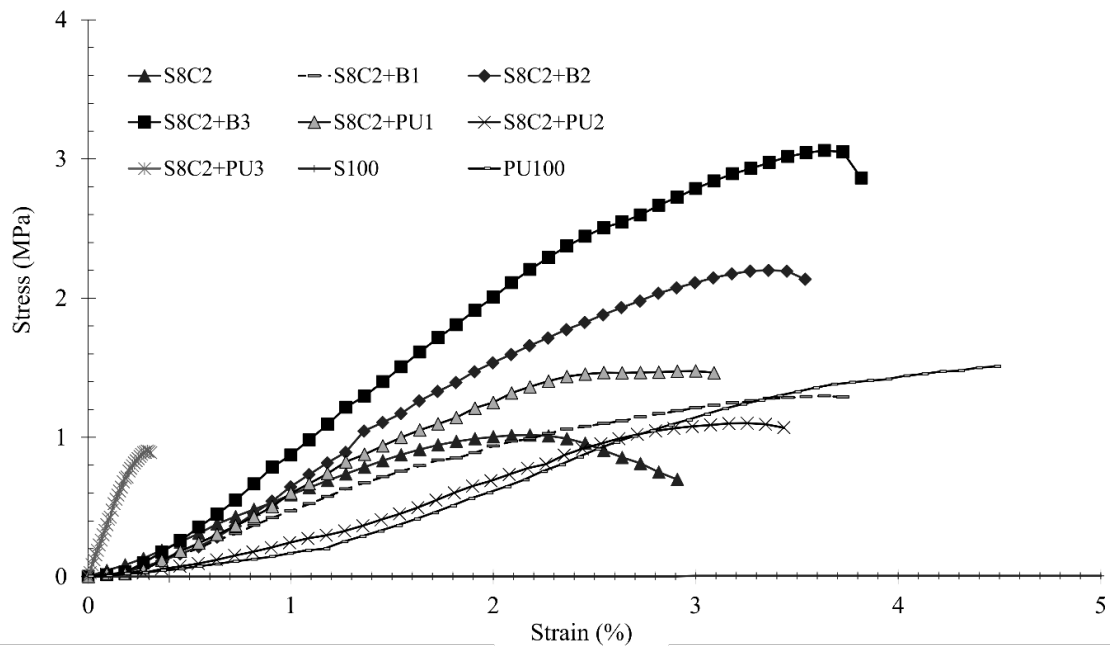


Figure 5 Stress-strain curves of soil-cement specimens at 28 days

When the behaviour of the bentonite addition is evaluated at the 2% strain level, commonly used as a reference for assessing soil-cement behaviour [38], it is evident that bentonite addition enhances material ductility. Therefore, the 2% strain level was used as the primary basis for strength comparison among mixtures, while the peak strength was used only to describe the post-yield and strain-hardening behaviour of the specimens.

At 2% axial strain, the compressive strengths of S8C2+B3 were 1.08 and 1.62 MPa at 7 and 28 days, respectively. However, the stress-strain response continued beyond the 2% strain level and exhibited strain-hardening behaviour, particularly at 28 days. The specimen reached a maximum compressive

strength of 2.78 MPa at approximately 3.8% strain before failure. This behaviour confirms that bentonite not only improves compressive strength but also enhances material toughness.

For the PU foam addition, evaluation at the 2% strain level [37] indicates a marked dependence of the mechanical behaviour on PU foam content. At 2% axial strain, the compressive strengths of S8C2+PU1 were 0.79 and 1.25 MPa at 7 and 28 days, respectively, while S8C2+PU2 showed values of 0.76 and 0.94 MPa. These specimens exhibited ductile behaviour, retaining load-bearing capacity beyond 2% strain, with deformation continuing to approximately 2.5–3.0%. This behaviour may be associated with the flexible polymeric structure of PU foam, which

contributes to improved deformability and energy absorption within the soil-cement matrix [8–9],[23].

However, when the PU foam content was increased to 30%wt (S8C2+PU3), the material exhibited brittle failure at a very low strain of approximately 0.2% and limited deformation capacity prior to 2% strain. Although PU foam exhibits high inherent flexibility [39], excessive PU foam content may cause the foaming effect and air-void formation to become dominant within the matrix. The formation of numerous large air voids severely disrupts structural continuity, reducing load-bearing capacity

and leading to premature failure under compressive loading. This behaviour is consistent with previous studies reporting the detrimental effects of excessive porosity on the mechanical stability of cementitious materials [10],[35],[40]. The compressive strength of raw materials was 0.01 MPa and 1.76 MPa for S100 and PU100, respectively. The B100 specimen could not be moulded; thus, no value was recorded. For all soil-cement mixtures, compressive strength consistently increased with curing time [37], with the 28-day strength exceeding the 7-day strength under all test conditions (Figure 6).

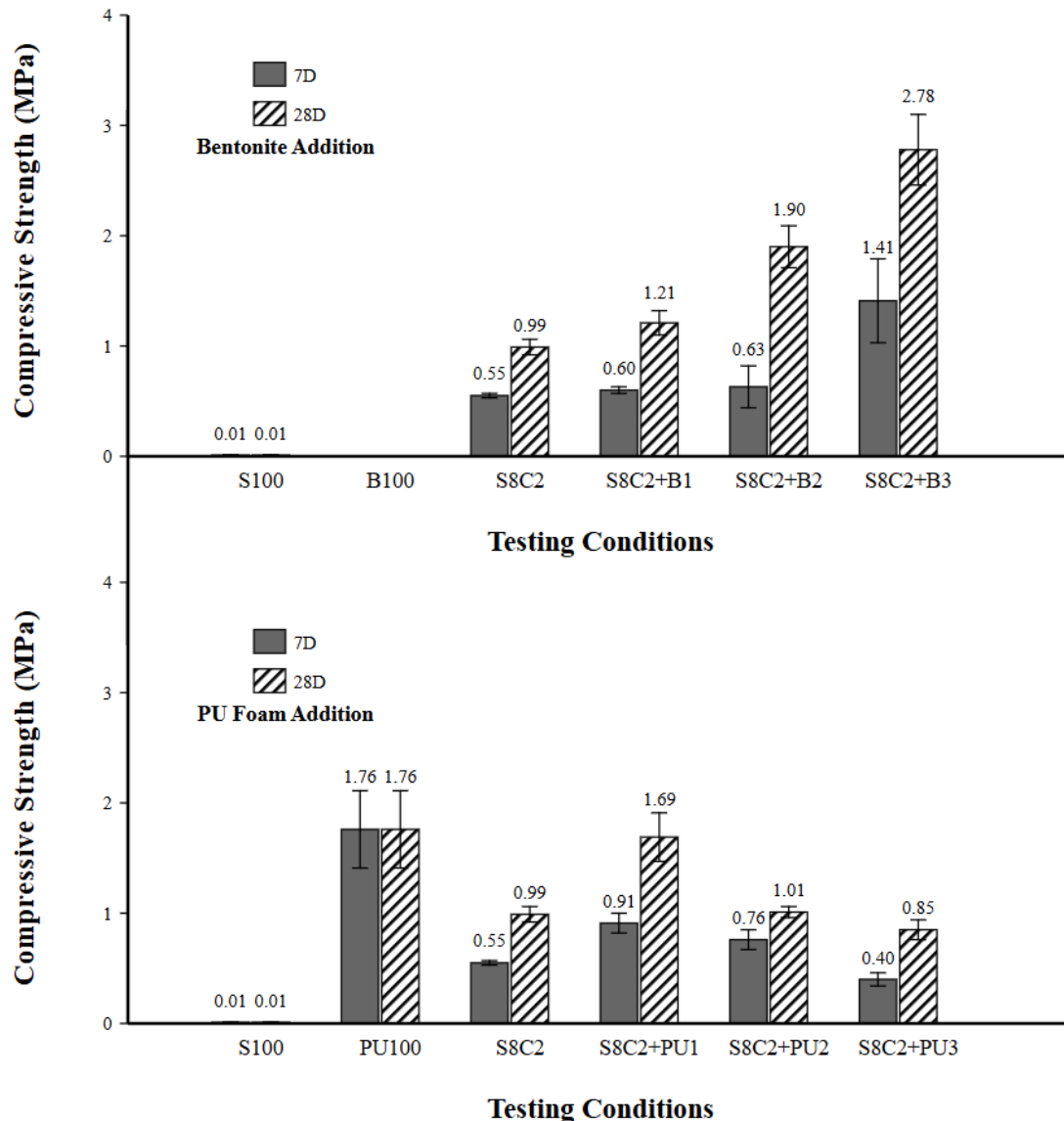


Figure 6 Compressive strength of the testing specimens at 7 and 28 days.

The addition of bentonite progressively increased the compressive strength of the soil-cement specimens as the bentonite content rose from 10%wt to 30%wt. At 28 days of curing, the compressive strengths were 0.99 MPa, 1.21 MPa, 1.90 MPa, and 2.78 MPa for S8C2 (Control), S8C2+B1, S8C2+B2, and S8C2+B3, respectively. The S8C2+B3 specimen, with a 30%wt

bentonite content, achieved the highest strength of 2.78 MPa, representing a significant 183% increase over the control specimen (0.99 MPa). This improvement demonstrates that bentonite is highly effective in enhancing compressive strength, with the strength gain directly proportional to the amount of bentonite added [7–8],[39],[41]. The improvement in

strength may be attributed to the filler effect of fine Ca-bentonite particles and their interaction with cement hydration products, which contributed to the formation of a denser and more compact soil–cement matrix [40]. XRF analysis revealed that the Ca-bentonite was predominantly composed of SiO_2 and Al_2O_3 , while XRD analysis confirmed the presence of montmorillonite and quartz phases. The high silica and alumina contents indicate the potential reactivity of the bentonite within the cementitious environment, which may enhance microstructural development through secondary hydration or pozzolanic-related interactions. However, since only 7- and 28-day curing periods were investigated, the long-term strength development associated with delayed pozzolanic reactions could not be fully evaluated.

Previous studies reported that Ca-bentonite may contribute to pozzolanic interactions and microstructural improvement in stabilized soil [34]. However, no direct mineralogical or thermal evidence, such as TGA, FTIR, or detailed post-treatment XRD analysis, was conducted in this study to conclusively verify the occurrence of pozzolanic reactions or the formation of secondary calcium silicate hydrate (C-S-H) phases. Therefore, the observed strength enhancement is primarily attributed to the physical filler effect of the fine bentonite particles, which reduced pore spaces and improved particle packing within the soil-cement matrix [41]. In addition, SEM observations revealed gel-like hydration products in both the control and bentonite-treated specimens, mainly associated with ordinary cement hydration. The identified quartz and montmorillonite minerals from mineral analysis, together with the silica-rich composition obtained from chemical analysis, further support the densification mechanism responsible for the improved strength and compact internal structure [41].

In contrast, the addition of PU foam showed an optimal mixing ratio for compressive strength [10]. The soil-cement specimens mixed with PU foam achieved their maximum compressive strength at a 10%wt PU foam content, reaching 1.69 MPa at 28 days of curing. However, further increases in PU foam content to 20%wt

and 30%wt led to a progressive decrease in compressive strength to 1.01 MPa and 0.85 MPa, respectively. This decline can be attributed to the porous structure of the PU foam, which creates numerous voids and air pockets that compromise the material's ability to withstand compressive loads [25],[35].

For the soil-cement-bentonite mixture, the strength increased with increasing bentonite content. In contrast, the strength of soil-cement with PU foam increased to a maximum at 10%wt PU foam content and decreased with further increases in PU foam content.

A two-factor ANOVA with replication was conducted to evaluate the effects of bentonite addition and curing period on compressive strength (**Table 3**). The testing conditions (sample) had a significant effect ($F = 192.53$, $P\text{-value} < 0.001$), indicating that the addition of cement and bentonite significantly improved the performance compared with S100 (untreated soil). The curing period (columns) also showed a significant effect ($F = 226.75$, $P\text{-value} < 0.001$), with higher values observed at 28 days than at 7 days. In addition, a significant interaction between testing conditions and curing period was observed ($F = 27.57$, $P\text{-value} < 0.001$), suggesting that the influence of curing time depended on the soil mixture composition. Among all mixtures, the specimen containing 30% bentonite (S8C2+B3) exhibited the highest average values at both curing periods.

Moreover, the two-factor ANOVA was also used to analyze the effects of PU foam addition and curing period on compressive strength (**Table 4**). The results showed that both testing conditions and curing period significantly affected the compressive strength ($P\text{-value} < 0.001$). A significant interaction effect was also observed, indicating that the influence of curing time varied with mixture composition. The S8C2+PU1 mixture had the highest average compressive strength among the soil-cement-PU foam mixtures, whereas increasing the PU foam content beyond 10% reduced compressive strength. In general, the 28-day curing period produced higher values than the 7-day curing period.

Table 3 ANOVA analysis for bentonite addition

SUMMARY	7 days	28 days
<i>S100</i>		
Average	0.01	0.01
Variance	5.97E-08	5.97E-08
<i>S8C2</i>		
Average	0.55	0.99
Variance	0.0002	0.0051
<i>S8C2+B1</i>		
Average	0.6	1.21
Variance	0.0008	0.0118
<i>S8C2+B2</i>		
Average	0.63	1.9

Table 3 ANOVA analysis for bentonite addition (cont.)

SUMMARY	7 days	28 days				
Variance	0.0049	0.0376				
<i>S8C2+B3</i>						
Average	1.41	2.78				
Variance	0.1412	0.1001				
ANOVA						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Sample	23.24	4	5.81	192.53	1.48E-25	2.61
Columns	6.84	1	6.84	226.75	4.47E-18	4.08
Interaction	3.33	4	0.83	27.57	5.00E-11	2.61
Within	1.21	40	0.03			
Total	34.62	49				

Table 4 ANOVA analysis for PU foam addition

SUMMARY	7 days	28 days				
<i>S100</i>						
Average	0.01	0.01				
Variance	5.97E-08	5.97E-08				
<i>PU100</i>						
Average	1.76	1.76				
Variance	0.1209	0.1209				
<i>S8C2</i>						
Average	0.55	0.99				
Variance	0.0002	0.0051				
<i>S8C2+PU1</i>						
Average	0.91	1.69				
Variance	0.0070	0.0479				
<i>S8C2+PU2</i>						
Average	0.76	1.01				
Variance	0.0069	0.0029				
<i>S8C2+PU3</i>						
Average	0.4	0.85				
Variance	0.0039	0.0082				
ANOVA						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Sample	17.86	5	3.57	132.36	7.22E-27	2.41
Columns	1.54	1	1.54	57.05	1.05E-09	4.04
Interaction	1.12	5	0.22	8.30	1.04E-05	2.41
Within	1.30	48	0.03			
Total	21.81	59				

4.3 Microstructure Analysis

Scanning electron microscopy (SEM) was employed to visualize microstructural changes induced by the admixtures. The SEM was used to support the evaluation of material strength. The SEM images of the S8C2+B3 (**Figure 7(b)**) show a denser and more homogeneous microstructure compared with the control S8C2 (**Figure 7(a)**). Bentonite particles fill the interstitial spaces among the cementitious constituents, and the increased presence of C-S-H contributes to higher strength and stability of the improved soil-cement matrix [28],[30]. This morphological evidence

explains the finding that bentonite enhances compressive strengths by improving structural integrity and reducing internal defects [7–8], [38–39]. Conversely, SEM images of soil-cement specimens mixed with PU foam, S8C2+PU1 (**Figure 7(c)**) and S8C2+PU3 (**Figure 7(d)**), reveal a highly porous microstructure with large voids generated by the PU foam. These voids are the primary cause of the observed reductions in weight and density [35][36]. Such microstructural discontinuities (pores or voids) explain the decline in compressive strength as PU foam content increases [35],[40].

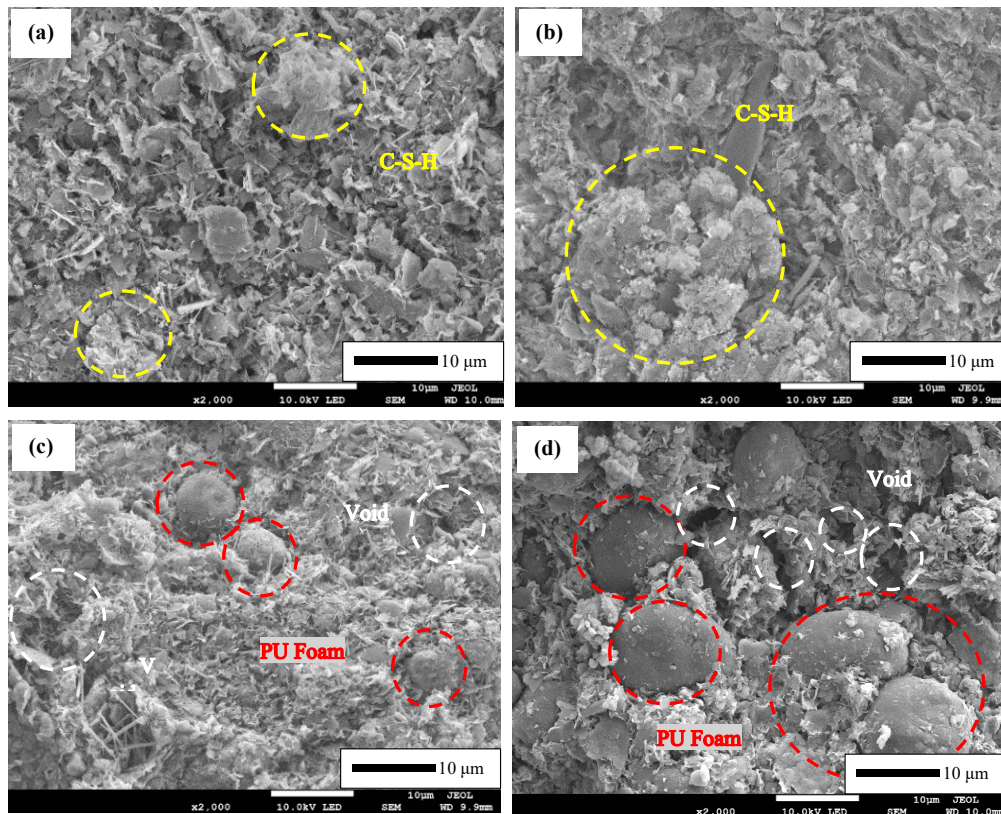


Figure 7 Microstructure of (a) S8C2, (b) S8C2+B3, (c) S8C2+PU1, and (d) S8C2+PU3 at 28 days

Quantitative chemical analysis using Energy Dispersive Spectroscopy (EDS) of the soil-cement specimen mixed with 30%wt bentonite (S8C2+B3) (**Figure 8**) and the soil-cement specimen mixed with 10%wt PU foam (S8C2+PU1) (**Figure 9**) primarily consist of Carbon (C), Oxygen (O), Aluminum (Al), Silicon (Si), Calcium (Ca), and Iron (Fe). However, the relative proportions of these elements differ significantly depending on the type of stabilizing admixture used.

The addition of bentonite 30%wt (S8C2+B3) showed relatively high levels of silicon, aluminum, and calcium, consistent with the aluminosilicate mineralogy of bentonite [28],[41]. In contrast, the addition of PU foam 10%wt (S8C2+PU1) showed a markedly higher carbon content, which is attributed to the polymer chain structure of PU foam [40]. Specifically, EDS analysis indicated that the S8C2+B3 specimen (**Figure 8**) contained only 9.63%wt carbon, whereas the S8C2+PU1 specimen (**Figure 9**) contained as much as 25.93%wt carbon. Meanwhile, the S8C2+B3 specimen showed aluminum (Al) and silicon (Si) contents of 6.57%wt and 17.25%wt, respectively, which are higher than the corresponding values of 5.16%wt Al and 12.02%wt Si observed in the S8C2+PU1 specimen. These differences highlight the role of bentonite as a supplementary source of reactive elements that promote the formation of hydration products in cement.

In terms of mechanical performance, the S8C2+B3 specimen (**Figure 6**) achieved a maximum compressive strength of 2.78 MPa, more than twice that of the control specimen (S8C2), which had a compressive strength of 0.99 MPa. This result is consistent with the SEM image

in **Figure 8(b)**, which reveals a denser, more homogeneous microstructure than that of S8C2 (**Figure 8(a)**). The main strengthening mechanism is attributed to the void-filling effect, in which fine bentonite particles fill the void spaces between binder constituents. In conjunction with enhanced cement hydration, this leads to increased formation of calcium silicate hydrate (C-S-H). These hydration products enhance structural stability and improve the efficiency of stress transfer within the stabilized soil-cement matrix [30],[28]. Such morphological evidence explains the experimental results indicating that bentonite enhances compressive strengths by reducing internal voids and improving overall structural integrity [7–8], [28].

In contrast, the SEM image of the PU foam addition (S8C2+PU1), as shown in **Figure 8(c)**, shows a highly porous microstructure with large air voids resulting from PU foam expansion. These voids disrupt structural continuity and reduce the effective load-bearing area, resulting in significant reductions in specimen weight and density. Moreover, such microstructural discontinuities significantly reduce compressive strength as the PU foam content increases, due to stress concentrations at air-void boundaries and disrupted load-transfer paths within the matrix [35],[40].

Figure 10 shows SEM micrographs and threshold images used for pore analysis of soil-cement specimens at 28 days. The comparison of S8C2+B3 and S8C2+PU3 highlights differences in microstructure and pore distribution. The pore area percentage of S8C2+B3 (14.36%) is lower than in S8C2+PU3 (26.42%), indicating a denser structure in the bentonite addition.

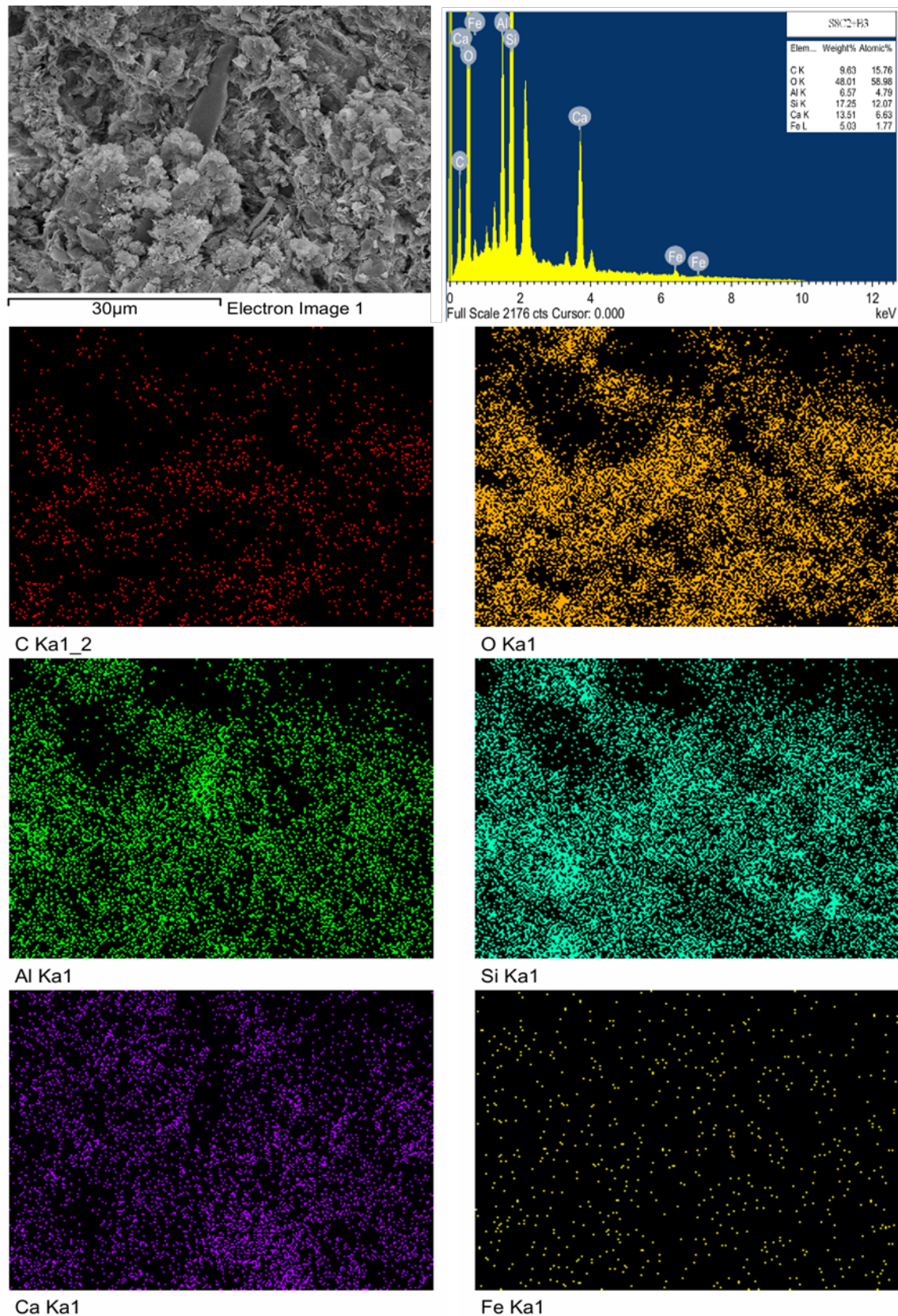


Figure 8 EDS microscopic characteristics of soil-cement-bentonite (S8C2+B3) at 28 days

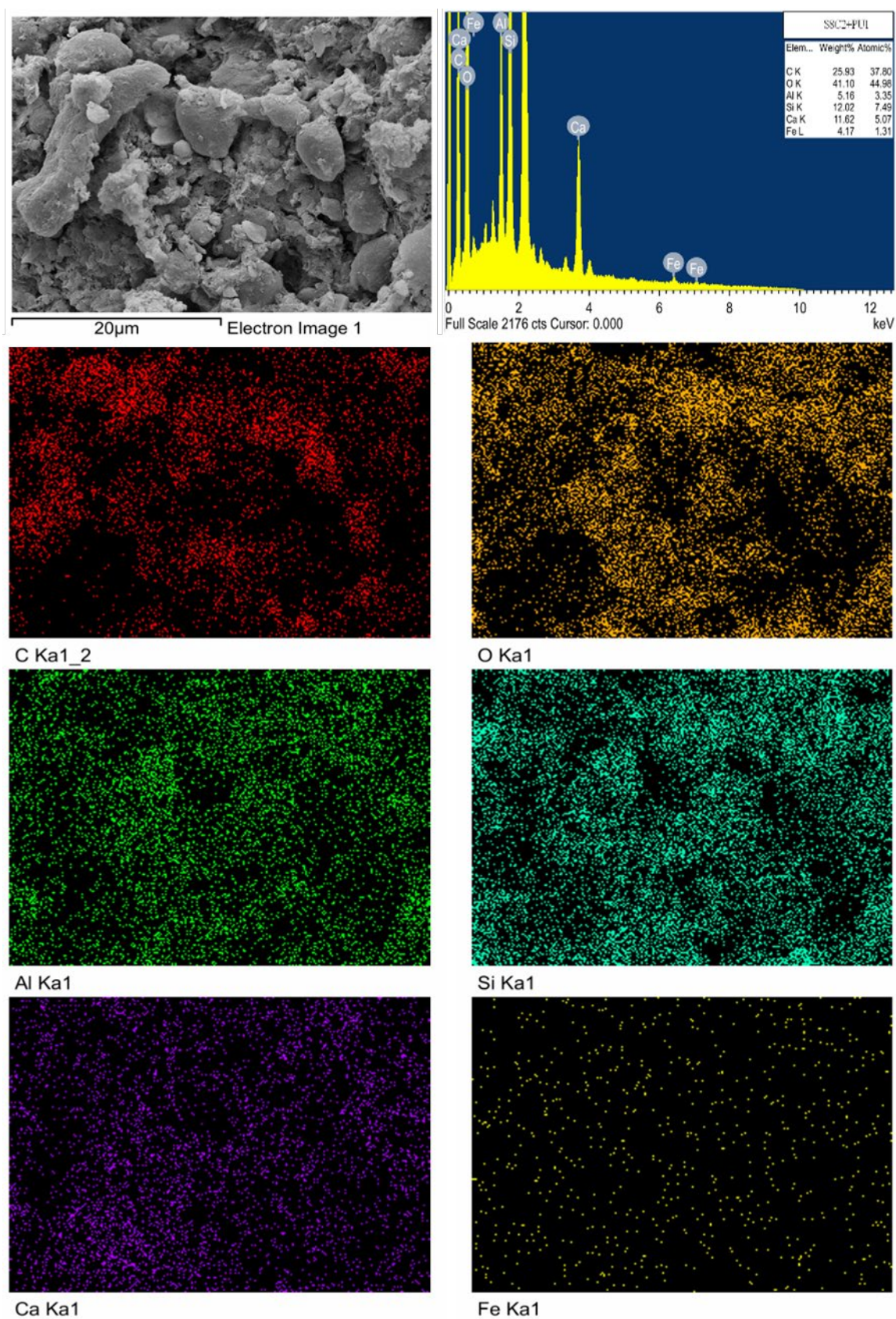


Figure 9 EDS microscopic characteristics of soil-cement-PU foam (S8C2+PU1) at 28 days

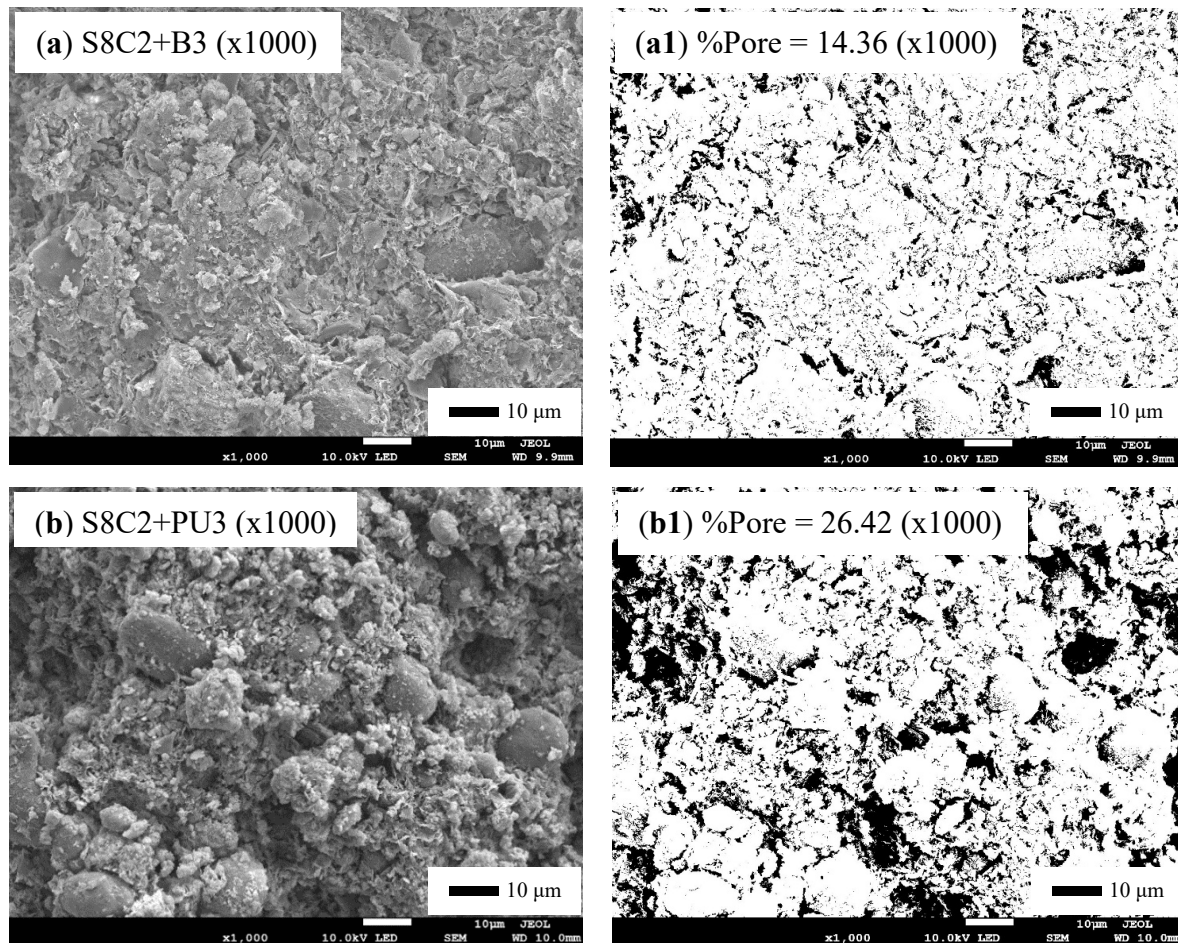


Figure 10 SEM images of soil cement at 28 days and threshold images for pore analysis: (a, a1) S8C2+B3 and (b, b1) S8C2+PU3. (a1) and (b1) show binary images of the % pore area measurement.

5. Conclusion

This study investigated the effects of adding bentonite and polyurethane (PU) foam to the soil-cement mixtures to improve the compressive strength of soft clay. The conclusions are as follows:

1. The strength of soil-cement specimens increased with curing time, with 28-day strength consistently higher than that at 7 days in all test conditions.
2. The bentonite addition significantly improved compressive strength by promoting a denser microstructure and enhancing the internal bonding within the soil-cement matrix.
3. PU foam effectively reduced the specimen weight and density by more than 10%wt, when higher PU foam content (above 10%wt) caused a decline in strength due to the formation of excess voids within the matrix.
4. Bentonite and PU foam showed contrasting effects on soil-cement properties. Bentonite enhanced the strength, whereas PU foam contributed to weight and density reduction.

Overall, the findings provide preliminary insight into the different roles of bentonite and PU foam in soil-cement mixtures under controlled laboratory conditions. Bentonite showed potential for strength

improvement, whereas PU foam may be beneficial for lightweight ground improvement applications when used at an appropriate dosage. However, this study was limited to laboratory-scale testing using soft clay from a single location under controlled curing conditions. Only short-term curing periods (7 and 28 days) and a single cement content (20 % wt) were investigated. Therefore, long-term performance and cement-admixture interaction effects were not evaluated. Future studies should investigate broader cement contents, longer curing periods, field-scale validation, and soft Bangkok clay from different locations to further confirm practical applicability.

6. Declaration of Competing Interest

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper.

7. Acknowledgments

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