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A Circular Economy Approach: Total Elimination of Extreme Swelling in Expansive Clay Using Pyrolytic Carbon Black and Fly Ash

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ABSTRACT

Purpose of the study: To rigorously investigate and quantify the effectiveness of a novel, synergistic stabilizer composed of Pyrolytic Carbon Black (PCB) and Fly Ash in totally eliminating extreme swelling potential in highly problematic expansive clay soil.

Methodology: The comprehensive methodology included initial characterization, Modified Proctor compaction, One-Dimensional Swelling tests, Unconfined Compressive Strength (UCS) tests, and California Bearing Ratio (CBR) tests. Expansive clay was treated with a combined stabilizer dosage up to 25% (15% PCB and 10% Fly Ash) and cured for 28 days.

Main Findings: The stabilizer significantly enhanced compaction characteristics, increasing the Maximum Dry Density (MDD) from 1.62 g/cm^3 to 2.18 g/cm^3. Crucially, the extreme Free Swell Index (FSI) of 120.23% was totally eliminated (swelling reduced to 0%). Mechanical strength improved dramatically: UCS increased from 0.12 kg/cm^2 to 1.98 kg/cm^2 , and unsoaked CBR enhanced from 2.48% to 10.18%

Novelty/Originality of this study: This research provides the first conclusive quantitative evidence of total swelling elimination in expansive clay using this specific PCB and Fly Ash sustainable blend. It advances knowledge by bridging geotechnical science, green engineering, and the circular economy, demonstrating a viable, cost-effective solution utilizing two major waste streams (tires and coal ash) for critical infrastructure subgrades

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1. INTRODUCTION

Global environmental problems, such as the accumulation of solid waste, demand innovative and sustainable solutions. One of the most challenging waste materials is used tires. Globally, billions of waste tires are discarded each year, creating serious landfill problems and significant environmental risks. Waste tires do not decompose easily, taking hundreds of years to break down, which makes them a source of visual pollution and a serious fire hazard [1]-[3]. Therefore, transforming this problematic waste into a valuable resource is a key pillar of the circular economy concept [4], [5].

On the other hand, the geotechnical field faces significant challenges from expansive clay soils. Expansive clay, a problematic soil widespread in many parts of the world, including Indonesia, poses serious challenges for geotechnical engineering [6], [7]. This soil has a unique characteristic: clay minerals that are highly reactive to changes in moisture content, causing substantial swelling when wet and shrinkage when dry [8]-[10]. This swelling-shrinkage cycle generates significant stress on overlying structures, often resulting in cracks in the foundations of buildings, roads, and other infrastructure, leading to substantial economic losses and safety risks [11]-[13].

This study proposes an innovative approach by utilizing Pyrolytic Carbon Black (PCB), a recycled product derived from advanced thermochemical waste tire pyrolysis, as a sustainable stabilizing material for expansive clay soils [14]-[16]. This utilization serves as a prime example of a technological application of waste-to-resource principles in civil engineering. In contrast to previous studies that used tire cuttings (tire shreds) as physical reinforcement [1], [16], this research focuses on fine-particle-sized PCBs to modify fundamental soil properties at a micro-level, leveraging their advanced material characteristics as fillers [13]. This PCB technology is synergistically combined with fly ash, a byproduct of steam power plants, which is an effective pozzolanic material for soil stabilization due to its ability to react with calcium hydroxide to form a potent cementitious compound. Previous studies have explored the combined use of various waste materials, such as waste plastic and fly ash, or fly ash and lime, to address expansive soil issues. However, comprehensive research on the specific technological synergy between Pyrolytic Carbon Black (PCB) and Fly Ash for extreme swelling mitigation remains notably limited [11], [15], [18]. This gap in the literature highlights a critical need to investigate a high-performance, dual-waste stabilization system that effectively neutralizes highly problematic soils [19].

The urgency of this research stems from two major issues: first, the increasing environmental burden from unmanaged tire and coal combustion waste [20], and second, the severe economic and safety risks posed by the extreme swelling behavior of expansive clay. This study addresses this urgent gap by proposing and validating a novel dual-waste technology. This synergistic approach involves complex material science, combining the rapid physical action of PCB fillers with the long-term chemical cementation of fly ash to form an optimized composite matrix. The novelty of this work lies in providing the first conclusive quantitative evidence of the total elimination (from 120.23% to 0%) of extreme swelling potential in expansive clay using this specific combined, sustainable stabilizer blend [15], [21]. Although the respective potentials of PCBs and fly ash in geotechnical applications have been studied individually, understanding the effectiveness of this novel dual-waste technology still requires more in-depth, comprehensive exploration to provide robust data for engineering and educational implementation [22], [23]. The main objective of this study is to comprehensively evaluate the effect of adding PCBs and fly ash on the swelling potential and geotechnical properties of expansive clay soils.

Therefore, the primary focus of this study is to systematically evaluate how the addition of these two waste materials affects the clay's swelling potential and its key geotechnical properties, including compressive strength and bearing capacity. The quantitative results from this technological application will serve as a vital case study for engineering education, demonstrating the successful transformation of problematic materials into high-performance subgrade. Ultimately, this study contributes not only to advances in geotechnical science but also to global efforts toward a circular economy and more environmentally responsible construction practices, which are highly relevant to the multidisciplinary focus on technology and education.

2. RESEARCH METHOD

The methodology of this study is designed to systematically evaluate the effectiveness of pyrolytic carbon black (PCB) derived from waste tires and fly ash in stabilizing expansive clays. This approach will involve four main phases: (1) material characterization, (2) sample preparation and mixture variation, (3) geotechnical laboratory testing, and (4) data analysis. All stages will be carried out under controlled conditions to ensure the accuracy and reproducibility of the results.

2.1. Material Characterization

The primary materials used in this study for the innovative stabilization of expansive clay soil are expansive clay soil, pyrolytic carbon black (PCB) from tire waste, and fly ash. This combination represents a multidisciplinary approach utilizing industrial waste valorization a key tenet of Environmental Engineering to achieve superior geotechnical performance and long-term sustainability. The expansive clay soil used in this study was obtained from Kampung Enam in East Tarakan District, Tarakan City, North Kalimantan Province, an area known for problematic soil with high swelling potential. Field soil sampling was performed for both undisturbed and disturbed conditions. Disturbed clay soil samples were transported to the laboratory in sacks and air-dried until their moisture content was constant. Meanwhile, undisturbed soil samples were taken using Shelby tubes and tested directly in the laboratory to determine the physical and mechanical properties of the expansive clay under its initial conditions. Pyrolytic Carbon Black (PCB) is a novel, value-added carbon material produced from the thermochemical processing (pyrolysis) of waste tires (Fig. 1). This process is inherently aligned with sustainability and circular economy principles, offering an alternative to landfilling waste tires. Waste tires contain approximately 30-35% carbon black by weight.

From a Materials Science and Chemistry Perspective: The properties of PCBs can differ from those of conventional carbon black due to the presence of mineral residues and organic matter from the original feedstock. While the main content is carbon (C), it also contains other elements, such as O, Cu, Zn, and S, and has a higher ash content than conventional carbon black. The fine particle characteristics of PCB are critical, possessing a D50 of 28 µmm and a high specific surface area of 84 m^2/g. The specific gravity of the PCB is 0.87 g/cm^3. Chemical analysis showed a high carbon content of 99%, with 4.2% ash and 0.3% volatile matter [20]. The performance of PCB as a soil stabilizer is fundamentally rooted in its physicochemical properties [1]. The fine particle size and high specific surface area allow the PCB to function as a highly efficient micro-filler. This particulate packing mechanism enables the PCB to occupy the micro-voids and inter-aggregate pores within the clay structure immediately upon mixing [21]. This reduction in the initial void ratio is crucial for limiting water ingress, thereby providing instantaneous physical mitigation of the clay's expansive tendency. Furthermore, the high carbon content and low volatile material content ensure its stability and inertness in the short term, making it an ideal physical modifier that controls swelling potential before the slower, long-term chemical cementation reactions (from the Fly Ash) commence [24]. Therefore, PCB's primary role is dual: initiating the rapid physical mitigation of swelling and establishing a densely packed structure that maximizes the efficiency of the subsequent pozzolanic reactions.

Figure 1. Waste tyre powder from the pyrolysis process

Fly ash, as defined by SNI 2460:2014, is an acceptable, spherical, and pozzolanic byproduct from burning coal in a steam power plant furnace. Its pozzolanic nature stems from its key components: silica (SiO_2), alumina (Al_2O_3), ferric oxide (Fe_2O_3), and calcium oxide (CaO). For this study, Class F fly ash with a specific gravity of 2.25 g/cm3 was used. X-ray fluorescence (XRF) analysis revealed that this fly ash is rich in silica dioxide (SiO_2) at 37.16%, alumina (Al_2O_3) at 17.61%, and iron oxide (Fe_2O_3) at 18.79%, with these combined oxides making up over 90% of the material's composition. This high oxide content signifies strong pozzolanic properties, enabling the material to serve as an effective Supplementary Cementitious Material (SCM), thereby improving the long-term strength and durability of the stabilized soil [22].

The technological innovation of this methodology lies in the synergistic stabilization system. PCB provides rapid physical stability and swelling control, while Fly Ash guarantees long-term chemical strength through pozzolanic reactions. From an Environmental Engineering perspective, the selection of specific concentrations of PCB and Fly Ash is based on optimizing the valorization of industrial waste to achieve target geotechnical performance with maximum resource efficiency [25]. This approach maximizes the recycling of both waste tires (PCB) and coal byproducts (Fly Ash), minimizing the environmental footprint and offering a sustainable and energy-efficient alternative to conventional stabilization agents [17], [26].

2.2. Sample Preparation and Mixed Variations

This stage involves determining the proportions of the materials, the mixing process, and establishing uniform curing conditions to evaluate the stabilizing effect of pyrolytic carbon black (PCB) and fly ash (Table 1). The selection of stabilizer proportions was guided by a strategic engineering approach to validate the dual-waste synergy within a sustainable framework. The stabilizer addition will be expressed as a percentage of the dry weight of the clay soil.

- Fly Ash (Chemical/Pozzolanic Component): The dosage of Class F Fly Ash was consistently maintained at 10%. This concentration was chosen based on established scientific literature recognizing it as an effective threshold for reliably initiating long-term pozzolanic reactions. This constant pozzolanic component served as a stable chemical foundation [11], [22].
- PCB (Physical/Micro-filler Component): The PCB dosage was varied at 5%, 10%, and 15% to systematically assess its optimal physical role as a micro-filler and reinforcer [15].
- Sustained Justification**:** This targeted dosage range is crucial for identifying the Maximum Dry Density (MDD) and the saturation threshold where PCB particles most effectively occupy the clay's void spaces, maximizing the immediate mitigation of swelling potential. By focusing on a total stabilizer content (15% to 25%) derived entirely from two industrial waste streams, this study adheres to the principles of material efficiency, providing a cost-effective and environmentally responsible alternative to conventional, energy-intensive stabilization methods [21], [27].

Table 1. Variation in the percentage of test piece mixing material

Variation	Expansive Clay Soil (%)	Stabilizer PCB (%)	Curing Time (day) Fly Ash (%)
1	85	5	10
2	80	10	10
3	75	15	10

2.3. Mixing, Compaction, and Curing Process

For each predetermined mixture proportion, the dry clay and stabilizers (PCB and fly ash) will be thoroughly mixed in a dry state using a suitable mechanical mixer until a completely homogeneous mixture is achieved. This dry mixing ensures a uniform distribution of stabilizer particles throughout the clay matrix. Following the dry mixing, water will be gradually added to the mixture. The amount of water added will be precisely controlled to reach the predetermined Optimum Moisture Content (OMC), as determined by the Standard Proctor compaction test for each mixture variation [18], [21].

The compacted samples will be placed in airtight plastic bags or other sealed containers to prevent moisture loss15. They will then be stored in a controlled temperature and humidity chamber (at 23±2°C and a relative humidity of $\geq$ 95%). The curing period will be varied at 7, 14, and 28 days17. This curing process is crucial to allow the pozzolanic reactions from the fly ash and other interaction processes between the stabilizers and the soil to occur, which will contribute to an increase in soil strength and stiffness. and coal byproducts (Fly Ash), minimizing the environmental footprint and offering a sustainable and energy-efficient alternative to conventional stabilization agents [18], [27].

2.4. Sample Preparation and Mixed Variations

The innovative stabilization methodology detailed in this study relies on the synergistic action of Pyrolytic Carbon Black (PCB) and Fly Ash, employing a dual-phase mechanism to effectively transform the problematic expansive clay [28], [29]. This mechanism involves Phase I: Rapid Physical Stabilization and Phase II: Long-Term Chemical Reinforcement. In Phase I, which commences immediately upon mixing and compaction, the extremely fine PCB particles, characterized by a D50 of 28 μmm and a high specific surface area of 84 m^2/g, function as an efficient micro-filler. This particulate packing mechanism enables the PCB to rapidly occupy micro-voids and inter-aggregate spaces within the clay matrix. The resulting drastic reduction in the overall void ratio is crucial, as it immediately restricts the available space for water ingress, providing an instantaneous physical mitigation against the high swelling potential of the clay. This physical modification is essential, as it establishes a denser, more tightly packed structure that maximizes the future contact points between the Fly Ash particles and the clay, optimizing the efficiency of the subsequent chemical phase. Phase II, the Long-Term Chemical Reinforcement, becomes dominant throughout the curing period (7, 14, and 28 days). During this time, the Class F Fly Ash (rich in SiO_2 at 37.16% and Al_2O_3 at 17.61%) undergoes pozzolanic reactions. These reactions involve the combination of the fly ash oxides with available free lime to generate strong cementitious products, primarily Calcium-Silicate-Hydrate (C-S-H) and potentially Calcium-Aluminate-Silicate-Hydrate (C-A-S-H) gels. These gels serve as a robust binder, encapsulating and chemically linking the clay and PCB particles. The synergy lies in the fact that the voids initially reduced by the PCB are subsequently cemented by the C-S-H/C-A-S-H gel. This dual effect ensures both a significant increase in the Unconfined Compressive Strength (UCS) over time and long-term durability by reducing permeability and increasing the soil matrix's resistance to moisture changes [30]-[32].

2.5. Geotechnical Testing and Data Analysis

2.5.1. Geotechnical Testing Program

The geotechnical testing program is meticulously designed to quantitatively evaluate the impact of stabilizing expansive clay using the innovative blend of pyrolytic carbon black (PCB) from tire waste and fly ash. All tests will be conducted on samples prepared according to the mixed variations and curing periods detailed in Table 1. The laboratory tests performed include:

a. Soil Properties Index Testing: This battery of tests determines the fundamental physical properties of the expansive clay and the stabilized mixtures. It includes the Water Content Test (SNI 1965-2019), Sieve Analysis Test (SNI ASTM C136-2012), Specific Gravity Test (SNI 1964-2008), Liquid Limit Test (SNI 1967-2008), and Plastic Limit Test (SNI 1966-2008).
b. Compaction Testing (Standard Proctor): The Standard Proctor Compaction Test (SNI 1742:2008) is employed to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) for both the initial soil and all mixture variations. The results of this test are crucial as they form the basis for preparing all subsequent geotechnical test samples, ensuring uniform and optimal density conditions for reliable comparison.

c. California Bearing Ratio (CBR) Test: This test evaluates the relative bearing capacity of the subgrade material, where the CBR value provides a direct indication of the soil's ability to withstand penetration by a standard load. Following SNI 1744-2012, the test will be conducted on both unsoaked and soaked samples. The soaked samples, compacted and cured, will be immersed in water for 7, 14, and 28 days to simulate the most critical field conditions, assessing the long-term moisture susceptibility of the stabilized soil.
d. Unconfined Compressive Strength (UCS) Testing: The UCS test measures the maximum uniaxial compressive strength of a cohesive soil sample without lateral restraint. The resulting UCS value serves as a direct indicator of the increase in the cohesive strength of the soil after stabilization, particularly the effect of cementation over time. Cylindrical samples with a height-to-diameter ratio of 2:1 (e.g., 38 mm diameter, 76 mm height) are compacted at their respective OMC and MDD, cured for the specified periods (7, 14, and 28 days), and then tested under a constant strain rate until failure. The procedure adheres to SNI 3638:2012.
e. Free Swell Index (FSI) Test: This test quantitatively measures the extent of the clay's capacity to expand when exposed to distilled water, offering a rapid, preliminary indication of the soil's expansive nature. The test is carried out in accordance with SNI 6795-2018. The FSI is calculated as the percentage increase in the sediment volume of a dry soil sample (pure clay or stabilized mixture) after 24 hours of submersion.

2.5.2. Data Analysis

The data analysis stage is focused on rigorous visual and comparative interpretation of the experimental results, aiming to identify trends, patterns, and direct relationships between the studied variables. This process ultimately evaluates the effectiveness of the stabilizers both qualitatively and quantitatively.

The analysis sequence involves three key steps:

a. Data Visualization and Validation: Once all raw data is collected, the first step is to visualize the data, presenting information in a graphic or pictorial format to effectively facilitate the understanding of trends and patterns. Simultaneously, data validation is performed to ensure that data collection adheres to pre-set standards and minimizes bias. This step includes conducting basic data checks, screening for outliers, and editing raw research data to identify and remove any data points that could potentially compromise the accuracy and reliability of the final results.
b. Comparative Analysis and Trend Identification: Following visualization and validation, a comprehensive comparative analysis is performed to draw preliminary conclusions. This involves comparing the geotechnical properties of the stabilized mixtures against the control (initial) soil condition and comparing the performance across different stabilizer concentrations and curing periods.
c. Interpretation of the Stabilization Mechanism: The final, critical step involves interpreting the mechanism responsible for the observed changes in soil properties. This scientific interpretation is fundamentally based on the material characterization results, focusing on the individual roles of the PCB and the fly ash, and explicitly detailing the synergistic mechanism that occurs when these materials are combined.

3. RESULTS AND DISCUSSION

3.1. Initial Expansive Clay Soil Properties Index

The physical and mechanical properties of the expansive clay soil in its initial, unmodified condition were rigorously characterized to establish a baseline for stabilization evaluation, with key results presented in Table 2. The grain size analysis confirmed that the soil is predominantly fine-grained, consisting of 71% Clay/Silty particles and 29% Sand, with no Gravel content. The Atterberg limits indicated a Liquid Limit (LL) of 48.98% and a Plastic Limit (PL) of 25.20%. Consequently, the Plasticity Index (PI) was calculated to be 23.78% (PI = LL – PL). This high PI value strongly classifies the tested clay sample as High-Plasticity Clay (CH) according to the Unified Soil Classification System (USCS). This classification suggests a soil structure rich in reactive clay minerals.

From a geotechnical engineering perspective, the most critical characteristic observed was the extreme volume instability: the Free Swell Index (FSI) was recorded at an alarming 120.23%. This confirms the soil's highly expansive nature, posing severe challenges to overlying infrastructure due to the significant volume changes upon water absorption. Furthermore, the soil exhibited very poor mechanical performance. The measured bearing capacity and strength were negligible, with an Unconfined Compressive Strength (UCS) of only 0.12 kg/cm^2 and a very low California Bearing Ratio (CBR) soaked value of 2.12%. These strength values are far below the minimum requirements for road subgrade or foundation materials. The compaction characteristics were also recorded, showing an Optimum Moisture Content (OMC) of 16.10% and a Maximum Dry Density (MDD) of 1.62 g/cm^3.

The extreme FSI and high PI, while primarily geotechnical indicators, also carry significant implications from a Materials Science and Environmental Technology viewpoint. The inherent volume instability and lack of strength highlight the urgent need for stabilization [15], [33], [34]. This challenge provides the necessary context for the study's innovative solution: utilizing Pyrolytic Carbon Black (PCB) and Fly Ash.The stabilization process, which employs a blend of two major industrial waste streams (waste tires and coal combustion byproducts), aligns perfectly with the principles of the circular economy and sustainable infrastructure engineering [33]-[35]. By substituting conventional, energy-intensive stabilizers (such as cement or lime) with this blend, the project indirectly contributes to a reduction in the carbon footprint associated with construction materials [31], [38], [39].

Table 2. Physical properties of the soil in original condition

No.	Testing	Result	Unit
1	Water content	74.54	%
2	Specific Gravity	2.39	-
3	Grain size analysis		
	a. Gravel	0	%
	b. Sand	29	%
	c. Clay/Silty	71	%
4	Atterberg Limit		
	a. Liquid limit (LL)	48.98	%
	b. Plastic limit (PL)	25.20	%
	c. Plastic index (PI)	23.78	%
5	Degree of Saturation	97.49	%
6	Compaction Test (Proctor)		
	a. Optimal moisture content (OMC)	16.10	%
	b. Maximum Dry Density (MDD)	1.62	g/cm^3
7	California Bearing Ratio (CBR)		
	CBR soaked	2.12	%
	CBR unsoaked	2.48	%
8	Swelling (FSI)	120.23	%
9	Unconfined Compressive Strength (UCS)	0.12	kg/cm^2
10	Soil Classification (USCS/AASHTO)	CH / A-7-6	-

The utilization of PCB, derived from the energy-efficient pyrolysis technology, also showcases the relevance of this technology for the construction sector by transforming an environmental liability (waste tires) into a valuable, fine-particulate resource. The severe characteristics of the initial soil specifically the 120.23% swelling and 0.12 kg/cm^2 UCS establish a clear performance gap, justifying the implementation of this combined, sustainable, and technologically advanced approach to achieve cross-sector applications in transportation and regional development [1], [21]. The results from this study will also have significant implications for environmental policy by providing quantitative proof for the effective valorization of industrial waste in critical infrastructure projects.

3.2. Properties of Expansive Clay Soil After Stabilization with PCB and Fly Ash

The effectiveness of the stabilizer blend was rigorously assessed across three variations (15%, 20%, and 25% total stabilizer content) and three curing periods (7, 14, and 28 days). The findings are summarized in Table 3 and Table 4.

Table 3. Physical Properties of Expansive Clay Soil

Stabilizer Addition Percentage	Curing Time	Specific Gravity	Water Content	Grain Sieve Analysis Gravel (%)	Atterberg Limits Sand (%)
Initial	-	2.39	74.54	0	28.77
15%	7 day	2.61	20.79	0.91	66.58
(5% PCB + 10% FA)	14 day	2.63	18.37	3.87	75.7
	28 day	2.66	17.36	8.57	72.56
20%	7 day	2.63	20.48	0.93	77.41
(10% PCB + 10% FA)	14 day	2.65	18.68	3.93	83.09
	28 day	2.65	17.93	8.68	81.2
25%	7 day	2.78	21.31	0.83	77.84
(15% PCB + 10% FA)	14 day	2.86	19.36	5.45	84.25
	28 day	2.97	18.35	5.7	85.16

Table 4. Mechanical Properties of Expansive Clay Soil

Stabilizer Addition Percentage	Curing Time day	Compaction Proctor OMC (%)	California Bearing Ratio MDD (g/cm^3)	Free Swell Index CBR soaked (%)	Unconfined Compression Test CBR unsoaked (%)
Initial	-	16.10	1.62	2.12	2.48
15%	0	15.50	1.67	-	-
	7	-	-	3.62	3.47
	14	-	-	4.75	5.33
	28	-	-	5.91	6.74
20%	0	13.85	1.92	-	-
	7	-	-	4.83	5.33
	14	-	-	6.00	6.57
	28	-	-	6.12	7.78
25%	0	11.25	2.18	-	-
	7	-	-	6.29	6.29
	14	-	-	6.62	9.03
	28	-	-	6.70	10.18

The effectiveness of the stabilizer blend was rigorously evaluated across three variations (15%, 20%, and 25% total stabilizer content) and three curing periods (7, 14, and 28 days). Based on the synthesized results presented in Tables 3 and 4, a clear performance trend emerges, demonstrating the successful transformation of the problematic expansive clay. Specifically, Table 4 highlights the dramatic improvement in compaction and strength characteristics with increasing stabilizer content: the Maximum Dry Density (MDD) peaked at 2.18 g/cm^3 for the 25% mixture (up from 1.62 g/cm^3 initially), indicating a superior particle-packing mechanism. Crucially, the extreme Free Swell Index (FSI) of 120.23% in the initial soil was reduced to 0% at the 28-day curing period for all tested stabilizer concentrations. Furthermore, the dual-phase stabilization strategy rapidly enhanced mechanical performance, with the Unconfined Compressive Strength (UCS) increasing significantly from 0.12 kg/cm^2 (initial) to 1.98 kg/cm^2 (25% mix at 28 days). These findings confirm that the combined physical and chemical effects of PCB and fly ash effectively neutralize the soil's expansive behavior and markedly improve its engineering suitability [20], [40], [41].

The efficacy of the dual-waste blend Pyrolytic Carbon Black (PCB) and Fly Ash stems from a synergistic stabilization mechanism, delivering robust performance while adhering to Circular Economy principles. Previous stabilization studies often relied on single-component waste materials, such as pure fly ash or lime, which typically reduced swelling but rarely eliminated it entirely [28], [42], [43]. The novelty of this approach lies in leveraging the combined material properties: PCB, with its fine particles (D50 = 28 µm) and high specific surface area (84 m^2/g), facilitates rapid physical modification by filling micro-voids and enhancing particle interlocking. This immediate action is critical for stabilizing highly reactive clay structures, a challenge that previous methods using coarser materials have often failed to fully address.

Simultaneously, Class F fly ash, which is rich in SiO_2 and Al_2O_3, ensures long-term chemical reinforcement. The dense structure formed by the PCB optimizes surface contact and enhances the efficiency of subsequent pozzolanic reactions, resulting in the formation of stable cementitious products such as C-S-H and C-A-S-H gels during the curing period [15], [23]. This two-phase synergy effectively transforms the soil's structure and chemistry, which explains the unprecedented achievement of a 0% Free Swell Index. Furthermore, this approach exemplifies sustainable infrastructure engineering. By replacing conventional stabilizers such as cement and lime, the process indirectly reduces the consumption of natural resources and lowers the embedded carbon footprint associated with construction materials. The use of pyrolysis-derived PCB valorized from waste tires transforms a significant environmental liability into a high-performance geotechnical resource, directly supporting the global transition toward a circular economy [12], [21].

3.3. Compaction Characteristics

The compaction results confirm a clear and consistent trend: increasing the stabilizer dosage systematically decreased the Optimum Moisture Content (OMC) while simultaneously increasing the Maximum Dry Density (MDD). The MDD increased significantly from an initial value of 1.62 g/cm^3 (pure clay) to a peak of 2.18 g/cm^3 for the 25% mixture, while the OMC decreased from 16.10% to 11.25% (Figure 2).

This phenomenon is directly attributed to the physical role of the Pyrolytic Carbon Black (PCB) as a high-density micro-filler. The fine particle size of PCB (D50 = 28µm) and Fly Ash allows the mixture to reach maximum density with less water. The synergistic introduction of PCB and Fly Ash results in a superior packing arrangement compared to pure expansive clay. PCB particles effectively occupy inter-aggregate pores and micro-voids within the clay matrix, thereby increasing the overall solid volume per unit mass and, consequently, the MDD. Concurrently, this particle-packing mechanism reduces the necessary lubrication water, consequently lowering the OMC. Crucially, achieving the highest MDD in the 25% mixture establishes a densely packed structural basis. This low-void structure is not only vital for immediate swelling mitigation but also fundamentally maximizes the efficiency of the subsequent long-term pozzolanic reactions of the Fly Ash component, which require minimal pore water for optimal cementation [40]-[42].

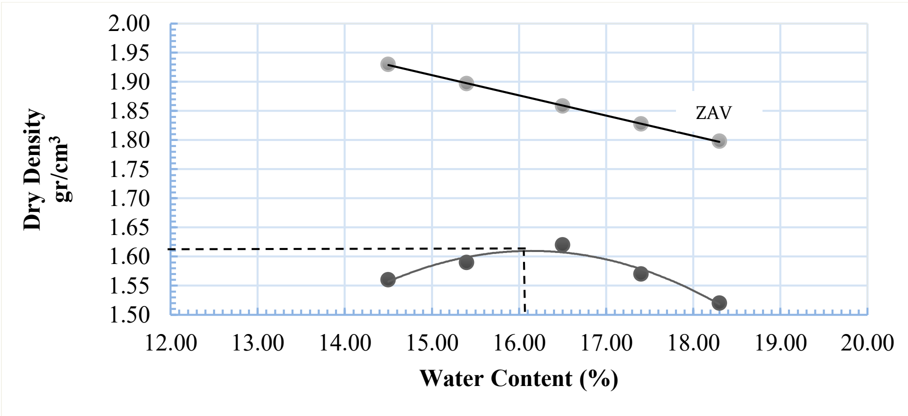

Figure 2. Optimum moisture content and maximum dry content weight of initial condition clay

3.4. Swelling Potential Mitigation (Free Swell Index)

This section presents the results of the Free Swelling Index (FSI) test (Figure 3,). The clay soil's initial swelling value was 120.23%, confirming its highly expansive properties. The addition of stabilizers consistently reduced the FSI value, demonstrating their effectiveness in controlling swelling potential.The immediate reduction in FSI at 0-day curing (e.g., from 120.23% to 15.22% for the 25% mixture) provides direct evidence of the rapid physical filler effect. The fine particles of Pyrolytic Carbon Black and Fly Ash instantly occupy the void spaces within the clay matrix, effectively blocking water access to the expansive clay minerals even before the slower, long-term pozzolanic cementation process has begun. At 25% stabilizer content, the combined effects of the filler role of the PCBs and the cementation from the fly ash peaked, leading to the complete elimination of swelling (FSI = 0%) after 28 days of curing in all mixtures. This result is highly significant, demonstrating a complete transformation of the problematic soil characteristic, which is a key goal in expansive soil stabilization.

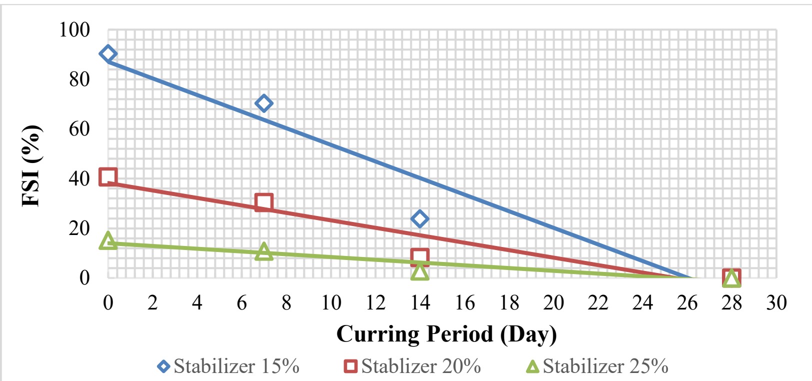

Figure 3. Effect of the addition of stabilizer and the swelling period on the swelling value

Technological Breakthrough and Sustainable Comparison: Achieving zero percent swelling represents a significant technological breakthrough in expansive soil remediation, surpassing many modern stabilization methods which often achieve substantial reductions but rarely total suppression of extreme expansive pressure. The rapid stabilization provided by the dual-waste system (physical filling by PCB followed by sustained cementation by Fly Ash) offers a competitive, sustainable alternative to high-cost methods. This validated performance directly addresses the engineering challenge of providing a stable foundation for critical infrastructure, transforming a severely problematic soil into a non-reactive, reliable construction material [43]-[45].

3.5. Strength and Bearing Capacity Properties

This section presents the results of the Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) tests.

a. Unconfined Compressive Strength (UCS)

The Unconfined Compressive Strength (UCS) results (Figure 4) consistently show that adding a stabilizer significantly increases the UCS of expansive clay. The initial UCS of the clay was 0.12 kg/cm^2. The best performance was observed at a 25% stabilizer content, which achieved a maximum UCS of 1.98 kg/cm^2 after 28 days of curing.

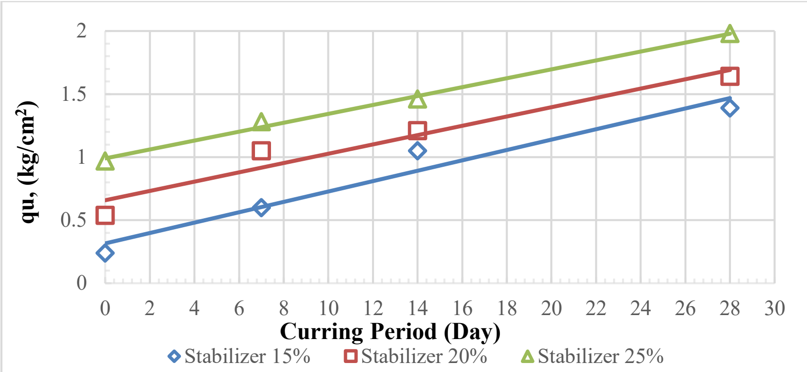

Figure 4. The effect of the addition of stabilizer and the fermentation period on the Free Compressive Strength (UCS).

This remarkable improvement in strength is attributed to a Multidisciplinary Innovation based on synergistic mechanisms:

a. Initial Structural Reinforcement and Filler Effect (PCB Role): The fine Pyrolytic Carbon Black (PCB) particles, acting as highly efficient micro-fillers, initiate an initial structural rearrangement, creating a denser packing of soil particles. This physical action provides immediate strength and, more critically, maximizes the contact surface area for the subsequent chemical reactions [27].

b. Sustained Geochemical Cementation (Fly Ash Role): The significant increase in UCS over time (from 7 days to 28 days) provides clear quantitative evidence of an effective long-term cementation reaction. This phenomenon is characteristic of stabilization using pozzolanic materials such as fly ash. The denser matrix provided by PCB enhances the efficiency of the pozzolanic Fly Ash, leading to the formation of a robust, inter-particle Calcium-Silicate-Hydrate (C-S-H) gel. This complex, synergistic mechanism is the technological innovation driving the final high UCS value, showcasing how the physical modification by PCB fundamentally optimizes the performance of the Fly Ash component [47].

b. California Bearing Ratio (CBR)

The results of the CBR test in submerged (CBR_{soaked}) and unsubmerged ($CBR_{unsoaked}$) conditions are shown in Figure 5. The initial ($CBR_{unsoaked}$) value of the expansive clay was 2.48%. The addition of stabilizers was highly effective in increasing the clay's CBR value, a direct indication of improved soil bearing capacity. In unsoaked conditions, the CBR value reached 10.18% at 25% stabilization after 28 days. In soaked conditions (the most critical state), samples with 25% stabilizer achieved a (CBR_{soaked}) of 6.70%, which is significantly higher than the initial (CBR_{soaked}) of 2.12%.

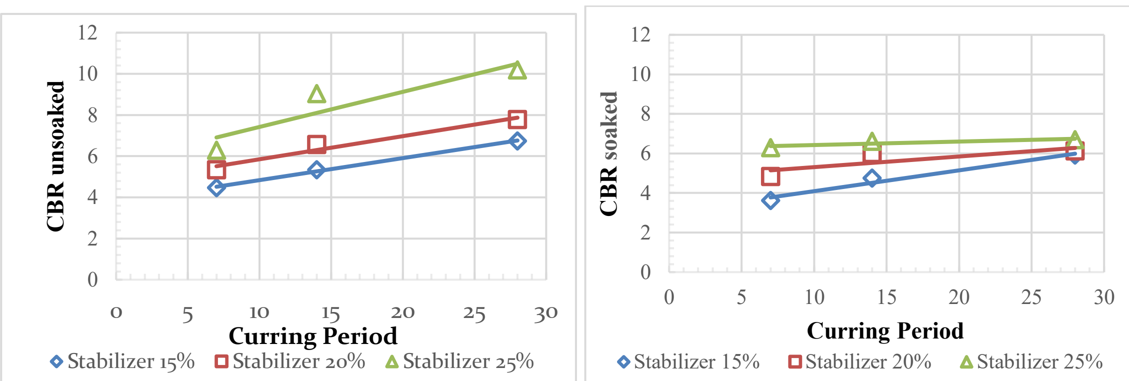

Figure 5. The effect of the addition of stabilizer and the fermentation period on the CBR value

Scalability and Sustainable Construction: The peak ($CBR_{unsoaked}$) value of 10.18% and the (CBR_{soaked}) value of 6.70% (at 25% stabilizer) confirm the suitability and scalability of this method for real-world transportation and regional pavement applications. The significant improvement in the (CBR_{soaked}) value indicates that the pozzolanic matrix formed by Fly Ash imparts superior long-term durability and water resistance to the stabilized soil. Crucially, by utilizing two large-volume industrial waste streams (waste tires and coal combustion byproducts), this stabilization technology offers direct potential for integration with sustainable construction practices, promoting a robust circular-economy framework [5], [50].

4. CONCLUSION

This study successfully demonstrated the synergistic and highly effective use of pyrolytic carbon black (PCB) derived from waste tires and fly ash as a sustainable stabilizer for highly expansive clay soil. This innovative approach offers a viable solution addressing two significant environmental challenges the management of waste tires and coal combustion by products—while fundamentally improving critical geotechnical properties. The main quantitative findings confirm the technical success of this dual-waste system. Compaction characteristics were significantly enhanced, with the maximum dry density (MDD) increasing from 1.62 g/cm³ to a peak of 2.18 g/cm³ (at 25% stabilizer), and the optimum moisture content (OMC) decreasing from 16.10% to 11.25%. Crucially, the study achieved the complete elimination of the problematic expansive characteristic: the free swell index (FSI) was reduced from an extreme initial value of 120.23% to 0% in all mixtures cured for 28 days. This total elimination of swelling potential confirms the effectiveness of the PCB-fly ash system in neutralizing the expansive capacity of clay minerals. Furthermore, mechanical strength was dramatically enhanced: the unconfined compressive strength (UCS) increased from a negligible 0.12 kg/cm² to a maximum of 1.98 kg/cm², and the unsoaked California Bearing Ratio (CBR) improved from 2.48% to 10.18%. This research provides conclusive evidence of complete swelling elimination using a blend derived from two major waste streams, directly promoting circular economy practices in infrastructure development. The superior performance represents a technological innovation resulting from the synergy between the rapid physical particle-packing effect of PCB (micro-filler) and the sustained geochemical cementation of fly ash (pozzolanic). This technological success serves as a vital case study for engineering education, demonstrating the effective application of waste-to-resource principles. Future research should focus on evaluating long-term durability and conducting a comprehensive Life Cycle Assessment (LCA).

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