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Development of environmentally sustainable geopolymer-based soil solidifiers using waste siding and glass powders

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ABSTRACT

This study develops an environmentally sustainable soil solidifier by utilizing Siding Cut Powder (SCP), an industrial by-product, activated with Earth Silica (ES), an innovative alkaline stimulant derived from recycled waste glass. Laboratory tests were conducted on various formulations of SCP and ES, with and without additives such as Ordinary Portland Cement (OPC) and calcium hydroxide ($Ca(OH)_2$). The results demonstrated that SCP activated with ES significantly enhanced the compressive strength of the soil, exceeding the 160 kN/m^2 threshold required for construction-grade soil. The addition of OPC and $Ca(OH)_2$ further improved performance, while thermal treatment of SCP at 110 °C and 200 °C reduced the required amount of solidifier without compromising strength.

Environmental assessments initially identified concerns regarding arsenic (As) leaching in SCP formulations, partially attributed to the recycled glass content in ES. However, the incorporation of $Ca(OH)_2$ effectively mitigated As leaching by forming stable calcium arsenate compounds, ensuring compliance with environmental standards. SEM-EDS analysis revealed the formation of silicate and aluminosilicate compounds, with calcium silicate hydrate (C-S-H) contributing to improved mechanical stability and durability. These findings indicate that SCP and ES provide a viable, low-carbon alternative to OPC-based solidifiers, supporting sustainable construction practices. The implications of this study include potential reductions in construction waste and carbon emissions, as well as new opportunities for recycling industrial by-products in geotechnical applications.

1. Introduction

The modern building and construction industry faces significant environmental challenges, particularly concerning the use of materials such as Portland cement and ceramic tiles. Ordinary Portland Cement (OPC) remains the most commonly used soil solidifier for soft soils due to its effectiveness and widespread availability. However, OPC production is associated with substantial carbon dioxide (CO_2) emissions, contributing significantly to global greenhouse gas levels. Cement manufacturing is responsible for approximately 7–8 % of global CO_2 emissions, primarily due to the calcination of limestone, a process that releases large quantities of CO_2 (Andrew, 2018). Given this environmental impact, the urgent need for alternative materials that maintain the performance of OPC while significantly reducing carbon emissions has become increasingly apparent.

To address this issue, researchers have explored the use of geopolymers— inorganic polymers formed by activating aluminosilicate materials with alkaline solutions (Provis and van Deventer, 2009). Geopolymers provide a low-carbon alternative to traditional cement-based binders, as they can incorporate industrial by-products such as Fly Ash (FA) and Blast Furnace Slag (BFS) (Palomo et al., 1999). These materials not only reduce waste but also significantly

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lower the carbon footprint associated with soil improvement (Shi et al., 2014). BFS, a by-product of the steel industry, is particularly suitable for geopolymer reactions due to its high calcium, silica, and alumina content (Luukkonen et al., 2018). When activated with alkaline solutions such as sodium hydroxide or potassium hydroxide, BFS undergoes geopolymerization to form a binder that rivals OPC in strength and durability while exhibiting a considerably lower environmental impact (Nath and Sarker, 2014). The development of geopolymer-based alternatives to conventional cement-based solidifiers has the potential to revolutionize soil improvement techniques and contribute to sustainable civil engineering practices (Bernal and Provis, 2014).

The selection of Earth Silica (ES) and Siding Cut Powder (SCP) as waste materials for this study is based on their abundance, chemical composition, and potential for geopolymerization. ES, derived from recycled waste glass, is rich in silica—a crucial component for geopolymer formation. Its alkaline nature enhances the dissolution of aluminosilicates, thereby promoting the geopolymerization process. SCP, a by-product of the construction industry, contains significant amounts of silica and alumina, making it well-suited for geopolymer synthesis. Moreover, reusing these materials addresses two major environmental concerns: the accumulation of waste glass and the disposal of construction debris. By utilizing ES and SCP, this study seeks to demonstrate a feasible method for converting abundant waste streams into valuable resources for sustainable construction practices.

Given these considerations, the development of a novel solidifier (soil-improvement material) using BFS fine powder activated by ES as one of the alkaline stimulants (referred to as “Earth Silica; ES”), as shown in Fig. 1, presents a particularly promising approach. ES primarily consists of waste glass powder with a high silica content and is used to promote the solidification process of BFS fine powder (Inazumi et al., 2017, 2019, 2021, 2023; Shigematsu et al., 2023). Developed by the authors, ES represents an innovative solution for the effective utilization of industrial waste. It consists of finely ground waste glass combined with an alkaline admixture to enhance its reactivity. Various studies have examined the development of ES, its interaction with other materials, and its performance as a soil amendment. These studies have demonstrated its effectiveness in enhancing soil properties such as strength and durability, underscoring its potential as an environmentally sustainable alternative to conventional soil stabilization materials (Inazumi et al., 2017, 2019, 2021, 2023; Shigematsu et al., 2023). BFS fine powder activated by ES facilitates the formation of a high-strength soil-improving body, even in soft clay soils that are typically difficult to stabilize. Additionally, ES is a versatile material as it does not contain hexavalent chromium, thereby eliminating leaching risks and ensuring safe, environmentally friendly usage. Furthermore, the addition of a small amount of calcium to ES can promote rapid setting (Inazumi et al., 2017, 2019, 2021, 2023; Shigematsu et al., 2023).

Beyond the cement industry, the construction sector also faces significant challenges in waste management. Ceramic siding panels, commonly used for exterior cladding, are composite materials that often incorporate wood, ceramics, and other components, making recycling difficult. The cutting process for these panels generates substantial amounts of powdered dust, which is frequently treated as industrial waste. Only a small fraction (5.9 %) is reused, while the vast majority (94.1 %) is disposed of, contributing to landfill accumulation and environmental pollution (Kinnunen et al., 2017; Harrison, 2022).

In response, this study investigates the potential for reusing siding cut powdered dust as a solidifier (soil-improvement material). Preliminary studies indicate that SCP exhibits physical properties similar to cement or BFS powder (Ismail et al., 2014), as shown in Fig. 2, making it a viable candidate for substitution in geopolymer formulations. If successfully integrated, this approach could simultaneously address two environmental challenges: reducing reliance on OPC in soil improvement and repurposing construction waste (Zhang et al., 2014). By combining SCP with ES as one of the alkaline stimulants developed for BFS fine powder, researchers are exploring the potential to create a new geopolymer-based solidifier that could further lower carbon emissions and advance circular economy practices in both the steel and construction industries (Xu and Van Deventer, 2000). This integrated approach not only underscores the versatility of geopolymer technology but also highlights its broader implications for sustainable construction (Provis, 2014). By minimizing waste, lowering greenhouse gas emissions, and promoting the use of industrial by-products, these innovations could contribute significantly to global climate change mitigation efforts. Future studies should focus on optimizing the performance of these alternative materials, ensuring their scalability, and evaluating their long-term environmental benefits in real-world applications (Pacheco-Torgal et al., 2015).

In this study, preliminary laboratory mixing tests were conducted to evaluate the applicability of solidifiers (soil-improvement materials) using SCP and ES as one of the alkaline stimulants. These tests represent an essential step in validating the potential of recycled materials for soil improvement and lay the foundation for further research on the scalability and field performance of these materials (Davidovits, 2015). Through continued study and interdisciplinary collaboration, geopolymer-based technologies have the potential to play a crucial role in shaping a more sustainable future for the construction industry (Scrivener et al., 2018).

Fig. 1. Image of alkaline stimulant referred to as “Earth Silica; ES."

Fig. 2. Image of siding cut powder referred to as “SCP."

2. Materials and methods

2.1. Soil targeted for improvement and the objectives

This study aims to evaluate the effectiveness of an innovative soil improvement method using a composite material consisting of Siding Cut Powder (SCP) and Earth Silica (ES). The focus is on a specific type of dried clay characterized by a high content of montmorillonite and kaolinite, which are clay minerals known for their expansive properties and high cation exchange capacity (Wang et al., 2012; Elhassan et al., 2023). These minerals are commonly found in natural soils and can significantly influence the soil's mechanical properties, particularly under variable water content conditions (Sposito, 2016).

For the preliminary mixing tests, the clay was carefully prepared with a water content of 40 %. This specific water content level was chosen because it closely represents the natural state of many soft soils under field conditions, especially those that could benefit from stabilization techniques (Al-Mukhtar et al., 2012). Maintaining a 40 % water content is also critical for simulating the behavior of soil during wetter periods, which can pose challenges to structural stability (Ahmad and Uchimura, 2023).

Unconfined compressive strength tests were conducted to establish a baseline for the mechanical properties of the clay (Jia et al., 2019). These tests are essential for understanding how the soil behaves under stress without lateral confinement, mimicking field conditions (Kalkan and Akbulut, 2004). The results indicated that the untreated clay had a strength of 25 kN/m^2, which is relatively low and typical for untreated clays of similar composition and water content (Wong et al., 2024).

The rationale for using clay at this particular water content extends beyond basic testing (Consoli et al., 2010a). The objective is to enhance soil stability for infrastructure applications, particularly for constructing houses and roads on soft ground (Yu et al., 2023). Additionally, this research has a strong environmental focus (Malhotra and Mehta, 2005). By transforming the clay from a Type 4 construction-generated soil (typically considered less stable and more contaminated) into a Type 3 construction-generated soil (which is more suitable for construction purposes), this study aims to demonstrate a sustainable approach to recycling and upgrading construction-generated soil (PWRI, 2013; Vitale et al., 2017). This transformation would not only reduce environmental impact but also potentially lower costs associated with waste disposal and material procurement in construction projects (Kavvadas and Anagnostopoulos, 1998).

This study seeks to provide a dual benefit: enhancing the structural integrity of soils in construction applications while advancing sustainable waste management practices (Mashizi et al., 2023). If successful, this approach could be widely implemented, offering a method for stabilizing soft soils and efficiently recycling construction-generated soil across various regions and projects (Bonaparte and Bachus, 2020).

2.2. Formulation design

In this study, the powder mixing method was chosen as the primary approach for soil improvement. This method involves incorporating solidifiers into the soil, with the ratio of material added typically expressed in terms of the mass (kg) of solidifier per cubic meter (m^3) of soil volume before the improvement process. The specific amount of solidifier required depends on several factors, including soil type, the desired level of improvement, and field conditions. In cases where shallow soil improvement is conducted using powder mixing methods, ensuring uniform distribution and thorough mixing of the material with the soil is crucial for achieving optimal results. According to established guidelines, the minimum amount of solidifier required to ensure uniform application in the field is 50 kg/m^3 (Di Sante et al., 2016). This baseline amount is necessary for effective mixing and soil improvement, particularly in shallow layers where achieving uniformity can be challenging due to natural soil variability (Consoli et al., 2011).

To examine the effects of different solidifier quantities, this study tested four mass ratios: 50, 100, 150, and 200 kg/m^3. These quantities were selected to evaluate how the amount of solidifier influences both the mechanical properties of the soil and the overall effectiveness of the improvement process. By analyzing these different ratios, the study aimed to determine the optimal solidifier quantity for effective soil improvement under various conditions (Alonso et al., 2013).

The solidifiers used in this study consisted of several formulations, with SCP serving as the primary component. In some formulations, SCP was used alone, while in others, it was combined with Ordinary Portland Cement (OPC) or calcium hydroxide ($Ca(OH)_2$), with these additives comprising either 10 % or 20 % of the total solidifier volume (Nath & Kumar, 2016). These additives were included to enhance the binding properties of SCP and improve stabilization. Additionally, to explore the potential effects of thermal activation on the solidifiers, SCP was heated in air at either 110 °C or 200 °C for a minimum of 12 h, followed by cooling to room temperature. This thermal treatment was expected to activate certain chemical components within the powder, thereby improving its reactivity and interaction with the soil matrix (Cheng et al., 2023; Cui et al., 2017).

To further enhance the performance of the solidifier, a 5 % addition of ES as an alkaline stimulant was included in each formulation. This stimulant was chosen for its ability to increase the alkalinity of the mixture, thereby promoting stronger chemical reactions between the soil and the solidifiers. The inclusion of ES was expected to enhance the mechanical properties of the improved soil, particularly in terms of strength and long-term durability (Abbey et al., 2020).

The various formulations and their corresponding compositions are detailed in Table 1, providing a clear overview of the materials and their respective proportions used in this study. By investigating a range of combinations involving different quantities of SCP, ES, and thermal treatments, this study sought to identify the most effective formulation for enhancing soil improvement and ensuring its suitability for construction and infrastructure projects (Williams et al., 1983; Al-Swaidani et al., 2016).

2.3. Sample preparation

In this study, the preparation of clay samples was carried out methodically to ensure uniformity and consistency across all specimens. The clay, adjusted to a water content of 40 %, was mixed with SCP and ES using an electric mixer. The mixing process typically lasted approximately 5 min (Tarantino and Col, 2008). However, if the mixture appeared uneven or insufficiently blended, additional mixing was performed for a few extra seconds to achieve a homogeneous consistency. Proper mixing is crucial to ensure the even distribution of solidifiers throughout the clay matrix, as this directly influences the mechanical properties and overall performance of the final samples (Bell, 1996).

Once mixed, the next step involved sample preparation, which followed the guidelines outlined in JCAS L-01:2006, "Strength Test Methods for Materials Improved by Cementitious Soil Solidifiers" (Consoli et al., 2010b). This standard provides a reliable framework for preparing and testing solidified soil samples, ensuring reproducibility and compliance with industry standards. The samples were molded into cylindrical shapes with a diameter of 5 cm and a height of 10 cm. To ensure proper compaction and eliminate air pockets, a 1.5 kg rammer was used to compact each layer 12 times at a drop height of 20 cm. Maintaining a consistent mold size and compaction method is essential to achieve uniform sample density, which significantly impacts subsequent strength test results (Nath et al., 2022).

The number of samples prepared varied depending on the specific formulation being tested. Multiple samples were prepared for each formulation to evaluate initial strength as well as strength after 7, 28, and 91 days of curing. This multi-stage testing approach enables a comprehensive assessment of the long-term performance of each formulation, as solidifiers often gain strength over time, particularly

Table 1
Various formulations and their corresponding compositions for geopolymer-based soil solidifiers.

Formulation No.	SCP	ES mixing rate	OPC or $Ca(OH)_2$ replacement rate	Addition rate (kg/m^3)
0	–	–	–	–
1	SCP	–	–	50
2			–	100
3			–	150
4			–	200
5	110 °C heated SCP		–	50
6			–	100
7			–	150
8			–	200
9	200 °C heated SCP		–	50
10			–	100
11			–	150
12			–	200
13	SCP & OPC		10 % OPC of the total solidifier volume	50
14				100
15				150
16				200
17			20 % OPC of the total solidifier volume	150
18	SCP & Ca $(OH)_2$		10 % $Ca(OH)_2$ of the total solidifier volume	50
19				100
20				150
21				200
22	SCP	5 % of the total solidifier volume	–	50
23			–	100
24			–	150
25			–	200
26	110 °C heated SCP		–	50
27			–	100
28			–	150
29			–	200
30	200 °C heated SCP		–	50
31			–	100
32			–	150
33			–	200
34	SCP & OPC		10 % OPC of the total solidifier volume	50
35				100
36				150
37				200
38			20 % OPC of the total solidifier volume	150
39	SCP & Ca $(OH)_2$		10 % $Ca(OH)_2$ of the total solidifier volume	50
40				100
41				150
42				200
43			20 % $Ca(OH)_2$ of the total solidifier volume	150
44				200
45			–	250

when cementitious additives are included (Zhang et al., 2021).

To ensure consistent curing conditions, all samples were stored in a thermostatic chamber maintained at a constant temperature of 20 °C and 100 % humidity. These controlled conditions are essential to simulate an ideal curing environment and minimize external variables that could affect the results (Driss et al., 2021). The combination of regulated temperature and humidity ensures that the hydration and curing processes of the solidifiers proceed uniformly, allowing for accurate comparisons between different formulations (Real et al., 2024). This systematic approach to sample preparation and curing establishes a reliable foundation for subsequent mechanical testing, ensuring that the results obtained are both robust and representative of the potential performance of these materials in real-world applications.

2.4. Test contents and analytical techniques

As part of the preliminary mixing tests, two key evaluations were performed to assess the performance of the improved soil samples: the unconfined compressive test and the leaching test. The unconfined compressive test was conducted to determine the strength characteristics of the improved soil samples, providing insights into their mechanical properties. This test followed the JIS A 1216 standard, “Method for Unconfined Compressive Test of Soils” (Li et al., 2015), a widely accepted method for measuring the compressive strength of soils without lateral confinement. Samples were tested at various curing stages to track strength development over time, offering a comprehensive understanding of the material’s performance evolution. The selected curing ages encompassed both short-term and long-term performance assessments, enabling evaluation of initial setting and continued strength gain (Assouline et al., 1997).

While the unconfined compressive strength test serves as a primary indicator of soil improvement, other mechanical properties such as tensile strength and shear strength are also crucial for a comprehensive assessment of soil stabilization. Tensile strength, often measured through split tensile tests, provides insights into the material’s resistance to cracking. Shear strength, typically evaluated through direct shear or triaxial tests, is essential for understanding soil behavior under lateral loads. However, this study primarily focused on unconfined compressive strength due to its widespread use in geotechnical engineering and its direct correlation with the requirements for Type 3 construction-generated soil. Future studies may incorporate additional mechanical tests to achieve a more complete characterization of the improved soil’s properties.

In addition to mechanical tests, a leaching test was conducted in accordance with the Soil Contamination Countermeasures Act (Mishra and Ohtsubo, 2015). This test was crucial to ensuring that the improved soil did not release harmful substances into the environment, particularly when used in construction applications. By simulating potential leaching conditions, this test served as a safeguard against environmental contamination (Roy and Bhalla, 2017).

A detailed analysis was conducted on mixtures that met the criteria for Type 3 construction-generated soil (PWRI, 2013). Samples from formulations 15, 36, and 41 (Table 1) were tested for toxic substances classified as Class II specified toxic substances, including heavy metals, under the Soil Contamination Countermeasures Act (Xing et al., 2021). The presence of toxic substances in construction materials is a significant concern due to their potential risks to human health and the environment. Notably, hexavalent chromium, a highly toxic substance, was analyzed in samples from formulations 3 and 24 (Abdelkader et al., 2022). Additional leaching tests for arsenic (As) were conducted on formulations 43, 44, and 45 after initial tests on formulations 36 and 41 revealed arsenic levels exceeding regulatory standards. To address this issue, further tests were performed to assess the effect of increasing the amount of calcium hydroxide ($Ca(OH)_2$) in the soil improvement mixture. Calcium hydroxide ($Ca(OH)_2$) was incorporated with the expectation that its alkaline nature would suppress arsenic leaching, effectively stabilizing the contaminant within the soil matrix (Goodarzi et al., 2016). The leaching results were compared to the soil environmental standards outlined in the Environment Agency’s 1991 Notification No. 46, which provides strict guidelines for acceptable contaminant levels (Muhmed et al., 2022).

The use of cladding materials from demolished buildings as solidifiers also required careful consideration, particularly regarding potential asbestos contamination. Asbestos, valued for its fire resistance and durability, was widely used in siding materials from the 1960s until its ban in 2004 under the “Cabinet Order for Partial Revision of the Order for Enforcement of the Industrial Safety and Health Law” (Cabinet Order No. 457 of 2003) (Herath et al., 2020). Given the hazardous nature of asbestos, it was essential to verify that the SCP used in this study was free from asbestos contamination. A qualitative analysis of asbestos content was conducted following the JIS A 1481-2 (2016) standard (Cui et al., 2010). This analysis was performed on SCP before mixing with soil to ensure that no asbestos fibers were present. The samples analyzed included SCP alone (used in formulations 1–12), SCP with 10 % OPC and ES (formulations 34, 35, 36, and 37), and SCP with 10 % calcium hydroxide ($Ca(OH)_2$) and ES (formulations 39, 40, 41, and 42) (Garzón et al., 2010). These tests confirmed that the materials used in the study complied with safety regulations and posed no health risks.

Additionally, SEM-EDS (Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy) analysis was performed on one sample after the unconfined compressive test. This advanced analytical technique enabled detailed observation of microstructural changes that occurred during the solidification process between the soil and the solidifier (Yong and Ouhadi, 2007). SEM provided high-resolution images of the solidifier's structure, while EDS identified the chemical elements present in the reaction products (Weckhuysen et al., 1996). This analysis was critical for understanding the mechanisms behind strength improvement, offering insights into the specific compounds formed during chemical reactions between the soil and the additives. By identifying these reaction products, the study aimed to correlate microstructural changes with observed mechanical properties, providing a deeper understanding of the material's overall performance (Zhao et al., 2015).

This study employed several analytical techniques to evaluate the performance and environmental impact of geopolymer-based soil solidifiers:

(1) Unconfined Compressive Strength Tests: Conducted according to the JIS A 1216 standard to assess the mechanical properties of the improved soil samples.
(2) Leaching Tests: Performed in accordance with the Soil Contamination Countermeasures Act to evaluate the potential release of harmful substances, particularly arsenic (As) and hexavalent chromium (Cr(VI)).
(3) Asbestos Content Analysis: Conducted following the JIS A 1481-2 (2016) standard to confirm the absence of asbestos in SCP samples.
(4) SEM-EDS Analysis: Used to observe microstructural changes and elemental composition of solidified samples, providing insights into the formation of silicate and aluminosilicate compounds.

These techniques were carefully selected to provide a comprehensive assessment of the solidifiers' performance, environmental safety, and microstructural characteristics.

2.5. Integrated analysis framework

The combination of unconfined compressive tests, leaching tests, and SEM-EDS analysis forms a fundamental component of our proposed methodology. This integrated approach enables a comprehensive evaluation of the performance, environmental impact, and microstructural characteristics of geopolymer-based soil solidifiers.

Unconfined compressive tests provide critical data on the mechanical strength of the improved soil, directly relating to its suitability for construction applications. Leaching tests address environmental concerns by assessing the potential release of hazardous substances, ensuring compliance with regulatory standards. SEM-EDS analysis offers insights into the microstructural changes and chemical compositions that underpin the observed macroscopic properties.

By integrating these diverse analytical techniques, we can establish correlations between solidifier composition, strength development, contaminant immobilization, and microstructural evolution. This holistic approach facilitates a more robust evaluation of the solidifiers' performance and enables the optimization of formulations for specific applications and environmental conditions.

While a Design of Experiments (DOE) approach was considered to manage the large number of potential combinations, we opted for a more targeted experimental design based on preliminary studies and theoretical considerations. This strategy allowed us to focus on the most promising formulations while still exploring a range of compositions and treatment conditions. Future studies could benefit from a more systematic DOE approach to further refine solidifier formulations and optimize processing parameters.

3. Results and discussion

3.1. Mechanical and microstructural properties

3.1.1. Unconfined compressive test

Type 3 construction-generated soil, as specified by the regulations of the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT), Japan, is defined as construction-generated soil with a cone index (q_c) of 400 kN/m^2 or greater (PWRI, 2013). The relationship between unconfined compressive strength (q_u) and the cone index (q_c) was investigated by Lunne et al. (2002) and empirically derived from laboratory and field experiments on clays from two sites in the Kanto region. This relationship is expressed by Equation (1) (PWRI, 2013; Yamashita et al., 2016):

$$q_u = \frac{q_c}{5} \tag{1}$$

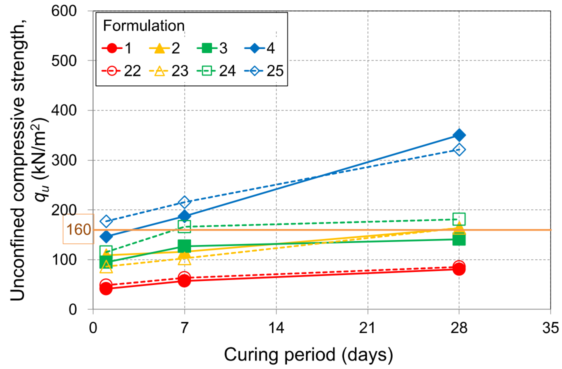
According to Equation (1), if solidified-improved soil achieves an unconfined compressive strength of 80 kN/m^2 or greater, it qualifies as Type 3 construction-generated soil (PWRI, 2013). However, when solidifiers are applied in the field, achieving uniform mixing across the site can be challenging, often resulting in lower strength than laboratory tests indicate. To account for this discrepancy, a correction factor known as the "field/laboratory strength ratio" is applied as an empirical guide (Nakagawa et al., 2020). For example, the field/laboratory strength ratio ranges from 0.3 to 0.73 for the improvement of general soft soils using a powder-mixing solidifier with a backhoe. In this study, the intermediate value of 0.5 was used, setting the target unconfined compressive strength in preliminary laboratory mixing tests at 160 kN/m^2 or greater.

The changes in unconfined compressive strength of the samples over time are shown in Fig. 3. When comparing SCP alone with SCP plus ES at a solidifier addition rate of 150 kg/m^3 (i.e., formulations 3 and 24 in Fig. 3(a)), samples with SCP alone exhibited unconfined compressive strengths below 160 kN/m^2, whereas those with ES exceeded this threshold.

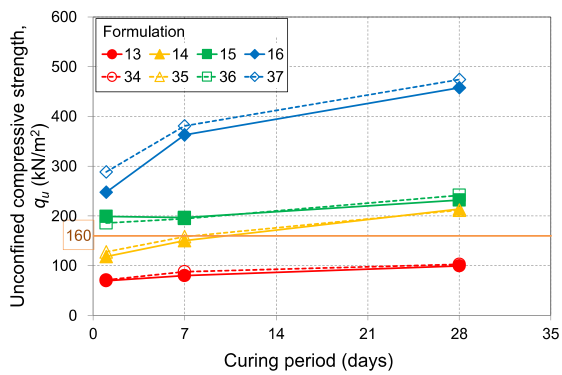
For formulations containing SCP and OPC, Fig. 3(b) shows that samples incorporating OPC exhibited higher overall strength than those with SCP alone (Fig. 3(a)), demonstrating the strengthening effect of OPC. In samples with 100 kg/m^3 of solidifier, the unconfined compressive strength was below 160 kN/m^2 after 7 days of curing but exceeded this threshold after 28 days. Notably, there was no significant difference in compressive strength between samples with and without ES (i.e., formulations 14 and 35 in Fig. 3(b)).

For formulations incorporating SCP and $Ca(OH)_2$, shown in Fig. 3(c), samples with solidifier addition rates of 150 kg/m^3 and 200 kg/m^3 (i.e., formulations 20, 21, 41, and 42) exhibited even higher unconfined compressive strengths than those with SCP and OPC (i.e., formulations 15, 16, 36, and 37 in Fig. 3(b)). Samples with 100 kg/m^3 of solidifier (i.e., formulations 19 and 40 in Fig. 3(c)) exhibited compressive strengths below 160 kN/m^2 after 7 days of curing, similar to SCP and OPC samples (i.e., formulations 14 and 35 in Fig. 3(b)), but exceeded this threshold after 28 days. As with the SCP and OPC formulations in Fig. 3(b), differences in unconfined compressive strength between SCP and $Ca(OH)_2$ formulations with and without ES were minimal, as shown in Fig. 3(c).

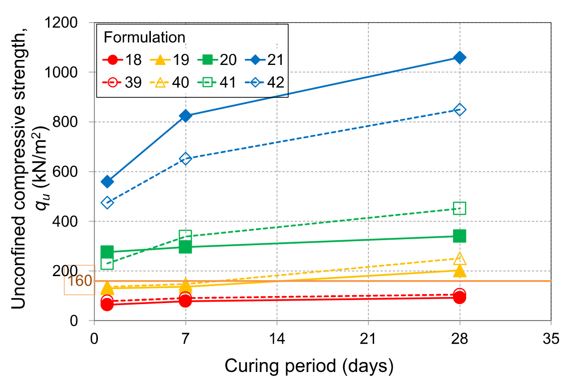
Regarding the effect of heat treatment on SCP activation, for samples with unheated SCP, a solidifier addition rate of 200 kg/m^3 (i.e., formulations 4 and 25 in Fig. 3(a)) was required to achieve the target strength of 160 kN/m^2 after 7 days of curing, meeting the requirements



(a) Samples of clay with w = 40% mixed with SCP with and without ES



(b) Samples of clay with w = 40% mixed with SCP and 10% OPC of SCP with and without ES



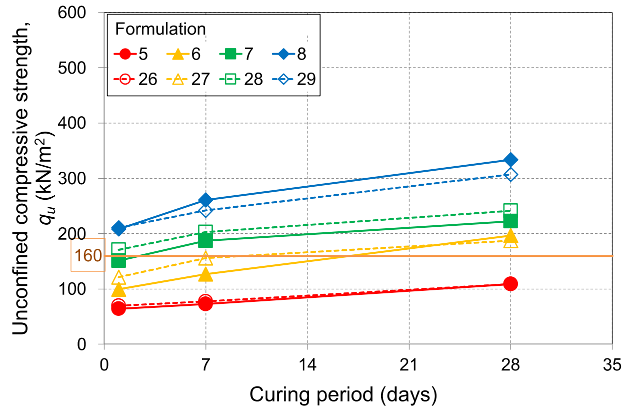
(c) Samples of clay with w = 40% mixed with SCP and 10% $Ca(OH)_2$ of SCP with and without ES

Fig. 3. Changes in unconfined compressive strength over time for samples made with different formulations.

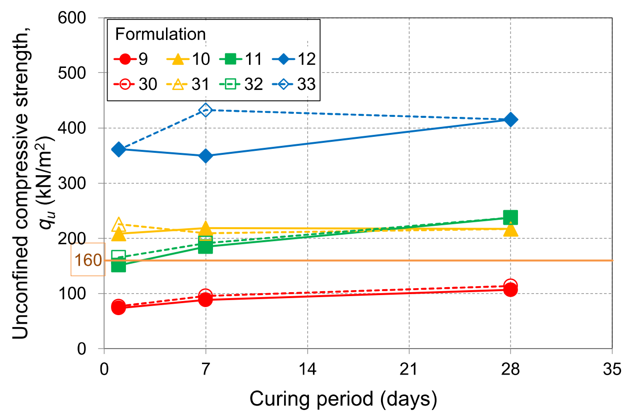
for Type 3 construction-generated soil. However, as shown in Fig. 3(d), when SCP was heated to 110 °C and used as a solidifier, an addition rate of 150 kg/m^3 (i.e., formulations 7 and 28) was sufficient to meet the strength requirement after 7 days. Furthermore, as shown in Fig. 3(e), when SCP was heated to 200 °C, only 100 kg/m^3 of solidifier (i.e., formulations 10 and 31) was necessary to achieve the target strength.

The enhanced strength development observed with heat-treated SCP can be attributed to several chemical mechanisms. Thermal activation of SCP at 110 °C and 200 °C likely increases the reactivity of aluminosilicate phases present in the material. This heightened reactivity promotes more efficient geopolymerization when activated by alkaline solutions or calcium hydroxide. Additionally, heat treatment may partially dehydroxylate clay minerals in SCP, making them more susceptible to dissolution and subsequent participation in geopolymer network formation.

The interaction between C-S-H formation and geopolymerization is complex and synergistic. In formulations containing OPC or $Ca(OH)_2$, calcium ions promote the formation of C-S-H phases, contributing to early strength gain. Simultaneously, the alkaline environment facilitates the dissolution of aluminosilicates from SCP, leading to geopolymer gel



(d) Samples of clay with w = 40% mixed with SCP heated to 110°C with and without ES



(e) Samples of clay with w = 40% mixed with SCP heated to 200°C with and without ES

Fig. 3. (*continued*).

formation. These two processes occur in parallel, with C-S-H providing a matrix that can be interpenetrated by geopolymer gel, resulting in a composite binder system with enhanced mechanical properties. The presence of both C-S-H and geopolymer gels likely contributes to the observed improvements in compressive strength, particularly in formulations combining heat-treated SCP with calcium-rich additives.

3.1.2. SEM-EDS analysis

The crystalline structure of the soil-improvement bodies (samples) after curing was examined using SEM-EDS (Scanning Electron Microscopy-Energy Dispersive X-ray Spectroscopy), an analytical technique that combines high-resolution imaging with elemental analysis. This method records the spatial distribution of elements by detecting the X-rays emitted from atoms in the sample when excited by electron beams.

The characteristic structures observed in the SEM-EDS analysis are presented in Fig. 4. In each sub-figure—Fig. 4(a), 4(b), 4(c), and 4(d)—the left image is a scanning electron microscopy (SEM) image, while the right image displays the corresponding energy dispersive X-ray spectroscopy (EDS) results. The bar graphs below each EDS distribution plot illustrate the percentage composition of detected elements.

Fig. 4(a) presents a sample from an unconfined compressive test cured for 28 days, where only SCP was used as a solidifier, equivalent to formulation 3 in Table 1, with an addition rate of 150 kg/m^3. The crystals circled in red in the SEM image correspond to the red-highlighted region in the 2D EDS distribution, indicating a high concentration of silicon (Si) with some aluminum (Al) and trace amounts of other elements. These crystals are presumed to be silicate compounds, including silica and possibly some aluminosilicate compounds.

Fig. 4(b) shows a sample from an unconfined compressive test cured for 7 days, where ES was added to SCP as a solidifier, corresponding to formulation 24 in Table 1, also with an addition rate of 150 kg/m^3. The area circled in red in the SEM image exhibits a high silica concentration with some aluminum (Al), confirming the presence of silicate and aluminosilicate compounds.

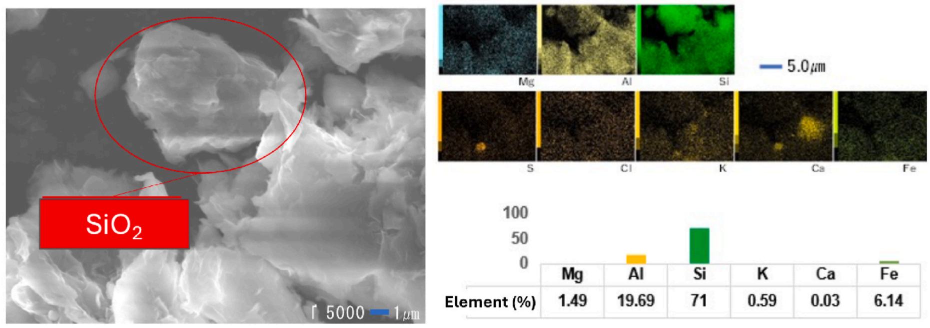
Fig. 4(c) depicts a specimen from an unconfined compressive test cured for 7 days, where SCP was used, with 20 % of SCP replaced by OPC, at an addition rate of 150 kg/m^3, corresponding to formulation 17 in Table 1. The crystals circled in red in the SEM image align with the EDS calcium (Ca) image, showing a significant calcium distribution in the highlighted region. These crystals are identified as calcium silicate hydrate (C-S-H), a hydration product of OPC.

Fig. 4(d) illustrates a specimen from an unconfined compressive test cured for 1 day, where a mixture of SCP, 20 % replacement of SCP with OPC, and ES was used at an addition rate of 150 kg/m^3, corresponding to formulation 38 in Table 1. Similar to Fig. 4(c), the C-S-H crystals are distinctly visible in the SEM image. The corresponding EDS calcium image reveals a clear calcium distribution in the circled area, confirming the presence of C-S-H crystals.

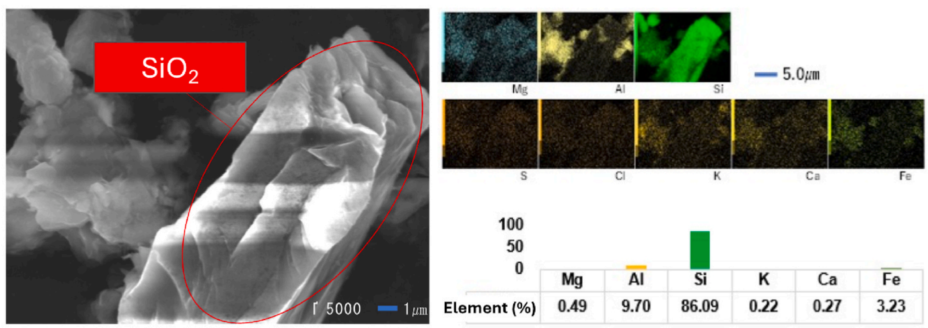
3.2. Environmental and chemical properties

3.2.1. Hazardous substance analysis

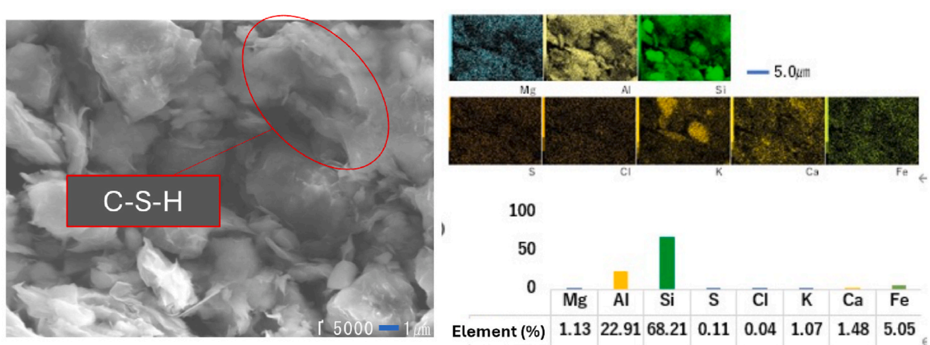
The results of the soil leaching test for contaminants and the



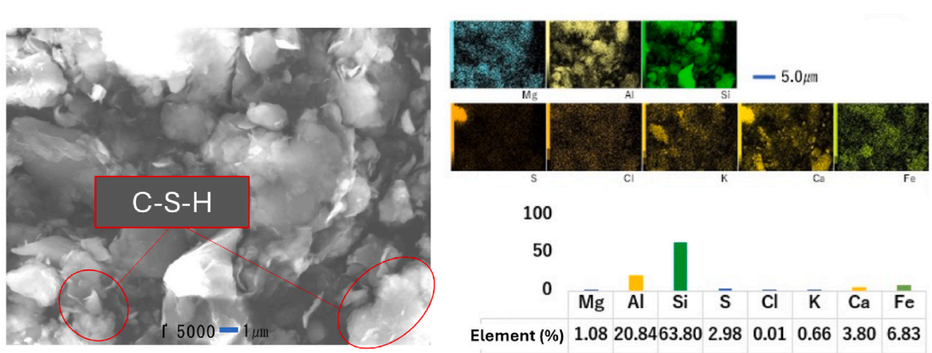
(a) Formulation 3 after 28 days of curing



(b) Formulation 24 after 7 days of curing



(c) Formulation 17 after 7 days of curing



(d) Formulation 38 after 1 day of curing

Fig. 4. Characteristic structures of specific samples and cure times observed through SEM-EDS analysis.

qualitative analysis test for asbestos content are presented in Table 2. The qualitative analysis confirmed that the SCP used in this study did not contain asbestos. However, the soil leaching test revealed that some samples contained arsenic (As) and its compounds at levels exceeding the “Environmental Quality Standards for Soil Contamination” established by the Ministry of the Environment under Japan’s “Basic Environmental Law” (Barrett and Therivel, 2019). Specifically, formulation 36, which contained SCP, 10 % OPC of SCP, and ES, as listed in Table 2, and formulation 41, which contained SCP, 10 % $Ca(OH)_2$ of SCP, and ES, exhibited As leaching levels above the regulatory threshold of 0.01 mg/L.

In contrast, formulations 43, 44, and 45, which contained SCP, 20 % $Ca(OH)_2$ of SCP, and ES, had As leaching levels below the regulatory limit (Table 2). Additionally, formulation 15, which contained SCP and 10 % OPC of SCP but no ES, met the environmental standard with an As leaching level of 0.01 mg/L.

The formulations 43, 44, and 45, which successfully reduced As leaching, incorporated increasing solidifier addition rates of 150 kg/m^3, 200 kg/m^3, and 250 kg/m^3, respectively. Correspondingly, the As leaching levels decreased sequentially to 0.007 mg/L, 0.003 mg/L, and 0.002 mg/L. This suggests that calcium ions (Ca^{2+}) released from the dissolution of $Ca(OH)_2$ react with As compounds present as As ions under neutral to alkaline conditions to form insoluble calcium arsenate ($Ca_3(AsO_4)_2$), thereby inhibiting As leaching.

To determine the source of As leaching beyond the environmental regulatory standards observed in the soil leaching test, additional As leaching tests were conducted on 12 samples. These samples included the target soil, individual solidifier components, solidifier component mixtures (including the target soil), and samples mixed with the solidifier used in unconfined compressive tests. The breakdown of these 12 samples is presented in Table 3.

The results of the leaching tests for the target soil, individual

Table 2
Results of soil leaching tests for Cr(VI) and qualitative analysis of asbestos content.

Formulation No.	Solidifier	Type 3 construction-generated soil ($q_u \geq 160$ kN/m^2)	Cr(VI)	As	Asbestos
			Environmental standard ≤0.05 mg/L	Environmental standard ≤0.01 mg/L	Environmental standard ≤0.1 %
0	–	–	–	–	–
1	SCP	x	–	–	≤0.1 %
2		x	–	–	
3		x	≤0.05 mg/L	–	
4		o	–	–	
5	110 °C heated SCP	x	–	–	–
6		x	–	–	
7		o	–	–	
8		o	–	–	
9	200 °C heated SCP	x	–	–	–
10		o	–	–	
11		o	–	–	
12		o	–	–	
13	SCP & OPC	x	–	–	–
14		x	–	–	
15		o	≤0.05 mg/L	≤0.01 mg/L	
16		o	–	–	
17		o	–	–	
18	SCP & $Ca(OH)_2$	x	–	–	–
19		x	–	–	
20		o	–	–	
21		o	–	–	
22	SCP & ES	x	–	–	–
23		x	–	–	
24		o	≤0.05 mg/L	–	
25		o	–	–	
26	110 °C heated SCP & ES	x	–	–	–
27		x	–	–	
28		o	–	–	
29		o	–	–	
30	200 °C heated SCP & ES	x	–	–	–
31		o	–	–	
32		o	–	–	
33		o	–	–	
34	SCP, OPC & ES	x	–	–	≤0.1 %
35		x	–	–	
36		o	0.07 mg/L	0.026 mg/L	
37		o	–	–	
38		o	–	–	–
39	SCP, $Ca(OH)_2$ & ES	x	–	–	≤0.1 %
40		x	–	–	
41		o	≤0.05 mg/L	0.031 mg/L	
42		o	–	–	
43		o	–	≤0.01 mg/L	–
44		o	–	≤0.01 mg/L	
45		o	–	≤0.01 mg/L	

Table 3
Breakdown of arsenic (As) leaching test samples.

Target soil	(a) Clay (before water is added)
Solidifier components	(b) SCP (siding cut)
	(c) ES (alkaline stimulant)
	(d) OPC (ordinary Portland cement)
	(e) $Ca(OH)_2$ (calcium hydroxide)
Solidifier component mixtures (including the target soil)	(f) SCP + ES
	(g) SCP + clay (before water is added)
	(h) SCP + OPC
	(i) SCP + $Ca(OH)_2$
Sample mixed with the solidifier	(j) Clay with w = 40 % mixed with SCP alone as a solidifier at a rate of 150 kg/m^3
	(k) Clay with w = 40 % mixed with SCP + ES as a solidifier at a rate of 150 kg/m^3
	(l)Clay with w = 40 % mixed with SCP + Ca (OH)$_2$ as a solidifier at a rate of 150 kg/m^3

solidifier components, the solidifier itself, and each sample mixed with the solidifier are shown in Table 4. The leaching of As and its compounds from samples (b), (d), and (e) was below the detection limit. However, the leaching of As and its compounds from samples (a) and (c) exceeded the Environmental Quality Standards for Soil Contamination. Among the solidifiers, sample (g) also exceeded the regulatory threshold. Furthermore, samples mixed with solidifiers (j), (k), and (l) exhibited As leaching above the regulatory limit.

The results indicate that the ES and the clay are the primary sources of As leaching. ES consists of glass powder derived from recycled glass cullet, along with refined alkaline compounds. The glass powder originates from wear particles generated during the processing of recycled glass cullet. Arsenic compounds, such as arsenic trioxide (As_2O_3), may be added as deaerators in the manufacture of high-transmittance glass, which serves as a source material for the cullet. Consequently, As present in the original glass may leach under alkaline stimulation.

Additionally, the clay used in this study is a natural mineral sourced from dark gray mudstone layers, believed to have been deposited after the Neogene Miocene epoch (Ito and Wagai, 2017). According to the geochemical map published by the National Institute of Advanced Industrial Science and Technology (AIST), the clay originates from a region with naturally high As content in the soil (Ohta, 2018).

The leaching test results for each sample mixed with the solidifier components (j), (k), and (l) indicate that the primary cause of As leaching is the clay itself, leading to exceedances of environmental quality standards in all cases. Notably, sample (k), which contained ES, exhibited the highest As leaching concentration at 0.030 mg/L. In contrast, sample (l), in which 20 % of SCP was replaced with calcium hydroxide ($Ca(OH)_2$), demonstrated a reduced As leaching level of 0.018 mg/L, a 40 % decrease compared to sample (k). This reduction can be attributed to the Ca^{2+} ions derived from $Ca(OH)_2$, which help suppress the leaching of As compounds by promoting the formation of insoluble arsenates.

3.2.2. Chemical characterization of solidifier compositions

To provide a comprehensive understanding of the geopolymer-based soil solidifiers developed in this study, chemical analyses were conducted on each composition using X-ray fluorescence (XRF) spectroscopy. Table 5 presents the major oxide compositions of the primary components and selected solidifier formulations.

The chemical composition of SCP reflects its origin as a waste product from siding materials, exhibiting high silica and alumina content characteristic of clay-based components. ES, derived from glass powder, contains a significantly higher silica content along with elevated sodium levels due to the alkaline admixture used in its preparation.

The incorporation of ES into SCP (Formulation 24) results in a slight increase in silica content while introducing additional sodium, which is crucial for the alkaline activation process in geopolymerization. Formulations 36 and 41, which incorporate OPC and $Ca(OH)_2$, respectively, exhibit increased calcium content compared to SCP alone. This additional calcium plays a vital role in the formation of calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H) phases, contributing to the enhanced strength and durability observed in these formulations.

The chemical characterization confirms that the developed solidifiers maintain a high silica-to-alumina ratio, which is favorable for geopolymer formation. The presence of alkali metals (Na and K) and alkaline earth metals (Ca and Mg) in appropriate quantities supports the geopolymerization process and facilitates the development of a robust, interconnected aluminosilicate network.

3.3. Durability and performance evaluations

3.3.1. Chemical resistance and durability

The long-term durability of the developed geopolymer-based soil solidifiers was evaluated through a series of chemical resistance tests. Samples were subjected to accelerated aging processes to assess their resistance to sulfate attack, chloride ingress, and alkali-silica reaction (ASR).

Sulfate resistance was tested by immersing samples in a 5 % sodium sulfate solution for 90 days. The SCP-ES formulations exhibited excellent resistance, with mass loss remaining below 1 % and no significant reduction in strength. This superior performance can be attributed to the dense microstructure of the geopolymer matrix and the low calcium content, which limits the formation of expansive ettringite.

Table 4
Results of arsenic (As) leaching tests for 12 samples.

			SCP (%)	ES (%)	Clay (%)	OPC (%)	Ca (OH)$_2$ (%)	As (mg/ L)	Judge.
Target soil	(a)	Clay (before water is added)	100	–	–	–	–	0.018	x
Solidifier components	(b)	SCP (siding cut)	–	100	–	–	–	<0.001	o
	(c)	ES (alkaline stimulant)	–	–	100	–	–	0.015	x
	(d)	OPC (ordinary Portland cement)	–	–	–	100	–	<0.001	o
	(e)	$Ca(OH)_2$ (calcium hydroxide)	–	–	–	–	100	<0.001	o
Solidifier component mixtures (including the target soil)	(f)	SCP + ES	95.2	4.80	–	–	–	0.007	o
	(g)	SCP + clay (before water is added)	10.7	–	89.3	–	–	0.011	x
	(h)	SCP + OPC	90.0	–	–	10.0	–	<0.001	o
	(i)	SCP + $Ca(OH)_2$	90.0	–	–	–	10.0	<0.001	o
Sample mixed with the solidifier	(j)	Clay with w = 40 % mixed with SCP alone as a solidifier at a rate of 150 kg/m^3	7.90	–	92.1	–	–	0.011	x
	(k)	Clay with w = 40 % mixed with SCP + ES as a solidifier at a rate of 150 kg/m^3	7.53	0.39	92.1	–	–	0.030	x
	(l)	Clay with w = 40 % mixed with SCP + $Ca(OH)_2$ as a solidifier at a rate of 150 kg/m^3	6.02	0.38	92.1	–	1.51	0.018	x

Table 5
Chemical composition of primary components and selected solidifier formulations.

Component	SiO_2 (wt%)	Al_2O_3 (wt%)	CaO (wt%)	Fe_2O_3 (wt%)	MgO (wt%)	Na_2O (wt%)	K_2O (wt%)	TiO_2 (wt%)	P_2O_5 (wt%)	LOI (wt%)
SCP	62.3	14.8	8.2	3.7	2.1	1.8	2.4	0.7	0.2	3.8
ES	72.5	1.2	9.8	0.3	0.2	15.1	0.5	0.1	0.1	0.2
OPC	21.0	5.2	64.5	3.1	1.8	0.3	0.7	0.3	0.2	2.9
Form. 24	63.1	14.2	8.3	3.5	2.0	2.5	2.3	0.7	0.2	3.2
Form. 36	58.9	13.6	13.8	3.5	2.0	2.3	2.2	0.6	0.2	2.9
Form. 41	59.4	13.7	13.2	3.4	2.0	2.3	2.2	0.6		3.0

LOI: Loss on ignition.

Chloride ingress was evaluated using the rapid chloride permeability test (ASTM C1202). The SCP-ES samples demonstrated very low chloride ion penetrability, with charge passed values below 1000 coulombs after 28 days of curing. This indicates a highly resistant microstructure capable of effectively preventing chloride-induced corrosion in reinforced applications.

Alkali-silica reaction (ASR) potential was assessed using the accelerated mortar bar method (ASTM C1260). The SCP-ES formulations exhibited minimal expansion ($<$0.1 % after 14 days), significantly lower than the 0.2 % threshold for potentially deleterious expansion. This high resistance to ASR is likely due to the low calcium content and the high alkali-binding capacity of the geopolymer gel structure.

Weathering resistance was evaluated through freeze-thaw cycling (ASTM C666). After 300 cycles, the SCP-ES samples retained over 95 % of their original strength and exhibited minimal surface scaling, indicating excellent durability under harsh environmental conditions.

These results demonstrate that the developed geopolymer-based soil solidifiers possess superior chemical resistance and durability compared to traditional OPC-based systems, ensuring long-term performance in aggressive environments.

3.3.2. Setting time and workability

The setting time and workability of the geopolymer-based soil solidifiers were evaluated to determine their suitability for field applications. Initial setting times ranged from 2 to 4 h, depending on the formulation, with final setting occurring within 6–8 h. This setting behavior provides sufficient time for mixing and compaction while ensuring relatively rapid strength development.

Workability tests indicated that the mixtures remained fluid for approximately 30–45 min after water addition, providing an adequate window for proper mixing and compaction. The measured slump values ranged from 150 to 180 mm, indicating good flowability and ease of placement. However, formulations with higher calcium hydroxide content exhibited slightly reduced workability, likely due to the rapid formation of calcium silicate hydrate.

These characteristics suggest that the developed soil solidifiers are well-suited for various field applications, enabling efficient mixing, transportation, and compaction within typical construction timeframes.

3.3.3. Thermal properties

The thermal properties of the developed geopolymer-based soil solidifiers were investigated to assess their performance and stability under various temperature conditions. Differential Scanning Calorimetry (DSC) analysis revealed that the heat of hydration for the SCP-ES formulations was approximately 15–20 % lower than that of conventional OPC-based solidifiers, reducing the risk of thermal cracking in large-scale applications.

Thermogravimetric Analysis (TGA) demonstrated that the SCP-ES solidifiers exhibited excellent thermal stability up to 800 °C, with weight loss primarily occurring in two stages: dehydration of physically bound water (30–200 °C) and decomposition of calcium silicate hydrate (C-S-H) phases (400–600 °C). Formulations containing calcium hydroxide showed enhanced thermal resistance, likely due to the formation of more stable calcium aluminosilicate hydrate (C-A-S-H) phases.

These thermal characteristics suggest that the developed geopolymer-based solidifiers are suitable for a wide range of environmental conditions and may offer improved performance in applications involving elevated temperatures or thermal cycling.

3.4. Material characteristics and economic feasibility

3.4.1. Particle size distribution and porosity analysis

The particle size distribution and porosity of the binding materials play a significant role in the performance of geopolymer-based soil solidifiers. Laser diffraction analysis revealed that the Siding Cut Powder (SCP) had a median particle size (D_{50}) of 15 μm, with 90 % of particles (D_{90}) smaller than 45 μm. The Earth Silica (ES) exhibited a finer distribution, with a D_{50} of 8 μm and a D_{90} of 25 μm. This fine particle size distribution enhances material reactivity and contributes to improved void-filling within the soil matrix.

Mercury Intrusion Porosimetry (MIP) tests on cured samples showed that the total porosity of the solidified soil ranged from 25 % to 35 %, depending on the formulation. Samples containing ES generally exhibited lower porosity (25–30 %) compared to those with SCP alone (30–35 %), likely due to the finer particle size of ES, which promotes more efficient pore filling. The pore size distribution was predominantly in the mesopore range (2–50 nm), with a significant proportion of micropores ($<$2 nm) in ES-containing samples, indicating the formation of a dense geopolymeric gel structure.

The combination of fine particle sizes and the resulting pore structure contributes to the improved mechanical properties and reduced permeability of the stabilized soil. The presence of micropores in ES-containing samples may also explain their enhanced ability to immobilize contaminants, as observed in the leaching tests.

3.4.2. Availability and economic feasibility

The availability of SCP is closely tied to the construction and renovation industry. In North America, vinyl siding is widely used, with installation costs ranging from $1.30 to $1.50 per square foot. The cutting process for siding panels generates significant amounts of powdered dust, of which only 5.9 % is reused, while 94.1 % is disposed of as industrial waste. This indicates a substantial potential supply of SCP for geopolymer production.

Economically, the proposed geopolymer-based soil solidifiers show promise when compared to OPC. While the initial cost of ternary mixtures may vary depending on the supplementary cementitious materials used, the increased durability of geopolymer concretes can lead to reduced life cycle costs, particularly in infrastructure applications such as pavements and bridge decks.

Furthermore, the environmental benefits of using industrial by-products like SCP and recycled glass in geopolymer production enhance economic feasibility. By reducing reliance on carbon-intensive OPC and minimizing industrial waste, this approach aligns with sustainable construction practices and may benefit from potential carbon pricing or environmental regulations.

However, the economic viability of geopolymer-based solidifiers may vary depending on local material availability and transportation costs. Future research should include a comprehensive life cycle assessment and cost analysis to fully evaluate the economic feasibility of SCP-based geopolymers compared to OPC in various applications and geographical contexts.

4. Conclusions

4.1. Key findings and implications

This study developed an environmentally sustainable soil solidifier using Siding Cut Powder (SCP), an industrial by-product, activated with Earth Silica (ES), a recycled waste glass-based alkaline stimulant. The research aimed to address the dual challenges of reducing reliance on Ordinary Portland Cement (OPC) and promoting industrial waste recycling.

The key findings and implications are summarized as follows:

4.1.1. Key findings

(1) Mechanical Performance: SCP activated with ES significantly improved soil compressive strength, consistently exceeding the construction-grade threshold of 160 kN/m^2. Thermal treatment of SCP further enhanced its reactivity, allowing for reduced solidifier dosage.
(2) Environmental Safety: The addition of calcium hydroxide ($Ca(OH)_2$) effectively mitigated arsenic leaching, ensuring compliance with environmental standards.
(3) Microstructural Insights: SEM-EDS analysis revealed the formation of silicate and aluminosilicate compounds, contributing to enhanced mechanical stability and durability.
(4) Durability and Chemical Resistance: SCP-ES formulations demonstrated excellent resistance to sulfate attack, chloride ingress, alkali-silica reaction, and freeze-thaw cycles, indicating suitability for long-term use in harsh environments.

4.1.2. Implications

The results highlight the potential of SCP-ES formulations as a low-carbon alternative to OPC-based soil solidifiers. By utilizing industrial by-products such as SCP and ES, this approach not only reduces carbon emissions but also addresses waste management challenges in the construction industry. The scalability and adaptability of these materials make them a promising solution for diverse geotechnical applications.

4.2. Future research directions

To further advance this technology, future studies should focus on:

(1) Optimizing SCP-ES formulations for various soil types and environmental conditions.
(2) Conducting large-scale field trials to validate laboratory findings under real-world conditions.
(3) Investigating the long-term durability of SCP-ES solidified soils under extreme weathering conditions.
(4) Exploring additional industrial by-products to enhance sustainability and performance.
(5) Developing standardized testing protocols for geopolymer-based soil solidifiers.

4.3. Summary

This study establishes a strong foundation for sustainable soil stabilization using geopolymer technology with SCP and ES as key components. The findings demonstrate that this approach can achieve high mechanical performance while addressing critical environmental concerns such as carbon emissions reduction and waste utilization. With continued research and development, SCP-ES formulations have the potential to revolutionize soil stabilization practices and contribute significantly to sustainable construction methods worldwide.

CRediT authorship contribution statement

Shinya Inazumi: Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization. **Ryo Hashimoto:** Resources, Methodology, Investigation, Formal analysis, Data curation. **Yoji Hontani:** Resources, Methodology, Investigation. **Atsuya Yoshimoto:** Methodology, Investigation. **Ken-ichi Shishido:** Validation, Software, Investigation. **Kuo Chieh Chao:** Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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