



Engineering and Microstructure Properties of Soft Clay Improved with Ordinary Portland Cement and Polymers

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Abstract

This study investigated properties of soft Bangkok clay stabilized with ordinary Portland cement (OPC) and various polymers. Variables included initial water content (1.0LL, 1.5LL, and 2.0LL; LL = liquid limit), polymer type (polyvinyl alcohol (PVA), polyethylene glycol (PEG), and polyvinylpyrrolidone (PVP), polymer concentration (1%, 3%, 5% and 7%), and curing time. The unconfined compressive strength (UCS), consolidation, permeability, and microstructure were analyzed. UCS decreased with increasing water content due to delayed polymer bonding; however, at 1.0LL, polymers effectively bonded clay particles, resulting in higher UCS. A 3% polymer concentration yielded the highest UCS, while 5–7% led to non-homogeneous structures and reduced UCS. The UCS of the sample with PEG outperformed those with PVA and PVP. At 1.0LL and 3% polymer, 28-day UCS values were 1.20 MPa (PEG), 1.12 MPa (PVA), and 1.04 MPa (PVP), all exceeding the Department of Highways' standard 1.0 MPa. Higher polymer concentrations decreased void ratios and permeability by forming hydrogel layers and thin films, increasing soil density. SEM/EDS analysis confirmed 3% polymers formed uniform films enhancing soil bonding, while 7% resulted in thicker, irregular films, reducing UCS. These findings suggest that polymers could be a promising alternative to OPC in environmentally friendly deep mixing applications.

Keywords: Unconfined Compressive Strength; Consolidation, Polyvinyl Alcohol; Polyethylene Glycol; Polyvinylpyrrolidone.

1. Introduction

Modern construction services have significantly advanced, particularly in the development of infrastructure essential for human well-being. Bangkok, the capital of Thailand, has experienced continuous development across various engineering fields, such as road construction, electric trains, building foundations, retaining structures, and flood barriers. Bangkok is situated on a soft clayey layer, ranging from 15 to 20 m in depth [1]. This fine-grained, soft clay contains various minerals, including kaolinite, montmorillonite, illite, and quartz. These clay deposits exhibit high moisture content, moderate sensitivity when disturbed, and low swelling properties [2-4]. Such characteristics directly affect the soil's engineering behavior, leading to low shear strength and poor load-bearing capacity. As a result, construction on this soil layer presents significant challenges, necessitating soil improvement to achieve suitable engineering properties.

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Over the years, researchers have developed various techniques to improve the quality of soft clay [5-11], making it suitable for engineering applications. Among these, deep mixing with Portland cement is one of the most widely applied methods, as it enhances the soil's engineering properties [12–18]. Horpibulsk et al. [18] studied the strength development of cement-stabilized soft Bangkok clay under both laboratory and in-situ conditions. They found that the mixing process and the water/cement (w/c) ratio significantly influenced the hydration reaction, with a w/c ratio of 1 yielding the highest unconfined compressive strength (UCS). Subsequently, Jiang et al. [19] investigated the use of silica fume in cement-soft soil mixtures and found that appropriate silica fume content led to higher compressive strength compared to mixtures without the additive. El-Feky et al. [20] studied the effect of nano clay and nano-cellulose fibers on the mechanical properties and microstructure of cement composites. They reported that a mix containing 0.75% nanocellulose fibers and 5% nano clay achieved a remarkable 53.5% increase in UCS compared to the control mix.

However, a major concern with using cement is the environmental impact of ordinary Portland cement (OPC) production, which emits significant amounts of carbon dioxide (CO₂), contributing to the greenhouse effect and global warming [21–23]. Thus, polymers (P) have emerged as an alternative material to reduce OPC usage. P can enhance compressive strength and transform the material behavior from brittle to ductile [24]. P had high molecular weight hydrocarbon compounds formed by monomer reactions, resulting in long chains of molecules. Also, P is classified as either natural or synthetic, with synthetic polymers such as polypropylene homopolymer (PPH), polyethylene glycol (PEG), polyvinyl alcohol (PVA), and polyvinylpyrrolidone (PVP) being widely used in construction due to their high flexibility, good adhesion, water solubility, and low cost [25–32]. Ayeldeen & Kitazume [24] investigated OPC-soft clay improved with PPH and reported that an optimal PPH content of 1% resulted in a maximum 28-day UCS of 650 kPa. Mirzababaei et al. [25] studied PVA-modified soft clay and found that a 1% PVA content led to a 29% increase in UCS compared to the control. Azzam [33] examined the hydraulic conductivity of clay mixed with PPH and concluded that 3% PPH reduced hydraulic conductivity by 68%. More recently, Suksiripattanapong et al. [34] investigated the effects of PEG, PVA, and PVP on cement-treated soil. They reported that UCS increased with higher OPC content for all polymer types. The maximum UCS improvements for samples with 5% OPC mixed with PVP, PVA, and PEG were 14.5%, 10.2%, and 5.1%, respectively, compared to control mixtures. While various studies have explored the incorporation of PVA, PVP, and PEG into OPC-stabilized lateritic soils, the use of polymers as a complete alternative to OPC for stabilizing soft clay remains underexplored.

The present research investigated the possibility of using polymers (PEG, PVA, and PVP) to stabilize soft clay mixed with cement for deep mixing applications. The variables studied comprise initial moisture content of 1.0LL, 1.5LL, and 2.0LL (LL is the liquid limit), type of P (PEG, PVA, and PVP), and P concentrations of 1, 3, 5, and 7%. The SC-OPC-P samples were tested for unconfined compressive strength (UCS) at 7, 28, and 60 days of curing time, consolidation at 28 days, and microstructure characteristics. The outcome of the research has the potential to make polymers a viable alternative material that can be utilized to replace cement OPC in the production of environment-friendly deep mixing applications. The structure of this article is as follows: Section 1 provides the introduction, while Section 2 outlines the materials and methods. Section 3 presents the results and discussion, and finally, Section 4 concludes the study.

2. Materials and Methods

2.1. Materials

Soft Bangkok clay (SC) was collected at a depth of approximately 5 m from Nong-Chok District, Bangkok, Thailand. It is considered a problematic soil due to its sensitivity to disturbance. The specific gravity (Gs) of SC was 2.68. The liquid and (LL), plastic limits (PL), and plasticity index (PI) of SC were 72.34%, 30.65%, and 41.69%, respectively. Laser particle size analysis revealed an average particle size (D₅₀) of 4.3 microns, as presented in Figure 1. According to the Unified Soil Classification System (USCS), SC was classified as highly plastic clay (CH).

Ordinary Portland cement (OPC) was used as the binding agent and had a specific gravity of 3.15. Its chemical composition is presented in Table 1. The combined content of SiO₃, Al₂O₃, and Fe₂O₃ was 30.23%, while the CaO content was 61.62%. The particle size distribution of OPC, analyzed using the laser particle size analysis, revealed an average particle size (D₅₀) of 13.8 microns.

Table 1. Chemical composition of SC and OPC

Chemical composition (%)	SC	OPC
SiO ₂	62.87	22.30
Al ₂ O ₃	16.91	4.23
Fe ₂ O ₃	7.12	3.70
CaO	1.57	61.62
SO ₃	5.22	4.62
K ₂ O	1.40	0.40
TiO ₂	0.94	0.26
MgO	3.67	2.21
LOI	8.79	0.95

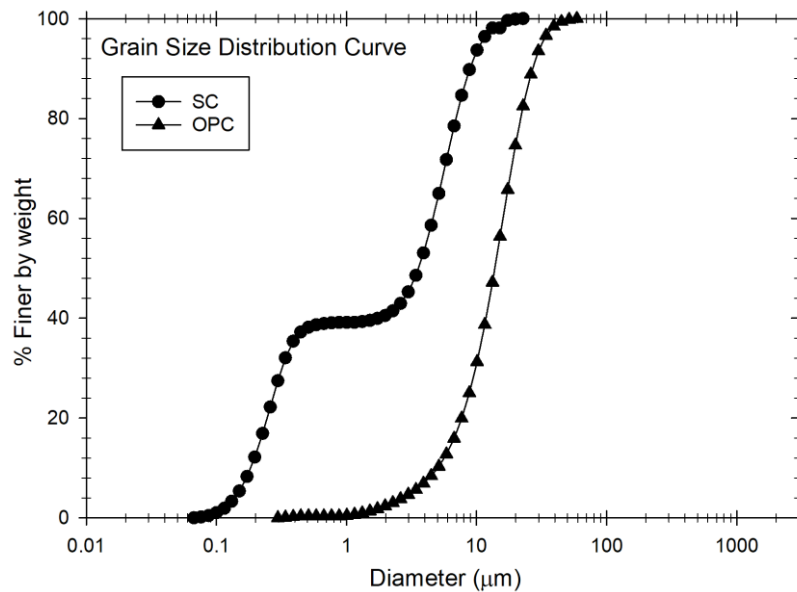


Figure 1. Grain size distribution curves of SC and OPC

Polyvinyl alcohol (PVA) was purchased from Chemipan Corporation Co., Ltd, Thailand, a synthetic polymer produced through the polymerization of vinyl acetate to form polyvinyl acetate, followed by hydrolysis to obtain the final product. PVA was classified as a biodegradable thermoplastic known for its solubility in water. Its colorlessness, scentlessness, and ability to form films with outstanding adhesive properties, flexibility, and high tensile strength characterized it. Additionally, PVA exhibited resistance to chemicals and was considered biologically safe. Generally, PVA presented specific gravity ranging from 1.27-1.31 and a molecular weight of approximately 22,000 g/mol. It typically dissolved within the temperature range of 80-95 °C. Viscosity at 25 °C of PVA ranged from 50-183.6 cP for PVA concentrations of 10-20% [35].

Polyethylene glycol type 4000 (PEG) was obtained from Chemipan Corporation Co., Ltd., Thailand, a synthesized polymer derived from the reaction of ethylene oxide, primarily recognized for its water-soluble properties. Its colorlessness, odorlessness, human safety, and non-toxicity distinguished it. When dissolved in water, PEG exhibited a viscous consistency similar to adhesive, enhancing its practical applications. It was extensively employed across various industries, particularly in producing films for the packaging of a wide range of products. The molecular weight of PEG typically ranged from 3500-4500 g/mol, with a melting point of approximately 57.5 °C. Viscosity at 25 °C of PEG ranged from 1.87-99.01 cP for PEG concentrations of 16.62-100% [36].

Polyvinylpyrrolidone type K30 (PVP) was sourced from Chemipan Corporation Co., Ltd., Thailand, which was a high molecular weight synthetic polymer devoid of ions, synthesized through the free radical polymerization of vinylpyrrolidone monomers. It was a soluble plastic in water and organic solvents, typically as a non-toxic white powder. When dissolved in water, PVP exhibited adhesive properties conducive to adhesion. Its specific gravity ranged from 1.23-1.29, and a molecular weight between 35,000-51,000 g/mol. Its melting point was approximately 150 °C. Viscosity at 25 °C of PVP ranged from 84-236 cP for PVP concentrations of 20-30% [35].

2.2. Specimen Preparation and Testing

The preparation of samples consisting of SC, OPC, and polymers (PVA, PEG, and PVP) involved a series of rigorously controlled steps. Initially, the water content of SC was adjusted to levels corresponding to 1LL, 1.5LL, and 2.0LL (where LL represents the liquid limit). The SC was then allowed to equilibrate for 24 hours. Subsequently, a cement paste was prepared by mixing OPC with P concentrations of 1, 3, 5, and 7% by volume of water, maintaining a water content/OPC ratio (w/OPC) of 1.0. This mixture was stirred for 5 minutes. The preconditioned SC was then thoroughly blended with the cement paste for an additional 5 minutes to ensure homogeneity. The resulting mixture was placed into PVC molds with diameters of 50 mm and heights of 100 mm, as well as into PVC molds with diameters of 100 mm and heights of 20 mm. The top and bottom surfaces of the samples were leveled to ensure uniformity. The molded samples were cured at room temperature for approximately 24 hours. After curing, the samples were removed from the molds and wrapped in plastic to avoid the disappearance of moisture, given the critical

importance of water content in influencing the strength of the samples. The samples were stored at room temperature (25-29 °C) and 65 ± 3 % relative humidity for 7, 28, and 60 days before performing unconfined compressive strength (UCS) testing, following ASTM D2166 standards. Additionally, consolidation testing was conducted at 28 days following ASTM D2435 standards. Fragments from the center of the 28-day SC-OPC-P samples were collected and frozen at -195 °C by immersion in liquid nitrogen for 5 minutes. These were then subjected to evacuation at a pressure of 0.5 Pa at -40 °C for 5 days [37]. Before microstructural analysis with Scanning Electron Microscopy (SEM) and energy-dispersive X-ray Spectroscopy (EDS), all samples were gold-coated. Figure 2 illustrates the preparation scheme of the SC-OPC-P samples.

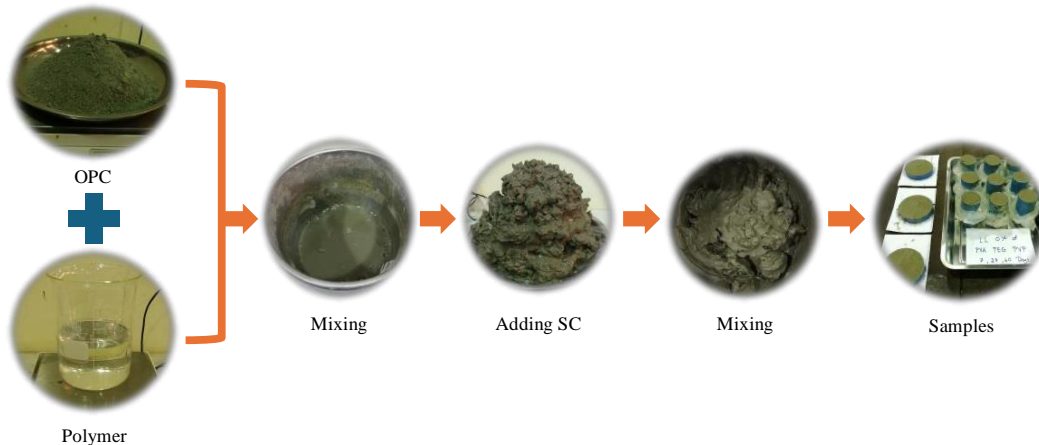


Figure 2. The preparation scheme of the SC-OPC-P samples

3. Result and Discussions

3.1. Unconfined Compressive Strength of SC-OPC-P

Figures 3 to 5 present the UCS of SC-OPC-P samples with different initial water contents: 1.0LL, 1.5LL, and 2.0LL, three types of polymers: PEG, PVA, and PVP, P concentrations: 0, 1, 3, 5, and 7%, and curing ages: 7, 28, and 60 days. It was observed that the UCS of the SC-OPC-P samples decreased with increasing initial water content. This reduction is attributed to the delayed formation of the P films under high water content conditions. However, at the optimal water content of 1.0LL, the P could form a film around the clay particles, promoting particle bonding and resulting in higher UCS values [28]. The influence of P concentration on UCS of SC-OPC-P samples is shown in Figures 3 to 5. An increase in P concentration resulted in an increase in the UCS of the samples for all P types, initial water contents, and curing ages. The highest UCS was observed at a P concentration of 3%. This improvement is due to the ability of P to penetrate and fill voids between clay particles and form a thin film between layers in the SC-OPC mixture, enhancing particle bonding. The P also helped reduce the void ratio and increase the density of the SC matrix. However, at higher P concentrations (5% and 7%), the UCS decreased, likely due to the formation of a non-homogeneous soil structure caused by excessively thick P films [34].

The effect of P type on the UCS of SC-OPC-P is also illustrated in Figures 3 to 5. PEG consistently resulted in the highest UCS at all water contents and curing time. This can be attributed to PEG's ability to effectively penetrate voids and create bonding forces between soil particles, thereby densifying the sample. In contrast, PVP, despite its high viscosity and elasticity, exhibited lower UCS values. This is likely because its excessive viscosity hindered its ability to penetrate and fill voids, reducing its effectiveness in strengthening the soil [3, 38].

The development of UCS of SC-OPC-P samples is shown in Figures 3 to 5. It was observed that the UCS increased rapidly with an increase in curing time for the first 28 days, then gradually slowed down for mixed ingredients. This trend is mainly due to the hydration reaction of OPC. After 28 days of curing, the influence of the type and concentration of the P continued to work synergistically with the OPC hydration process, contributing to a denser soil structure. The Department of Highways' standard specifications for cement columns are that the 28-day UCS of the sample must be at least 1000 kPa [39]. For the UCS of SC-OPC-P samples that met the Department of Highways' cement soil standards, it was found that at 28 days of curing, with a P concentration of 3% and an initial water content of 1.0LL, the UCS of the samples was 1201, 1124, and 1043 kPa for PEG, PVA, and PVP, respectively, as shown in Figures 3 to 5.

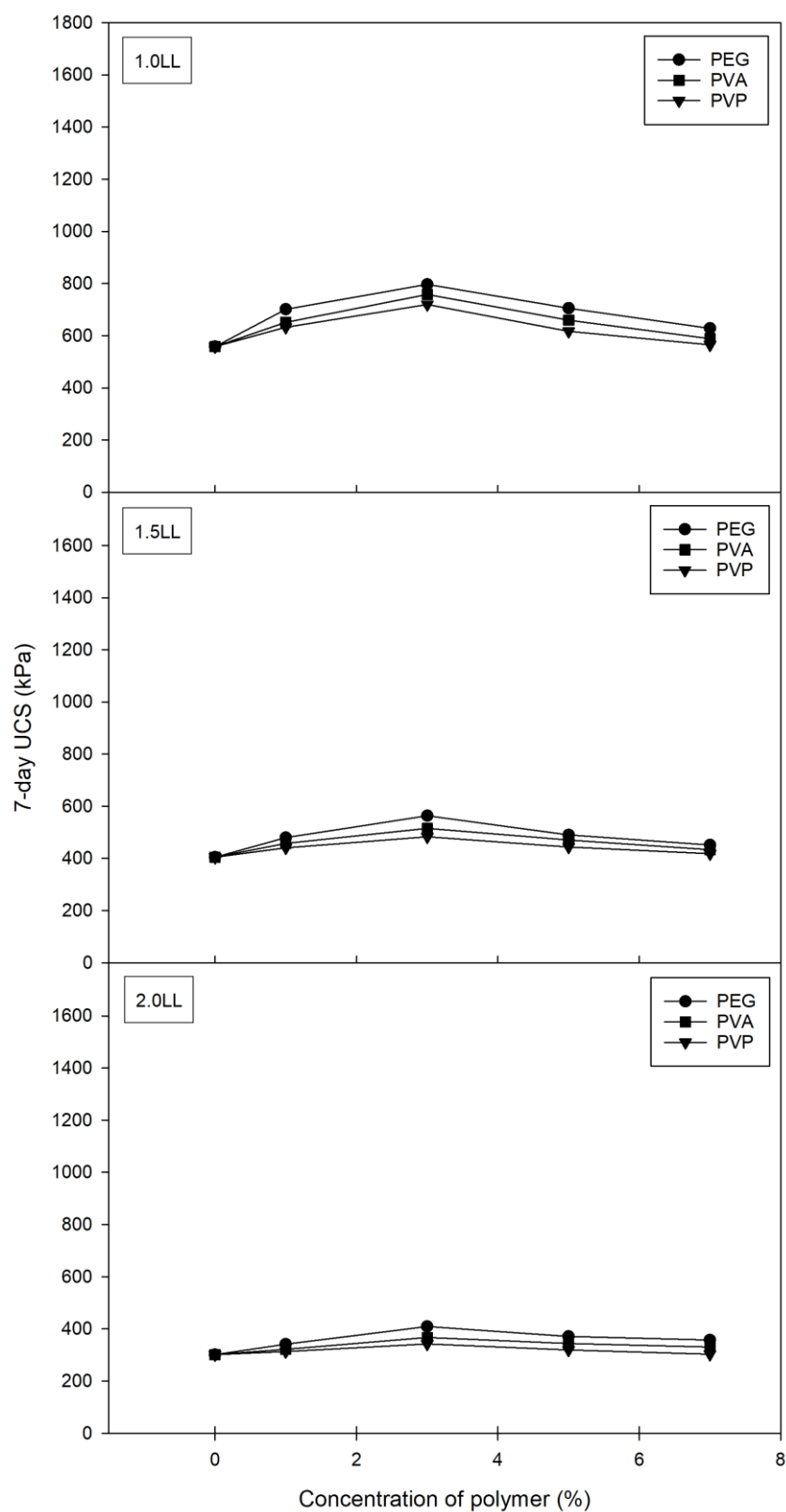


Figure 3. 7-day UCS of SC-OPC-P samples with different initial water contents, polymer types, and P concentrations

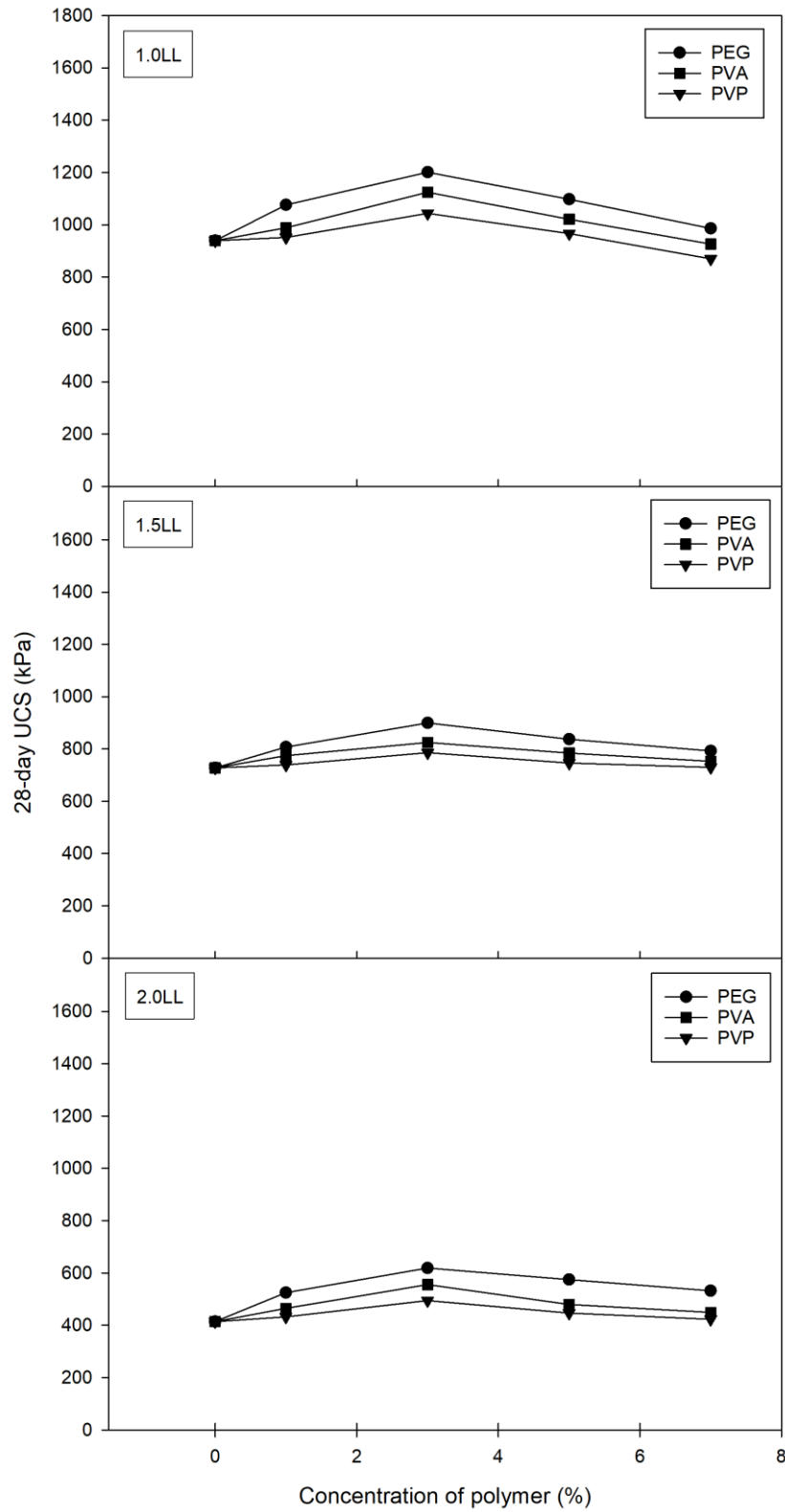


Figure 4. 28-day UCS of SC-OPC-P samples with different initial water contents, polymer types, and P concentrations

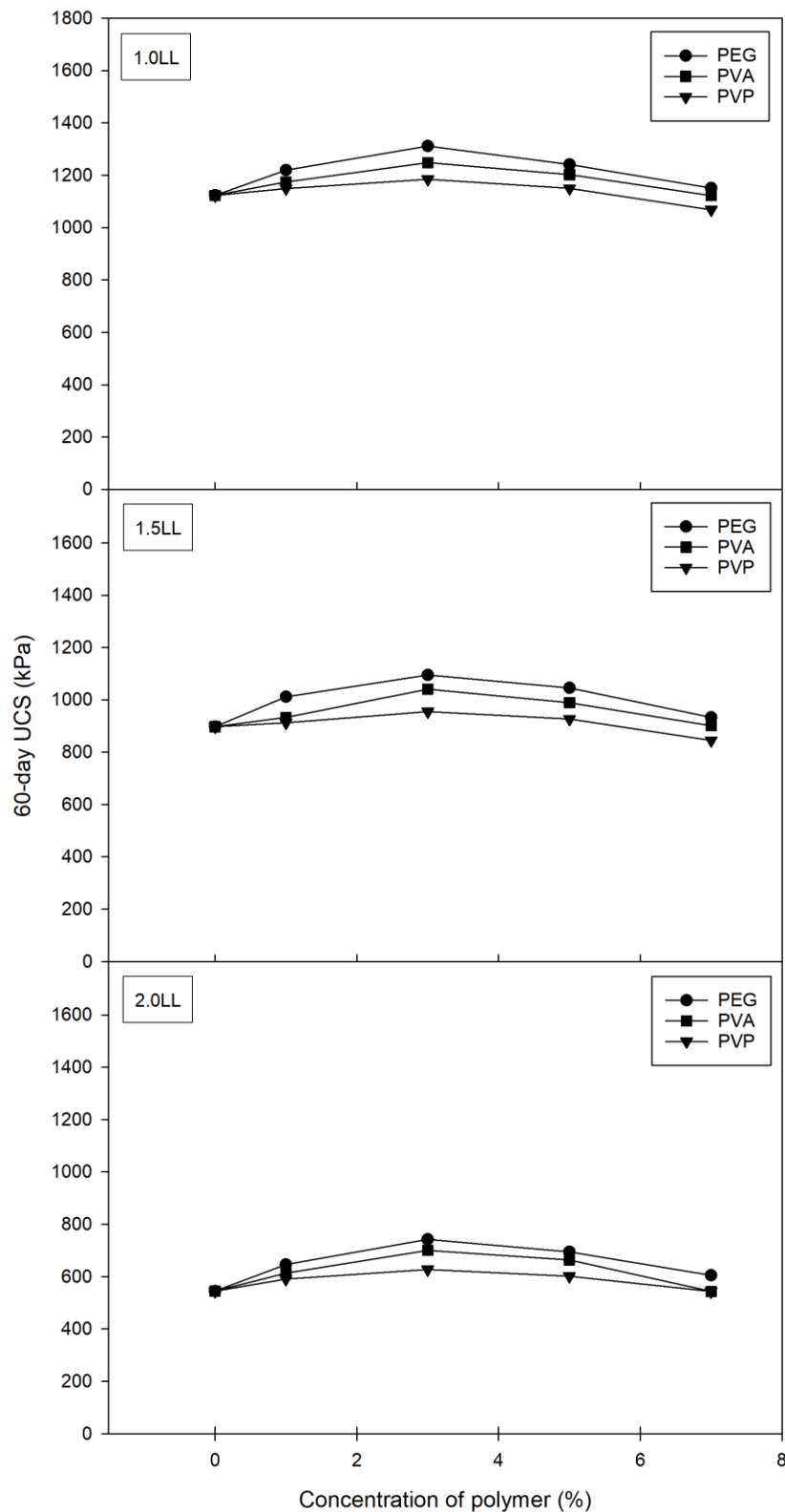


Figure 5. 60-day UCS of SC-OPC-P samples with different initial water contents, polymer types, and P concentrations

The relationship between stress and strain of SC-OPC-P samples at the initial water content of 1.0LL, curing age of 28 days, and three types of P: PEG, PVA, and PVP, with P concentrations of 0, 1, 3, 5, and 7% are shown in Figures 6. The strain at failure for SC-OPC-P samples was found to be higher than that of SC-OPC samples without P. This is because of the synergistic effect of polymer formation and the hydration reaction of OPC, which enhanced particle bonding, reduced the void ratio, and increased both ductility and cohesion [40]. Furthermore, the behavior of the samples changed from brittle to ductile, allowing the SC-OPC-P samples to better resist stress before failure [41]. However, at excessive polymer concentrations, the high viscosity and thick polymer films surrounding soil particles hindered the hydration process, delayed polymer formation, and increased porosity [1].

The influence of the type of polymer on the stress-strain relationship of SC-OPC-P samples is also illustrated in Figure 6. The strain at failure for all polymer types (PEG, PVA, and PVP) was higher than that of the samples without P at all mixed ingredients. Among them, PEG exhibited the highest strain at failure. This is because PEG, in combination with OPC hydration, dispersed clay particles and penetrated voids, creating strong bonding forces between soil particles and resulting in a higher tensile modulus [30]. Meanwhile, PVP, which has the highest molecular weight (35,000–50,000 g/mol), formed thicker film layers. Due to its high viscosity and elasticity, it was more readily adsorbed onto the surface of soil particles than PVA, contributing to a higher strain at failure [32].

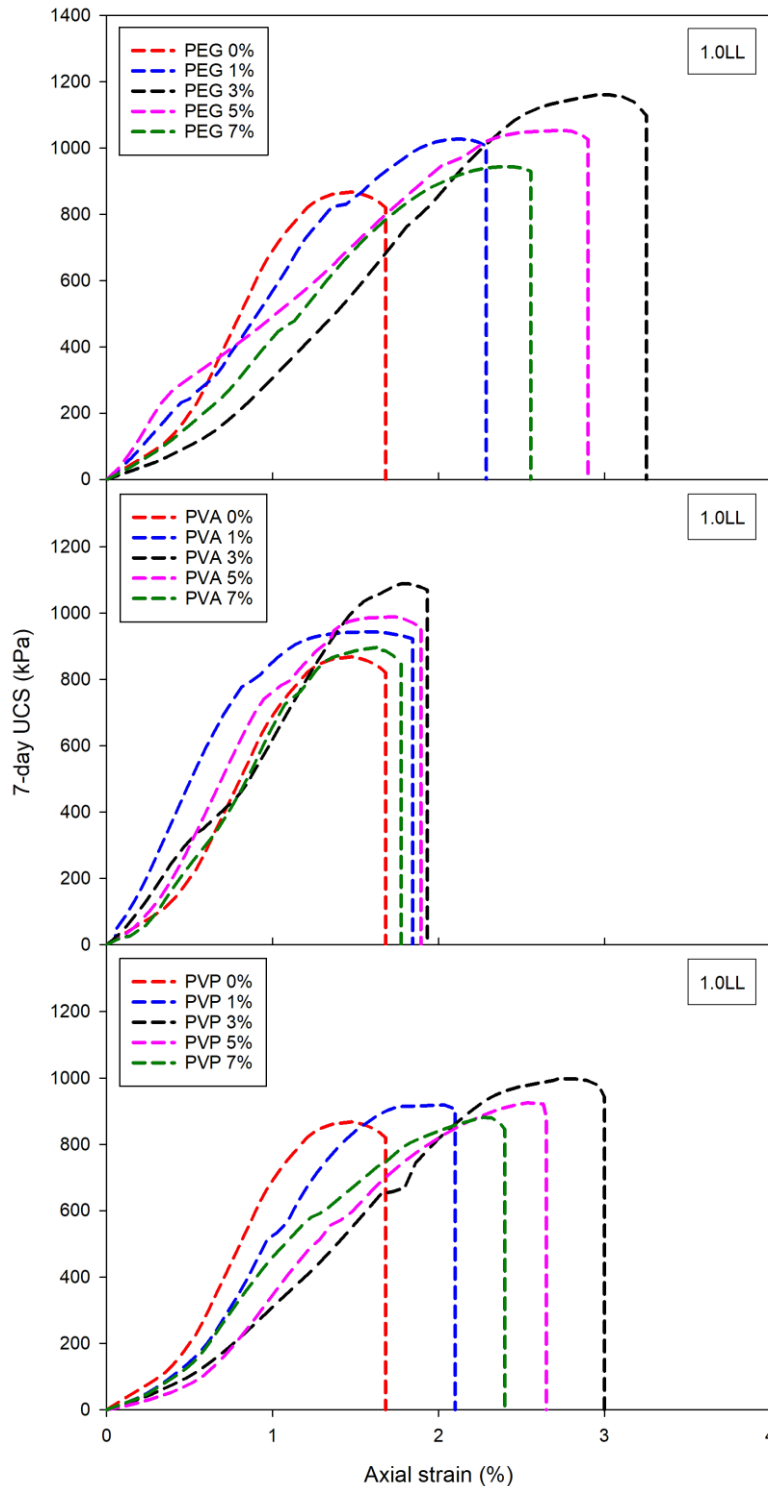


Figure 6. 7-day UCS of SC-OPC-P samples with different initial water contents, polymer types, and P concentrations

The modulus of toughness of SC-OPC-P samples is shown in Table 2. It represents the strain energy absorbed by the material before failure and is calculated as the area under the stress-strain curve using the modulus of toughness formula ($0.5 \times \text{maximum stress} \times \text{strain at fracture}$) [41, 42]. The PEG had the highest modulus of toughness due to its

ability to disperse soil particles through hydration reactions combined with the formation of PEG and the creation of a thin film around the soil particles. This results in high inter-particle bonding forces, reduced void ratio, and an increased capacity to absorb energy before failure. The highest modulus of toughness values for the three P, in the case of SC-OPC-P samples with an initial water content of 1.0LL and a concentration of 3%, were 20.50, 11.70, and 16.28 KJ/m³ for PEG, PVA, and PVP, respectively. PVP exhibited a higher modulus of toughness than PVA, which can be attributed to its higher molecular weight (35,000–50,000 g/mol). This resulted in greater strain at failure due to its high viscosity and elasticity [32]. Consequently, PVP's behavior shifted from brittle to ductile, leading to a higher modulus of toughness. For PVA, the highest modulus of toughness was observed in samples with an initial water content of 1.0LL and a polymer concentration of 1%. At a 3% concentration, the increased viscosity led to poor polymer dispersion, which adversely affected the material's energy absorption capacity.

Table 2. 28-day modulus of toughness of SC-OPC-P samples

Polymers	Water Content	Modulus of toughness with different polymer concentrations (%)				
		0	1	3	5	7
PEG	1.0LL	8.24	13.96	20.5	19.14	13.77
	1.5LL	8.93	12.62	19.06	14.58	13.94
	2.0LL	3.73	6.04	11.51	9.39	7.5
PVA	1.0LL	8.24	12.45	11.7	11.57	9.02
	1.5LL	8.93	9.22	11.93	10.69	10.34
	2.0LL	3.73	4.64	7.62	5.77	5.6
PVP	1.0LL	8.24	10.76	16.28	12.99	11.95
	1.5LL	8.93	9.52	16.11	15.73	11.65
	2.0LL	3.73	5.99	8.32	6.61	6.32

3.2. Consolidation of SC-OPC-P

Figures 7 to 9 show the 28-day consolidation of SC-OPC-P samples with initial water contents of 1.0LL, 1.5LL, and 2.0LL, P types of PEG, PVA, and PVP, and P concentrations of 0, 1, 3, 5, and 7%. It was found that increasing vertical stress resulted in a decrease in the void ratio of both SC-OPC samples without P and SC-OPC-P samples. For example, the void ratio of SC-OPC-P samples with an initial water content of 2.0LL and 7% PVP concentration was 0.90, 0.89, 0.87, 0.85, 0.82, 0.78, and 0.74 for vertical stress of 25, 50, 100, 200, 400, 800, and 1600 kPa, respectively. This behavior was similar previously by Horpibulsuk et al. [43], who investigated cement-stabilized soft clay.

The influence of the P concentration and the type of polymer on the consolidation of SC-OPC-P is shown in Figures 7 to 9. It was observed that increasing the P concentration resulted in a decrease in the void ratio of the sample for all types of polymers and initial water contents until the P concentration of 3%. This is because the P can absorb water in the soil, which causes the bonding of soil particles and the formation of a hydrogel layer between soil particles, replacing the voids in the sample and thus helping to reduce the void ratio in the sample [25]. This finding is consistent with the research presented by Mirzababaei et al. [25], who found that polymer-stabilized soft clay soils remained intact after being soaked in water for four days, while untreated soft clay soils disintegrated within 30 minutes of soaking. For excessive P concentrations (5% and 7%), the void ratio increased as the P concentration rose. This is due to poor dispersion of P, resulting from its increased viscosity [32].

Figures 10 to 12 show the coefficient of permeability of SC-OPC-P samples with initial water contents of 1.0LL, 1.5LL, and 2.0LL, P types of PEG, PVA, and PVP, and P concentrations of 0, 1, 3, 5, and 7%. In this research, the permeability coefficient (k) is calculated by the consolidation coefficient (c_v), the coefficient of volume change (m_v), and the unit weight of water (γ_w) as presented in Equation 1:

$$k = c_v \cdot m_v \cdot \gamma_w \quad (1)$$

It was found that the relationship between the void ratio and the coefficient of permeability of the sample was linear. The initial water content affected the permeability coefficient of the SC-OPC-P samples. The permeability coefficient of the SC-OPC-P samples increased as the initial water content rose. This is because excessive water content created larger voids within the sample. For particularly vertical stress, the coefficient of permeability of the SC-OPC-P samples was lower than that of SC-OPC-P samples without P. This is because forming a thin film layer of polymer covering and penetrating between the voids of soil particles reduces the voids and increases the density, making the sample more impermeable. As a result, the amount of water that can pass through the soil decreases [26, 44].

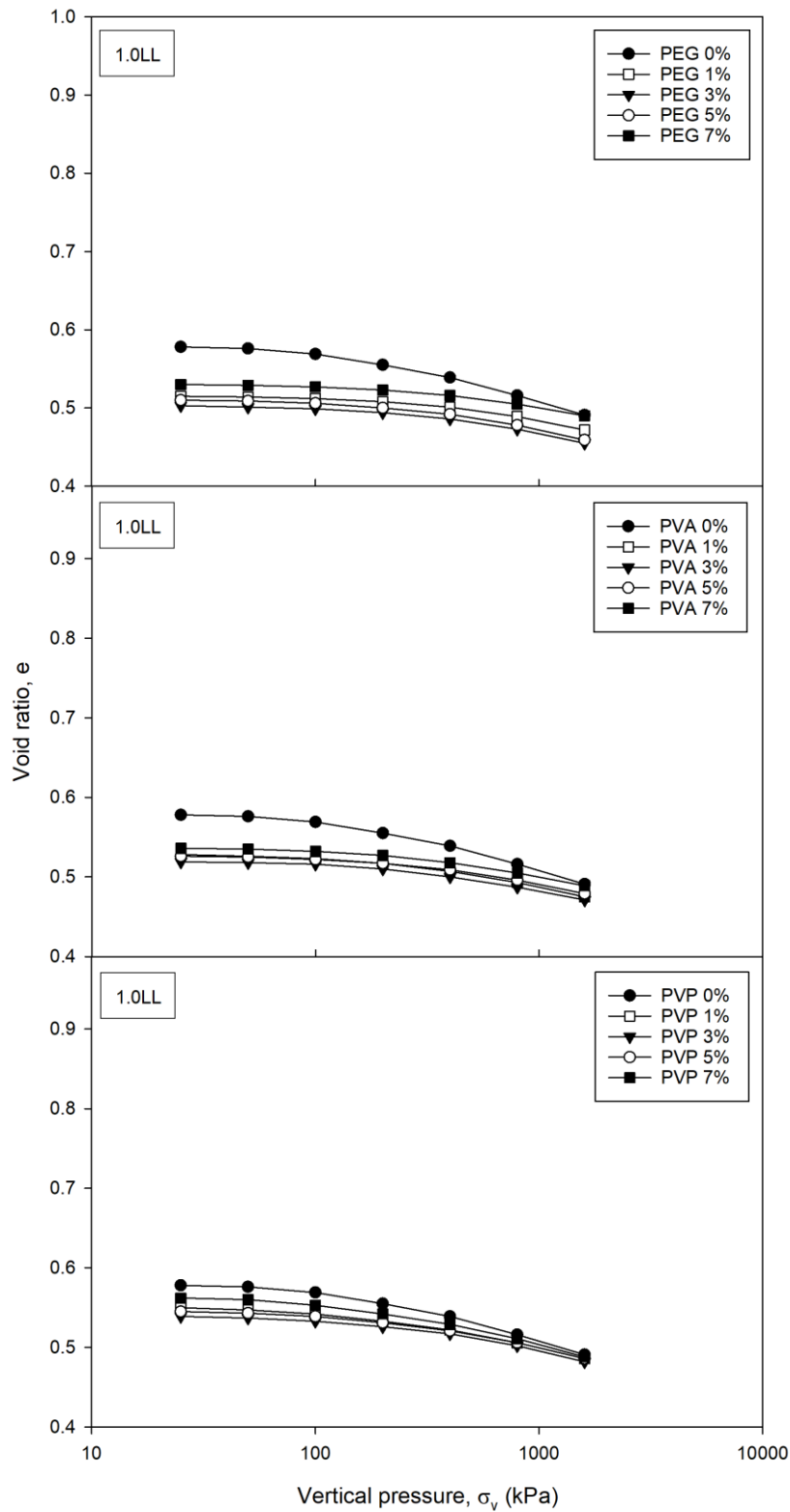


Figure 7. 28-day consolidation of SC-OPC-P samples with different initial water contents of 1.0LL, P types of PEG, PVA, and PVP, and P concentrations of 0, 1, 3, 5, and 7%

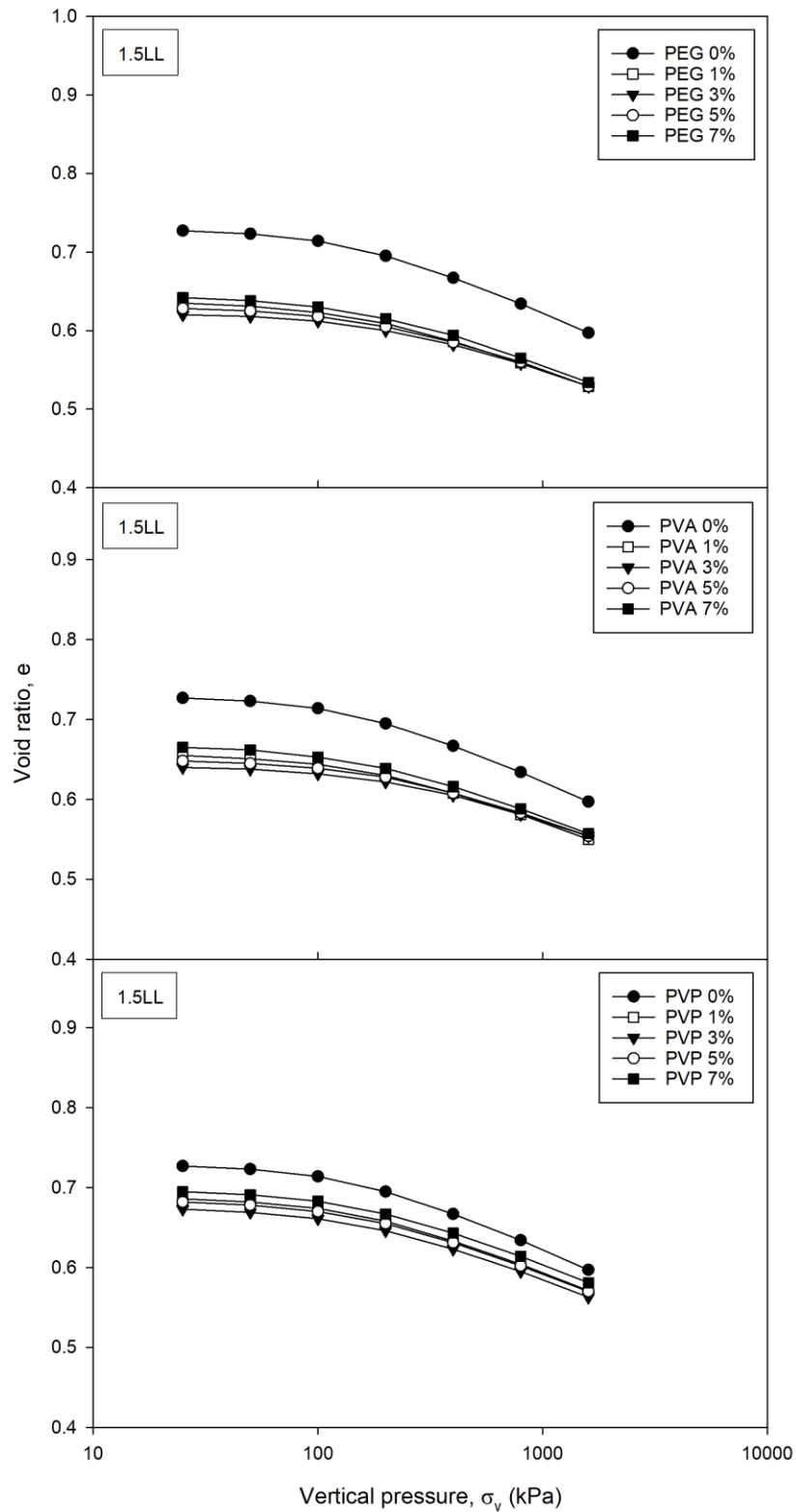


Figure 8. 28-day consolidation of SC-OPC-P samples with different initial water contents of 1.5LL, P types of PEG, PVA, and PVP, and P concentrations of 0, 1, 3, 5, and 7%

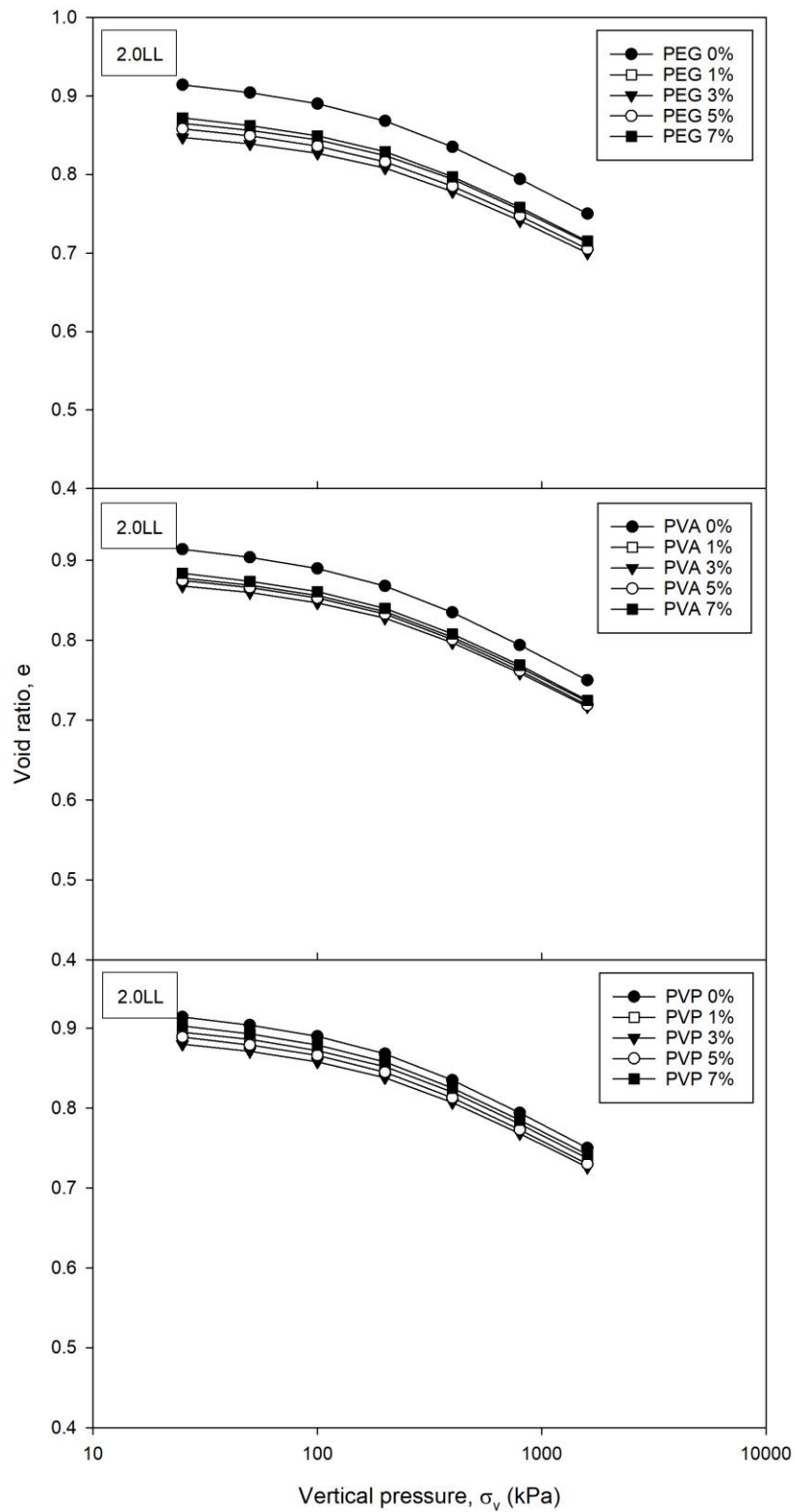


Figure 9. 28-day consolidation of SC-OPC-P samples with different initial water contents of 2.0LL, P types of PEG, PVA, and PVP, and P concentrations of 0, 1, 3, 5, and 7%

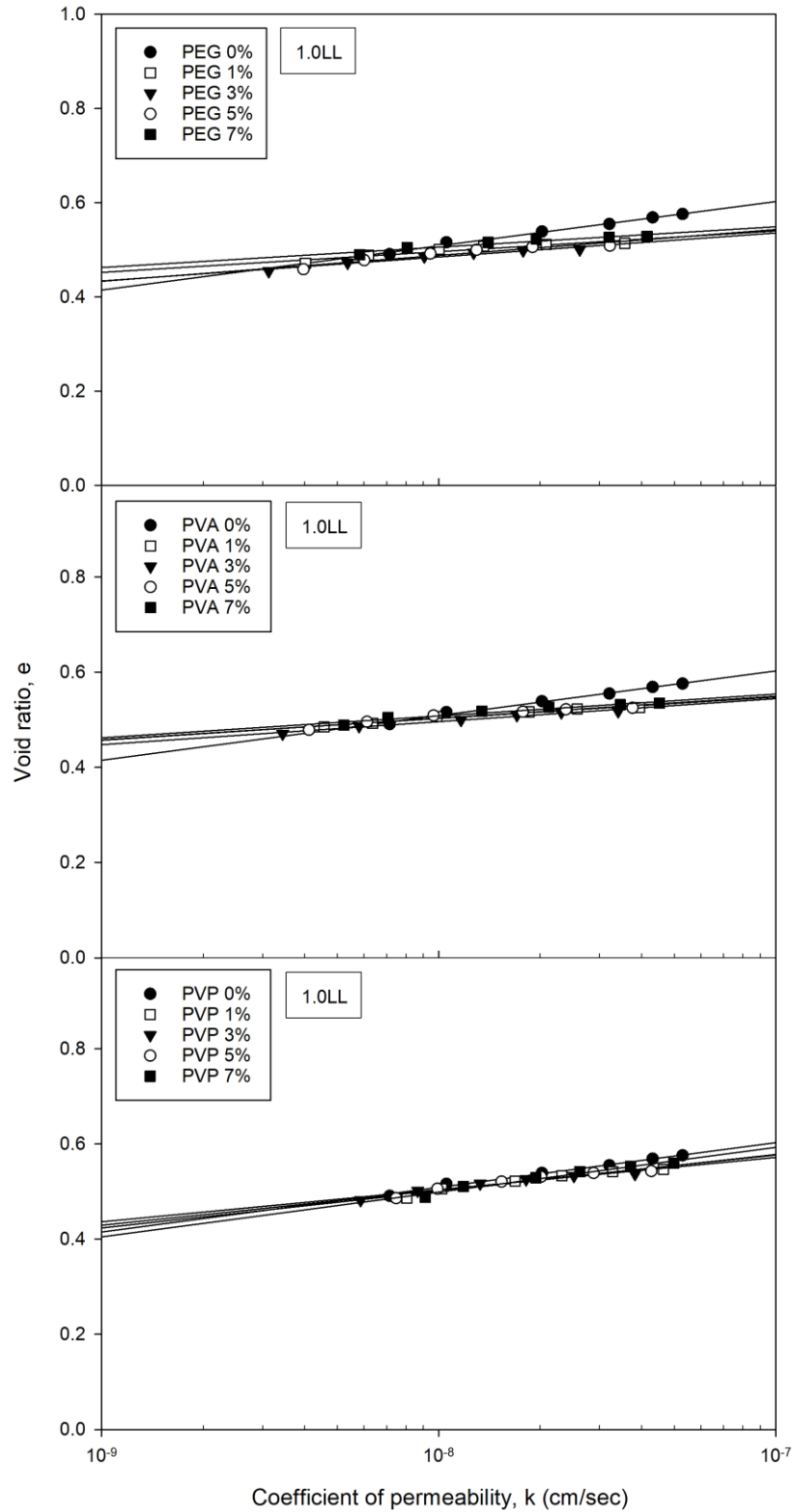


Figure 10. 28-day coefficient of permeability of SC-OPC-P samples with different initial water contents of 1.0LL, P types of PEG, PVA, and PVP, and P concentrations of 0, 1, 3, 5, and 7%

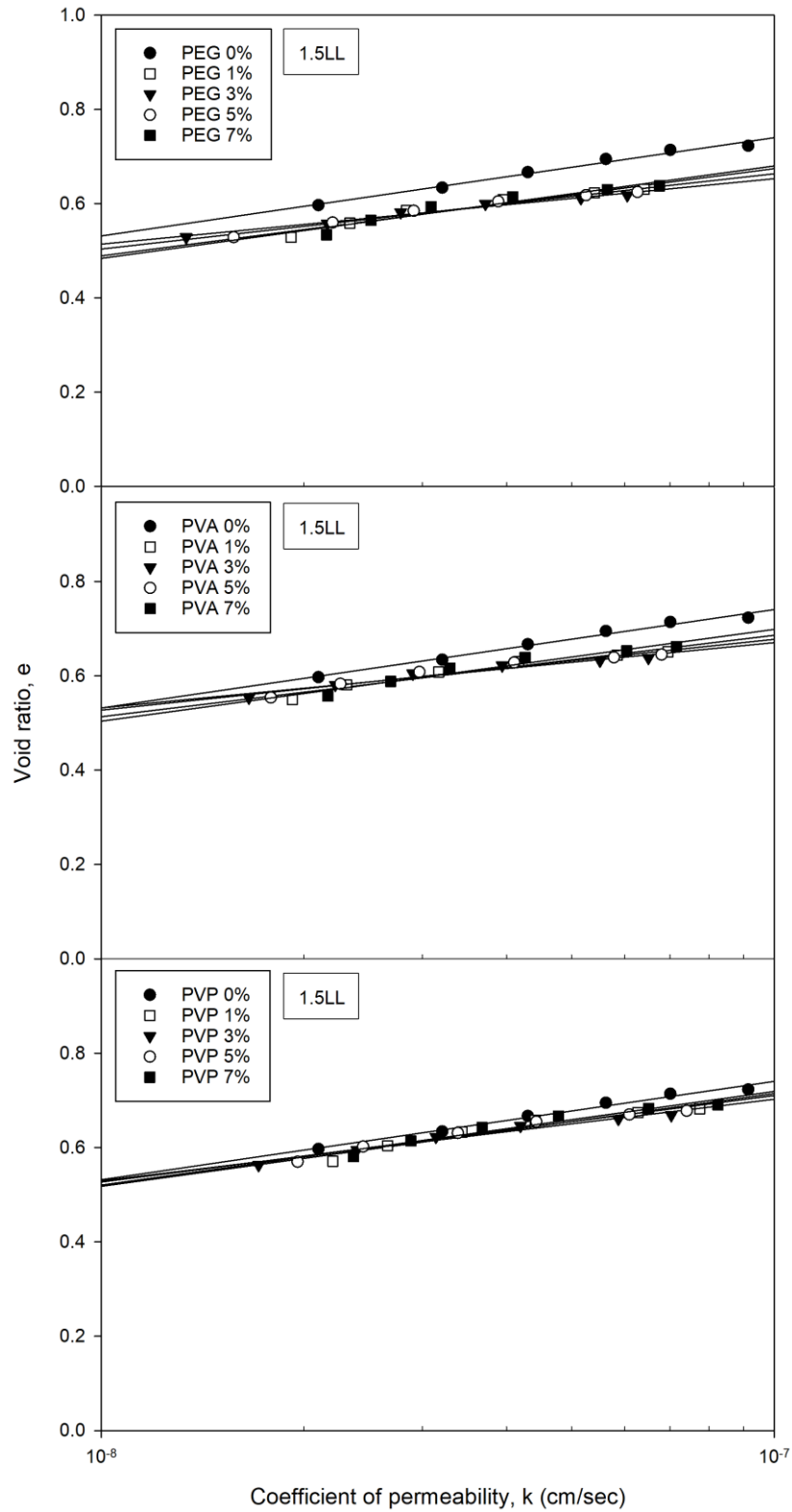


Figure 11. 28-day coefficient of permeability of SC-OPC-P samples with different initial water contents of 1.5LL, P types of PEG, PVA, and PVP, and P concentrations of 0, 1, 3, 5, and 7%

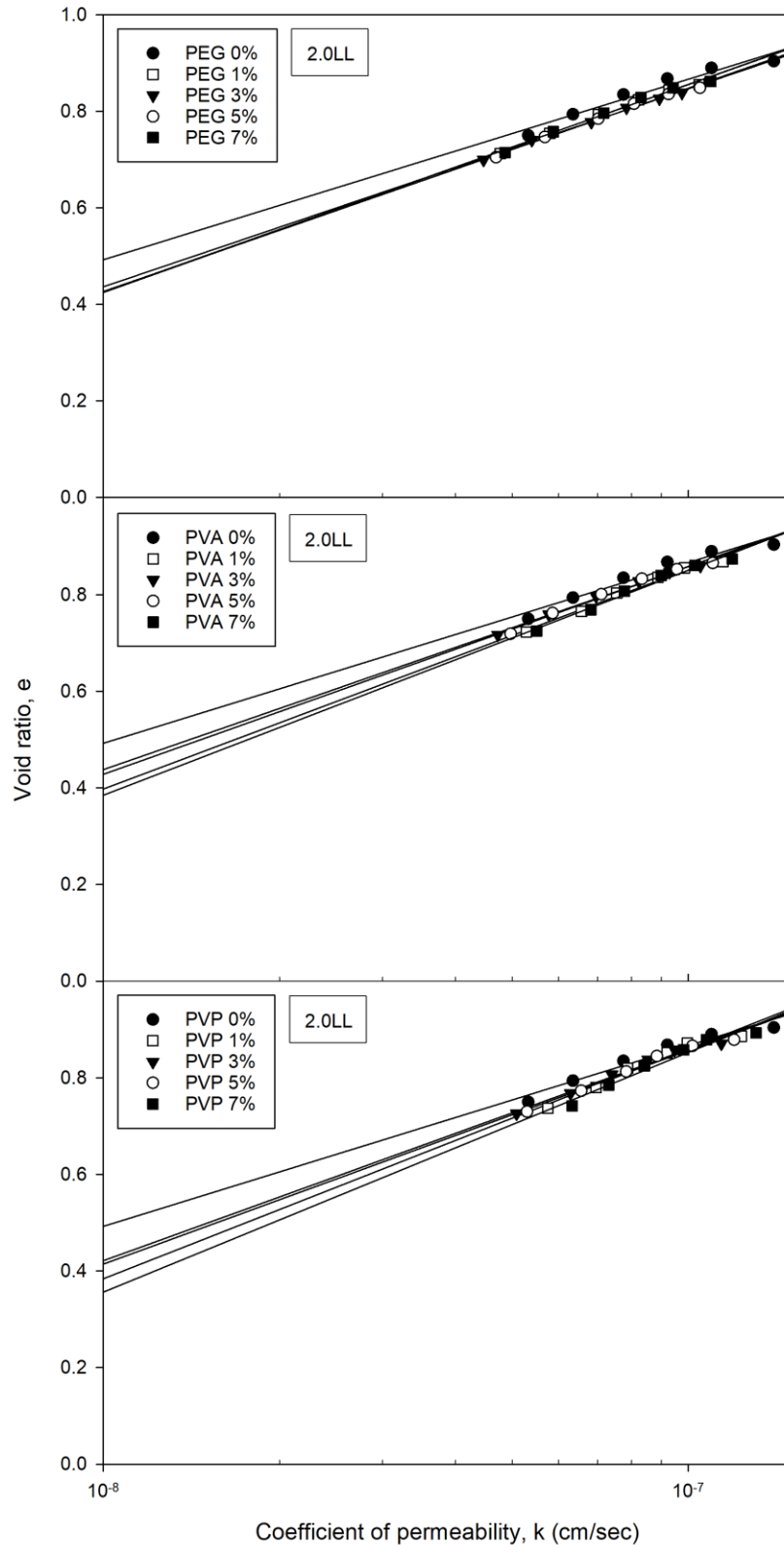
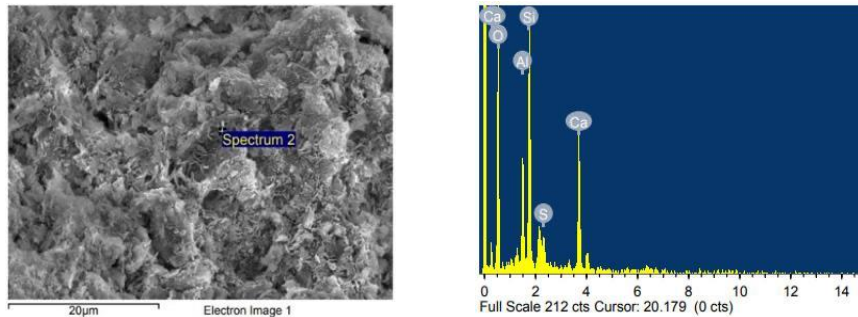


Figure 12. 28-day coefficient of permeability of SC-OPC-P samples with different initial water contents of 2.0LL, P types of PEG, PVA, and PVP, and P concentrations of 0, 1, 3, 5, and 7%

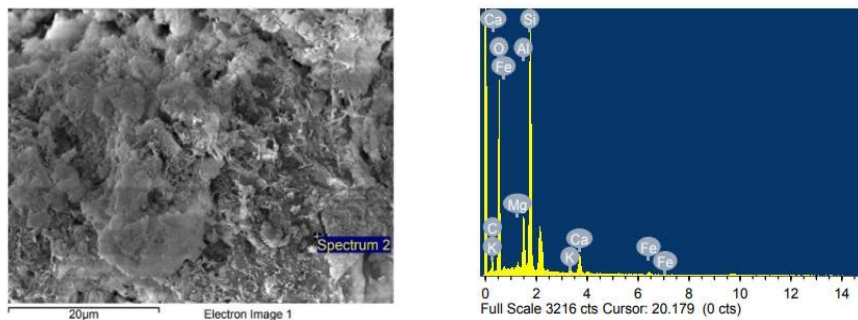
3.3. Microstructural Analysis of SC-OPC-P

The elemental composition of SC-OPC-P samples with an initial moisture content of 1.0LL was analyzed using SEM/EDS (Scanning Electron Microscopy/Energy Dispersive X-ray Spectrometer). Figure 13 shows 28-day SEM images and EDS analysis results of soft clay mixed with cement and polymer, types PEG, PVA, and PVP, with 3% and

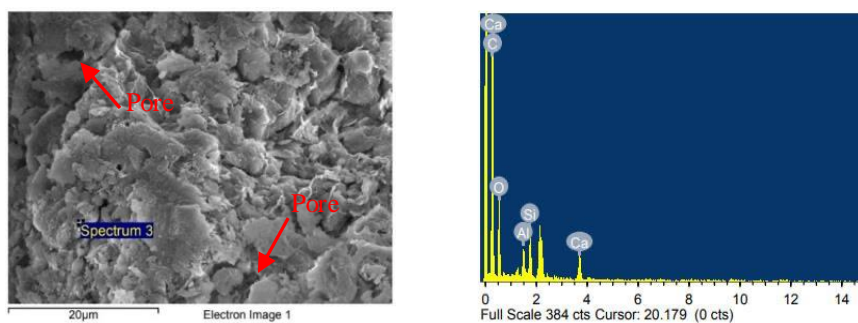
7% concentrations. It was found that the P was composed mainly of carbon (C), hydrogen (H), and oxygen (O) atoms. The formation of the P and the hydration reaction, at a P concentration of 3%, showed the formation of a thin film layer covering the soil particles sample and the dispersion of carbon (C) atoms, indicating the formation of the P. This P film not only increased the bonding between soil particles but also reduced the voids in the soil, resulting in denser soil with a higher UCS than that of SC-OPC samples without P for all P concentrations and types of polymers. However, when the P concentration was excessive, as seen at a polymer concentration of 7%, which had a high carbon (C) content, the P formed a thicker film layer, resulting in an uneven and non-homogeneous soil layer structure, leading to a decrease in UCS, as shown in Table 3.



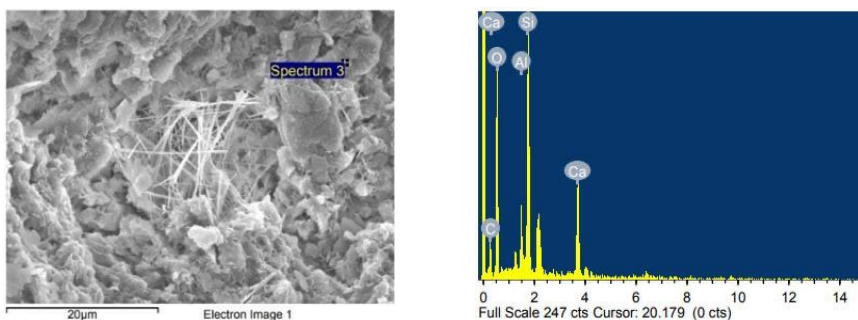
(a) SC-OPC



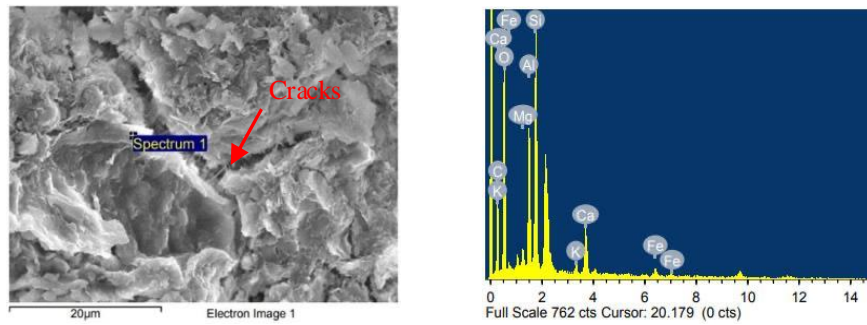
(b) PEG 3%



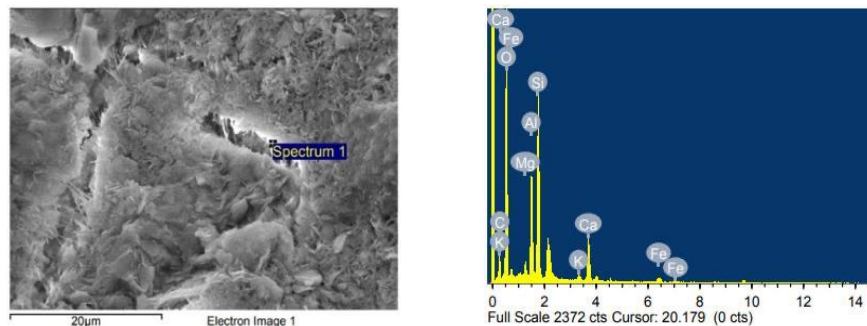
(c) PEG 7%



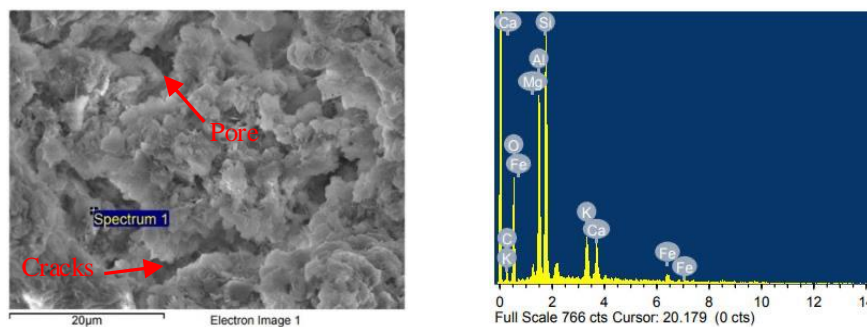
(d) PVA 3%



(e) PVA 7%



(f) PVP 3%



(g) PVP 7%

Figure 13. 28-day SEM images and EDS analysis of SC-OPC-P samples with PEG, PVA, and PVP and P concentrations of 3% and 7%

Table 3. EDS results of SC-OPC-P samples

Chemical composition	SC-OPC-P samples with P concentrations						
	SC-OPC	PEG 3%	PEG 7%	PVA 3%	PVA 7%	PVP 3%	PVP 7%
C	n/a	9.58	10.16	7.78	24.18	6.76	7.43
O	59.72	51.16	46.30	47.66	45.23	53.21	32.68
Si	7.32	10.71	3.10	35.12	6.90	33.02	13.98
Al	4.03	14.23	2.05	2.12	13.06	2.75	24.58
Ca	22.41	8.41	4.64	4.66	5.54	3.93	6.95

4. Conclusions

The research analyzed the UCS, consolidation, permeability, and microstructure of SC-OPC-P samples with varying initial water contents, P types, P concentrations, and curing ages. The main conclusions are as follows:

- UCS decreased with increasing water content due to delayed P formation. However, at an optimal water content of 1.0LL, the P effectively bonded clay particles, resulting in increased UCS.
- A P concentration of 3% yielded the highest UCS under all conditions. Higher concentrations (5% and 7%) resulted in a non-homogeneous soil structure and a reduction in UCS.

- PEG showed superior performance due to its ability to penetrate voids and enhance soil bonding. UCS increased with curing time up to 28 days, after which the rate of increase slowed. Notably, samples with a 3% P concentration and 1.0LL water content met the Department of Highways' standard of 1,000 kPa at 28 days, indicating the optimal condition for improving soil strength.
- The 28-day consolidation showed that increasing P concentration and type reduced the void ratio in SC-OPC-P samples by forming a hydrogel layer that filled the voids in the SC-OPC-P samples.
- The coefficient of permeability in SC-OPC-P samples decreased with higher P concentrations due to a thin P film reducing voids and increasing density, making the soil more impermeable.
- SEM/EDS analysis revealed that the P in SC-OPC-P samples, primarily composed of carbon atoms, formed a thin film at a 3% P concentration, which improved soil bonding and increased UCS. However, at a 7% P concentration, the thicker film led to a non-homogeneous structure and reduced UCS.

5. Declarations

5.1. Author Contributions

Conceptualization, J.T. and C.S.; methodology, J.T. and K.P.; investigation, N.W., J.T., and K.P.; resources, K.P. and C.S.; writing—original draft preparation, N.W.; writing—review and editing, J.T., K.P., S.T., W.T., P.O., B.V.D., and C.S.; supervision, C.S.; project administration, C.S.; funding acquisition, C.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding and Acknowledgements

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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