

ALTERNATIVE SOIL IMPROVEMENT USING HYDRAULIC CEMENT COMBINATION WITH STEEL SLAG AND BIOCHAR: STRENGTH AND MICROSTRUCTURAL CHARACTERISTICS

*Supakij Nontananandh¹, Nattapas Khumsuprom², Apiniti Jotisankasa³, Susit Chairakaikeow⁴ and Shinya Inazumi⁵

^{1,2,3,4}Department of Civil Engineering, Kasetsart University, Bangkok, Thailand;

⁵College of Engineering, Shibaura Institute of Technology, Tokyo, Japan

*Corresponding Author, Received: 30 May 2025, Revised: 13 Jan. 2026, Accepted: 15 Jan. 2026

ABSTRACT: Soil improvement is a critical challenge in geotechnical engineering, especially for weak soils like dredged sediments. This study proposes an alternative stabilization method using hydraulic cement (HC), partially replaced with steel slag (SS), and enhanced with bamboo biochar in both soaked and dry forms. Various tests, including unconfined compressive strength (UCS), free-free resonance (FFR), X-ray diffraction (XRD), and scanning electron microscopy (SEM), were conducted to evaluate mechanical and microstructural behavior. Results indicated that the mixture with 25% steel slag substitution achieved a 7-day UCS of 900.15 kPa, exceeding the standard subbase requirement of 689 kPa. The inclusion of both kinds of biochar significantly enhanced early-stage strength development, with certain combinations reaching UCS values of 769.37 kPa and 658.47 kPa after only 3 days of curing, whereas the mixture without biochar exhibited a lower UCS of just 562.59 kPa. Stiffness development, reflected by E_{50} and small-strain elastic moduli (E_0 and G_0) derived from FFR, exhibited trends consistent with UCS, indicating coherent mechanical behavior across different strain levels. XRD and SEM analyses confirmed the formation of calcium silicate hydrate (CSH) and ettringite, validating the chemical stabilization mechanism. This approach promotes sustainability through reduced cement usage and the beneficial reuse of industrial by-products and natural agricultural waste. The findings demonstrate potential for integrating these materials into low-carbon geo-environmental soil stabilization practices, in alignment with circular economy principles and the Sustainable Development Goals (SDGs).

Keywords: Soil Improvement, Steel Slag, Biochar, Unconfined Compressive Strength, Sustainable Geotechnics

1. INTRODUCTION

All types of civil engineering construction should be founded on stable and strong foundations. The structure constructed on soft soils often encounter long-term stability issues such as cracking and settlement. However, due to the limitations imposed by urban expansion and national economic development, construction on soft ground is often unavoidable. Therefore, soil improvement techniques are essential to enhance the engineering properties of the soil such as reducing settlement, decreasing the void ratio, increasing load-bearing capacity, and controlling permeability. The basic technical concepts of soil improvement generally comprise four main approaches: densification, reinforcement, drainage, and cementation [1].

Thailand is a developing country both socially and economically, resulting in a significant rise in construction activities. However, many of these projects encounter challenges due to poor ground conditions. For example, in Bangkok, the capital city, the soil profile comprises 15 to 25 meters of clay, including very soft to soft clay at depths of 3 to 12 meters and medium stiff to very stiff clay below 15 meters [2], creating major challenges for infrastructure projects. This soil consistently presents

geotechnical issues, requiring various improvement techniques to ensure construction feasibility and long-term stability.

Similarly, sediments derived from water sources such as seas, reservoirs, dams, and canals are also problematic soils. These sediments are generally considered waste materials, often classified as fine-grained soils with high initial water content and low strength, making them unsuitable for using in construction. However, their substantial volume presents the problems in terms of disposal and storage. Therefore, there is a proposal to improve the quality of these sediments for use as construction material by using mechanical and chemical stabilization techniques. Ordinary Portland cement (OPC) and quicklime or hydrate lime is commonly used as the primary binder and combined with industrial wastes such as stainless-steel slag, fly ash, and geopolymer materials. The findings of these studies revealed that sediments stabilized with OPC and industrial waste exhibit sufficient unconfined compressive strength (UCS) for potential use as road construction materials. The development of UCS can be confirmed by the formation of chemical reaction products, which are identifiable through X-ray diffraction (XRD) analysis and microstructural observations using a scanning electron microscope

(SEM). Moreover, to better understand the strength-development mechanism of treated soil, many studies have demonstrated that free-free resonance (FFR) test is useful techniques for clarifying the physical and engineering properties such hardness, wave velocity and moduli [3-9].

However, the world is facing the problem of global warming, leading many countries to implement strategies for reducing greenhouse gases (GHGs) emissions. In response to environmental concerns and carbon reduction goals, hydraulic cement (HC) incorporating industrial waste has gained attention as a more sustainable alternative to OPC [10]. Additionally, biochar, which is a porous and carbon-rich material derived from biomass, has shown promise in enhancing soil properties while sequestering atmospheric CO₂. Despite growing interest, few studies have investigated the combined effects of HC, steel slag (SS), and biochar on the early strength and stiffness development of stabilized sediments.

Therefore, this study aims to evaluate the performance of dredged sediment stabilized using HC partially replaced with SS, along with either soaked or dry bamboo biochar (BB). The study assesses unconfined compressive strength (UCS), secant modulus (E_{50}), wave velocities (V_p , V_s), small strain modulus (E_0 , G_0) and microstructural development using XRD and SEM. The goal is to promote the sustainable reuse of industrial and agricultural wastes in geotechnical applications, contributing to geo-environmental engineering and the Sustainable Development Goals (SDGs).

2. RESEARCH SIGNIFICANCE

The increasing generation of industrial, agricultural, and underutilized natural wastes, such as dredged sediments, poses a growing environmental challenge. This study proposes a sustainable approach for stabilizing such materials using HC partially replaced with steel slag and enhanced with bamboo biochar. It uniquely examines the combined effects of these materials, including comparisons of soaked and dry biochar. Free-free resonance (FFR) testing is applied to develop correlations between UCS and wave velocities, offering a non-destructive method for strength assessment. This approach supports the SDGs and advances geo-environmental engineering.

3. MATERIALS

3.1 Dredged Sediment from Drainage Canal

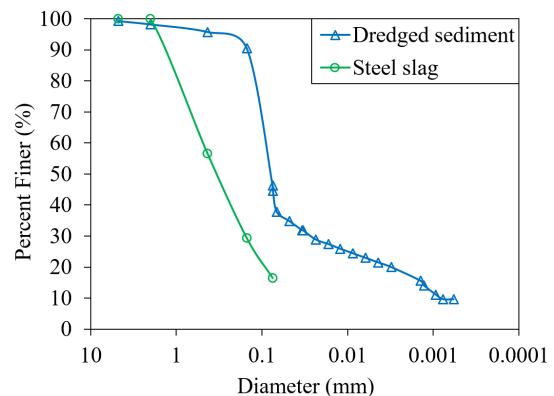
The sediment used in this study was collected from a drainage canal in Phetchaburi province, approximately 176 km southwest of Bangkok. Sediment accumulation in canal significantly affects water management efficiency, as illustrated in Fig. 1.

To address this, the Royal Irrigation Department conducts annual dredging operations. In 2022, approximately 478,000 m³ of sediment was dredged at a total cost of USD 367,126.



Fig. 1 Drainage canal in Phetchaburi province

After six months of air drying, the natural water content of the sediment decreased from 117% to 5%. The sediment was classified as silty sand (SM) under the USCS, and A-4 (0) under AASHTO, indicating suitability for low to medium construction applications [11-12]. It had a specific gravity of 2.67, with 46.29% of particles passing through the No. 200 sieve as illustrated in Fig. 2. The particle size distribution consisted of 0.71% gravel, 51.94% sand, 28.79% silt, and 17.50% clay.



posing a significant challenge for disposal and reuse. In this study, slag was sourced from Siam Machinery and Equipment Co., Ltd. in Ayutthaya province, approximately 82 km north of Bangkok.

The steel slag was dark gray in colour and initially in lump form. Approximately 300 kg of the material was ground and thoroughly homogenised to ensure consistency across all experiments. The processed slag was sieved through a No. 10 sieve, resulting in a mixture that retained some residual steel particles. No intentional removal of these metallic inclusions was carried out, in order to reflect the use of steel slag in its typical industrial form. This may have implications for long-term environmental performance, including the potential generation of metal-rich leachate from the steel particles. Notably, the inclusion of biochar in the mix may offer additional benefits by adsorbing or immobilizing such contaminants, thus contributing to the overall environmental safety of the amended soil. Particle size analysis showed that 16.44% of the slag passed through the No. 200 sieve, as illustrated in Fig. 2. For the chemical compositions of SS, the major constituents were SiO₂ (67.32%) and Al₂O₃ (11.13%), which are comparable to those of the dredged sediment. SS was used as a partial replacement for HC in selected mix designs.

3.3 Biochar

Biochar is a carbon-rich material produced through pyrolysis, a thermal decomposition of biomass in an oxygen-limited environment. Unlike combustion, this process stabilizes carbon into a solid form, making biochar effective for carbon sequestration and reducing greenhouse gas emissions [14-15]. The improvement in water retention of biochar-amended soil has been reported, which provides favorable effects for nature-based soil cover system in geotechnical engineering application [16]. In this study, bamboo biochar produced by Thai Carbon Co., Ltd., located in Nakhon Pathom province (55.2 km from Bangkok), using an industrial scale pyrolysis (US EPA approved technology) was utilized. The obtained sample was in fine black powder form. The manufacturer's datasheet indicates its high specific surface area of 223 m²/g with the pH of 9.60 indicating its alkalinity. This is further supported by the XRF results of BB, which revealed a high potassium oxide (K₂O) content of 28.79% along with 1.15% Na₂O, reflecting the alkaline nature of the biochar. Both dry and water-soaked biochar were incorporated into the mixtures to assess their influence on the mechanical behavior and strength development of the stabilized sediment.

4. METHODOLOGY

4.1 Specimen Preparation and UCS Test

Based on prior research [11-12], dredged sediment was stabilized using a base binder of hydraulic cement at 250 kg/m³ (mass of cement by volume of soil), with a constant soil's moisture content of 17.0%. SS was used as a partial or full replacement for HC at 25% and 100%, respectively. Bamboo biochar was added at 2.68% by weight of dry soil in either dry or soaked form. Seven mix designs (Mix 0-Mix 6) are summarized in Table 1.

Each mix was blended using a Hobart-type mechanical mixer and molded into cylindrical specimens ($\phi = 5.0$ cm, $h = 10.0$ cm) following the method for making and curing non-compacted stabilized soil specimens (JSF T821-1990) [17] as suggested by [4]. Specimens were demolded after 24 hours and cured in plastic sealed for 3 and 7 days.

Unconfined compression tests were conducted on triplicate specimens using a universal testing machine (UTM) at a strain rate of 0.01 min⁻¹, following ASTM D2166 [18]. The maximum strength was recorded either at the peak load or at 15% axial strain, whichever occurred first.

Table 1 Mix proportions and symbols

Symbol	Cement content (% of 250 kg/m ³)		Biochar (% by weight)	
	HC	SS	Dry	Soaked
Mix-0	100	0	0	0
Mix-1	75	25	0	0
Mix-2	0	100	0	0
Mix-3	75	25	0	2.68
Mix-4	0	100	0	2.68
Mix-5	75	25	2.68	0
Mix-6	0	100	2.68	0

4.2 Free-free resonance (FFR) Test

The FFR method, a non-destructive testing technique, was applied to evaluate compressional (V_p) and shear (V_s) wave velocities in the same UCS specimens. Each specimen was excited with an impact at one end, and the response was detected by an accelerometer at the opposite end.

The fundamental resonance frequency (f) was determined, and small-strain modulus including Young's modulus (E_0) and shear modulus (G_0), were calculated using the established relationships:

$$V_p = f_L \lambda = 2 f_L L \quad (1)$$

$$V_s = f_T \lambda = 2 f_T L \quad (2)$$

$$E_0 = \rho (V_p)^2 \quad (3)$$

$$G_0 = \rho (V_s)^2 \quad (4)$$

Where ρ is bulk density, L is the specimen length, f_L and f_T are the longitudinal and torsional resonance frequencies, respectively.

5. RESULTS AND DISCUSSIONS

5.1 Unconfined Compression Test Results

The UCS results of all mixtures after 3 and 7 days are shown in Fig. 3 and Table 2 and Table 3. The findings indicate that both SS and bamboo biochar influence strength development. Although the UCS of Mix-1 (75% HC and 25% SS) at 7 days was lower than that of Mix-0 (100% HC), it represented the highest strength among all mixtures incorporating SS, reaching 900.15 kPa and exceeding the subbase requirement of 689 kPa [19]. Notably, Mix-3, which included 75% HC, 25% SS, and soaked biochar, exhibited the highest early strength, with a 3-day UCS of 769.37 kPa, equivalent to approximately 94% of its 7-day value (830.01 kPa). This 3-day strength exceeded that of both Mix-0 and Mix-1, highlighting the positive contribution of soaked biochar to early strength development.

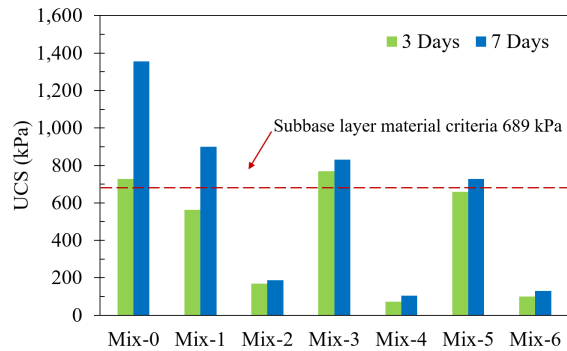


Fig. 3 UCS of stabilized sediment

In contrast, Mix-4, which consisted of 100% SS and soaked biochar, yielded the lowest UCS among all mixtures, reaching only around 104.20 kPa at 7 days. This result suggests that the combination of SS and biochar alone lacks sufficient binding potential to effectively stabilize the soil. Nevertheless, the UCS of Mix-4 was still slightly higher than that of untreated soil, indicating a marginal improvement in strength despite the absence of HC.

When considering the E_{50} value, which represents the stiffness of cement-treated soil at a medium strain level, at curing ages of 3 and 7 days as presented in Tables 2 and 3 and Fig. 4. It was observed that E_{50} increased with curing time like UCS. At 3 days of curing, E_{50} values showed a pronounced difference between mixtures containing hydraulic cement and those without HC. The HC-containing mixtures (Mix-0, Mix-1, Mix-3, and Mix-5) exhibited E_{50} values ranging from 31,376.05 to 42,135.63 kPa at 3 days, which further increased to 41,382.29–87,235.08 kPa at 7 days. This indicates that these mixtures developed a relatively stiff internal structure from the early stage of curing, with stiffness progressively increasing over time, consistent with the trend

observed for UCS.

Meanwhile, the E_{50} /UCS ratios of the HC-containing mixtures ranged from 40.78 to 78.48, which is comparable to values reported in previous studies [20] that proposed typical E_{50} /UCS ranges for stabilized soils prepared using the wet method. Notably, the lowest ratio (40.78) corresponded to Mix-3 incorporating soaked biochar, which also exhibited the highest UCS at 3 days. This suggests that although Mix-3 experienced continuous strength development, its structure remained relatively more deformable than mixtures with higher binder contents. In contrast, mixtures without HC (Mix-2, Mix-4, and Mix-6) exhibited significantly lower E_{50} values, ranging from 2,275.94 to 10,117.11 kPa, which are comparable to those of medium to stiff clay [21]. This reflects a weak soil structure that remains highly deformable. Nevertheless, their E_{50} /UCS ratios were found to be of similar magnitude to those of the HC-containing group, despite their substantially lower strength levels.

Table 2 Result of UCS test at 3 days curing

Symbol	UCS (kPa)	E_{50} (kPa)	E_{50} /UCS
Mix-0	727.17	42,135.63	57.94
Mix-1	562.59	33,992.78	60.42
Mix-2	169.47	7,515.89	44.35
Mix-3	769.37	31,376.05	40.78
Mix-4	72.49	2,275.94	31.40
Mix-5	658.47	34,825.82	52.89
Mix-6	100.15	4,505.24	44.98

Table 3 Result of UCS test at 7 days curing

Symbol	UCS (kPa)	E_{50} (kPa)	E_{50} /UCS
Mix-0	1,355.87	87,235.08	64.34
Mix-1	900.15	59,133.12	65.69
Mix-2	187.63	10,087.28	53.76
Mix-3	830.01	41,382.29	49.86
Mix-4	104.20	6,142.90	58.95
Mix-5	727.03	43,667.02	60.06
Mix-6	128.92	10,117.11	78.48

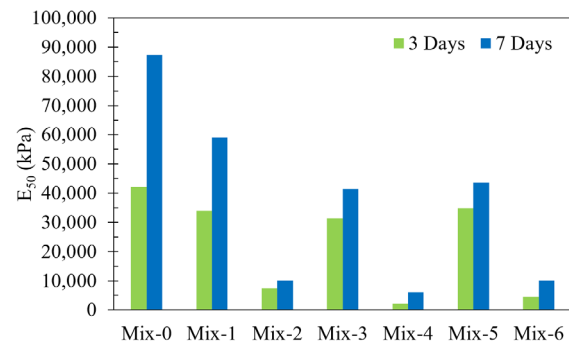


Fig. 4 E_{50} of stabilized sediment

Moreover, Mix-3 exhibited a reduced water content after curing (13.97%) as illustrated in Fig. 5, likely due to moisture uptake and gradual release

from soaked biochar. This contributed to more effective hydration and matrix densification. Comparing Mix-3 and Mix-5 (same binder, different biochar condition), soaked biochar led to higher UCS, indicating its superior contribution to early strength. Overall, the combination of HC, SS, and soaked biochar enhanced UCS, particularly at early ages, likely through improved hydration and filler effects from the porous structure of biochar.

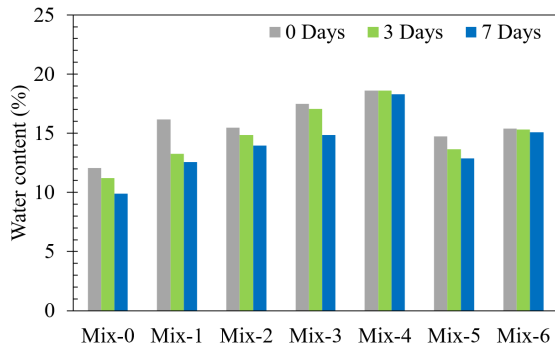


Fig. 5 Water content of stabilized sediment

5.2 Wave Velocity and Moduli from FFR Test

FFR test results for all mixtures are presented in Fig. 6 and Fig. 7. Both compressional (V_p) and shear (V_s) wave velocities increased with curing time and showed similar trends to the UCS results. Mix-1, composed of 75% HC and 25% SS, exhibited the highest wave velocities after 7 days ($V_p = 1,151.32$ m/s, $V_s = 657.90$ m/s), indicating superior stiffness and well-developed internal structure. Mix-3, which additionally incorporated soaked biochar, also demonstrated relatively high wave velocities ($V_p = 1,129.74$ m/s, $V_s = 593.44$ m/s), reflecting its notable early strength and enhanced material continuity.

In contrast, Mix-4, comprising 75% SS and soaked biochar without cement, recorded the lowest velocities ($V_p = 203.02$ m/s, $V_s = 124.45$ m/s), consistent with its poor mechanical properties. Overall, mixtures containing soaked biochar tended to show improved wave propagation characteristics compared to those with dry biochar or without biochar, especially when combined with HC.

In addition to wave velocity measurements, the small-strain Young's modulus (E_0) and shear modulus (G_0) can also be calculated, both of which exhibited increasing trends with curing time, consistent with strength development. Mixtures containing hydraulic cement showed significantly higher E_0 and G_0 values than those without cement, highlighting the dominant role of cementation in enhancing stiffness. In particular, Mix-1 exhibited the highest modulus values, which is consistent with its wave velocities and UCS, indicating the formation of a dense and well-interconnected load-bearing structure.

Mix-3, incorporating soaked biochar combine with HC and SS, also demonstrated relatively high E_0 and G_0 values. This behavior suggests that soaked biochar contributes to improved particle bonding and microstructural continuity, likely through enhanced water retention and more effective hydration of the binder. In contrast, the mixes without cement such as Mix-4 exhibited low E_0 and G_0 values, reflecting weak interparticle bonding and a loose internal structure, which is consistent with the poor mechanical performance of these mixtures.

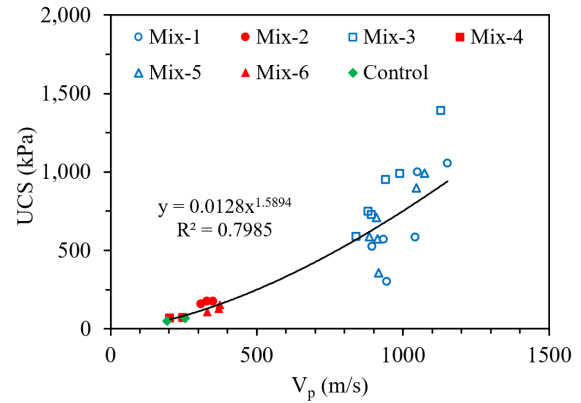


Fig. 6 UCS versus V_p

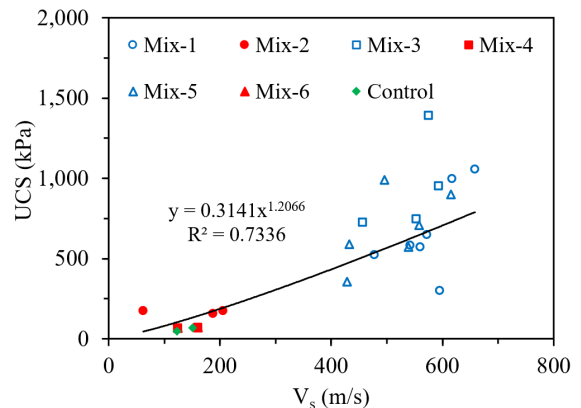


Fig. 7 UCS versus V_s

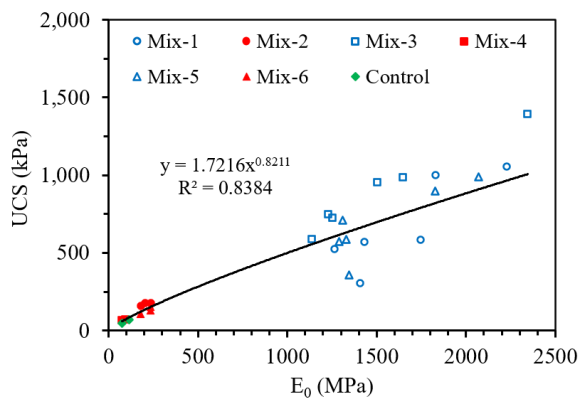


Fig. 8 UCS versus E_0

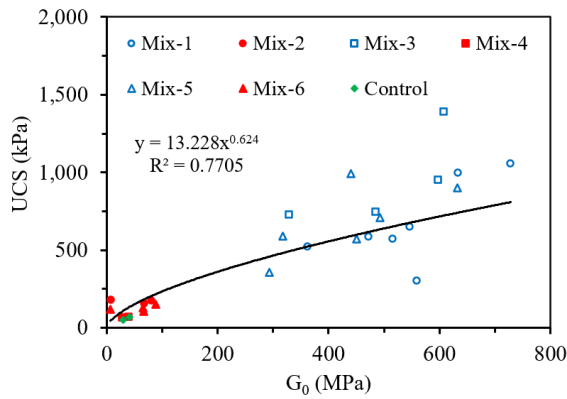


Fig. 9 UCS versus G_0

Based on these relationships, the empirical correlations between wave velocities, small-strain elastic moduli, and UCS can be expressed as follows:

$$UCS = 0.0128 V_p^{1.5894} \quad (R^2 = 0.7985) \quad (5)$$

$$UCS = 0.3141 V_s^{1.2066} \quad (R^2 = 0.7336) \quad (6)$$

$$UCS = 1.7216 E_0^{0.8211} \quad (R^2 = 0.8384) \quad (7)$$

$$UCS = 13.228 G_0^{0.624} \quad (R^2 = 0.7705) \quad (8)$$

These correlations indicate that FFR testing provides a promising non-destructive approach for estimating strength development and moduli in stabilized dredged sediments.

Moreover, the consistent trends observed among E_0 , G_0 , E_{50} , and UCS indicate that stiffness enhancement occurs across different strain ranges as cementation develops. This consistency confirms that the treated sediments exhibit a coherent mechanical response, in which improvements in microstructural bonding contribute to both stiffness and strength at higher strain levels.

5.3 X-ray Diffraction Analysis

The mineralogical composition of stabilized sediment was investigated using X-ray diffraction, and the results are presented in Fig. 10. The diffraction patterns indicated that quartz (PDF 05-0490) was the dominant mineral in the untreated dredged sediment. Secondary minerals identified included montmorillonite (PDF 03-0010), illite (PDF 43-0686), and kaolinite (PDF 05-0143), which correspond with the soil classification results.

In addition, characteristic peaks corresponding to hydration products, namely calcium silicate hydrate (CSH, PDF 00-012-0739) and ettringite (PDF 04-013-3691), were observed in the treated mixtures. Notably, the ettringite peak in Mix-3 was more pronounced than in Mix-5, consistent with its higher unconfined compressive strength (UCS). These findings confirm that chemical reactions occurred during the curing process and contributed to the observed strength development.

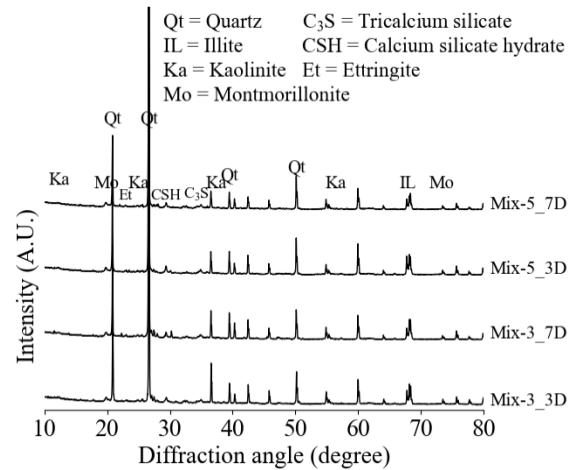


Fig. 10 XRD pattern of Mix-3 and Mix-5

5.4 Scanning Electron Micrographs

Microstructural analysis was performed using scanning electron microscopy (SEM) on fractured surfaces of selected specimens. The results are shown from Fig. 11 to Fig. 14. The SEM micrograph of Mix-3 at 3 and 7 days curing reveals a substantial presence of rod-shaped ettringite crystals, one of the key hydration products in cement-treated soils.

These needle-like formations are known to contribute to strength development by filling voids and bridging soil particles, thus enhancing matrix integrity. The presence of ettringite observed here is consistent with the XRD results (Section 5.3), which also confirmed distinct peaks for ettringite in Mix-3. results observed in the UCS and FFR tests.

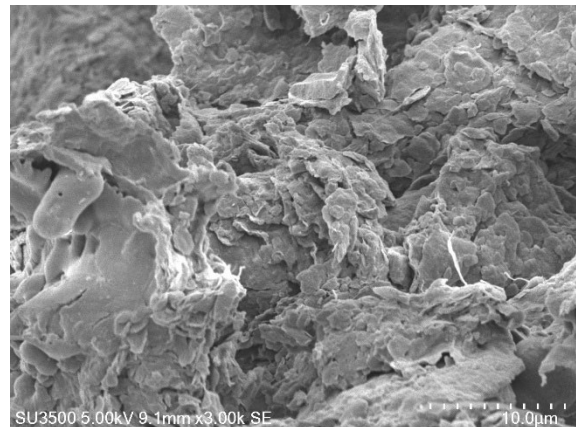


Fig. 11 SEM micrograph of Mix-3 at 3 days ($\times 3000$)

When examining the microstructure of Mix-5 at curing ages of 3 and 7 days, distinct differences from Mix-3 were clearly observed. At 3 days, the SEM image of Mix-5 revealed incomplete bonding between soil particles and the blended materials, with a relatively high amount of voids and pores. Only a limited presence of hydration reaction products could

be observed, indicating that the microstructural development was still at an early stage. As the curing age increased to 7 days, the microstructure of Mix-5 became denser, with improved interparticle bonding and a greater amount of hydration products compared to the 3-day condition. However, the quantity and continuity of the observed reaction products in Mix-5 remained lower than those in Mix-3.

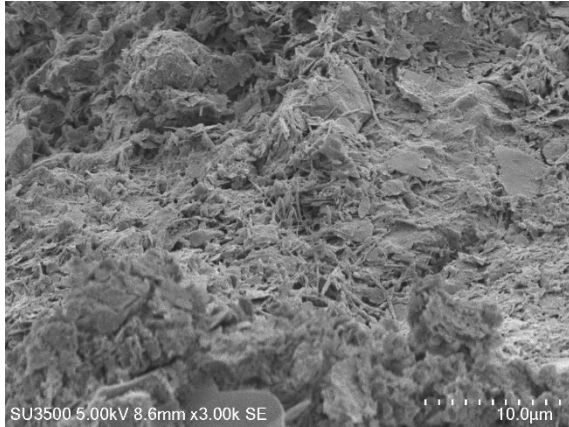


Fig. 12 SEM micrograph of Mix-3 at 7 days (×3000)

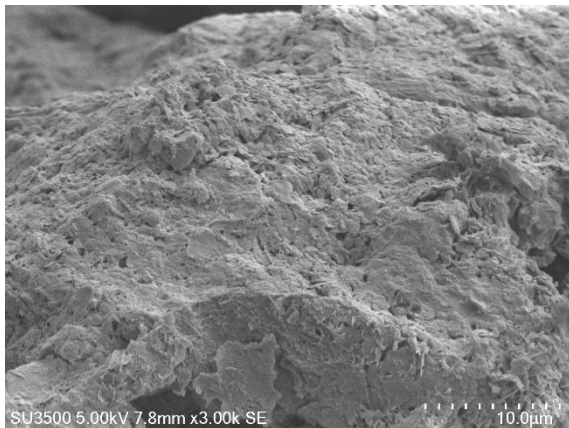


Fig. 13 SEM micrograph of Mix-5 at 3 days (×3000)

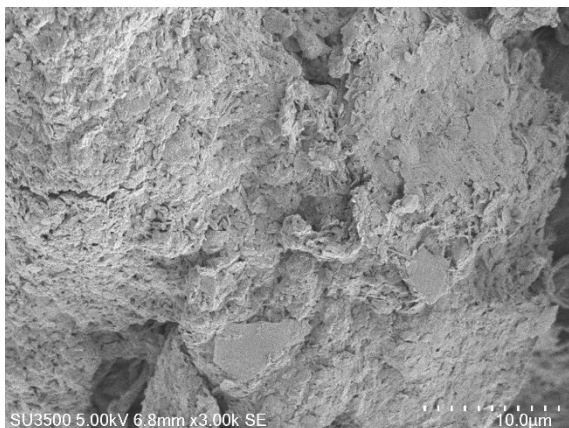


Fig. 14 SEM micrograph of Mix-5 at 7 days (×3000)

When interpreted together with the XRD results, it can be concluded that Mix-3 generated a larger amount of hydration products with more continuous distribution, resulting in a denser and more well-developed microstructure. In contrast, although Mix-5 exhibited progressive microstructural improvement with curing time, voids and locally discontinuous bonding were still evident in some areas. The agreement between SEM and XRD findings validates the occurrence of hydration reactions in the treated soils, supporting the mechanical performance.

6. CONCLUSION

This study investigated the stabilization of dredged sediment from drainage canals using hydraulic cement partially replaced with steel slag and enhanced with bamboo biochar. The main findings are summarized as follows:

1. Partial replacement of hydraulic cement with steel slag (up to 25%) improved the mechanical performance of the stabilized sediment. Mix-1 achieving a 7-day UCS of 900.15 kPa exceeding 689 kPa, meeting subbase material standards.

2. The addition of bamboo biochar, particularly in the soaked condition, significantly accelerated early strength development. Mix-3 and Mix-5 reached UCS values of 769.37 kPa and 658.47 kPa, respectively, at 3 days, outperforming mixes without biochar.

3. The secant modulus (E_{50}) increased consistently with curing time and UCS development. Cement-treated mixtures significantly higher E_{50} values than non-cemented mixtures, indicating the formation of a stiffer internal structure.

4. Free-free resonance testing revealed strong correlations between UCS and wave velocities (V_p and V_s), as well as small-strain elastic moduli (E_0 and G_0). Higher cementation levels resulted in increased E_0 and G_0 , demonstrating enhanced stiffness at small strain levels.

5. XRD and SEM analyses confirmed the formation of key hydration products, notably CSH and ettringite. Their presence validated the hydration mechanisms responsible for strength development.

6. In addition to enhancing strength, hydraulic cement may help reduce environmental risks. Its alkalinity promotes heavy metal precipitation, while hydration products like CSH and ettringite can immobilize contaminants [22]. Although leachability of steel slag was not assessed in this study, the addition of biochar with high sorptive capacity may further limit pollutant mobility. Further research is recommended to assess long-term performance.

Overall, the combination of hydraulic cement, steel slag, and biochar is a promising and sustainable solution for reusing dredged sediments in civil engineering applications. This approach not only improves geotechnical performance but also promotes circular use of industrial and natural wastes,

aligning with low-carbon geo-environmental engineering practices and SDGs.

7. ACKNOWLEDGMENTS

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