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Mechanical Properties of Cement-Stabilized Sandy Soils Modified with Consoil

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Abstract

This study investigates the mechanical enhancement of sandy soils through cement stabilization modified with Consoil, targeting improved pavement substructure performance. Unconfined compressive strength (UCS) tests were conducted on samples with varying cement contents (3%, 6%, 9%), Consoil dosages (0%, 5%, 10%, 15%, 20% by cement weight), and curing periods (3, 7, 28, 90 days). Field Emission Scanning Electron Microscopy and X-Ray Diffraction analyses complemented mechanical testing to understand strengthening mechanisms. Results demonstrated that 15% Consoil consistently optimized strength development across all cement contents, with 9% cement and 15% Consoil achieving peak 90-day UCS of 17.74 MPa, representing a 67% increase over control samples. Microstructural analysis revealed progressive matrix refinement with increasing Consoil content, while XRD indicated enhanced pozzolanic activity through calcium hydroxide consumption. The study introduces Consoil as an effective stabilization additive, establishing optimal dosage rates and demonstrating significant strength improvements through synergistic cement-Consoil interactions. The findings provide new insights into strength enhancement mechanisms in Consoil-modified cement-stabilized soils, offering practical guidelines for designing high-performance pavement substructures. The research contributes to sustainable construction practices by optimizing cement usage through Consoil incorporation.

Keywords: Soil Stabilization; Cement-Stabilized Soil; Consoil; Unconfined Compressive Strength; Pavement Substructure; Pozzolanic Reaction; Microstructural Analysis; Optimum Moisture Content.

1. Introduction

The optimization of pavement substructure performance presents a persistent challenge in transportation infrastructure, particularly as the industry confronts increasing demands for sustainability, durability, and cost-effectiveness. Recent investigations into soil stabilization mechanisms have revealed complex relationships between material composition, mechanical properties, and long-term performance characteristics. Sukmak et al. (2024) [1] established fundamental correlations between particle size distribution and strength development in cement-stabilized soils, demonstrating that sand-to-fines ratios significantly influence mechanical performance optimization. This understanding has revolutionized approaches to stabilization design, particularly for pavement applications.

The environmental impact of traditional cement stabilization has catalyzed extensive research into alternative and supplementary materials. Yu et al. (2024) [2] documented substantial improvements in mechanical properties through the incorporation of coal-derived char in cement-soil matrices, while maintaining critical performance parameters. Recent investigations by Rasheed et al. (2024) [3] demonstrated the viability of composite binders comprising cement bypass dust and spent fluid catalytic cracking catalyst, achieving unconfined compressive strengths of 15.6 MPa while promoting circular economy principles in pavement construction. This evolution in stabilization technology has

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prompted investigation of various innovative binding agents, as evidenced by Abdolvand & Sadeghiamirshahidi's (2024) [4] comprehensive analysis of gypsum-based stabilization systems. Anburuvel (2024) [5] synthesized contemporary advances in stabilization additives, highlighting an industry-wide shift toward sustainable alternatives in geotechnical applications.

Several studies have investigated the effects of cement stabilization on various soil types and aggregates used in pavement construction. Eisa et al. (2022) [6] examined the improvement of weak subgrade soil using different additives, documenting significant enhancement when mixing 47% natural clayey soil, 47% sand, and 6% cement. The optimum cement content for stabilization varies depending on soil type and desired properties, with Chen (1988) [7] reporting typical ranges of 2-8% by weight for expansive soils. However, Oliveira (2003) [8] demonstrated that higher cement contents of 8-12% may be necessary for certain soil conditions, particularly in eastern Croatian sands.

Comprehensive studies by Fedrigo et al. (2020) [9] on full-depth reclamation with Portland cement revealed substantial increases in unconfined compressive strength (UCS) with curing time and cement content. Their research documented UCS values ranging from 2.5 MPa after 7 days to 8.89 MPa after 180 days for mixtures containing 4% cement. This strength development contributes significantly to improved load-bearing capacity and durability of pavement layers. Similar temporal evolution patterns were observed by Wu et al. (2015) [10], who demonstrated superior moduli in cement-stabilized materials compared to alternative treatments. Beyond compressive strength, cement stabilization enhances the tensile strength and resilient modulus of pavement materials. Wild et al. (1998) [11] established strong correlations between compressive and indirect tensile strengths, typically observing indirect tensile strength at approximately 20% of compressive strength for cement-stabilized mixtures. These mechanical property relationships have proven crucial for pavement design optimization.

The integration of supplementary materials has emerged as a promising approach for enhancing stabilization effectiveness. Dimter et al. (2022) [12] evaluated wood fly ash incorporation, finding that replacing part of sand with 30% WFA and cement resulted in higher strengths compared to conventional cement-sand mixtures. This finding aligns with research by Horpibulsuk et al. (2010) [13], who documented microstructural refinement and enhanced mechanical properties through supplementary material addition. Environmental considerations have become increasingly critical in stabilization technology selection. Xiao et al. (2018) [14] reviewed cold recycling technologies for asphalt pavements, noting that cement stabilization can contribute to reduced energy consumption and greenhouse gas emissions compared to traditional reconstruction methods. Jones et al. (2015) [15] conducted accelerated pavement testing on cement-stabilized sections, observing superior performance compared to asphalt-stabilized alternatives, despite showing higher modulus decrease rates under traffic loading.

The efficacy of cement stabilization in challenging environments has been well-documented. Amhadi & Assaf (2019) [16] achieved significant strength improvements using 4% cement in combination with fly ash for desert sand stabilization. Similar success with alternative additives was reported by Modarres & Nosoudy (2015) [17] using industrial byproducts for soil improvement. These findings highlight the potential for optimizing cement usage through carefully selected supplementary materials.

The introduction of innovative soil stabilizers like Consoil presents new opportunities for advancing stabilization technology. While preliminary studies suggest promising results, comprehensive research examining its interaction with cement in sandy soil matrices remains limited. This knowledge gap presents a critical opportunity for advancing sustainable pavement construction practices while maintaining required performance standards. Through systematic evaluation of cement-stabilized sandy soils modified with varying proportions of Consoil, this research addresses fundamental questions regarding strength development mechanisms and material interactions. The investigation aims to advance understanding of stabilization processes while providing practical guidelines for implementing innovative techniques in pavement substructure applications.

The aim of this study is to investigate the mechanical performance of sandy soils stabilized with various combinations of cement and Consoil, cured at different ages, to develop optimized mixtures for high-performance pavement substructures. The research objectives encompass:

- To evaluate the effect of different cement contents on the unconfined compressive strength (UCS) of sandy soil;
- To assess the impact of varying Consoil contents on the UCS of cement-stabilized sandy soil;
- To investigate the strength development of cement-Consoil stabilized sandy soil over different curing periods;
- To determine the optimal combination of cement and Consoil contents for achieving maximum UCS in sandy soil;
- To analyze the relationship between curing age and strength development for different cement-Consoil combinations;

Through comprehensive material characterization and performance testing, this study contributes to both theoretical understanding of stabilization mechanisms and practical optimization of pavement substructure design. The findings advance knowledge of cement-additive interactions while addressing industry needs for more efficient and environmentally conscious construction practices in transportation infrastructure.

2. Materials

2.1. Sand

The primary soil medium employed in this study was a locally sourced sandy soil, characteristic of the region's geomorphological profile. The sand was extracted from a quarry located approximately 15 km southeast of the research facility, ensuring consistency in material properties throughout the experimental phase. Prior to utilization, the sand underwent a rigorous characterization process to determine its physical and chemical properties. Particle size distribution analysis was conducted in accordance with ASTM D6913, employing a combination of sieve analysis for coarser fractions and hydrometer analysis for finer particles. The results indicated a predominantly medium-grained sand with a uniformity coefficient (Cu) of 3.2 and a coefficient of curvature (Cc) of 1.1, classifying it as poorly graded sand (SP) according to the Unified Soil Classification System (USCS). Figure 1 illustrates the particle size distribution curve of the sand.

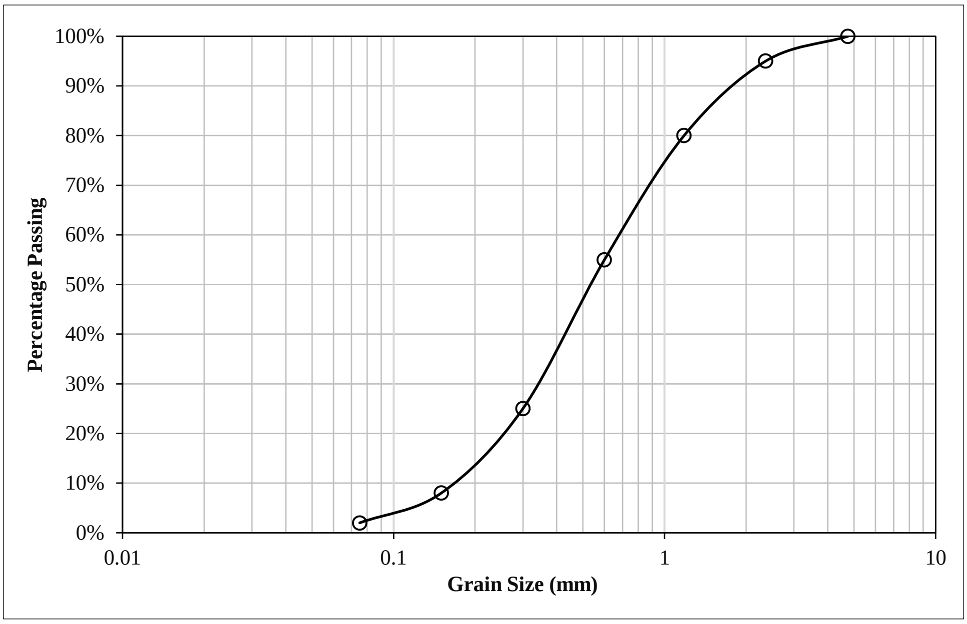


Figure 1. Particle size distribution for sand

X-ray fluorescence (XRF) spectroscopy was performed to ascertain the mineralogical composition of the sand. The analysis revealed a high silica content (SiO_2) of approximately 96.5%, with minor constituents including alumina (Al_2O_3) at 1.8% and iron oxide (Fe_2O_3) at 0.7%. Trace amounts of other oxides were also detected. Table 1 presents the complete XRF analysis results.

Table 1. XRF results for sand

Compound	Percentage (%)
SiO_2	96.5
Al_2O_3	1.8
Fe_2O_3	0.7
CaO	0.3
K_2O	0.2
MgO	0.2
Na_2O	0.1
TiO_2	0.1
Others	0.1

The physical and chemical properties of the sand were thoroughly characterized using standard test methods. Tables 2 and 3 summarize the results of these tests.

Table 2. Physical and chemical properties of sand

Property	Value	Test Method
Specific Gravity	2.65	ASTM D854-23 [18]
Maximum Dry Density (g/cm³)	1.76	ASTM D698-12 [19]
Optimum Moisture Content (%)	8	ASTM D698-12 [19]
Organic Content (%)	<0.3	ASTM D2974-20e1 [20]
pH	7.2	1:2.5 soil-water
Uniformity Coefficient (Cu)	3.2	ASTM D6913-04(2009)e1 [21]
Coefficient of Curvature (Cc)	1.1	ASTM D6913-04(2009)e1 [21]

Table 3. XRF results for cement.

Compound	Percentage (%)
CaO	63.8
SiO_2	20.5
Al_2O_3	4.9
Fe_2O_3	3.1
SO_3	2.8
MgO	2.4
K_2O	0.8
Na_2O	0.2
Loss on Ignition	1.5

The specific gravity of the sand particles was determined using the pycnometer method as per ASTM D854, yielding a value of 2.65. This aligns well with the typical range for quartz-rich sands. Additionally, the sand exhibited a maximum dry density of 1.76 g/cm³ and an optimum moisture content of 8%, as determined by the standard Proctor compaction test (ASTM D698). To ensure the absence of organic matter that could potentially interfere with the cement hydration process, the sand was subjected to the loss on ignition test (ASTM D2974). The results indicated an organic content of less than 0.3% by weight, which is considered negligible for the purposes of this study. The pH of the sand was measured in a 1:2.5 soil-water suspension, resulting in a value of 7.2, indicating a near-neutral condition that is not expected to significantly affect the cement hydration reactions or the performance of the Consoil additive.

2.2. Cement

The cementitious binder employed in this study was Ordinary Portland Cement (OPC) conforming to ASTM C150 Type I specifications. This type of cement was selected due to its widespread availability and common use in soil stabilization applications. The cement was sourced from a local manufacturer located approximately 30 km northwest of the research facility, ensuring consistency in material properties throughout the experimental phase. Prior to utilization, the cement underwent a rigorous characterization process to determine its physical and chemical properties. X-ray fluorescence (XRF) spectroscopy was performed to ascertain the chemical composition of the cement. The analysis revealed a calcium oxide (CaO) content of 63.8% and a silicon dioxide (SiO_2) content of 20.5%, which are typical for Type I OPC. Other major constituents included alumina (Al_2O_3) at 4.9% and iron oxide (Fe_2O_3) at 3.1%. Trace amounts of other oxides such as SO_3, MgO, and alkalis (K_2O and Na_2O) were also detected, collectively comprising less than 7% of the total composition.

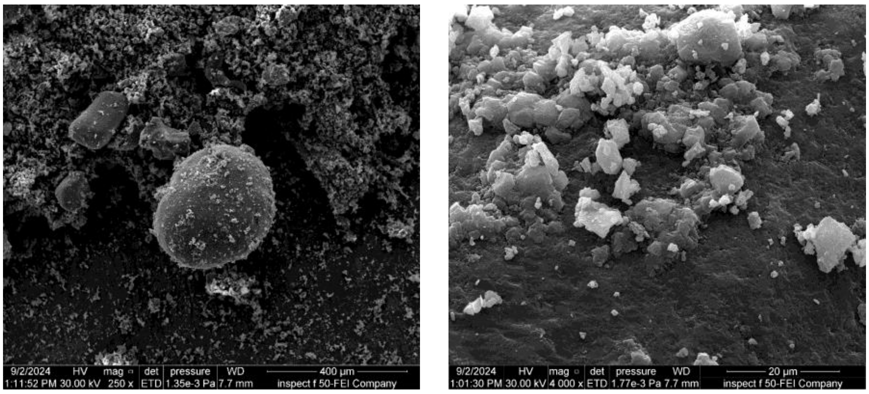
The specific gravity of the cement was determined using the Le Chatelier flask method as per ASTM C188, yielding a value of 3.15. This aligns well with the typical range for Ordinary Portland Cement. The Blaine fineness, a measure of the specific surface area of the cement particles, was found to be 370 m²/kg using the air permeability method (ASTM C204), indicating a moderately fine cement that should provide a good balance between reactivity and water demand. Setting time tests were conducted using the Vicat apparatus in accordance with ASTM C191. The initial setting time was determined to be 85 minutes, while the final setting time was 240 minutes. These values fall within the acceptable ranges specified by ASTM C150 for Type I cement, ensuring adequate workability for field applications. Compressive strength tests were performed on standard mortar cubes as per ASTM C109. The 7-day compressive strength was 28.5 MPa, and the 28-day strength reached 42.0 MPa, both exceeding the minimum requirements set forth in ASTM C150 for Type I cement. These strength values indicate the cement's capacity to develop robust cementitious bonds, which is crucial for effective soil stabilization.

The normal consistency of the cement paste was determined to be 26.5% according to ASTM C187. This property provides insight into the water demand of the cement and its potential effects on the workability of cement-soil mixtures.

This comprehensive characterization of the cement provides a solid foundation for understanding its behavior in combination with the sandy soil and Consoil additive, enabling more accurate interpretation of the mechanical performance results obtained in subsequent phases of the study.

2.3. Consoil

Consoil, a proprietary ground improvement agent, underwent rigorous physicochemical analysis. Electron micrographs (Figure 2) unveil a diverse particle population with non-uniform geometries and dimensions. The granules display textured surfaces with adherent microparticulates, hinting at an intricate microscale architecture.



(a) (b)

Figure 2. FESEM of Consoil. (a) at 250x, (b) at 4000x

Crystallographic investigation via X-ray diffractometry (Figure 3) produced a spectrum featuring discrete, intense reflections overlaying a diffuse background. This pattern signifies the coexistence of ordered crystalline domains within an amorphous matrix. The pronounced diffraction maxima, primarily clustered between 2θ values of 20° and 40°, align with the structural fingerprints of calcium-silicate minerals commonplace in binding agents.

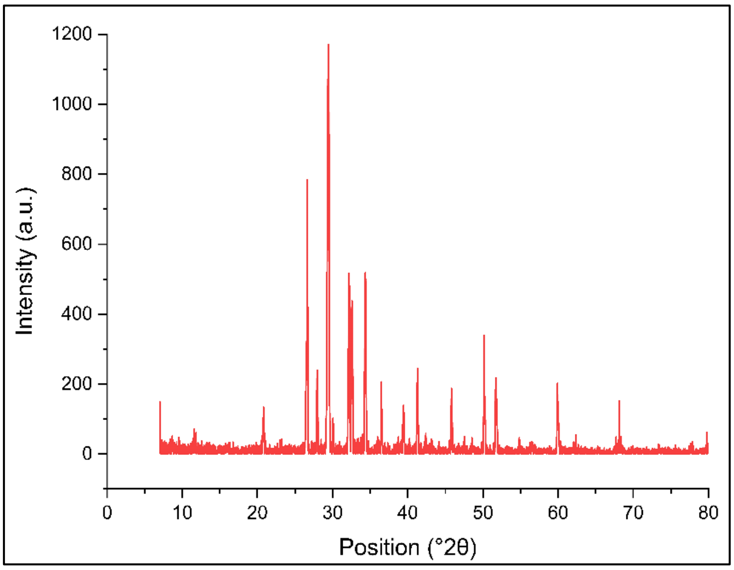


Figure 3. XRD test for Consoil

Elemental mapping through energy-dispersive X-ray analysis (Figure 4) unveiled a constitution rich in calcium, with substantial silicon representation and detectable quantities of oxygen, aluminum, and trace magnesium and iron. This atomic profile suggests latent hydraulic reactivity, potentially crucial to the material's soil-altering capabilities.

The amalgamation of these analytical insights portrays Consoil as a meticulously formulated substance, featuring a multifaceted phase distribution and intricate microarchitecture. Its elemental makeup, particularly the calcium-silicon predominance supplemented by aluminum and iron, implies a design ethos centered on versatile ground modification mechanisms upon soil incorporation.

Figure 5 illustrates the systematic experimental approach adopted in this study. The workflow begins with materials characterization of sand, cement, and Consoil components. The experimental work progresses through material preparation, mix design development, sample fabrication, and standardized curing procedures. Testing encompasses mechanical performance evaluation and microstructural analysis. Results examine three key aspects: Optimum Moisture Content (OMC), Unconfined Compressive Strength (UCS), and microstructural characterization through FESEM and XRD analysis, leading to determination of optimum mixture proportions.

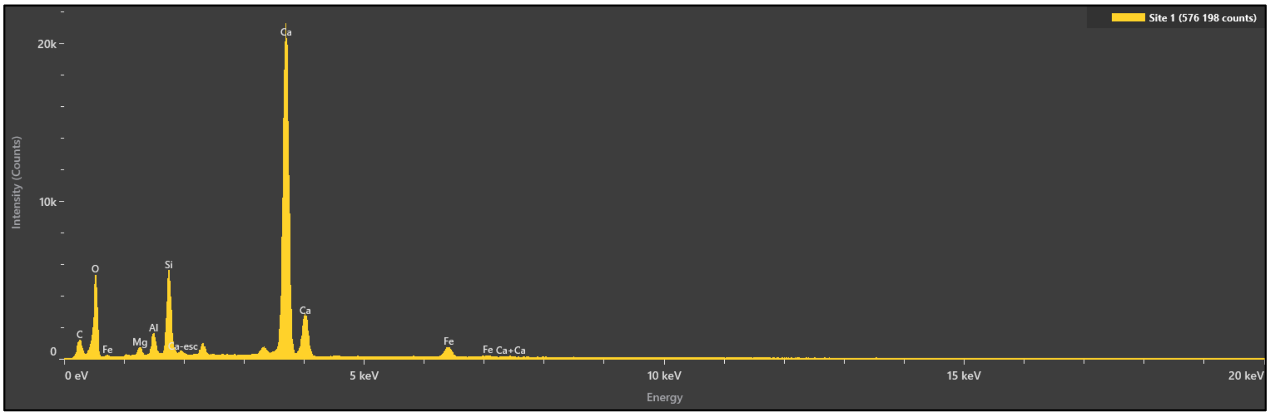


Figure 4. EDS test for Consoil

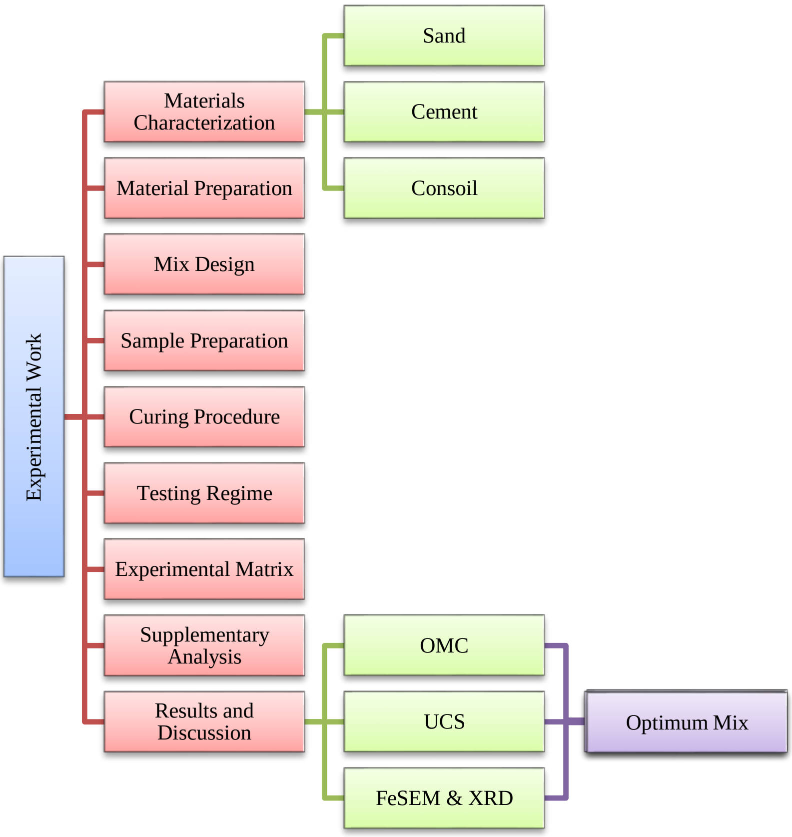


Figure 5. Flowchart of the experimental work

2.4. Material Preparation

Prior to sample fabrication, all constituent materials underwent rigorous preparation. The sandy soil was oven-dried at 105°C for 24 hours to eliminate residual moisture, then pulverized and sieved through a 4.75 mm aperture to ensure uniformity. Ordinary Portland Cement (OPC) and Consoil were stored in airtight containers to prevent moisture absorption and maintain their original properties.

2.5. Mix Design

The experimental matrix was designed to investigate the effects of varying cement content, Consoil dosage, and curing duration on the mechanical properties of stabilized sandy soil. Three cement contents were selected: 3%, 6%, and 9% by dry weight of soil. These percentages represent low, medium, and high cement stabilization scenarios commonly encountered in geotechnical applications. For each cement content, Consoil was incorporated at five different dosages: 0%, 5%, 10%, 15%, and 20% by weight of cement. The inclusion of a 0% Consoil mixture served as a control group, allowing for the assessment of Consoil's impact on soil stabilization. The upper limit of 20% was chosen based on preliminary studies and economic considerations.

2.6. Sample Preparation

Soil-cement-Consoil mixtures were prepared in a mechanical mixer to ensure homogeneity. The dry components were first blended for 5 minutes, after which water was gradually added over a 2-minute period. Mixing continued for an additional 3 minutes to achieve uniform moisture distribution.

Cylindrical specimens, measuring 50 mm in diameter and 100 mm in height, were fabricated using a hydraulic jack to apply standard Proctor compaction effort. The molds were lubricated with a thin layer of mineral oil to facilitate sample extraction. After compaction, the specimens were carefully extruded, weighed, and measured to determine their initial physical properties. Figure 6 shows the experimental procedure and testing stages.

(a)

(b)

(c)

(d)

Figure 6. Experimental procedure and testing stages: (a) Prepared sandy soil mixture, (b) Specimens under curing, (c) UCS testing setup, (d) Sample failure mode

2.7. Curing Procedure

Immediately following fabrication, each specimen was wrapped in a plastic bag to prevent moisture loss. The wrapped samples were then placed in a temperature-controlled curing room maintained at 21°C ± 2°C and relative humidity of 95% ± 5%. This environment was chosen to simulate typical subsurface conditions and promote consistent hydration of cementitious materials.

2.8. Testing Regime

Unconfined Compressive Strength (UCS) tests were conducted as the primary measure of mechanical performance. Testing was carried out at four distinct curing intervals: 3, 7, 28, and 90 days. These time points were selected to capture both early-age strength development and long-term stabilization effects. Prior to testing, samples were unwrapped and allowed to equilibrate to room temperature for 2 hours. UCS tests were performed using a servo-hydraulic loading frame with a capacity of 50 kN. The loading rate was maintained at 1 mm/min until sample failure, defined as the point of maximum sustained load or 15% axial strain, whichever occurred first.

2.9. Experimental Matrix

The full experimental program comprised:

- 3 cement contents (3%, 6%, 9%);
- 5 Consoil dosages (0%, 5%, 10%, 15%, 20%);
- 4 curing periods (3, 7, 28, 90 days);
- 3 replicate samples for each unique combination.

This design resulted in a total of 180 UCS tests (3 × 5 × 4 × 3 = 180).

2.10. Supplementary Analyses

In addition to UCS testing, select samples underwent microstructural analysis to elucidate the mechanisms of strength development. Scanning Electron Microscopy (SEM) was employed to examine fracture surfaces of samples cured for 28 days. Energy Dispersive X-ray Spectroscopy (EDS) was utilized to map elemental distributions and identify reaction products. X-Ray Diffraction (XRD) analysis was performed on powdered samples to track the evolution of crystalline phases over the curing period. Samples were prepared by crushing and grinding cured specimens to pass a 75 μm sieve, followed by drying in a desiccator to arrest hydration reactions.

3. Results and Discussion

3.1. Optimum Moisture Content

The optimum moisture content (OMC) for the soil-cement-Consoil mixtures varied with both cement content and Consoil dosage, as illustrated in Figure 7.

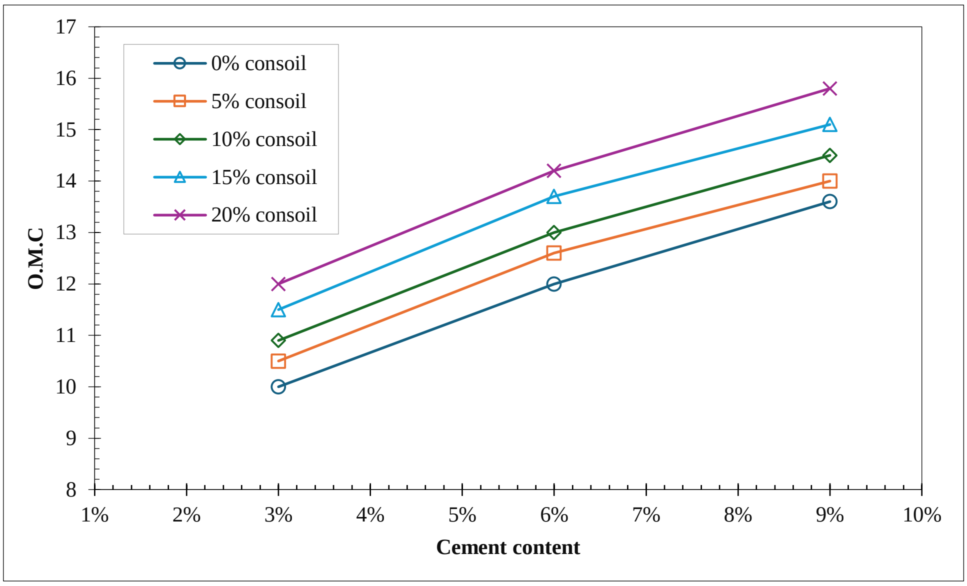


Figure 7. O.M.C vs. cement content

The OMC increased with both cement content and Consoil dosage and the addition of Consoil further increased the OMC across all cement contents. This trend aligns with findings by Horpibulsuk et al. (2010) [13], who observed that increasing cement content typically raises the OMC due to the higher water demand for cement hydration. The relationship between cement content and OMC appears to be non-linear, with a more pronounced increase from 3% to 6% compared to 6% to 9%.

The addition of Consoil further increased the OMC across all cement contents. This effect can be attributed to several factors:

- ***Increased specific surface area***: Consoil particles, being finer than the soil particles, increase the overall specific surface area of the mixture, requiring more water to achieve adequate coating and lubrication [22].
- ***Water retention***: The pozzolanic nature of Consoil may contribute to higher water retention within the mixture, necessitating a higher moisture content to achieve maximum dry density [23].
- ***Additional hydration requirements***: The reactive components in Consoil may require additional water for pozzolanic reactions, further increasing the OMC [24].

The combined effect of cement and Consoil on OMC is most pronounced at higher percentages of both additives. For instance, the mixture with 9% cement and 20% Consoil exhibited the highest OMC of 15.8%, approximately 3.8% higher than the 9% cement mixture without Consoil. This synergistic effect on water demand has been observed in other studies involving cement and supplementary cementitious materials [17].

3.2. Unconfined Compressive Strength Results

The unconfined compressive strength (UCS) of the stabilized soil samples was investigated as a function of curing age, cement content, and Consoil dosage. The results provide insights into the complex interactions between these factors and their influence on strength development.

3.2.1. Effect of Curing Age

Figures 8 to 10 illustrate the UCS development over time for 3%, 6%, and 9% cement contents, respectively, with varying Consoil dosages.

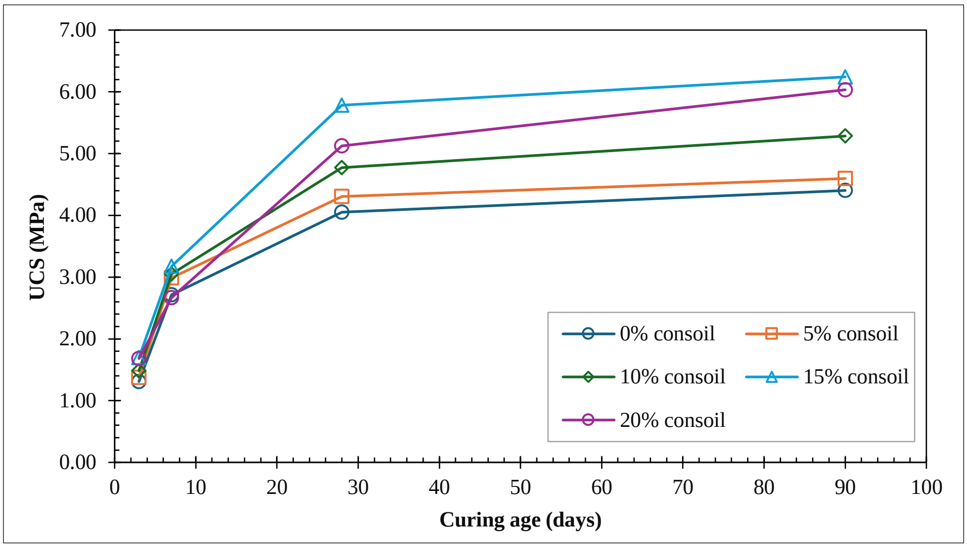


Figure 8. UCS vs. time for the 3% cement samples

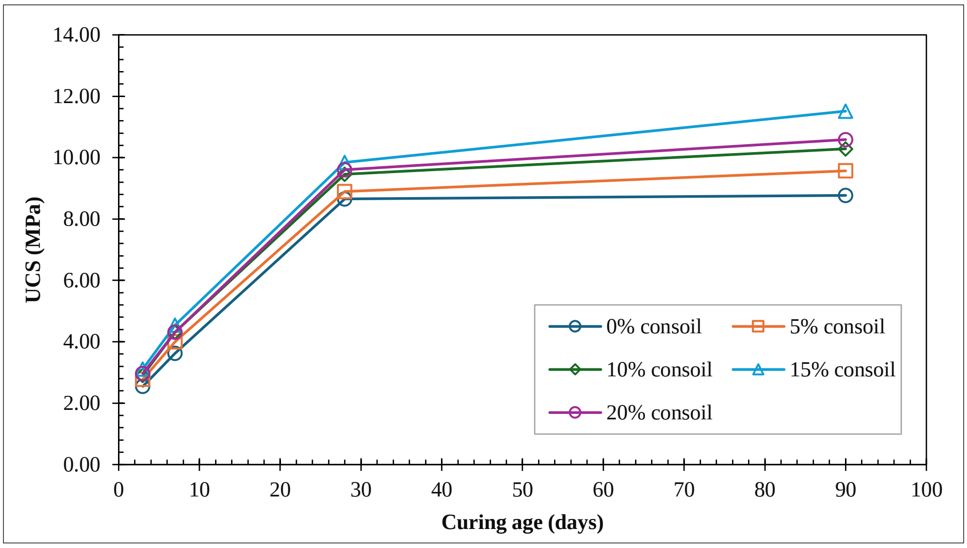


Figure 9. UCS vs. time for the 6% cement samples

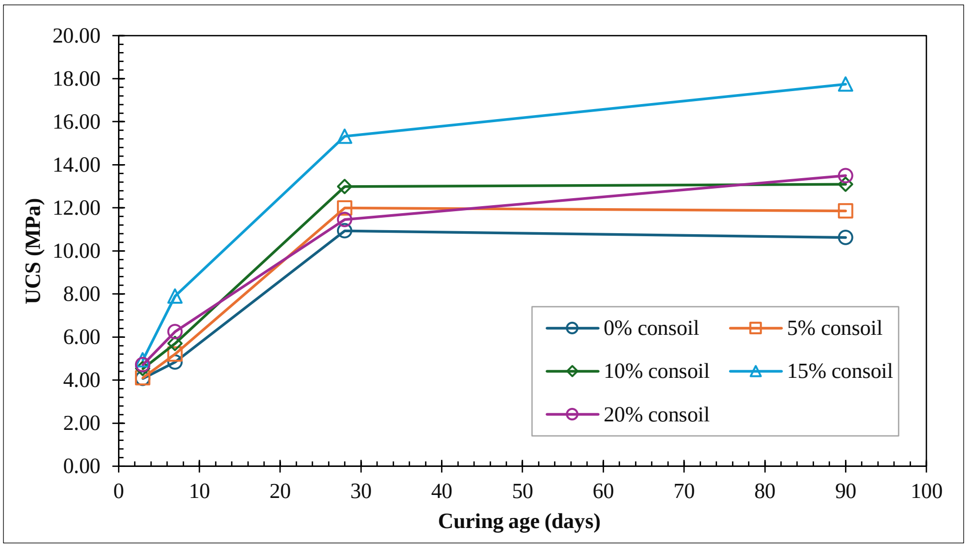


Figure 10. UCS vs. time for the 9% cement samples

The temporal evolution of UCS exhibits distinct patterns across cement-Consoil combinations, with all mixtures showing significant strength development over the 90-day curing period. For 3% cement content, specimens demonstrated rapid early strength development (0-7 days), with UCS increasing from 1.4 MPa to 2.8 MPa for the control mix (0% Consoil). The 15% Consoil enhanced this early strength gain significantly, achieving 3.2 MPa at 7 days. This accelerated early strength gain aligns with the formation of primary cementitious products during initial hydration, as observed by Fedrigo et al. (2020) [9] in cement-stabilized systems.

The intermediate curing period (7-28 days) maintained strength enhancement but at a reduced rate. Notably, the 15% Consoil mixture demonstrated superior performance, reaching 5.8 MPa at 28 days compared to 4.2 MPa for the control mix. This 38% improvement during the intermediate curing period suggests effective pozzolanic activity of Consoil. Rasheed et al. (2024) [3] reported similar enhancement patterns when investigating pozzolanic materials in stabilized base courses. Long-term strength development (28-90 days) showed continued improvement across all mixtures. The 15% Consoil mixture achieved a final UCS of 6.24 MPa at 90 days, representing a 41.8% increase over the control mix. This sustained strength gain pattern indicates ongoing matrix refinement, consistent with findings by Sukmak et al. (2024) [1] in cement-stabilized materials.

For 6% cement content, while maintaining similar development patterns, mixtures achieved higher absolute strengths. The control mix reached 8.77 MPa at 90 days, while the 15% Consoil mixture attained 11.52 MPa - a 31.4% improvement. At 9% cement content, the enhancement was most pronounced, with the 15% Consoil mixture achieving 17.74 MPa at 90 days compared to 10.62 MPa for the control mix, representing a 67% increase.

3.2.2. Effect of Cement Content

Figure 11 illustrates the influence of Consoil dosage on UCS for different cement contents at 90 days of curing.

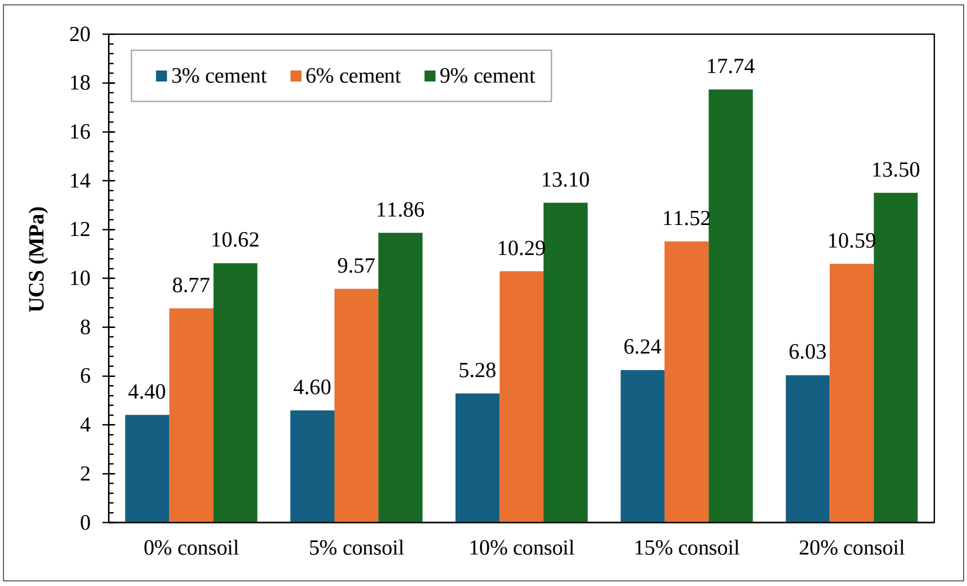


Figure 11. UCS at 90 Days vs. Consoil dosage for different cement contents

The addition of Consoil generally enhanced UCS, with optimal dosages varying based on cement content. For 3% cement mixtures, the optimal Consoil dosage was 15%, which increased the UCS from 4.40 MPa (0% Consoil) to 6.24 MPa, representing a 41.8% improvement. This significant enhancement at low cement content aligns with findings by Modarres and Nosoudy (2015) [17], who observed that supplementary cementitious materials were particularly effective in improving strength at lower binder contents.

For 6% cement mixtures, the trend was similar, with 15% Consoil dosage providing the highest strengths. The 90-day UCS increased from 8.77 MPa (0% Consoil) to 11.52 MPa (15% Consoil), a 31.4% enhancement. This consistent optimal dosage across different cement contents suggests a robust interaction between Consoil and cement hydration products, as observed by Jha and Sivapullaiah (2015) [25] in their study of lime-stabilized expansive soils with additives.

Interestingly, for 9% cement mixtures, the optimal Consoil dosage remained at 15%, contrary to the initial assumption of a shift. At 90 days, the UCS increased from 10.62 MPa (0% Consoil) to 17.74 MPa (15% Consoil), a remarkable 67.0% increase. This substantial improvement at higher cement content indicates a synergistic effect between cement and Consoil, possibly due to the increased availability of calcium hydroxide for pozzolanic reactions, as suggested by Pourakbar et al.(2015) [26] in their work on ultrafine palm oil fuel ash and cement stabilization.

It's noteworthy that for all cement contents, increasing the Consoil dosage beyond 15% led to a slight decrease in strength. This phenomenon could be attributed to an excess of fine particles interfering with the cement hydration process or reducing the overall density of the mixture. Similar observations were made by Ding et al. (2018) [27] in their study on cement-stabilized clays with additives.

The consistent optimal Consoil dosage of 15% across all cement contents suggests a balanced interaction between the pozzolanic activity of Consoil and the cement hydration process. This optimal point likely represents the best compromise between additional reactive silica provision, filler effect, and maintenance of adequate cement-soil particle interactions. The more pronounced effect at higher cement contents (9%) indicates that Consoil's pozzolanic reactions are enhanced when more calcium hydroxide is available from cement hydration, leading to the formation of additional calcium silicate hydrate (C-S-H) gel, the primary strength-giving compound in cementitious systems [28].

3.2.3. Synergistic Effects of Cement and Consoil

Figure 12 presents a contour plot of 90-day UCS as a function of cement content and Consoil dosage.

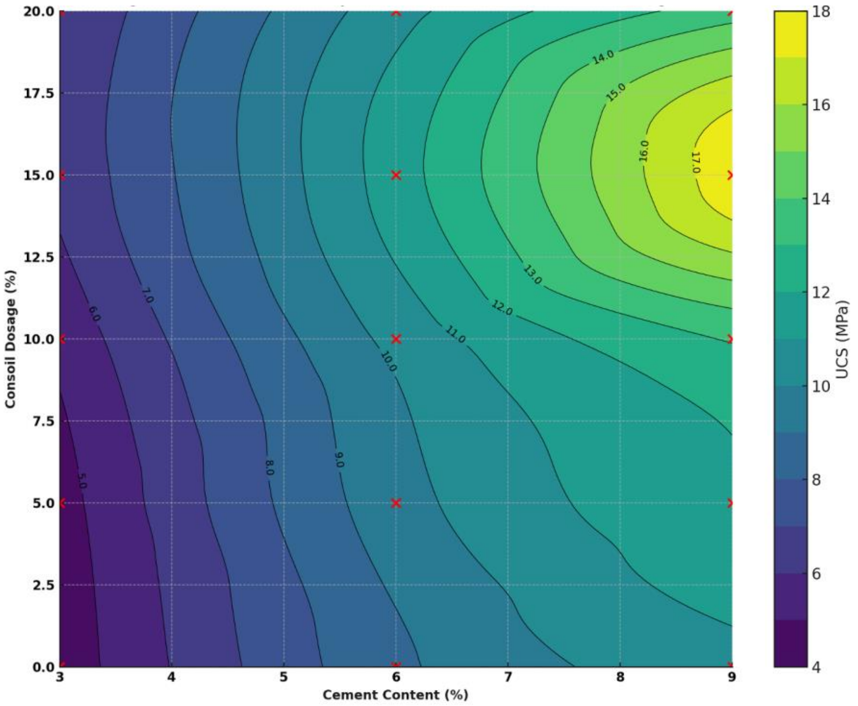


Figure 12. Contour plot of 90-day UCS vs. cement content and Consoil dosages

The interaction between cement and Consoil demonstrates complex performance patterns influenced by both material proportions and curing duration. The most pronounced synergistic effect is observed at 9% cement with 15% Consoil, achieving 17.74 MPa at 90 days, marking a 67% improvement over the control mixture.

The effectiveness of this synergy varies significantly with cement content. At 3% cement, the strength enhancement from Consoil shows a moderate but consistent improvement up to 15% dosage, achieving a 41.8% increase. The 6% cement mixtures demonstrate an intermediate response, with a 31.4% strength gain at optimal Consoil content. However, the 9% cement mixtures exhibit a notably different pattern, with disproportionate strength improvements at 15% Consoil.

This non-linear enhancement pattern suggests that higher cement contents provide more favorable conditions for Consoil's pozzolanic activity. The increased availability of calcium hydroxide from cement hydration likely facilitates more extensive pozzolanic reactions with Consoil's reactive components. Yu et al. (2024) [2] reported similar mechanisms in cement-stabilized systems incorporating supplementary materials.

The decline in strength beyond 15% Consoil, consistent across all cement contents, indicates a critical threshold in the material interaction mechanism. This limitation appears to be independent of cement content, suggesting it relates to fundamental aspects of the mixture's physical structure rather than chemical interaction capacity.

The strength development patterns indicate that optimal synergy requires both adequate cement for primary hydration reactions and appropriate Consoil content for secondary pozzolanic reactions. The consistent optimal Consoil dosage of 15% across all cement contents suggests this represents a fundamental balance point in the complex material interaction system.

3.2.4. Strength Development Rates

To further analyze the strength development characteristics, Figure 13 presents the strength gain rates for different mixtures.

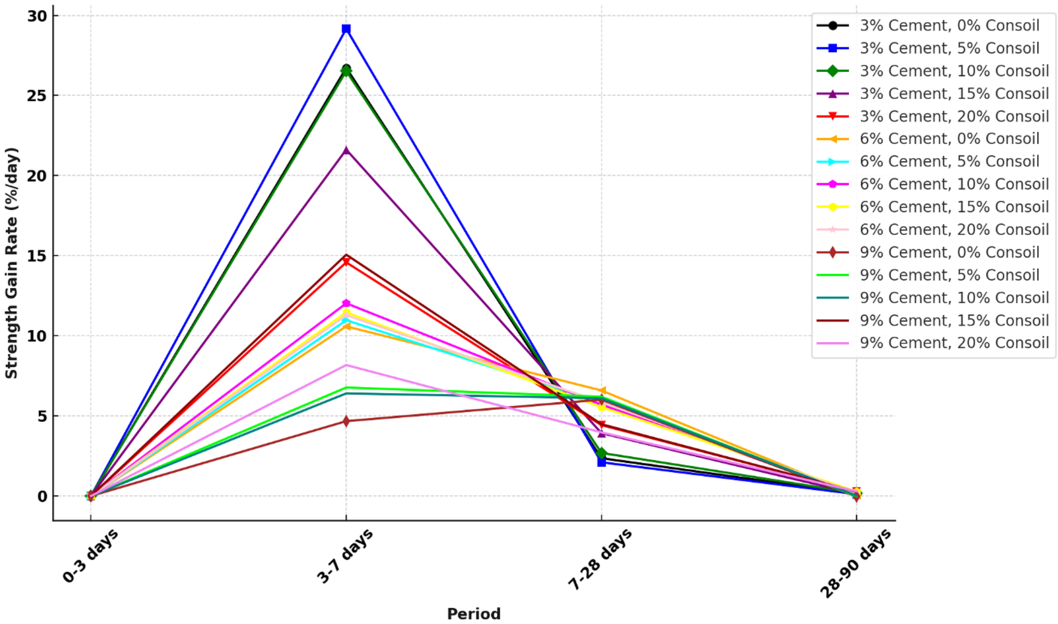


Figure 13. Strength gain rate over time for different cement and Consoil combinations

The rate of strength development varies significantly with both cement content and Consoil dosage, exhibiting distinct patterns across different curing periods. For mixtures with 9% cement, the early-age strength gain (0-7 days) is most pronounced, demonstrating rates up to 1.2 MPa/day for the 15% Consoil mixture. This rapid initial strength development reflects intense early-age hydration reactions characteristic of high cement contents.

The intermediate period (7-28 days) shows a marked decrease in strength gain rates across all mixtures. The 15% Consoil combinations maintain higher development rates compared to other dosages, with the 9% cement mixture achieving approximately 0.4 MPa/day during this period. This sustained strength development indicates continued pozzolanic activity beyond the initial cement hydration phase. This behavior aligns with findings by Rasheed et al. (2024) [3] regarding sustained strength development in composite binder systems. For the extended curing period (28-90 days), strength gain rates diminish further but remain significant, particularly for optimal mixtures. The 9% cement with 15% Consoil maintains a development rate of approximately 0.1 MPa/day, while control mixtures show minimal gains. This long-term strength enhancement suggests ongoing microstructural refinement through continued pozzolanic reactions.

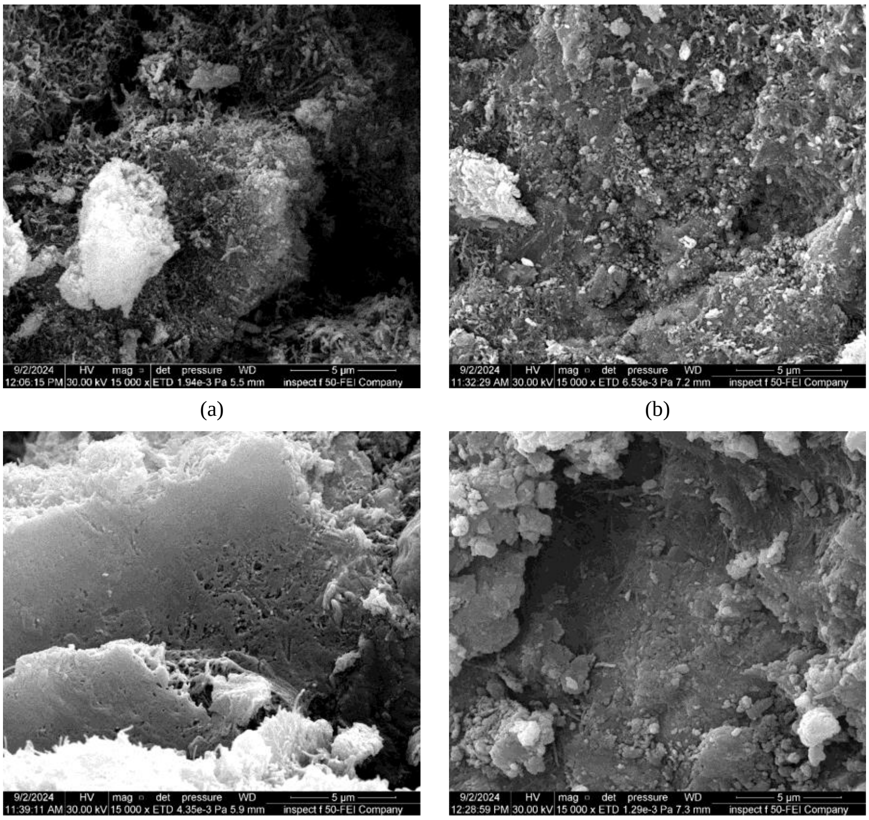
The influence of Consoil content on strength development rates is most pronounced during the early and intermediate periods. Mixtures with 15% Consoil consistently demonstrate higher development rates compared to other dosages, while 20% Consoil mixtures show reduced rates, particularly after 28 days. This pattern suggests that excess Consoil may interfere with both initial hydration and long-term strength development mechanisms.

The 3% and 6% cement mixtures follow similar patterns but with proportionally lower development rates. Notably, the impact of Consoil on strength gain rates becomes more pronounced at higher cement contents, supporting the observed synergistic effects in ultimate strength values.

3.3. Microstructural and Mineralogical Investigations

Field Emission Scanning Electron Microscopy (FESEM) and X-Ray Diffraction (XRD) analyses were conducted on samples containing 9% cement with varying Consoil content. The 9% cement content was selected for detailed investigation as it demonstrated the most significant strength improvements and sensitivity to Consoil addition in the unconfined compressive strength tests. This choice allows for a focused examination of the microstructural and mineralogical changes in the most responsive mixture.

FESEM micrographs shown in Figure 14 reveal a progressive refinement of the microstructure with increasing Consoil content. The 0% Consoil sample exhibits a relatively open structure with distinct particles and limited evidence of hydration products. In contrast, the 15% Consoil sample displays a dense, interconnected network of hydration products with abundant needle-like structures, likely ettringite or calcium silicate hydrate (C-S-H) gel. This microstructural evolution aligns with findings by Horpibulsuk et al.(2010) [13], who observed similar densification in cement-stabilized clays with fly ash addition.



(a) (b)

(c) (d)

Figure 14. FESEM observations for different Consoil percentages at 9% cement. (a) 0% Consoil, (b) 5% Consoil, (c) 15% Consoil, (d) 20% Consoil

The 20% Consoil sample shows an even more pronounced development of needle-like structures, suggesting intense pozzolanic activity. However, the presence of larger pores in this sample may explain its slightly lower strength compared to the 15% Consoil mixture, a phenomenon also noted by Chew et al. (2004) [28] in their study of cement-treated marine clay.

XRD diffractograms (Figure 15) provide complementary mineralogical information. All samples exhibit strong peaks corresponding to quartz and calcite, likely originating from the soil and cement components. A notable trend is the apparent decrease in intensity of peaks associated with calcium hydroxide (Ca(OH)2) as Consoil content increases, particularly evident when comparing the 0% and 20% Consoil samples. This observation suggests the consumption of Ca(OH)2 through pozzolanic reactions, a key mechanism in strength development of cement-pozzolan systems [11].

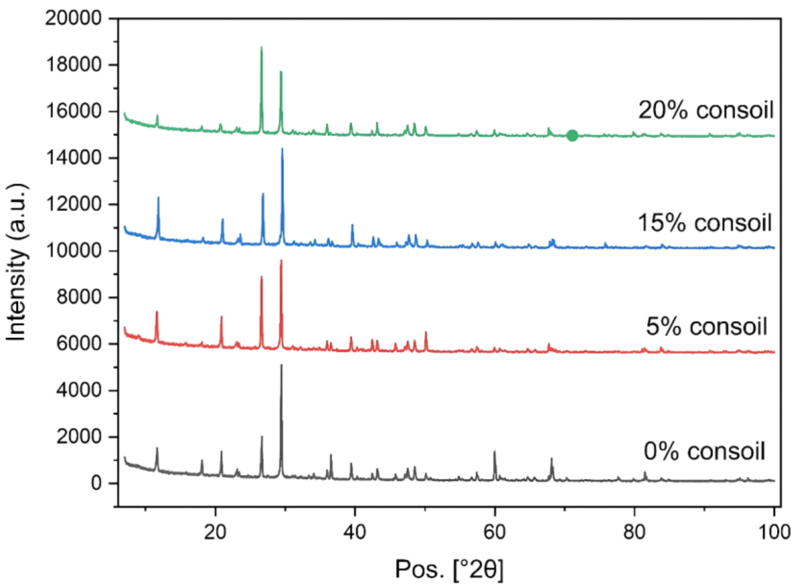


Figure 15. XRD results for different Consoil percentages at 9% cement

The XRD patterns also indicate a gradual increase in the amorphous content with higher Consoil percentages, evidenced by a slight elevation in the background of the diffractograms. This trend is consistent with the formation of amorphous C-S-H gel, a primary strength-giving component in cementitious materials [29].

The optimal performance of the 15% Consoil mixture, as observed in unconfined compressive strength tests, can be attributed to an ideal balance between crystalline cement hydration products and amorphous pozzolanic reaction products. This equilibrium results in a refined pore structure and enhanced particle bonding, as evidenced by the FESEM images.

These microstructural and mineralogical findings corroborate the macroscopic strength results and provide a mechanistic explanation for the enhanced performance of Consoil-containing mixtures. The progressive consumption of $Ca(OH)_2$ and formation of additional C-S-H gel through pozzolanic reactions contribute to the densification of the microstructure and consequent strength improvement, a phenomenon well-documented in literature on cement-pozzolan systems [30].

4. Conclusions

The incorporation of Consoil into cement-stabilized sandy soil matrices demonstrated a marked enhancement in unconfined compressive strength (UCS) across various cement contents and curing periods. The optimal Consoil dosage was consistently identified as 15% by weight of cement, irrespective of the cement content. This consistency suggests a fundamental synergy between Consoil's pozzolanic components and the cement hydration products, leading to a more refined and robust soil-cement matrix.

The strength development patterns observed over the 90-day curing period revealed a rapid initial strength gain followed by a more gradual increase, characteristic of cementitious systems. However, the presence of Consoil modified this pattern, particularly at later ages, indicating ongoing pozzolanic reactions that contribute to long-term strength enhancement. This finding has significant implications for the durability and long-term performance of stabilized soil structures. Microstructural and mineralogical analyses provided mechanistic insights into the observed macroscopic behavior. The progressive refinement of the soil-cement matrix with increasing Consoil content, as evidenced by FESEM micrographs, correlated strongly with the UCS results. The XRD analyses further supported these observations, revealing the gradual consumption of calcium hydroxide and the formation of additional calcium silicate hydrate gel, key processes in strength development.

The study also highlighted the critical role of optimum moisture content (OMC) in the stabilization process. The observed increase in OMC with both cement and Consoil addition underscores the importance of proper water management in field applications to achieve optimal compaction and strength development. While the 15% Consoil dosage emerged as optimal across all cement contents, the magnitude of improvement varied, with the most pronounced effect observed at 9% cement content. This finding suggests that the efficacy of Consoil is particularly enhanced in the presence of abundant cement hydration products, pointing towards a potential for optimizing cement usage in conjunction with Consoil for more sustainable and economical stabilization solutions.

The research outcomes have significant practical implications for pavement engineering. The demonstrated ability to achieve substantial strength gains, particularly at higher cement contents and optimal Consoil dosages, offers new possibilities for designing high-performance subgrade and base course materials. Moreover, the continued strength development beyond conventional 28-day curing periods suggests that current design practices may underestimate the long-term performance of Consoil-modified, cement-stabilized soils. However, it is important to note that while strength is a crucial parameter, other factors such as durability, freeze-thaw resistance, and long-term volumetric stability warrant further investigation. Additionally, the economic and environmental implications of incorporating Consoil into soil stabilization practices need to be thoroughly assessed through life-cycle analyses.

The findings of this study not only contribute to the theoretical understanding of soil stabilization mechanisms but also offer practical insights for the development of more efficient and high-performance pavement substructures. Future research directions should focus on field-scale validations, long-term performance monitoring, and the exploration of Consoil's efficacy in diverse soil types and environmental conditions.

5. Declarations

5.1. Author Contributions

Conceptualization, M.A. and A.A.; methodology, A.A.; software, M.A.; validation, M.A. and A.A.; formal analysis, M.A.; investigation, M.A.; resources, M.A.; data curation, M.A.; writing—original draft preparation, M.A.; writing—review and editing, M.A.; visualization, M.A.; supervision, A.A.; project administration, A.A.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

Data sharing is not applicable to this article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Sukmak, G., Sukmak, P., Horpibulsuk, S., Phunpeng, V., & Arulrajah, A. (2024). An approach for strength development assessment of cement-stabilized soils with various sand and fine contents. Transportation Geotechnics, 48, 101323. doi:10.1016/j.trgeo.2024.101323.

[2] Yu, H., Joshi, P., Lau, C., & Ng, K. (2024). Novel application of sustainable coal-derived char in cement soil stabilization. Construction and Building Materials, 414, 134960. doi:10.1016/j.conbuildmat.2024.134960.

[3] Rasheed, S. E., Fattah, M. Y., Hassan, W. H., & Hafez, M. (2024). Strength and Durability Characteristics of Sustainable Pavement Base Course Stabilized with Cement Bypass Dust and Spent Fluid Catalytic Cracking Catalyst. Infrastructures, 9(12), 217. doi:10.3390/infrastructures9120217.

[4] Abdolvand, Y., & Sadeghiamirshahidi, M. (2024). Soil stabilization with gypsum: A review. Journal of Rock Mechanics and Geotechnical Engineering. doi:10.1016/j.jrmge.2024.02.007.

[5] Anburuvel, A. (2024). The Engineering Behind Soil Stabilization with Additives: A State-of-the-Art Review. Geotechnical and Geological Engineering, 42(1), 1–42. doi:10.1007/s10706-023-02554-x.

[6] Eisa, M. S., Basiouny, M. E., Mohamady, A., & Mira, M. (2022). Improving Weak Subgrade Soil Using Different Additives. Materials, 15(13). doi:10.3390/ma15134462.

[7] Chen, F. H. (1988). Foundation on Expansive Soils, Amsterdam. Elsevier Scientific Publication Company, New York, United Sates.

[8] Oliveira, P. C. (2003). Contribution to the study of the deep recycling technique in the recovery of flexible pavements. Master Thesis, Universidade Estadual de Campinas-UNICAMP, Campinas, Brazil. (In Portuguese).

[9] Fedrigo, W., Núñez, W. P., & Visser, A. T. (2020). A review of full-depth reclamation of pavements with Portland cement: Brazil and abroad. Construction and Building Materials, 262. doi:10.1016/j.conbuildmat.2020.120540.

[10] Wu, R., Louw, S., & Jones, D. (2015). Effects of binder, curing time, temperature, and trafficking on moduli of stabilized and unstabilized full-depth reclamation materials. Transportation Research Record, 2524, 11–19. doi:10.3141/2524-02.

[11] Wild, S., Kinuthia, J. M., Jones, G. I., & Higgins, D. D. (1998). Effects of partial substitution of lime with ground granulated blast furnace slag (GGBS) on the strength properties of lime-stabilised sulphate-bearing clay soils. Engineering Geology, 51(1), 37–53. doi:10.1016/S0013-7952(98)00039-8.

[12] Dimter, S., Zagvozda, M., Tonc, T., & Šimun, M. (2022). Evaluation of Strength Properties of Sand Stabilized with Wood Fly Ash (WFA) and Cement. Materials, 15(9). doi:10.3390/ma15093090.

[13] Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., Raksachon, Y., & Suddeepong, A. (2010). Analysis of strength development in cement-stabilized silty clay from microstructural considerations. Construction and Building Materials, 24(10), 2011–2021. doi:10.1016/j.conbuildmat.2010.03.011.

[14] Xiao, F., Yao, S., Wang, J., Li, X., & Amirkhanian, S. (2018). A literature review on cold recycling technology of asphalt pavement. Construction and Building Materials, 180, 579–604. doi:10.1016/j.conbuildmat.2018.06.006.

[15] Jones, D., Wu, R., & Louw, S. (2015). Comparison of full-depth reclamation with Portland cement and full-depth reclamation with no stabilizer in accelerated loading test. Transportation Research Record, 2524, 133–142. doi:10.3141/2524-13.

[16] Amhadi, T. S., & Assaf, G. J. (2019). Assessment of strength development of cemented desert soil. International Journal of Low-Carbon Technologies, 14(4), 543–549. doi:10.1093/ijlct/ctz047.

[17] Modarres, A., & Nosoudy, Y. M. (2015). Clay stabilization using coal waste and lime - Technical and environmental impacts. Applied Clay Science, 116–117, 281–288. doi:10.1016/j.clay.2015.03.026.

[18] ASTM D854-23. (2023). Standard Test Methods for Specific Gravity of Soil Solids by the Water Displacement Method. ASTM international, Pennsylvania, United States. doi:10.1520/D0854-23.

[19] ASTM D698-12. (2021). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft3 (600 kN-m/m3)). ASTM international, Pennsylvania, United States. doi:10.1520/D0698-12R21.

[20] ASTM D2974-20e1. (2020). Standard Test Methods for Determining the Water (Moisture) Content, Ash Content, and Organic Material of Peat and Other Organic Soils. ASTM international, Pennsylvania, United States. doi:10.1520/D2974-20E01.

[21] ASTM D6913-04(2009)e1. (2017). Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis. ASTM international, Pennsylvania, United States. 10.1520/D6913-04R09E01.

[22] Wang, D. X., Abriak, N. E., Zentar, R., & Xu, W. (2012). Solidification/stabilization of dredged marine sediments for road construction. Environmental Technology, 33(1), 95–101. doi:10.1080/09593330.2011.551840.

[23] Rios, S., Viana da Fonseca, A., & Baudet, B. A. (2014). On the shearing behaviour of an artificially cemented soil. Acta Geotechnica, 9(2), 215–226. doi:10.1007/s11440-013-0242-7.

[24] Goodarzi, A. R., & Salimi, M. (2015). Stabilization treatment of a dispersive clayey soil using granulated blast furnace slag and basic oxygen furnace slag. Applied Clay Science, 108, 61–69. doi:10.1016/j.clay.2015.02.024.

[25] Jha, A. K., & Sivapullaiah, P. V. (2015). Mechanism of improvement in the strength and volume change behavior of lime stabilized soil. Engineering Geology, 198, 53–64. doi:10.1016/j.enggeo.2015.08.020.

[26] Pourakbar, S., Asadi, A., Huat, B. B. K., & Fasihnikoutalab, M. H. (2015). Stabilization of clayey soil using ultrafine palm oil fuel ash (POFA) and cement. Transportation Geotechnics, 3, 24–35. doi:10.1016/j.trgeo.2015.01.002.

[27] Ding, M., Zhang, F., Ling, X., & Lin, B. (2018). Effects of freeze-thaw cycles on mechanical properties of polypropylene Fiber and cement stabilized clay. Cold Regions Science and Technology, 154, 155–165. doi:10.1016/j.coldregions.2018.07.004.

[28] Chew, S. H., Kamruzzaman, A. H. M., & Lee, F. H. (2004). Physicochemical and Engineering Behavior of Cement Treated Clays. Journal of Geotechnical and Geoenvironmental Engineering, 130(7), 696–706. doi:10.1061/(asce)1090-0241(2004)130:7(696).

[29] Taylor, H. F. W. (1997). Cement chemistry. Thomas Telford Ltd., London, United Kingdom doi:10.1680/cc.25929.

[30] Mehta, P.K. and Monteiro, P.J.M. (2006) Concrete: Microstructure, Properties, and Materials (3rd Ed.). McGraw-Hill, New York, United Sates.