

Geotechnical and environmental evaluation of cement-stabilized lateritic soil with wood bottom ash for road subbase

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Abstract

This article investigates the characteristics of the marginal lateritic soil stabilized with cement and wood bottom ash (WBA) as subbase materials. A comprehensive methodology involved modified Proctor compaction and unconfined compression tests, supplemented by microstructural analyses, as well as pilot-scale field construction and leachate monitoring. Results revealed that compressive strength increased with WBA content up to 60%, and was further enhanced by higher cement dosages. Compressive strength was inversely correlated with porosity and voids-to-cement ratio. Field monitoring showed that Cr was the only metal consistently detected in leachate, decreasing over time but remaining above permissible limits, indicating insufficient immobilization due to weaker incorporation into cementitious phases. This study highlights the synergistic effects of WBA and cement in improving soil subbase performance while supporting sustainable reuse of industrial by-products.

Keywords: Cement-treated subbase, Leachate, Porosity, Unconfined compressive strength, Wood bottom ash

1. Introduction

The increasing demand for sustainable infrastructure has prompted researchers and engineers to seek alternative materials and methods that minimize environmental degradation while maintaining structural performance. In tropical regions like Thailand, road construction frequently relies on lateritic soil due to its wide availability and cost-effectiveness. However, the geotechnical performance of natural lateritic soil is often inadequate for subbase applications without improvement, particularly in terms of strength and durability [1]. Traditional soil-cement stabilization practices have been widely employed to enhance the engineering characteristics of subgrade and subbase layers. Nevertheless, the excessive use of cement contributes significantly to greenhouse gas emissions, raising environmental concerns and prompting the need for more sustainable alternatives [2, 3]. One such alternative is the incorporation of industrial by-products such as municipal solid waste (MSW) incineration ash or biomass bottom ash into cement-treated soils [4, 5]. Thailand generates substantial amounts of bottom ash annually from biomass power plants and MSW incinerators, most of which are underutilized or landfilled, posing long-term ecological risks due to leaching of heavy metals and other hazardous components [2, 6]. Currently, Thailand has made significant progress in expanding biomass power plants as part of its sustainable energy strategy, with over 200 facilities currently operating and a total installed capacity exceeding 2,100 MW [7]. These plants primarily use agricultural and industrial residues such as rice husk, bagasse, and rubberwood waste. Among these by-products, wood bottom ash (WBA), produced by the combustion of rubberwood in biomass power plants, has emerged as a significant waste stream. Although WBA is readily available, it remains underutilized and is frequently disposed of in landfills, raising environmental concerns about leachate generation and the potential release of heavy metals [8, 9]. Therefore, valorizing WBA as a component in road construction not only offers a promising solution for sustainable waste management but also aligns with circular economy principles by substituting virgin materials and reducing environmental burdens [4, 10, 11].

Despite the growing interest in incorporating biomass bottom ash into pavement materials, several challenges persist. One of the primary limitations is its variable chemical composition and potential environmental impacts, particularly related to leachate toxicity and long-term durability [12-14]. Moreover, while cement stabilization is effective in enhancing strength and reducing permeability, its ability to immobilize heavy metals from ash-based composites remains under investigation [15, 16]. For instance, Nawaz et al. [17] demonstrated that mechanical and chemical activation can significantly influence the effectiveness of solidification-stabilization when applied to metal-rich tailings. Similarly, Kogbara [18] emphasized the need to assess the dual role of binders in improving mechanical properties and controlling contaminant mobility. However, such dual-performance evaluations are limited in the literature, creating an urgent need for comprehensive experimental validation. The WBA can be used as supplementary cementitious material due to its pozzolanic activity [4]. Recent studies have shown promising results in integrating WBA into cement-treated lateritic soil mixtures. Most findings showed that the inclusion of ash at an optimal level in cement-based materials is valuable for sustainable development and waste management. For instance, Iyaruk et al. [1] reported that the inclusion of WBA with cement substantially improved compressive strength, demonstrating feasibility for road applications. Similarly, Gupta et al. [19] and Yan et al. [20] investigated the structural and microstructural mechanisms underlying the role of bottom ash as a pozzolanic or filler material in stabilized mixtures, attributing performance gains to its fine particles and reactive silica content. From an environmental perspective, researchers such as

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Bansal et al. [21] and Rochanavibhata et al. [6] have explored the immobilization potential of ash-cement-laterite blends and their effects on leachability and toxicity. Nevertheless, these studies often focus narrowly on individual performance aspects without concurrently addressing strength and leachate behavior under the same experimental framework.

From a sustainability perspective, several full-scale and laboratory investigations have validated the use of bottom ash in pavement base layers. Toraldo and Saponaro [22] conducted a full-scale road test on a track. They found that stabilized bottom ash performed satisfactorily under traffic loading, provided that proper mix design and compaction standards were maintained. Paine et al. [23] and Bessa et al. [24] similarly affirmed the engineering viability of incinerator bottom ash and recycled unbound layers in field conditions. However, the incorporation of lateritic soil into such systems remains underrepresented in field and lab investigations. The combined physicochemical interactions between laterite, cement, and ash, particularly under varying compaction and curing conditions, require rigorous assessment to inform region-specific design guidelines.

A notable research gap exists in the simultaneous evaluation of strength and environmental performance in cement-stabilized bottom ash and laterite mixtures. Most studies to date have focused on one or two performance indices, without holistic integration. Furthermore, Thailand-specific research on waste utilization in road bases tends to focus on ash replacement ratios or short-term strength gains, neglecting longer-term leaching behavior and hydro-mechanical stability under field conditions [6, 25]. As Thailand continues to expand its energy-from-waste infrastructure, the resulting increase in bottom ash volumes necessitates research that not only affirms structural performance but also ensures environmental safety and regulatory compliance over extended service periods. This research addresses a critical knowledge gap by systematically investigating the strength and environmental performance of cement-stabilized mixtures composed of locally available lateritic soil and WBA, making them viable materials for pavement construction.

The study employs an integrated experimental framework to evaluate the replacement of marginal lateritic soil with WBA, treated with cement, for use as soil-cement or cement-treated subbase (CTS) road materials. Two significant characteristics of the CTS sample were highlighted, namely, strength, permeability, and environmental impact. Firstly, the unconfined compression (UC) test is performed to determine the compressive strength of the CTS sample, in accordance with the Department of Highways (DOH), Thailand, specifications. Furthermore, the influence of WBA content, volumetric cement content, and porosity on the strength development of CTS specimens is also discussed. Secondly, the concentration of heavy metal leachate from a pilot-scale road subbase is examined through leaching analysis to evaluate its environmental impact. Additionally, a pilot-scale road subbase experiment was constructed to validate laboratory findings under realistic conditions. This study is expected to provide critical insights into the interrelationships among porosity, cement content, strength development, and environmental impact, thereby promoting the safe and effective reuse of industrial by-products in infrastructure development.

2. Materials and methods

2.1 Materials characterization

The materials used in this study comprise lateritic soil (LS), wood bottom ash (WBA), and hydraulic cement, as illustrated in Figure 1. The physical properties of all materials were tested in the laboratory in accordance with ASTM standards. LS samples were collected from a site located in the Hat Yai district, Songkhla Province, Thailand. LS exhibits a reddish-yellow color and is classified as clayey gravel with sand (GC) based on the Unified Soil Classification System (USCS). Microscopic examination (Figure 1) of LS reveals a small particle and a plate-like shape. LS had a specific gravity of 2.75, 68% wearing resistance, and a 4% soaked CBR value, which did not meet the DOH, Thailand subbase specification. The X-ray fluorescence (XRF) analysis identified three major components: 59.79% SiO_2 , 20.59% Al_2O_3 , and 8.07% Fe_2O_3 . WBA is a by-product of burning Para rubber wood from the Panel Plus CO., Ltd., located in Songkhla province. According to the USCS method, WBA was classified as a non-plastic, poorly graded sand (SP). WBA has a specific gravity of 2.40, and the particles were round with a rough texture (Figure 1). The main chemical compositions identified from the XRF analysis were 61.73% SiO_2 , 11.4% CaO , 8.57% Al_2O_3 , and 5.32% Fe_2O_3 . The high content of the sum of oxides of SiO_2 , Al_2O_3 , and Fe_2O_3 (>70%) confirmed the pozzolanic characteristics of WBA, which could be applicable in the production of cementitious materials [4]. This study utilized a general-use (GU) type of hydraulic cement (hereafter referred to as cement) with a specific gravity of 3.13. The SEM image in Figure 1 shows an irregularly shaped object with sharp corners. Calcium oxide (CaO), at approximately 65%, was the dominant cement mineral. Figure 2 presents the particle-size distributions of LS, WBA, and cement. As shown in Figure 2, LS and WBA were obtained from a standard sieve test, while the cement was determined by laser diffraction.

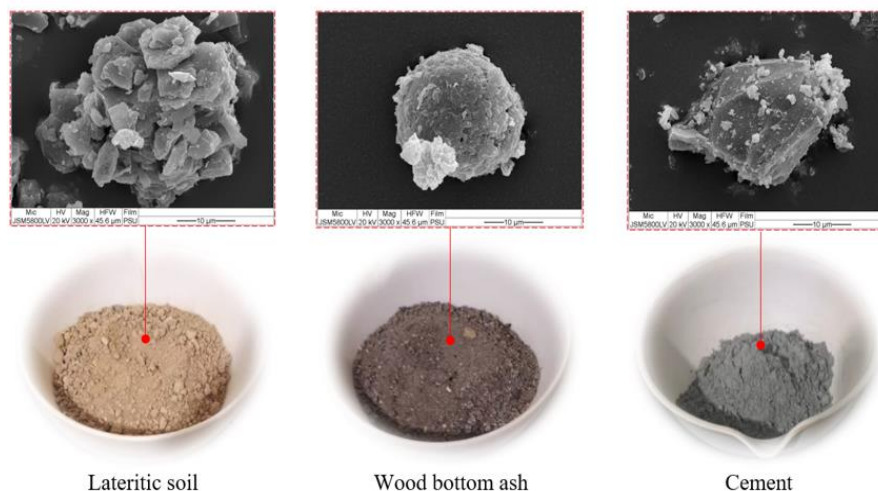


Figure 1 Images of materials used in an experiment

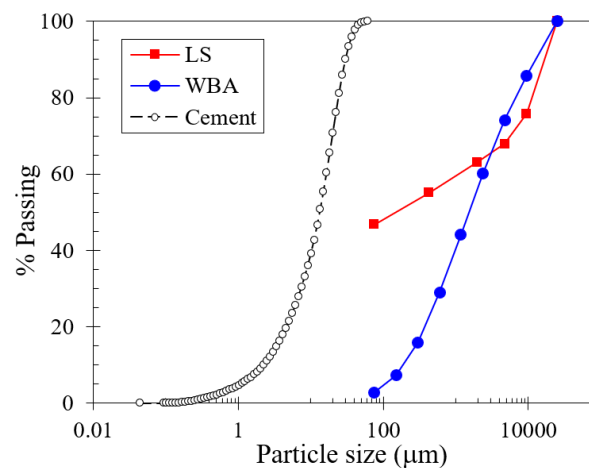


Figure 2 Particle size distribution of LS, WBA, and cement

2.2 Experimental programs

Generally, bottom ash is a natural aggregate suitable for civil engineering works, particularly in road applications [22]. However, using road materials containing WBA without assessing the environmental impact of the mixture could raise concerns. Thus, the concept of this study is to treat such pavement materials with cement throughout both laboratory and field scales. The experimental program could be separated into three main stages, including (i) laboratory experiment, (ii) pilot-scale experiment, and (iii) leachate analysis. The laboratory testing consists of the modified Proctor test and UC test, which are performed according to ASTM D1557 [26] and ASTM D2166/D2166M [27], respectively (Figure 3). Pilot-scale testing (Figure 4) involves constructing a simulated road soil-cement subbase made from the selected mixture based on the UC test result. The primary objective of this stage is to assess both the development of strength and the concentration of heavy metals throughout the field subbase layer. Microstructural testing using field-emission scanning electron microscopy (FESEM), energy-dispersive X-ray spectroscopy (EDX), and X-ray diffraction (XRD) was performed to investigate microstructural changes in the CTS specimens resulting from the stabilization process. Finally, the environmental impact of using WBA as a subbase material was investigated through a leachate analysis. In this stage, leachate samples were collected from the pilot-scale tests. The details of the experimental programs are described as follows.

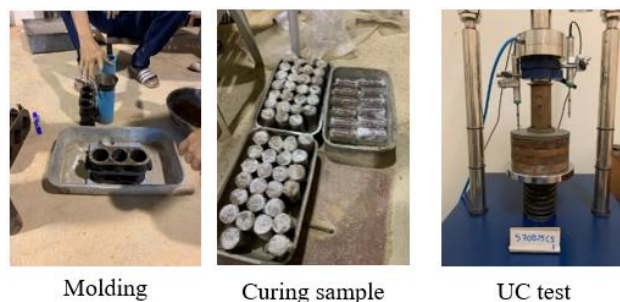


Figure 3 Laboratory experiments



Figure 4 Pilot-scale experiments

2.2.1 Compaction test

The CTS specimen is a mixture of LS, WBA, and cement. The specific proportions of LS treated with varying WBA and cement content are displayed in Table 1. For each mixture, LS was replaced with varying percentages of WBA and cement. In this study, LS contents ranged from 0–60% (in 10% increments) of the total mix. While the WBA-cement contents also varied from 40–100%, with 3, 5, and 7% of the total mix. For example, the CTS specimen of S60:B47:C3 denotes a mix with 60% LS, 47% WBA, and 3% cement. The letters S, B, and C depicted in Table 1 refer to the lateritic soil, wood bottom ash, and cement, respectively. The selected proportions were based on maximizing the use of WBA and relevant literature [e.g., 6, 18, 23]. Specifically, a range of WBA and cement contents was investigated to identify the optimal combination that satisfies engineering requirements while maintaining environmental benefits. A modified Proctor test was conducted to determine the optimum moisture content (OMC) and maximum dry unit weight (γ_{dmax}) for all CTS mixtures. The summary of OMC and γ_{dmax} values is shown in Table 1. As shown in Table 1, the γ_{dmax} values of CTS specimens decrease with an increase in WBA content. A reduced trend of γ_{dmax} is due to the increase in WBA content in the specimens. On the other hand, an increasing trend was observed in the relationship between OMC and WBA content.

2.2.2 Unconfined compression test

Cylindrical split molds of 50 mm in diameter and 100 mm in height were used to prepare CTS specimens. The oven-dried LS and WBA were blended first and then mixed with cement and water at OMC until a completely homogeneous mixture was achieved. The prepared mixture was subsequently compacted in a mold at the desired compaction energy. The specimens were carefully extracted from the mold, wrapped in a plastic bag to minimize moisture content variation, and cured in the curing room at $25 \pm 2^\circ\text{C}$ for 7 and 28 days. Before the compression test, the specimens were immersed in water for 2 hours, as specified in the DOH specification [28]. The UC test was performed on the 50 kN compression machine under a vertical strain rate of 1 mm/min. Continue loading until the load values decrease with increasing strain or until 15% strain is reached. The maximum load is used to calculate the unconfined compressive strength (UCS). The UC tests were conducted in triplicate, and an average value was reported.

Table 1 Mixtures designed for laboratory experiments

CTS specimens	Mix proportions (%)			Compaction results		Curing time (days)
	LS content (S)	WBA content (B)	Cement content (C)	OMC (%)	γ_{dmax} (kN/m ³)	
S100B0C0	100	0	0	14.40	18.80	-
S60B37C3	60	37	3	13.39	17.88	7, 28
S50B47C3	50	47		13.36	17.50	
S40B57C3	40	57		13.63	17.19	
S30B67C3	30	67		13.71	17.13	
S20B77C3	20	77		13.98	16.73	
S10B87C3	10	87		15.20	15.93	
S0B97C3	0	97		16.04	15.23	
S60B35C5	60	35	5	13.22	17.42	7, 28
S50B45C5	50	45		14.28	16.94	
S40B55C5	40	55		14.44	16.60	
S30B65C5	30	65		14.36	16.68	
S20B75C5	20	75		14.76	16.41	
S10B85C5	10	85		15.35	15.53	
S0B95C5	0	95		15.18	15.48	
S60B33C7	60	33	7	13.13	17.98	7, 28
S50B43C7	50	43		13.22	17.59	
S40B53C7	40	53		13.28	17.55	
S30B63C7	30	63		14.79	16.83	
S20B73C7	20	73		15.43	16.77	
S10B83C7	10	83		16.22	16.09	
S0B93C7	0	93		17.11	15.26	

2.2.3 Pilot-scale experimental

The experimental road structure was constructed in the outdoor building area of the Rajamangala University of Technology Srivijaya (Figure 4). The road structure consists of 4 layers, from bottom to top: subgrade, stabilized subbase, sand cushion, and concrete pavement. After grading and compacting the subgrade layer, a concrete block was built as a side wall of the experimental road. To prevent leachate leakage, HDPE geomembrane was used as a waterproof liner beneath the subbase layer. PVC screen pipe (2" in diameter) was placed on a geomembrane layer for the collection of leachates. After completion of the waterproof system, the CTS layer was applied. It is essential to note that the mixture S30B65C5 was selected as the CTS layer based on the UC testing results that met the DOH criteria [28], as described in the materials and methods section. Thus, a mixture of 30% LS, 65% WBA, and 5% cement was prepared and mixed using a mixing truck (Figure 4) with an additional water content of 14.36%. The mixing process takes approximately 15 minutes to ensure that all CTS materials are thoroughly homogenized. After that, stabilized materials were poured in place in preparation for the road site, then compacted with a vibratory compaction tamper. To achieve a degree of field compaction at 95% of γ_{dmax} , the sand cone replacement field density test (Figure 4) was conducted. To investigate the leachate quality, the CTS layer was covered with tap water. The leachates generated by the incoming water passing through the CTS layer were collected in a pipeline system placed at the bottom [29, 30]. A sample of the leachate generated each time was collected immediately at the pipe system's exit using a 10-liter polyethylene container. Subsequently, a sample was taken for chemical analysis. Note that the leachate samples were collected at 7, 14, 30, 60, and 120 days. After 4 months of leachate monitoring, a 0.15-meter-thick concrete pavement was laid.

2.2.4 Microstructure tests

To monitor the development of strength and the microstructural changes induced by the stabilization process, core samples were drilled from the field CTS layer at 28 and 120 days of curing. Subsequently, SEM and EDX were performed. Finally, an XRD test was conducted to observe the cement hydration products (e.g., calcium silicate hydrate, CSH) for the same CTS sample.

2.2.5 Leaching analysis

The effluent leachate samples collected in the containers illustrated earlier were transferred into sampling bottles for leachate analysis [31]. According to the leachate results from a study by Iyaruk et al. [1], pure WBA samples do not detect cadmium (Cd) and lead (Pb). Therefore, this study analyzed heavy metals, including As, Cr, Cu, Ni, and Zn, using an Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES).

3. Results and discussions

3.1 Unconfined compressive strength

The mean values of UCS for the CTS specimens at the curing times of 7 and 28 days are displayed in Figure 5. The minimum criterion of 689 kPa for soil-cement subbase materials, designated by the DOH [28], was benchmarked in this study. The influence of WBA content (C_{ba}) and cement content (C_c) on strength development is described through variations in UCS values. As shown in Figure 5, the UCS of all specimens increased with increasing curing time. At 7 days of the curing period, almost all specimens meet the minimum criteria, except for the specimen labeled S0B97C3. The variation of UCS in Figure 5 depends on the increase of both C_{ba} and C_c . For example, the UCS of the mixture with a C_c of 5% increases from 987 to 1,574 kPa when the C_{ba} increment changes from 35% to 65%. After that, increasing C_{ba} beyond 65% led to a decrease in UCS value, with the lowest value of 883 kPa occurring at $C_{ba} = 95\%$ (i.e., S0B95C5). The UCS variation with a C_c of 7% is comparable in strength to mixtures with a C_c of 5%. This phenomenon suggests that replacing LS with WBA and cement significantly enhances the mixtures' strength. The discussion of other factors influencing the strength development of the CTS specimens is described in the following sections.

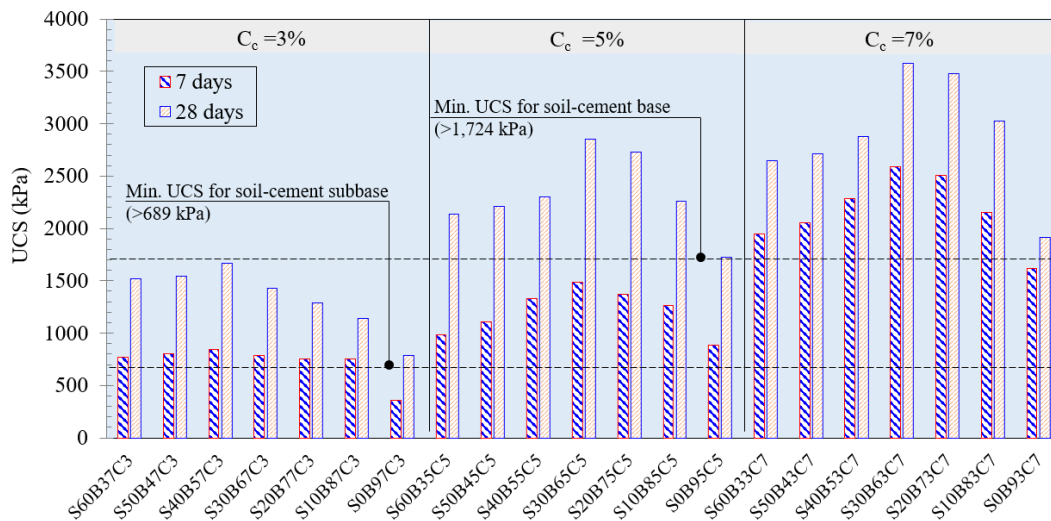


Figure 5 Variation of UCS of the CTS mixtures at the curing times of 7 and 28 days

3.1.1 Effect of porosity on UCS

The effect of porosity on the UCS is a crucial parameter to consider when evaluating the feasibility of the cement-treated subbase. Theoretically, porosity (n) is expressed as the ratio of void volume to the total volume of the specimen (V_t). According to the study by Consoli et al. [32, 33], the UCS of the soil-cement mixture can be expressed as a function of the specimen porosity and volumetric cement content ratio (n/C_v), also called the void/cement ratio (VCR) [34], shown in Eq. (1).

$$\frac{n}{C_v} = \frac{\left(\frac{V_v}{V_t}\right)}{\left(\frac{V_c}{V_t}\right)} = \frac{V_v}{V_c} \quad (1)$$

where V_v = volume of void (water + air), and V_c = volume of cement of the CTS specimen.

The porosity and volumetric cement content (C_v) can be calculated via Eqs. (2) and (3), respectively. C_v is expressed as a percentage of the total cement volume.

$$n (\%) = 100 - \frac{100 \left\{ \left[\left(\frac{\gamma_d V_t}{1 + \frac{C_c}{100}} \right) \left(\frac{C_s}{100} \right) / \gamma_{s[S]} \right] + \left[\left(\frac{\gamma_d V_t}{1 + \frac{C_c}{100}} \right) \left(\frac{C_{ba}}{100} \right) / \gamma_{s[B]} \right] + \left[\left(\frac{\gamma_d V_t}{1 + \frac{C_c}{100}} \right) \left(\frac{C_c}{100} \right) / \gamma_{s[C]} \right] \right\}}{V_t} \quad (2)$$

$$C_v (\%) = 100 \left\{ \left(\frac{\gamma_d V_t}{1 + \frac{C_c}{100}} \right) \left(\frac{C_c}{100} \right) \right\} / \gamma_{s[C]} \quad (3)$$

In this study, the CTS specimens are composed of five volumetric and weight phases: lateritic soil, bottom ash, cement, water, and air. As present in Eq. (2), porosity (n) is obtained based on the dry unit weight (γ_d) of mixture and contents of soil (C_s), bottom ash (C_{ba}), and cement (C_c), and solid unit weights of soil ($\gamma_{s[S]}$), bottom ash ($\gamma_{s[B]}$), and cement ($\gamma_{s[C]}$). Eq. (4) is adopted to describe the effect of VCR on the UCS value [33] of the CTS specimen in this study.

$$UCS = A \left[\frac{n}{(C_v)^\alpha} \right]^{-\beta} \quad (4)$$

where A , α , and β are fitting parameters.

As shown in Figure 6a, the porosity showed slight variation until the WBA replacement ratio (C_{ba}) decreased to approximately 55%, after which it rose sharply. The regression model reflects this nonlinear, increasing trend because the internal pore structure is susceptible to increased WBA inclusion. This characteristic is primarily explained by the morphological features of WBA, which typically retain irregular, angular geometries and a porous surface topography, thereby inefficiently packing and restricting the thickness of the voids filled by hydration products during the curing process. This irregularity in shape leaves permanent micro-voids in the matrix, even after it has hardened [4]. The finer fraction of the mixture decreases as C_{ba} increases, thereby reducing the matrix's densification capacity and leading to a more porous structure [35]. Moreover, inactivated WBA plays a minimal role in hydration reactions, resulting in fewer durable cementitious compounds and reduced overall binder efficiency [36]. The evidence for this reduction is shown in Figure 6b, where C_v continuously decreases with increasing C_{ba} across cement contents of 3%, 5%, and 7%.

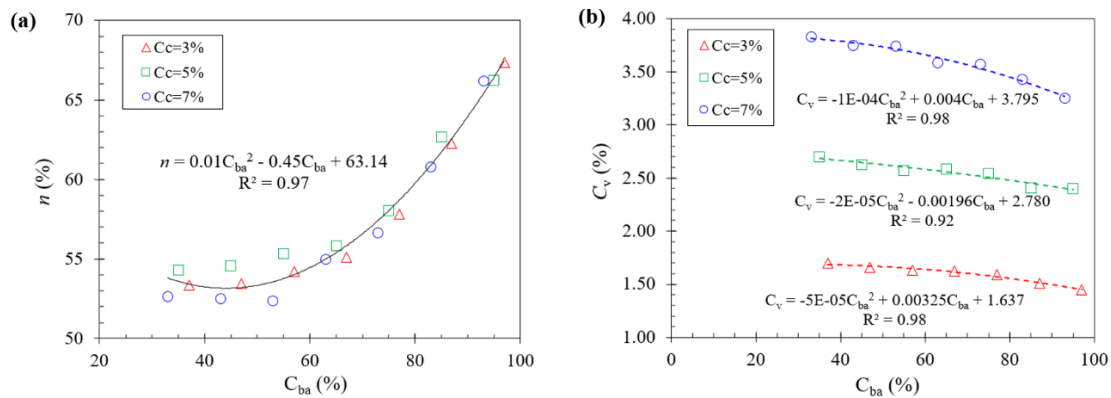


Figure 6 Effects of C_{ba} on: (a) porosity, n , and (b) volumetric cement content, C_v

Figure 7 illustrates the mechanical consequences of changing porosity in terms of UCS versus porosity (n) at 7- and 28-day cure times, as shown in Figures. 7a and 7b, respectively. An interesting observation is that, among mixtures with higher cement content (5% and 7%), the correlation between UCS and porosity shows an initial increase in strength followed by a decrease in porosity, indicating a parabolic relationship. This result suggests that moderate porosity can increase strength when combined with an optimal binder content, due to improved particle arrangement and the formation of hydration products. These results align with the conclusion of Baldovino et al. [37], which demonstrates the existence of an optimal VCR for achieving maximum strength in soil-cement systems. The 3% cement mix, conversely, exhibited a more linear and monotonic trend in strength as porosity increased, indicating that, due to low binder systems, the mechanical properties of the CTS specimen are primarily defined by the connectivity of the voids and the absence of continuous cement phases. This conclusion aligns with the results of Consoli et al. [32], which demonstrated that as porosity increases, compressive strength continues to decline in mixtures with insufficient binder content. Quantitatively, porosity was reduced by approximately 5% at 7% cement content, resulting in additional increases of 16% and 19% in strength at 7 and 28 days, respectively. Such improvements can be attributed to better particle packing and a more compact microstructure, leading to greater efficiency in load transfer, particularly when there is sufficient cement to promote the formation of hydration products [38].

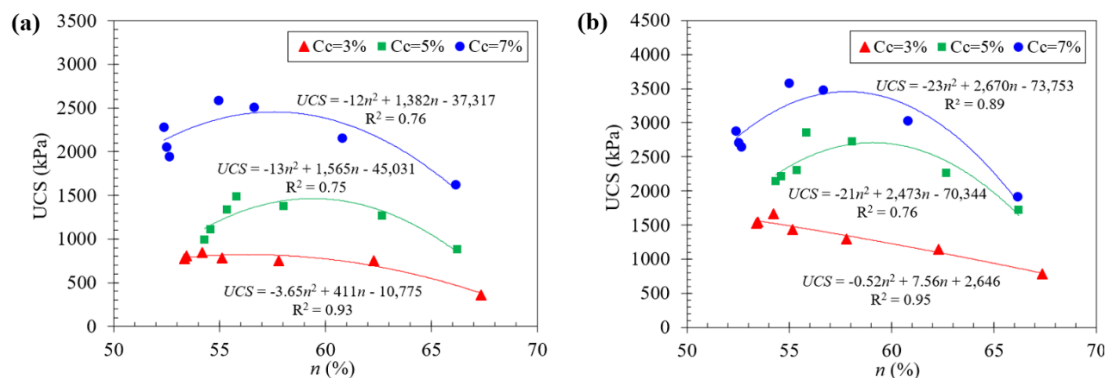


Figure 7 Relationship of UCS and porosity (n) of the CTS: (a) for 7 days and (b) for 28 days

3.1.2 Effect of WBA and cement content on UCS

The influence of WBA and cement content (C_c) on the UCS of the CTS mixtures was evaluated for curing periods of 7 and 28 days. Figure 8 presents three-dimensional plots showing the relationships among UCS, C_c , and C_{ba} . As illustrated in Figure 8a, at 7 days of curing, UCS steadily increases with increasing C_c across all WBA contents, signifying the critical role of cement hydration in early strength development. For example, at 60% WBA ($C_{ba} = 60\%$), increasing C_c from 3% to 7% increased UCS from approximately 850 to 2,250 kPa. This phenomenon is more severe at 28 days, as shown in Figure 8b, where the UCS of the same mixture exceeded 3,300 kPa, highlighting the importance of pozzolanic reactions that can persist longer with increased curing time. The increase in strength with increasing cement content is consistent with earlier observations on blended ash-cement systems [39, 40]. Calcium hydroxide provided by the cement in its process of hydration then reacts with the amorphous silica and alumina in the WBA to form strength-conferring compounds of calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). These responses compact the soil matrix, providing adequate mechanical integrity. Other similar processes were described by Jongpradist et al. [41] in their research on rice husk ash, which highlights that WBA, as well as other pozzolanic additives, serves as an effective secondary binder.

Regarding WBA content, the findings suggest a nonlinear relationship with UCS. As WBA increases from 30% to approximately 60%, UCS increases significantly, particularly at higher cement dosages. This improvement is attributed to the filler effect and improved particle packing, facilitated by the angular ash particles, which provide greater frictional resistance in the mix. Such enhancement is not only an example of the evolution of cementitious materials but also enables further strength gain due to the presence of WBA after initial hydration, which is in line with the delayed pozzolanic effect observed by Liu et al. [42]. The same development is observable in the plots of Figures. 8a and 8b, where at the duplicate WBA content, the influence of an increment in the C_c variable is stronger at younger ages. For example, when WBA is at 40%, UCS increases by approximately 110% as C_c increases, ranging from 3% to 7% at 7 days but reaching 75% at 28 days. The finding suggests that cement plays a more significant role in early strength, whereas the pozzolanic and physical effects of WBA become more relevant at later ages.

3.1.3 Effect of VCR on UCS

To more effectively compare the effects of mix density, cement volume, and ash-soil composition, the compressive strength of the CTS mixtures was normalized by the voids-to-cement ratio (VCR). Figure 9 depicts the correlation between UCS and the VCR (n/C_v) of the mixtures cured for 7 and 28 days, incorporating the effects of varying density, WBA content, and cement content in a single predictive model. There is a strong inverse relationship: as UCS decreases, VCR increases. The effects of distinct γ_d , C_{ba} , and C_c are included in the calculation of the VCR index [43]. A power equation with an empirical value β of 1.10 is the best fit for the UCS value curing at 7 days (Eq. 5) and 28 days (Eq. 6). The fitting parameter A varies depending on soil type and curing time [44]. In this study, parameter A presented values of 41,570 and 63,529 for UCS at 7 and 28 days, respectively. The VCR values range from about 12 to 47 for UCS. Consider a parameter α typically less than 1.00 for cement-treated fine soil and close to 1.00 for cement-sandy soil mixes [37, 45]. From the result shown in Figure 9, a value of $\alpha = 1.00$ means that all factors (i.e., n , C_{ba} , and C_c) have the same influence magnitude on the UCS of the CTS mixture. Good correlations ($R^2 = 0.87$ and 0.83 in Eqs. (5) and (6), respectively) could be used to determine the value of UCS at a particular value of VCR and time of the CTS mixture in field application [34, 43, 46].

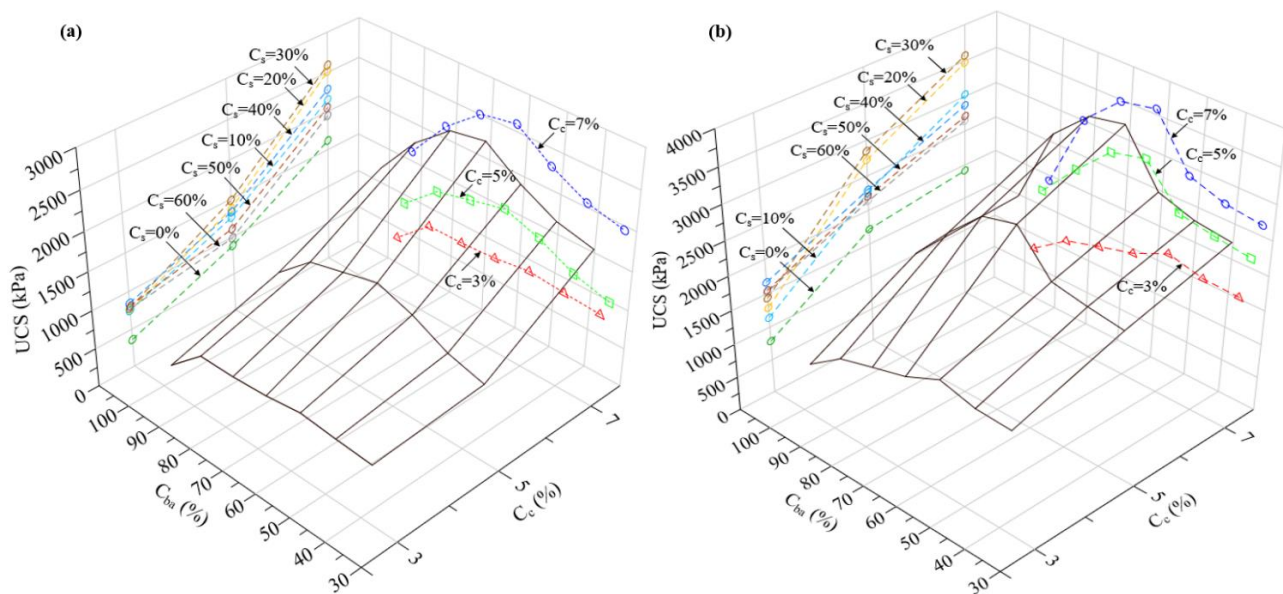


Figure 8 Relationship among UCS, C_c , and C_{ba} of the CTS mixtures: (a) 7 days, (b) 28 days

Figure 9 also illustrates two practical stabilization strategies using the VCR framework: reducing the VCR through densification (lower n) with a constant cement content, or maintaining a lower dry unit weight while increasing the cement dosage (higher C_v). Both approaches can yield high strength, but their feasibility depends on field constructability and cost constraints. According to Baldovino et al. [37], high compaction is more economical than dosage in substantial pavement projects, which supports the efficient practice of using VCR as an influential design measure in sustainable road construction.

$$UCS = 41,570 \left[\frac{n}{C_v} \right]^{-1.1} \quad (5)$$

$$UCS = 63,529 \left[\frac{n}{C_v} \right]^{-1.1} \quad (6)$$

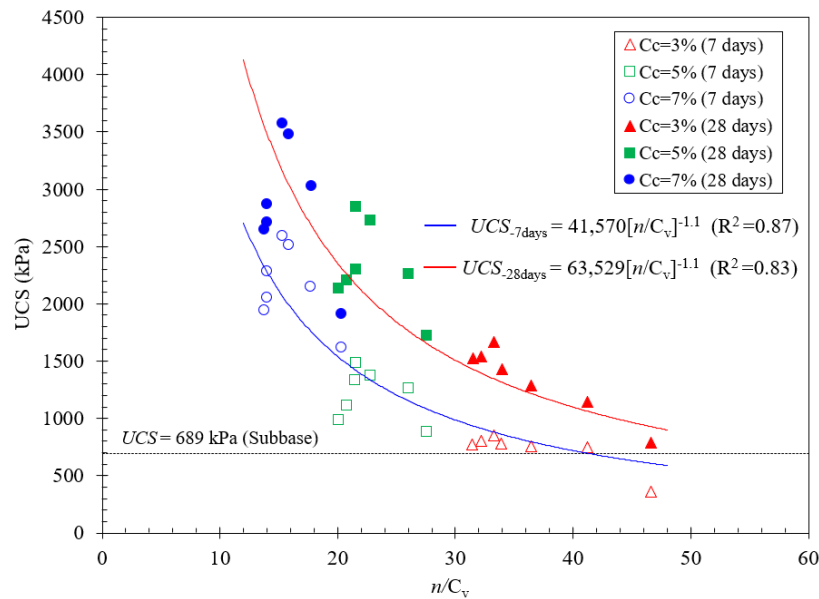


Figure 9 Influence of the n/C_v on UCS of the CTS mixtures for 7 and 28 days of curing

3.1.4 Optimization of CTS mix

As mentioned earlier, maximizing the WBA content is the primary goal of this research. To define a suitable mixture for field construction, the UCS is set to the minimum strength requirement of 689 kPa at 7 days of curing, as prescribed by the DOH [28]. As shown in Figure 5, the minimum UCS was achieved with C_c of 3%, 5%, and 7% in almost all CTS mixtures (except S0B97C3). Regarding leachate from heavy metals, using a mixture with a C_c of 3% may be inadequate. The mixtures with C_c of 5% and 7% are selected. However, a cement content of 7% is excessive for a soil-cement subbase and not environmentally friendly. Thus, based on performance and sustainability, the mixture S30B65C5 ($C_s = 30\%$, $C_{ba} = 65\%$, and $C_c = 5\%$) with the highest UCS for $C_c = 5\%$ was chosen for pilot-scale testing.

3.2 Mineralogical and microstructure

To observe the strength development of field CTS, the drilled core sample was tested using the UC test and subjected to microstructural analysis. Figure 10 illustrates the UCS of the mixture S30B65C5 from lab and field samples at 7, 28, and 120 days of curing time. As curing time increases, the UCS increases significantly in both laboratory and field samples. As observed, the strength of lab samples is consistently slightly higher than that of field samples for similar curing periods. The graph exhibits a logarithmic trend ($R^2 = 0.96$), indicating a strong correlation. This finding suggests that the UCS increases rapidly initially (e.g., between 0 and 28 days) and then slows down over time. The hydration reaction and frictional resistance primarily influence the material's strength development during its early curing stages, whereas, for longer curing times, the pozzolanic reaction also plays a role [47-49]. Mineralogical and microstructure analysis is described as follows to confirm the enhancement of LS properties by cement and WBA.

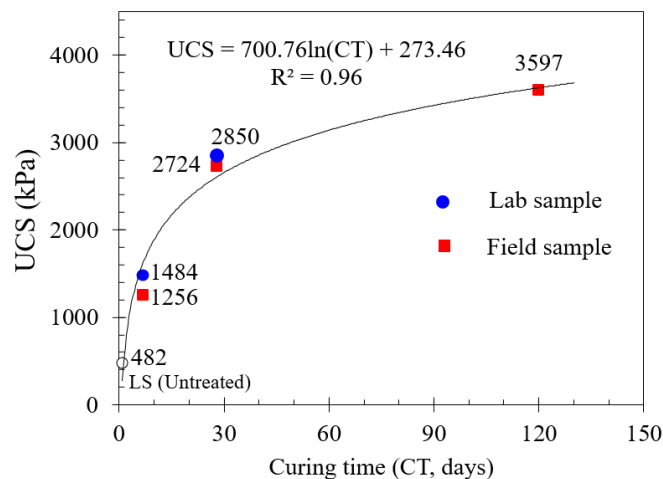


Figure 10 Strength development of the S30B65C5 mixture

3.2.1 XRD analysis

The hydration reaction and the pozzolanic reaction phenomenon could illustrate the strength development of the CTS specimens obtained in this study. The CTS specimens stabilized with a combination of cement and WBA produced a large portion of CSH products, resulting from cement hydration in the short term and a pozzolanic reaction in the long term, due to the presence of SiO_2 in the WBA [50]. Figure 11 displays the XRD results for the mixture S30B65C5 at 28 days (short-term) and 120 days (long-term) of curing time. Additionally, XRD analysis of the mixture without cement (S30B65C0) at 28 days of curing, as reported in Iyaruk et al. [1], is also compared. Notably, a high intensity of CSH was found in the cement-treated sample compared to the uncemented sample.

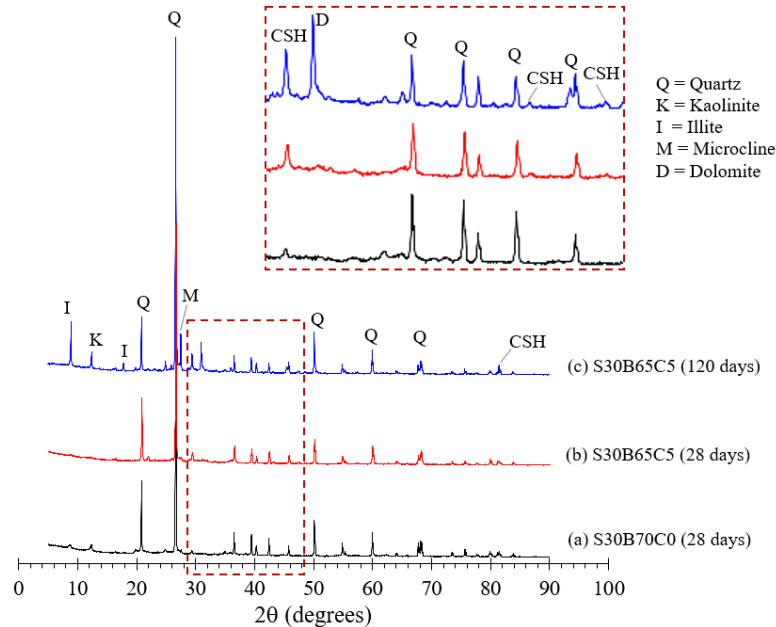


Figure 11 XRD patterns of the CTS samples after 28 and 120 days

3.2.2 FESEM and EDX analysis

Figures 12a and 12b show FESEM images of the field CTS sample at 28 and 120 days of curing, respectively, at a magnification of 5000. As observed, a large amount of CSH gels can be visualized at several points of the image. However, hydration and pozzolanic reaction products were more prominent after 120 days than after 28 days of curing. Moreover, some voids were detected between soil particles. The EDX analysis results of the field CTS samples at 28 days and 120 days of curing, conducted on the same sample used for the FESEM analysis, are depicted in Figures 13a and 13b, respectively. The presence of silica (Si), calcium (Ca), and aluminum (Al) weight proportions, especially Ca, is crucial for analyzing the strength development of the specimen [6, 51]. At 28 days of curing, the weight proportions of Si, Ca, and Al are 16.1%, 9.0%, and 6.8%, respectively. After 120 days, the weight proportions of Si, Ca, and Al are 12.6%, 13.2%, and 6.9%, respectively. Previous research has demonstrated that the $\text{Ca}/(\text{Si}+\text{Al})$ ratio is linked to the bond strength of the soil-cement mixture and significantly affects the hydration process [52]. The $\text{Ca}/(\text{Si}+\text{Al})$ ratio of the sample at 28 days was 0.39% and then increased to 0.68% after 120 days of curing. The increase in the $\text{Ca}/(\text{Si}+\text{Al})$ ratio resulted in an increase in the strength of the CTS sample due to the associated increase in CSH gel formation and bond strength [50].

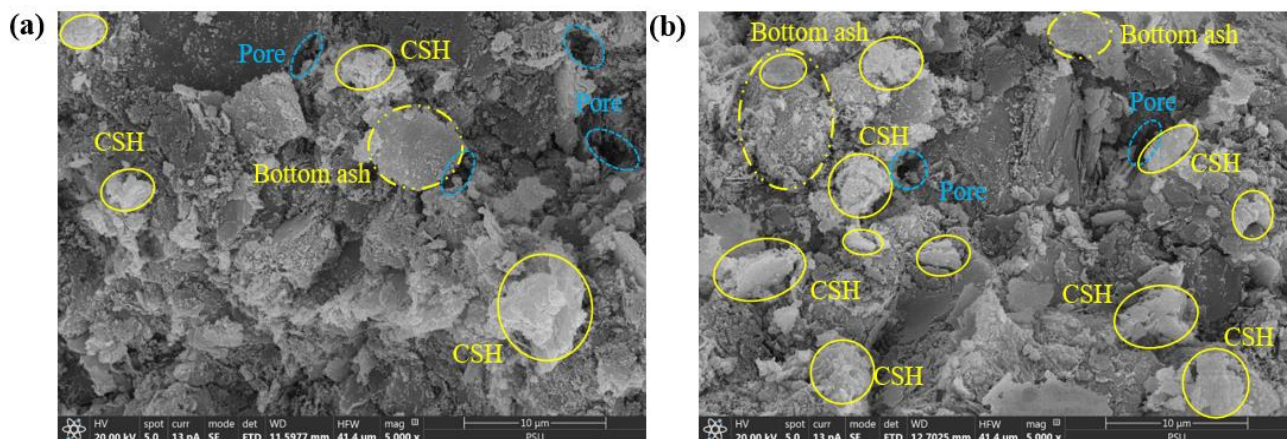


Figure 12 FESEM images: (a) 28 days and (b) 120 days

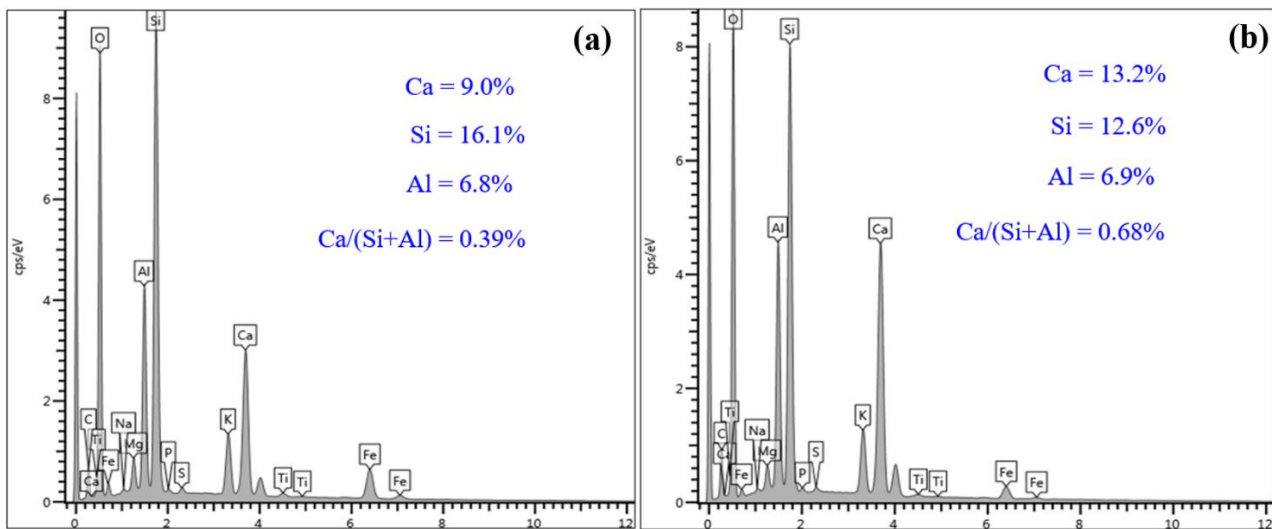


Figure 13 EDX analysis: (a) 28 days and (b) 120 days

3.3 Heavy metals

Table 2 summarizes the concentration of heavy metal leachate from the field CTS samples, determined using ICP-OES equipment. The concentration of Cr in the solid matrix was 82.86 mg/kg, above the MNSE acceptable limit of 17.5 mg/kg. Chromium was the sole metal detected in the leachate throughout all test periods, with a concentration of 1.377 ppm on day 7 and declining to 0.566 ppm by day 120. Despite this reduction, all measured values remained significantly above the permissible limit of 0.05 ppm, indicating potential environmental concerns regarding Cr leaching. This behavior suggests that although partial immobilization of Cr may occur over time, the stabilization mechanism is insufficient to effectively control Cr mobility, likely because it is less readily incorporated into cementitious phases than other heavy metals.

Table 2 Heavy metal concentration

	From a solid sample [54]		Field leachate sample (ppm)					Allowable limit (ppm) [53]
	WBA	Allowable limit (mg/kg)	7 days	14 days	30 days	60 days	120 days	
As	14.80	6	< 0.30	< 0.30	< 0.30	< 0.30	ND	0.01
Cr	82.86	17.5	1.377	0.70	1.055	0.797	0.566	0.05
Cu	16.60	2,920	< 0.30	< 0.30	< 0.30	< 0.30	< 0.50	1.00
Ni	16.64	436.5	< 0.30	ND	ND	ND	ND	0.02
Zn	32.02	-	ND	ND	ND	ND	ND	5.00

Note: ND = not detected

Although arsenic and copper were detected in the solid WBA at concentrations of 14.80 mg/kg and 16.60 mg/kg, respectively, they exhibited minimal leaching potential. Throughout all monitoring periods, the leachate As content remained below 0.30 ppm and became undetectable by day 120. The Cu leachate concentrations remained low, consistently below 0.30 ppm throughout the duration, decreasing to 0.50 ppm by day 120, which is well within the 100 ppm threshold. Karnchanawong and Veerakajohnsak [55] reported that As and Cu preferentially associate with aluminosilicate phases over time, thereby mitigating environmental concerns, despite their initial mobility in soils treated with wood ash. The undetectable levels of Ni and Zn in the leachates corroborate the notion that these elements are effectively immobilized, especially when co-stabilized by the elevated iron and aluminum oxide content of lateritic soil, which is recognized for its metal adsorption properties [56].

4. Conclusions

The research was motivated by the current demand for an environmentally sustainable, mechanically feasible substitute for conventional subbase materials, particularly in tropical countries. It is regarding this twofold issue that this study has sought to explore the possibility of mixing WBA with lateritic soil and cement to develop a new cement-treated subbase (CTS) material that meets the structural and environmental requirements for use as a subbase layer. From the laboratory and field experimental results presented in this paper, the following conclusions can be drawn:

- The experimental results showed that the optimum combination of CTS mix was 30% lateritic soil, 65% WBA, and 5% cement, as it met the strength criteria for road soil-cement subbase applications. The strength of CTS mixtures increases with cement and WBA contents and curing time. It is influenced by frictional resistance and pozzolanic reactions, indicating that the combination of WBA and cement significantly enhances the strength of the marginal lateritic soil.
- The VCR effectively combined the influence of density, cement, and ash content on UCS, showing a strong inverse relationship with strength. Practical strategies to improve strength include reducing porosity through compaction or increasing cement content, with densification identified as a more economical approach for field applications.
- Field subbase monitoring of heavy metal concentration revealed that Cr was the only metal consistently detected in leachate, decreasing over time but remaining above permissible limits, indicating insufficient immobilization and potential environmental risk. In contrast, As and Cu showed minimal leaching despite their presence in WBA, while Ni and Zn were

effectively immobilized. The results suggest selective stabilization behavior, with Cr exhibiting greater mobility than other metals due to weaker incorporation into cementitious phases.

- The theoretical and practical knowledge acquired in this study will support the synergistic nature of WBA and cement in improving the mechanical and environmental capacity of soil-subbase systems. Not only can WBA improve strength profiles at the correct dosage, but it also contributes to a circular economy by upcycling by-products from industrial processes.

In the future, research may focus on the long-term strength of CTS systems under dynamic loading conditions, including those influenced by traffic, seasonal average moisture levels, or wet-dry processes. It would also be helpful to conduct life-cycle assessment (LCA) research on WBA-stabilized subbases, as well as scalability studies of regional road-building projects.

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6. References

- [1] Iyaruk A, Promputthangkoon P, Lukjan A. Evaluating the performance of lateritic soil stabilized with cement and biomass bottom ash for use as pavement materials. *Infrastructures*. 2022;7(5):66.
- [2] Lu Y, Tian A, Zhang J, Tang Y, Shi P, Tang Q, et al. Physical and chemical properties, pretreatment, and recycling of municipal solid waste incineration fly ash and bottom ash for highway engineering: a literature review. *Adv Civ Eng*. 2020;2020:8886134.
- [3] Silva RV, de Brito J, Lynn CJ, Dhir RK. Environmental impacts of the use of bottom ashes from municipal solid waste incineration: a review. *Resour Conserv Recycl*. 2019;140:23-35.
- [4] Ayobami AB. Performance of wood bottom ash in cement-based applications and comparison with other selected ashes: overview. *Resour Conserv Recycl*. 2021;166:105351.
- [5] Bansal D, Gupta G, Ramana GV, Datta M. Environmentally responsible disposal and reuse of MSW incineration bottom ash: assessment from two Indian plants. *Clean Technol Environ Policy*. 2024;26(5):1439-54.
- [6] Rochanavibhata U, Lhajai S, Jongpradist P, Makaratat N, Jing G, Jamsawang P. Sustainable use of laterite replaced with bottom ash as road construction materials. *Int J Sustain Eng*. 2024;17(1):650-67.
- [7] DEDE. Thailand alternative energy annual report 2024. Bangkok: Department of Alternative Energy Development and Efficiency, Ministry of Energy; 2025. (In Thai)
- [8] He L, Tao M, Liu Z, Cao Z, Zhu J, Gao J, et al. Biomass valorization toward sustainable asphalt pavements: progress and prospects. *Waste Manag*. 2023;165:159-78.
- [9] Tabyang W, Kuasakul T, Sookmanee P, Laksanakit C, Chusilp N, Bamrunghphon Y, et al. Use of a rubber wood fly ash-based geopolymer for stabilizing marginal lateritic soil as green subbase materials. *Clean Technol Environ Policy*. 2024;26(6):2059-73.
- [10] Zhao Z, Xiao F, Amirkhanian S. Recent applications of waste solid materials in pavement engineering. *Waste Manag*. 2020;108:78-105.
- [11] Clavier KA, Ferraro CC, Townsend TG. Pilot-scale cement production using treated waste incineration bottom ash: physical and environmental performance. *Resour Conserv Recycl*. 2021;175:105862.
- [12] Åberg A, Kumpiene J, Ecker H. Evaluation and prediction of emissions from a road built with bottom ash from municipal solid waste incineration (MSWI). *Sci Total Environ*. 2006;355(1-3):1-12.
- [13] Dabo D, Badreddine R, De Windt L, Drouadaine I. Ten-year chemical evolution of leachate and municipal solid waste incineration bottom ash used in a test road site. *J Hazard Mater*. 2009;172(2-3):904-13.
- [14] Li L, Zhu Y, Hu Y, Zhao L, Wang Y. Impacts of wet treatment on leaching toxicity of municipal solid waste incineration bottom ash. *Int J Environ Sci Technol*. 2024;21:6313-24.
- [15] Shi C, Spence RD. Designing of cement-based formula for solidification/stabilization of hazardous, radioactive, and mixed wastes. *Crit Rev Environ Sci Technol*. 2004;34(4):391-417.
- [16] Wang K, Li K, Huang X, Ni W, Zhang S. Leaching characteristics of Cr in municipal solid waste incineration fly ash solidified/stabilized using blast furnace slag-based cementitious materials. *Int J Environ Sci Technol*. 2022;19:7457-68.
- [17] Nawaz K, Yu G, Noman M, Jintao F, Ahmad W. Heavy metals stabilization in lead zinc mine tailings by using mechanical, mechano-chemical, and microwave oven activation; tailing waste utilization in building materials. *Mater Struct*. 2025;58:52.
- [18] Kogbara RB. A review of the mechanical and leaching performance of stabilized/solidified contaminated soils. *Environ Rev*. 2014;22(1):66-86.
- [19] Gupta A, Arora VK, Biswas S. Contaminated dredged soil stabilization using cement and bottom ash for use as highway subgrade fill. *Int J Geo-Eng*. 2017;8:1-13.
- [20] Yan K, Sun H, Gao F, Ge D, You L. Assessment and mechanism analysis of municipal solid waste incineration bottom ash as aggregate in cement stabilized macadam. *J Clean Prod*. 2020;244:118750.
- [21] Bansal D, Ramana GV, Datta M, Ramaiah BJ. Waste to resource: enviro-mechanical suitability of MSW incineration bottom ash in flexible pavements and embankments. *Int J Geosynth Ground Eng*. 2024;10(2):17.
- [22] Toraldo E, Saponaro S. A road pavement full-scale test track containing stabilized bottom ashes. *Environ Technol*. 2015;36(9):1114-22.
- [23] Paine KA, Dhir RK, Doran VPA. Incinerator bottom ash: engineering and environmental properties as a cement bound paving material. *Int J Pavement Eng*. 2002;3(1):43-52.
- [24] Bessa IS, Aranha AL, Vasconcelos KL, Silva AHM, Bernucci LL. Laboratory and field evaluation of recycled unbound layers with cement for use in asphalt pavement rehabilitation. *Mater Struct*. 2016;49:2669-80.
- [25] Kantatham K, Hoy M, Sansri S, Horpibulsuk S, Suddepong A, Buritatum A, et al. Natural rubber latex-modified concrete with bottom ash for sustainable rigid pavements. *Civ Eng J*. 2024;10(8):2485-501.
- [26] ASTM. ASTM D1557: Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lbf/ft³ (2,700 kN-m/m³)). West Conshohocken: ASTM International; 2015.

- [27] ASTM. ASTM D2166/D2166M: Standard test method for unconfined compressive strength of cohesive soil. West Conshohocken: ASTM International; 2016.
- [28] DOH. Standard of soil-cement subbase. DH-S 206/2021. Bangkok: Department of Highways; 2021. (In Thai)
- [29] Sormunen LA, Kaartinen T, Rantsi R. MSWI BA treated with advanced dry recovery: a field scale study on materials' leaching properties. *Int J Sustain Eng*. 2018;11(4):261-71.
- [30] del Valle-Zermeño R, Formosa J, Prieto M, Nadal R, Niubó M, Chimenos JM. Pilot-scale road subbase made with granular material formulated with MSWI bottom ash and stabilized APC fly ash: environmental impact assessment. *J Hazard Mater*. 2014;266:132-40.
- [31] Ghosh A, Subbarao C. Hydraulic conductivity and leachate characteristics of stabilized fly ash. *J Environ Eng*. 1998;124(9):812-20.
- [32] Consoli NC, Cruz RC, Floss MF, Festugato L. Parameters controlling tensile and compressive strength of artificially cemented sand. *J Geotech Geoenviron Eng*. 2010;136(5):759-63.
- [33] Consoli NC, Viana da Fonseca A, Cruz RC, Heineck KS. Fundamental parameters for the stiffness and strength control of artificially cemented sand. *J Geotech Geoenviron Eng*. 2009;135(9):1347-53.
- [34] Baldovino JDJA, Izzo RLDS, Pereira MD, Rocha EVDG, Rose JL, Bordignon VR. Equations controlling tensile and compressive strength ratio of sedimentary soil–cement mixtures under optimal compaction conditions. *J Mater Civ Eng*. 2020;32(1):04019320.
- [35] Kim B, Prezzi M. Evaluation of the mechanical properties of class-F fly ash. *Waste Manag*. 2008;28(3):649-59.
- [36] Mehta PK, Monteiro PJM. Concrete: microstructure, properties, and materials. 3rd ed. New York: McGraw-Hill; 2006.
- [37] Baldovino JDJA, Moreira EB, Carazzai É, Rocha EVDG, dos Santos Izzo R, Mazer W, et al. Equations controlling the strength of sedimentary silty soil–cement blends: influence of voids/cement ratio and types of cement. *Int J Geotech Eng*. 2021;15(3):359-72.
- [38] Consoli NC, Festugato L, da Rocha CG, Cruz RC. Key parameters for strength control of rammed sand–cement mixtures: Influence of types of Portland cement. *Constr Build Mater*. 2013;49:591-7.
- [39] Wongkvanklom A, Sata V, Sanjayan JG, Chindaprasit P. Setting time, compressive strength and sulfuric acid resistance of a high calcium fly ash geopolymer containing borax. *Eng Appl Sci Res*. 2018;45(2):89-94.
- [40] Phutthananon C, Tippracha N, Jongpradist P, Tunsakul J, Tangchirapat W, Jamsawang P. Investigation of strength and microstructural characteristics of blended cement-admixed clay with bottom ash. *Sustainability*. 2023;15(4):3795.
- [41] Jongpradist P, Homtragoon W, Sukkarak R, Kongkitkul W, Jamsawang P. Efficiency of rice husk ash as cementitious material in high-strength cement-admixed clay. *Adv Civ Eng*. 2018;2018:8346319.
- [42] Liu M, Saberian M, Li J, Zhu J, Perera STAM, Roychand R, et al. Evaluation of brown coal fly ash for stabilising expansive clay subgrade: a sustainable solution for pavement construction. *Resour Conserv Recycl*. 2024;204:107533.
- [43] Consoli NC, Párraga Morales D, Saldanha RB. A new approach for stabilization of lateritic soil with Portland cement and sand: strength and durability. *Acta Geotech*. 2021;16:1473-86.
- [44] Horpibulsuk S, Katkan W, Sirilerdwattana W, Rachan R. Strength development in cement stabilized low plasticity and coarse grained soils: laboratory and field study. *Soils Found*. 2006;46(3):351-66.
- [45] Rios S, Viana da Fonseca A, Baudet BA. Effect of the porosity/cement ratio on the compression of cemented soil. *J Geotech Geoenviron Eng*. 2012;138(11):1422-6.
- [46] Teixeira W, Baldovino JA, Izzo R. Control parameters for the long-term tensile and compressive strength of stabilized sedimentary silt. *Civ Eng J*. 2023;9(4):799-814.
- [47] Kim YT, Do TH. Effect of bottom ash particle size on strength development in composite geomaterial. *Eng Geol*. 2012;139-140:85-91.
- [48] Bagriacik B, Kahraman ESM, Kılıç AM. Large-scale experimental model study: soil improvement with olive mill solid residue ash. *Int J Environ Sci Technol*. 2022;19:12581-92.
- [49] Karmakar A, Pal S, Bhattacharya K, Mandal MK, Ghosh Chaudhuri R, Chaudhuri H. Performance evaluation of cement-stabilized coalmine overburden-furnace slag-fly ash mixes as economical and sustainable base course material for flexible pavement. *Clean Technol Environ Policy*. 2025;27:4129-47.
- [50] Yoobanpot N, Jamsawang P, Simarat P, Jongpradist P, Likitlersuang S. Sustainable reuse of dredged sediments as pavement materials by cement and fly ash stabilization. *J Soils Sediments*. 2020;20:3807-23.
- [51] Wang G, Zhang X, Liu X, Gao H, Song S, Lu J. Enhancing mechanical properties of micaceous weathered granitic soil: a synergetic approach using natural fibers and fly ash. *Bull Eng Geol Environ*. 2024;83(6):257.
- [52] Tastan EO, Edil TB, Benson CH, Aydilek AH. Stabilization of organic soils with fly ash. *J Geotech Geoenviron Eng*. 2011;137(9):819-33.
- [53] MNRE. Groundwater quality standards. Bangkok: Ministry of Natural Resources and Environment; 2004. (In Thai)
- [54] MNRE. Soil quality standards. Bangkok: Ministry of Natural Resources and Environment; 2021. (In Thai)
- [55] Karnchanawong S, Veerakajohnsak C. Arsenic, chromium, and copper leaching from CCA-treated wood and their potential impacts on landfill leachate in a tropical country. *Environ Technol*. 2010;31(4):381-94.
- [56] Martínez-García R, Jagadesh P, Zaid O, Șerbănoiu AA, Fraile-Fernández FJ, de Prado-Gil J, et al. The present state of the use of waste wood ash as an eco-efficient construction material: a review. *Materials*. 2022;15(15):5349.