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Improvement of Cement-Stabilized Compacted Lateritic Soil Reinforced with Steel Fibers Recovered from Waste Tires

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Research Article

Keywords: Lateritic Soil, Cement stabilization, Recycled steel fibers, Indirect tensile strength, Flexural strength, Wetting–drying cycles, Durability

Posted Date: March 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9199524/v1

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Geotechnical and Geological Engineering on July 3rd, 2026. See the published version at https://doi.org/10.1007/s10706-026-03801-7.

Abstract

This study investigates the engineering properties of lateritic soil stabilized with Type I Portland cement and reinforced with recycled steel fibers recovered from end-of-life tires (0–5% by dry soil weight), aiming to enhance tensile/flexural performance and durability under moisture variations. The lateritic soil was classified as coarse-grained A-1-a with a low plasticity index (PI ≈ 2.32%). Specimens were prepared under controlled compaction conditions using MDD ≈ 1.952 t/m³ and OMC ≈ 11.8%. Unconfined compressive strength (UCS) tests were conducted to determine an appropriate cement content (1–7%) under both dry and 2-hour-soaking conditions, resulting in the selection of 3% cement as the baseline mixture. Subsequently, indirect tensile strength (ASTM C496) and flexural strength of beam specimens (ASTM C1609) were evaluated for fiber contents of 0–5% at curing ages of 7–28 days, together with durability assessment under wet–dry cycling (ASTM D559/D559M). The results indicate that approximately 3% fiber content provides the most favorable overall performance, increasing the 28-day indirect tensile strength from ~ 350 to ~ 481 kPa and the flexural strength from ~ 276 to ~ 851 kPa, while also promoting a more ductile post-cracking response. However, excessive fiber addition adversely affected compaction due to bulking and clustering, resulting in non-proportional strength gains and, in some cases, reduced durability. Overall, cement-treated lateritic soil reinforced with recycled steel fibers shows strong potential for pavement base/subbase applications requiring improved crack resistance and durability under fluctuating moisture conditions.

1. Introduction

The development of transportation infrastructure, particularly roadworks and pavement layer systems, plays a critical role in strengthening economic competitiveness and improving quality of life. However, many regions worldwide are facing increasing constraints in securing high-quality natural aggregates for pavement construction. These constraints arise from sustained resource exploitation, stricter environmental regulations, and rising transportation costs. Consequently, growing attention has been directed toward the utilization of locally available soils and alternative materials, either as replacements or as improvement agents for pavement layers, in order to enhance sustainability, reduce reliance on natural resources, and lower the overall costs of road construction and maintenance.

Lateritic soil is widely distributed in tropical and subtropical regions, including Southeast Asia, Africa, and South America (Mahalinga-Iyer & Williams, 1997). Owing to its local availability and relatively low cost, lateritic soil has been extensively used in secondary roads and rural road networks. Nevertheless, the engineering properties of lateritic soil often vary considerably with provenance, degree of weathering, and moisture condition. As a result, untreated lateritic soil commonly exhibits limited strength and durability, particularly in wet environments or near-saturated conditions (Okeke et al., 2020).

A widely adopted approach for improving soil performance in pavement layers and foundation applications is cement stabilization, which enhances unconfined compressive strength, stiffness, and overall durability (Roshan & Rashid, 2023; Suebsuk et al., 2019; Tran et al., 2022). The principal

mechanism is cementing hydration, which generates cementitious bonding products—most notably calcium silicate hydrate (C–S–H)—that bind soil particles, reduce internal voids, and decrease moisture susceptibility (Dong et al., 2023; Horpibulsuk et al., 2011; Niu et al., 2024). Moreover, increasing cement content promotes the formation of additional C–S–H and ettringite, both of which are key contributors to strength development in cement-treated soils (Wahab et al., 2021).

Although cement-treated soils offer clear advantages in compressive strength, they still exhibit significant mechanical limitations, notably low tensile and flexural capacities and a brittle mode of failure (Jawad & Taha, 2023). These deficiencies can lead to sudden cracking under tensile or bending actions. Several studies have reported that cement-treated soils are susceptible to shrinkage-induced cracking and possess relatively low splitting tensile strength (Wang et al., 2020). In addition, their durability may deteriorate markedly when exposed to moisture or soaking conditions, particularly at low cement contents, where specimen disintegration can occur (Wahab et al., 2021).

To mitigate these limitations, fiber reinforcement has attracted increasing attention in geotechnical engineering and construction materials. Fibers can enhance tensile capacity, delay crack initiation and propagation, and improve ductility through the crack-bridging mechanism (Tran et al., 2019). A substantial body of research indicates that both synthetic and metallic fibers can effectively improve the mechanical behavior of soils and cement-treated soils by shifting the failure response from brittle to more ductile, while increasing post-cracking residual strength. In addition, guidelines for selecting appropriate fiber dosage and length have been proposed to achieve optimal performance in cement-treated soils (Tinoco et al., 2021; Wang et al., 2020).

Over the past decade, industrial by-products—such as recycled steel fibers recovered from end-of-life tires—have gained attention as alternative reinforcement materials because they reduce waste generation and support circular-economy principles (Banthia & Onuaguluchi, 2021). Experimental evidence indicates that tire-derived steel fibers can significantly enhance tensile strength, flexural capacity, and crack resistance in cementitious materials (Alsaif & Alshannag, 2022; Polydorou et al., 2022). Studies on pavement concrete have shown that recycled steel fibers can deliver flexural performance and post-cracking toughness comparable to those of new steel fibers (Zarei et al., 2021).

Nevertheless, research specifically addressing the application of tire-derived steel fibers in cement-treated soil systems—especially lateritic soil—remains limited. Moreover, a clear mechanistic understanding of the load-carrying behavior and crack-control mechanisms governing such composites is still lacking.

Another practical issue in humid tropical regions is the durability

of cement-treated soils in moisture-rich environments. While many studies have reported strength enhancement of cement-treated soils under dry conditions, relatively few have systematically examined the effects of water soaking and wetting–drying cycles on the mechanical behavior of fiber-reinforced cement-treated soils. Field observations from certain areas further indicate that moisture-related

deteriorations (Liang et al., 2023; Hoy et al., 2023), such as erosion and cracking, constitute a major factor limiting the service life of cement-treated soil materials under real environmental exposure.

Accordingly, this study aims to investigate the engineering properties of cement-treated lateritic soil reinforced with recycled steel fibers recovered from end-of-life tires. The research focuses on characterizing the compressive, tensile, and flexural behavior under both dry and soaked conditions, and on evaluating durability trends under fluctuating moisture environments. The findings are expected to help address current knowledge gaps regarding the use of waste-derived reinforcement in cement-treated soil systems, and to support the development of sustainable, high-performance pavement-layer materials suitable for humid tropical conditions.

2. Materials

2.1. Lateritic Soil

The lateritic soil used in this study was obtained from a natural deposit in Thailand. This soil is a product of the chemical weathering of parent rock under tropical climatic conditions and is typically characterized by the presence of iron and aluminum oxides as major constituents. Consequently, it generally exhibits a coarse-grained structure, and its engineering behavior is strongly influenced by moisture conditions and soil fabric (Oyelami et al., 2022; Katte et al., 2020).

The soil sample was subjected to basic index property tests and classified in accordance with the AASHTO soil classification system as A-1-a (Table 1), indicating a coarse-grained material predominantly composed of sand and gravel with a low percentage of fines. In general, this type of soil is considered suitable for use in pavement layers and shallow foundation applications.

The Atterberg limits test results (Table 1) indicated that the soil exhibited very low plasticity, with a plasticity index (PI) of 2.32%, reflecting limited sensitivity to moisture variation. In addition, the shrinkage limit of 4.33% suggests a low potential for volumetric change during wetting–drying cycles, which is favorable for dimensional stability and reduces the risk of strength deterioration upon subsequent saturation after cement stabilization (Oyelami et al., 2022).

Based on the Standard Proctor compaction test, the lateritic soil exhibited a maximum dry density (MDD) of 1.952 t/m³ and an optimum moisture content (OMC) of 11.8% (Table 1). These values were adopted as the control conditions for preparing all specimens to ensure consistency and reliability in the comparison of mechanical performance in the subsequent testing program (Katte et al., 2020).

2.2. Cement Binder

The binder used in this study was Type I Portland cement, which was selected for its favorable compressive strength development, consistent quality, and suitability for soil improvement and pavement layer applications where no special resistance to severe environmental conditions is required (Maskell et al., 2014). Upon hydration, cement generates reaction products, particularly calcium silicate

hydrate (C–S–H) and ettringite, which act to bond soil particles, reduce internal voids, and enhance the continuity of the soil matrix, thereby improving the overall compressive strength of the treated material (Maskell et al., 2014).

However, cement-treated soils commonly exhibit brittle failure behavior and possess limited tensile and flexural resistance. In addition, variations in environmental exposure and curing conditions during construction may lead to variability in mechanical performance. For this reason, cement was used as the primary binder to improve the structure and compressive strength of the lateritic soil, before further enhancement of crack control and post-failure behavior through the incorporation of steel fibers in the subsequent stage.

2.3. Recycled Steel Fibers from Waste Tires

The recycling process of steel fibers is illustrated in Fig. 1, where the material undergoes sequential cutting, shredding, crushing, and separation stages prior to use. The steel fibers used in this study were obtained from the recycling process of end-of-life tires. As a waste-derived material with high tensile strength and elastic modulus, recycled steel fiber has considerable potential for use as a reinforcing material in cementitious composites and cement-treated soils (Revuelta et al., 2021; Samarakoon et al., 2019).

Based on physical observation (Fig. 2), the fibers exhibited irregular lengths and were often found in clustered form, which is characteristic of the recycling process. In this study, the fibers had lengths of approximately 1.5–2.0 cm and an average diameter of 0.30–0.35 mm. Most fibers were deformed or curved, which is beneficial for mechanical interlocking with the cement–soil matrix and improves pull-out resistance under loading.

In addition, some fibers retained rubber residues on their surfaces (Fig. 2D), resulting in a rougher texture and potentially enhancing interfacial friction between the fibers and the cement-treated soil matrix (Samarakoon et al., 2019). When incorporated into cement-treated soil, the fibers act as crack-bridging elements, facilitating stress transfer, restricting crack opening, and transforming the failure mode from brittle to semi-ductile, while preserving part of the load-carrying capacity after crack initiation.

However, the effectiveness of fiber reinforcement depends strongly on both fiber content and dispersion quality. Excessive fiber addition may lead to fiber clustering, increased void ratio, and reduced compactability, such that the mechanical properties do not improve proportionally and may even deteriorate. Therefore, this study focuses on identifying an appropriate range of fiber content that can provide a balance between mechanical enhancement and the preservation of a suitably dense material structure.

3. Mix Design and Specimen Preparation

3.1. Mix Design Concept

The mix design was developed by considering cement as the primary binder for improving the structure and compressive strength of the lateritic soil, while recycled steel fibers from waste tires were incorporated as reinforcing elements to enhance the tensile and flexural performance, as well as the crack-control capacity, of the cement-treated soil (Sahlabadi et al., 2021). This approach allows the individual role of each constituent material in governing the mechanical behavior of the composite to be identified and interpreted in a systematic manner.

The mixture proportions were established with reference to practical field conditions by controlling the water content in terms of both the water-to-cement ratio (w/c) and the optimum moisture content (OMC), so as to provide sufficient water for cement hydration while facilitating compaction to achieve a uniform density (Yadav and Tiwari, 2016; Sahlabadi et al., 2021). The mass of each constituent was determined based on the maximum dry density (MDD) obtained from the Standard Proctor compaction test, thereby ensuring comparable initial conditions among all specimens.

In the experimental program, the first step was to determine the optimum cement content based on the unconfined compressive strength (UCS) of lateritic cement-treated soil without fiber reinforcement, to establish a sufficiently strong and stable matrix as the base material (Cao et al., 2019). Once the cement content was fixed, the effects of fiber reinforcement on tensile strength, flexural strength, and post-cracking behavior were subsequently investigated.

3.2. Control of Water Content

A water-to-cement ratio (w/c) of 0.5 was adopted to promote adequate cement hydration (Nili and Afroughsabet, 2010). At the same time, the total water content was controlled to be consistent with the optimum moisture content (OMC) of the lateritic soil (approximately 12%) obtained from the Standard Proctor compaction test, to ensure effective compaction and minimize variations in dry density among specimens (Yadav and Tiwari, 2016; Sahlabadi et al., 2021). This approach helped maintain a balance between cement strength development and the soil structure arrangement after compaction. After molding, the specimens were tightly sealed with plastic wrapping and cured under controlled moisture conditions at 25°C to reduce early moisture loss and maintain the continuity of the hydration process (Sahlabadi et al., 2021).

3.3. Mixing Procedure

The oven-dried lateritic soil was first blended thoroughly with cement in the dry state until a uniform mixture was obtained. Water was then added in the predetermined amount, and mixing was continued until the moisture was evenly distributed throughout the mixture (Ferrara et al., 2012). After a homogeneous soil–cement mixture had been achieved, the recycled steel fibers were introduced. During mixing, the fibers were continuously separated and dispersed to minimize fiber clustering and promote a more uniform distribution within the matrix (Zhao et al., 2017). The quality of fiber dispersion was assessed by visual observation during the mixing process, following the practice adopted in related studies (Zhao et al., 2017).

3.4. Specimen Molding

The prepared mixtures were molded and compacted under controlled conditions to obtain comparable densities for all specimens, thereby reducing the influence of variability in the initial state. Two specimen types were prepared according to the test method employed:

(1) Cylindrical specimens of 50 mm in diameter and 100 mm in height were prepared for the unconfined compressive strength (UCS) and splitting tensile strength tests. These specimens were demolded immediately after casting (Yadav and Tiwari, 2016; Fang et al., 2022).

(2) Beam specimens with dimensions of 80 × 80 × 350 mm were prepared for the flexural strength test. These specimens were retained in the molds for 24 h prior to demolding to allow initial structural stabilization before curing (Fang et al., 2022).

3.5. Curing Condition

After demolding, the specimens were tightly wrapped in plastic and stored in a moisture-controlled container at approximately 25°C until the designated curing ages of 7, 14, and 28 days (Yadav and Tiwari, 2016; Sahlabadi et al., 2021). These curing conditions helped minimize early moisture evaporation and promoted consistent strength development.

3.6. Sample Replication

Three replicate specimens were prepared for each testing condition (n = 3) to improve the reliability and reproducibility of the experimental results (Ferrara et al., 2012). The test results are reported as the mean value with the standard deviation to reflect data variability and assess the consistency of the specimen preparation and testing procedures.

4. Testing Program

4.1. Overview of the Testing Program

The testing program was designed to evaluate the effectiveness of lateritic soil improvement using cement in combination with reinforcement by recycled steel fibers recovered from waste tires. The study focused on the mechanical behavior of the treated material in terms of unconfined compressive strength (UCS), splitting tensile strength, and flexural strength, as well as its failure characteristics under different loading conditions (Soltanzadeh et al., 2019; Çelik and Bingöl, 2020).

All tests were conducted under controlled conditions to enable systematic comparison of the effects of cement content and fiber content while minimizing the influence of extraneous variables.

Unconfined compressive strength (UCS) tests were performed using a compression testing machine with appropriate loading capacity. The axial load was applied at a constant strain rate in accordance with

ASTM D2166/D2166M until failure occurred. Failure was defined as the maximum stress reached during loading, and this value was recorded as the unconfined compressive strength.

4.2. Unconfined Compressive Strength Test

The unconfined compressive strength (UCS) test was conducted to evaluate the effect of cement content on the compressive strength development of lateritic soil prior to fiber reinforcement. The primary objective was to determine an optimum cement content capable of providing a sufficiently strong and stable cement-treated soil matrix for the subsequent investigation of fiber reinforcement effects. Cylindrical specimens with a diameter of 50 mm and a height of 100 mm were prepared using cement contents of 1%, 3%, 5%, and 7% by dry weight of soil. The specimens were then cured at room temperature for 7, 14, and 28 days to examine strength development with curing age.

Prior to testing, the specimens were divided into two groups. One group was tested under unsoaked conditions immediately after curing, while the other group was immersed in water for 2 hours to simulate wet environmental conditions that may occur in practical applications. After immersion, the specimens were allowed to stand at room temperature until no free water remained on the surface. Each specimen was then placed under axial loading and compressed at a constant loading rate until failure. The maximum compressive stress recorded during the test was taken as the representative compressive strength of the cement-treated soil under the specified condition (Fig. 4A).

The UCS results obtained after water immersion were used to assess both strength development with curing time and the material's ability to retain strength after water exposure. The cement content that provided the most suitable performance and the highest stability was selected as the base mixture for subsequent reinforcement with recycled steel fibers.

4.3. Splitting Tensile Strength Test

Recycled steel fibers recovered from waste tires represent a difficult-to-manage waste material due to contamination by residual rubber. Their use as reinforcing inclusions in cement-treated lateritic soil therefore offers a practical means of valorizing this waste while enhancing the engineering performance of geomaterials. Owing to their deformed geometry and the presence of adhered rubber residue on some fiber surfaces, these fibers are expected to promote mechanical interlocking and stress transfer within the cement–soil matrix.

The splitting tensile strength test was conducted in accordance with ASTM C496 using cylindrical specimens measuring 50 × 100 mm. Steel fibers were incorporated at contents of 0%, 1%, 2%, 3%, 4%, and 5% by weight of dry soil, and the specimens were cured at room temperature for 7, 14, and 28 days prior to testing (Fig. 4B).

The load was applied continuously at a constant rate until failure occurred. The splitting tensile strength was calculated based on the maximum applied load and specimen dimensions in accordance with ASTM C496. The measured tensile strength was used as an indicator to evaluate the role of fiber

reinforcement in improving crack resistance, stress transfer capacity, and post-cracking behavior under tensile loading.

4.4. Flexural Strength Test

To evaluate the performance of the material under conditions more representative of field applications, where bending is commonly accompanied by internal tensile stresses, a flexural strength test was conducted on the steel fiber-reinforced cement-treated lateritic soil.

Beam specimens with dimensions of 80 × 80 × 350 mm were prepared using the cement content selected from the UCS results and reinforced with recycled steel fibers at contents ranging from 0% to 5% by dry weight of soil to investigate the influence of fiber dosage on flexural behavior. The specimens were cured at room temperature for 7, 14, and 28 days and then tested using a loading configuration adapted from ASTM C1609 under a prescribed loading configuration until failure (Çelik and Bingöl, 2020).

In addition to the maximum flexural strength, particular attention was given to the post-cracking behavior of the specimens, including the pattern and distribution of cracks as well as the ability of the material to sustain load after the onset of first cracking (Soltanzadeh et al., 2019; Çelik and Bingöl, 2020). These observations were used to elucidate the role of the fibers in crack-bridging and internal stress transfer mechanisms, which are closely related to the toughness and residual strength of the fiber-reinforced cement–soil system.

4.5. Durability Test (Wetting–Drying Cycles)

The durability test was designed to evaluate the ability of steel fiber-reinforced cement-treated lateritic soil to maintain its performance under repeated wetting–drying cycles, which represent field conditions commonly encountered in pavement layers and earth structures subjected to seasonal moisture fluctuations (Zhang and Tao, 2008). The test was conducted in accordance with ASTM D559/D559M (Method A), using unconfined compressive strength (UCS) as an indicator of material degradation after wetting–drying cycles. Specimen preparation and compaction control were performed in accordance with procedures consistent with ASTM D698, as adopted in the experimental program.

The specimens consisted of lateritic soil treated with the selected cement content and reinforced with different fiber dosages. After curing under controlled conditions to the designated age, the specimens were subjected to the wetting–drying procedure. In each cycle, the specimens were first immersed in water at room temperature for approximately 5 h to allow water to penetrate the material. They were then oven-dried at 71 ± 3°C for at least 42 h, thereby completing one full cycle, which required approximately 2 days per cycle (Ramezani et al., 2025).

The test was carried out for 0, 3, 7, and 12 cycles, and at the end of each designated cycle, the specimens were immediately subjected to the UCS test for comparison with the 0-cycle condition (Rauf et al., 2025). This procedure enabled a systematic evaluation of the degradation rate, the strength

retention capacity of the material (Zhang and Tao, 2008), and the role of recycled steel fibers in improving the durability of cement-treated lateritic soil under fluctuating moisture conditions (Wang et al., 2024).

5. Results

5.1. Physical Properties and Compaction Characteristics of Lateritic Soil

The physical properties of the lateritic soil are summarized in Table 1. The soil exhibited a liquid limit (LL) of 23.10% and a plastic limit (PL) of 20.78%, resulting in a plasticity index (PI) of 2.32%. This indicates that the soil has very low plasticity and only limited sensitivity to changes in moisture content, a typical characteristic of coarse-grained soils.

Table 1
Index and Compaction Properties of Lateritic Soil

Property	Value
Liquid limit, LL (%)	23.10
Plastic limit, PL (%)	20.78
Plasticity index, PI (%)	2.32
Shrinkage limit (%)	4.33
Specific gravity, G_s	2.58
AASHTO classification	A-1-a
Maximum dry density, $\gamma_{d,\max}$(Standard Proctor) (ton/m³)	1.952
Optimum moisture content, OMC (%)	11.8

In addition, the shrinkage limit of only 4.33% suggests that the soil has a low potential for volumetric change under repeated wetting–drying cycles. This behavior is favorable for volumetric stability and helps reduce the risk of cracking or strength loss under environmental conditions involving moisture fluctuations.

The AASHTO classification results indicate that the soil falls within the A-1-a group, which corresponds to a coarse-grained material with a low fines content and favorable engineering quality. This classification suggests that the soil is suitable for application in pavement layers and shallow foundation systems. The Standard Proctor compaction test results, show the relationship between dry density and moisture content. The soil exhibited a maximum dry density (MDD) of 1.952 t/m³ at an optimum

moisture content (OMC) of 11.8%. These values indicate good compaction characteristics and efficient particle arrangement under the optimum water content condition (Wahab et al., 2021).

Overall, the combination of low plasticity, low shrinkage potential, and good compactability indicates that the lateritic soil used in this study is well-suited for improvement with cementitious binders (Sani et al., 2019). These characteristics are also favorable for developing a dense and stable soil structure, providing appropriate base material for investigating the effects of fiber reinforcement in the subsequent stage.

5.2. Unconfined Compressive Strength

In general, lateritic soil possesses limited strength and may not be suitable for direct engineering application without improvement. In this study, Portland cement was used as the primary binder to enhance soil strength and produce a cement-treated lateritic material suitable for engineering use.

The lateritic soil was mixed with cement contents of 1%, 3%, 5%, and 7% by weight of dry soil and tested for unconfined compressive strength (UCS) in accordance with ASTM D2166-98. The test was performed under both unsoaked and soaked conditions, with the latter involving 2 h of water immersion prior to testing, to evaluate the influence of water exposure on mechanical performance.

The test results (Fig. 5) showed a clear trend of increasing compressive strength with increasing cement content under both conditions. Under the unsoaked condition, the UCS increased from approximately 1,961 kPa at 1% cement to 4,413 kPa at 7% cement. Under soaked conditions, the UCS increased from approximately 637 kPa to 2,942 kPa, respectively. This trend reflects the role of cement in improving the soil structure through hydration products that bond soil particles and enhance matrix continuity.

However, when the rate of strength gain was considered, the results indicated that low to moderate cement contents (1–3%) produced a more pronounced increase in strength than higher cement contents, suggesting a diminishing returns trend at elevated cement dosage. Based on the experimental results, a cement content of 3% yielded an unsoaked UCS of approximately 2,942 kPa, which is considered adequate for general cement-treated soil applications and represents a reasonable balance between strength improvement and cement consumption. Although the strength decreased to approximately 1,176.8 kPa after soaking, this material would typically be used beneath the pavement surface in practical applications, where direct exposure to water is limited. For this reason, 3% cement was selected as the base mixture for the subsequent investigation of steel fiber reinforcement.

5.3. Effect of Water Soaking on UCS Reduction

In geotechnical engineering practice, pavement materials and earth structures are frequently subjected to high moisture conditions or even saturation, both of which can significantly affect soil strength. Although lateritic soil is commonly used in road construction as a sub-base layer, evaluating the performance of cement-treated lateritic soil under soaked conditions remains essential for design and safety assessment.

A comparison of the UCS values obtained under unsoaked and 2 h-soaked conditions showed that water soaking caused a significant reduction in strength at all cement contents. At a cement content of 1%, the UCS decreased by approximately 67.4%. For cement contents of 3%, 5%, and 7%, the reductions were approximately 51.9%, 40.2%, and 35.0%, respectively. This trend clearly indicates that increasing the cement content can substantially reduce the material's sensitivity to water exposure.

The reduction in strength under soaked conditions can be attributed to the intrusion of water into the soil structure, which weakens interparticle bonding and reduces the effectiveness of bonds between soil particles and cement hydration products. This effect is particularly pronounced in specimens with low cement content, where the cemented structure has not yet developed into a continuous and stable bonding network. In contrast, specimens with higher cement content exhibit a denser, more continuous matrix and are therefore better able to resist the adverse effects of water.

These findings confirm that UCS testing under soaked conditions is an important step in evaluating the practical performance of cement-treated soils (Wahab et al., 2021). The observed strength reduction should therefore be considered together with the unsoaked strength when establishing appropriate design criteria for field applications (Zhang and Tao, 2008).

5.4. Tensile Strength Enhancement Mechanism of Fiber-Reinforced Lateritic Cement Soil

The splitting tensile strength test results of lateritic cement soil reinforced with recycled steel fibers from waste tires indicate that the fibers played a significant role in enhancing tensile performance, as shown in Fig. 6. The control specimens without fiber reinforcement (0% fiber) exhibited splitting tensile strengths of approximately 123, 156, and 350 kPa at curing ages of 7, 14, and 28 days, respectively. In contrast, the incorporation of an appropriate fiber content led to a marked increase in tensile strength at all curing ages.

With increasing fiber content, the tensile strength increased progressively from 1% to 3% fiber addition. The specimens reinforced with 3% fiber achieved the highest values, approximately 270 kPa at 7 days, 314 kPa at 14 days, and 481 kPa at 28 days, corresponding to an increase of about 120–150% compared with the unreinforced specimens. The improvement was particularly pronounced at 28 days, indicating that the reinforcing efficiency of the fibers became more significant as the cement-treated soil matrix matured and developed a more complete bonding structure.

However, when the fiber content exceeded 3%, the rate of strength improvement began to diminish and tended to level off. Specimens containing 4–5% fiber exhibited tensile strengths comparable to, or in some cases slightly lower than, those of the 3% fiber group. This behavior can be attributed to limitations associated with compaction and internal structure. At high fiber contents, the fibers tend to interlock and rebound during mixing, causing the mixture to become bulkier, more difficult to compact, and more prone to void formation. As a result, the dry density decreases and the efficiency of stress transfer does not improve in proportion to the increase in fiber content (Samarakoon et al., 2019).

From a mechanical perspective, the steel fibers act as crack-bridging elements, transferring tensile stress from the cement–soil matrix to the fibers and thereby delaying crack propagation and improving the tensile resistance of the material. In addition, the deformed geometry of the fibers and the presence of adhered rubber residue on their surfaces enhance mechanical interlocking and pull-out resistance. Nevertheless, these mechanisms can operate effectively only when the fibers are uniformly dispersed within the matrix. This interpretation is consistent with the experimental results, which indicate that a fiber content of approximately 3% was the optimum level for tensile reinforcement in the present study.

5.5. Flexural Strength and Post-Cracking Behavior

The flexural strength test results clearly demonstrate that steel fiber reinforcement improved both the flexural strength and the post-cracking behavior of cement-treated lateritic soil at all curing ages when compared with unreinforced specimens. In general, the flexural strength increased with both fiber content and curing age, highlighting the role of fibers in crack control and internal stress transfer within the material.

As shown in Fig. 7, the unreinforced specimens (0% fiber) exhibited flexural strengths of approximately 243–276 kPa over the curing period of 7–28 days. In contrast, the addition of 1–3% steel fibers resulted in a significant increase in flexural strength. At a fiber content of 3%, the flexural strength reached approximately 446, 657, and 851 kPa at curing ages of 7, 14, and 28 days, respectively, demonstrating the effectiveness of fiber reinforcement in enhancing bending resistance.

Although the specimen containing 4% fiber achieved the highest flexural strength, approximately 918 kPa at 28 days, the improvement relative to the 3% fiber group was only marginal. When the fiber content was further increased to 5%, the flexural strength decreased slightly to approximately 835 kPa in 28 days. This trend indicates that excessive fiber addition does not result in proportional strength enhancement, mainly because of structural and compaction-related limitations within the mixture.

The improvement in flexural strength is primarily associated with the ability of the fibers to act as crack-bridging elements after crack initiation, allowing the material to sustain load beyond first cracking and thereby develop a more pronounced residual strength. The deformed geometry of the fibers and the presence of adhered rubber residue on their surfaces further increase interfacial friction and pull-out resistance, leading to more efficient stress transfer within the composite (Kong et al., 2022).

Conversely, when the fiber content becomes excessively high, the fibers interfere with the arrangement of soil particles and the cementitious matrix, reducing compactability and causing a bulking effect as well as fiber rebound during compaction. These factors lead to a reduction in specimen density, resulting in a decline in flexural strength.

Overall, the experimental results indicate that a steel fiber content of approximately **3%** provides the most appropriate engineering balance for improving flexural strength and post-cracking performance, while still maintaining adequate compactability and a stable internal structure.

In addition, observations of the crack patterns of the beam specimens after testing (Fig. 8) showed that the unreinforced specimens, or those reinforced with a low fiber content, tended to develop a single long and distinct crack, which is characteristic of brittle failure. By contrast, specimens reinforced with approximately 3% fiber exhibited shorter cracks and better crack-width control, consistent with the mechanisms of crack bridging and post-cracking stress transfer. However, at higher fiber contents, the crack length tended to increase again, which is consistent with poorer fiber dispersion and reduced compaction efficiency.

5.6. Effect of Wetting–Drying Cycles on UCS

The durability test results under repeated wetting–drying cycles showed that the UCS decreased with increasing number of cycles for all fiber contents (Fig. 9), reflecting the detrimental effect of repeated moisture fluctuations on the cement-treated soil structure (Rauf et al., 2025).

At 0 cycles, all specimens exhibited comparable UCS values, ranging from approximately 2,600 to 2,900 kPa, indicating similar initial mechanical performance. However, after 3 cycles, the UCS decreased markedly, particularly in the unreinforced specimens and those containing low fiber contents. This behavior indicates that water exposure had a pronounced effect on reducing the internal bonding of the cement-treated soil matrix during the early stage of deterioration (Wu et al., 2024). This trend is consistent with previous findings showing that the greatest strength loss typically occurs during the first few cycles, after which the rate of deterioration tends to decrease.

As the number of cycles increased to 7 and 12, the UCS continued to decline, although the rate of reduction became more gradual. Specimens reinforced with 3% fiber demonstrated favorable strength retention under wet–dry cycles., highlighting the role of fibers in supporting the internal structure, limiting crack propagation, and delaying cumulative damage caused by repeated moisture cycling (Wang et al., 2024).

In contrast, specimens reinforced with as much as 5% fiber exhibited a greater reduction in strength than those containing moderate fiber contents, particularly at higher numbers of cycles. This behavior may be associated with poorer compaction efficiency caused by fiber rebound and increased void ratio, which facilitate water penetration and accelerate material degradation (Zhang and Tao, 2008).

Overall, the results indicate that reinforcement with recycled steel fibers from waste tires can improve resistance to wetting–drying cycles when used at an appropriate dosage. The experimental findings suggest that a fiber content of approximately 3–4% provides a suitable balance among initial strength, compactability, and strength retention under repeated moisture exposure, thereby demonstrating strong potential for practical engineering applications.

6. Discussion

The results demonstrate that the behavior of steel fiber-reinforced cement-treated lateritic soil is controlled by the interaction between a cemented load-bearing matrix and a fiber-mediated crack-control

mechanism. Cement primarily enhanced compressive strength through the progressive formation of a bonded soil skeleton, whereas fiber reinforcement contributed mainly to tensile resistance, flexural performance, and post-cracking stability. This distinction explains why cement improved peak strength, while fibers more effectively modified the failure mode from brittle to semi-ductile.

The marked reduction in UCS after soaking and wetting–drying exposure indicates that the long-term vulnerability of the material is mainly governed by degradation of the cementitious bond network rather than by the intrinsic plasticity or gradation of the untreated soil. Moisture ingress through microcracks progressively disrupted matrix continuity and weakened internal stress transfer. In this context, recycled steel fibers improved durability by bridging cracks, limiting crack connectivity, and retarding cumulative damage under cyclic moisture changes (Wang et al., 2024). Their effectiveness was greatest when dispersion was sufficiently uniform to mobilize mechanical interlocking and pull-out resistance.

These findings suggest that the engineering value of recycled steel fibers lies less in increasing compressive strength than in improving damage tolerance, residual capacity, and durability. For geotechnical applications, this is a significant outcome because serviceability and long-term integrity often depend more on crack restraint and moisture resistance than on peak compressive strength alone (Zhang et al., 2022). The results also confirm that fiber dosage must be optimized: beyond the beneficial range, reduced compactability and increased void ratio can offset the gains from fiber reinforcement. Accordingly, the use of recycled tire steel fibers offers both mechanical and sustainability benefits if mixture design is controlled to balance reinforcement efficiency with matrix integrity.

7. Conclusions

This study evaluated the engineering performance of lateritic soil stabilized with cement and reinforced with recycled steel fibers recovered from waste tires under both dry and moisture-varying conditions. The principal conclusions are as follows:

1. Cement stabilization markedly enhanced the unconfined compressive strength of lateritic soil, and the strength increased consistently with increasing cement content and curing age. This improvement is attributed to the progressive formation of a cemented soil skeleton. However, the cement-treated material still exhibited brittle behavior and remained vulnerable to moisture-induced strength loss.
2. Recycled steel fiber reinforcement significantly improved the tensile response and post-cracking performance of the cement-treated lateritic soil. The fibers acted as crack-bridging elements, transferring stress across developing cracks and thereby delaying crack initiation and propagation.

3. The flexural test results further confirmed that steel fibers modified the failure behavior of cement-treated lateritic soil from brittle to semi-ductile, enabling the material to retain part of its load-carrying capacity after first cracking. This behavior is particularly beneficial for geotechnical applications where tensile and flexural stresses may develop in service.
4. Under wetting–drying cycles, fiber-reinforced specimens exhibited better strength retention than unreinforced cement-treated soil. This improvement is associated with the ability of the fibers to restrain crack opening, reduce crack connectivity, and mitigate moisture-induced deterioration within the cemented matrix.
5. Overall, the combined use of cement and recycled steel fibers from waste tires provides a promising approach for enhancing both the mechanical performance and durability of lateritic soil for geotechnical applications. In addition to improving material performance, this approach supports sustainable construction practices by enabling the beneficial reuse of waste-derived materials.

Declarations

Funding

This research was funded by Faculty of Technical Education, King Mongkut's University of Technology North Bangkok (KMUTNB) Contract FTE-2566-11

Author Contribution

Siriphat Maneekeaw: writing—original draft, methodology, data curation, formal analysis, investigation, funding acquisition. Panich Voottipruex: writing—review & editing, supervision, conceptualization, project administration. Ittipon Meepon: investigation, data curation, resources, validation. Piyarat Paoleng: investigation, visualization, formal analysis, data interpretation. Wilailak Sramoon: writing—review & editing, visualization, validation. Krairoj Mahannopkul: writing—original draft, conceptualization, validation, corresponding author.

Acknowledgement

This research was funded by Faculty of Technical Education, King Mongkut's University of Technology North Bangkok (KMUTNB) Contract FTE-2566-11.The authors sincerely thank Professor Dr. Panich Voottipruex for his valuable guidance and advice throughout the research. They also appreciate all members of the research team for their dedication and support.

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Figures



Figure 1

Recycling process of steel fibers recovered from waste tires: (A) cutting of tire pieces, (B) shredding process, (C) mechanical crushing, and (D) separation of steel fibers.



Figure 2

Physical and morphological characteristics of recycled steel fibers recovered from waste tires.

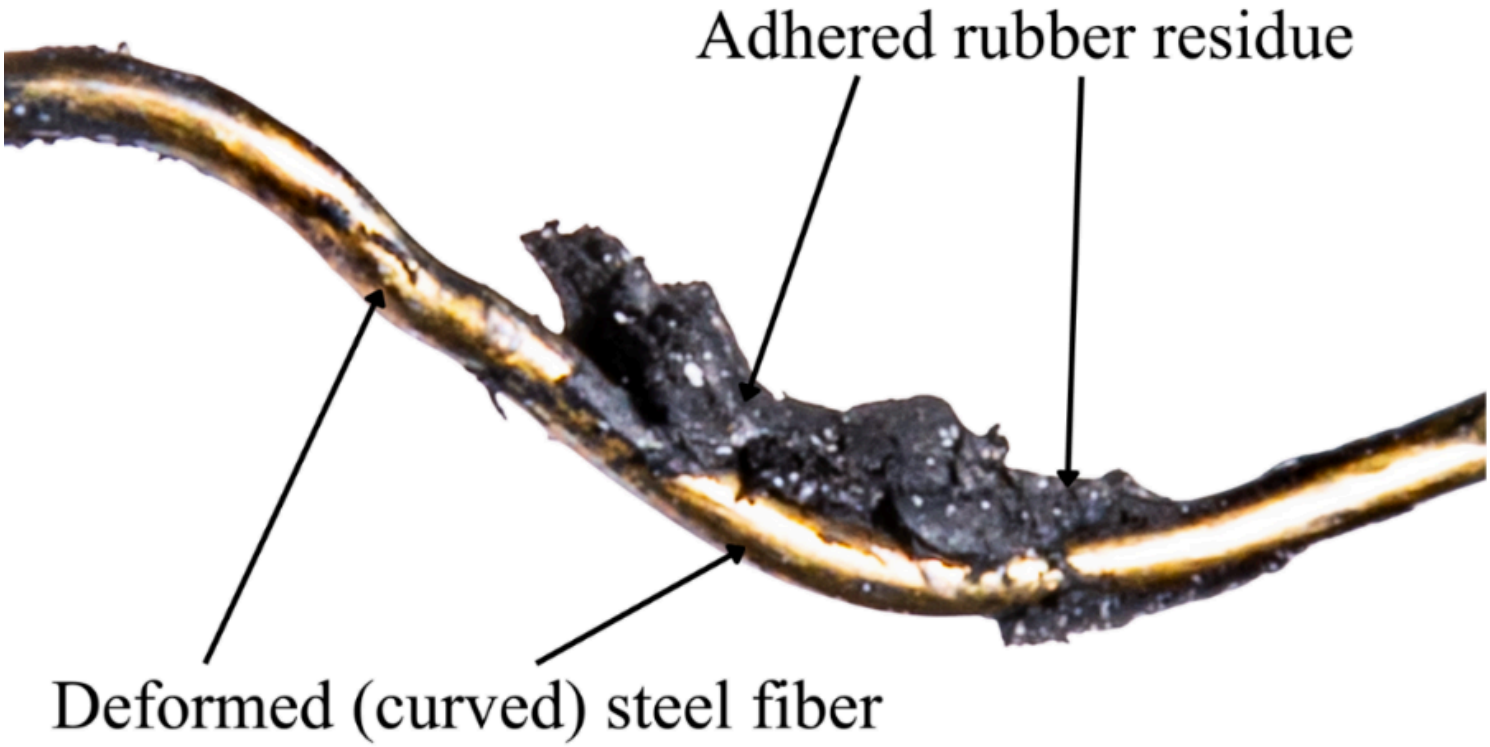


Figure 3

Enlarged view of a recycled steel fiber illustrating its deformed geometry and the presence of adhered rubber residue.

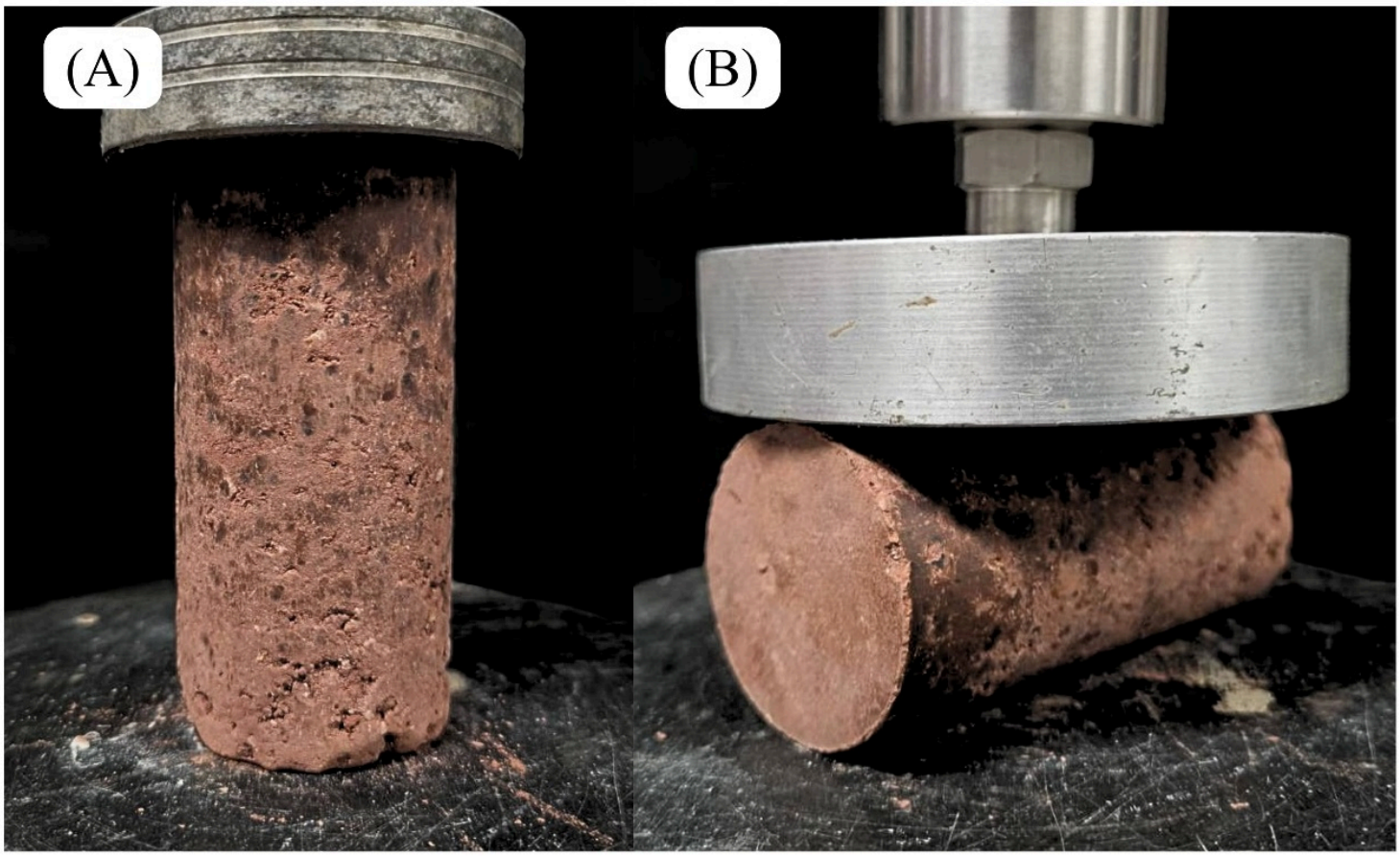


Figure 4

Experimental setup for mechanical testing of cement-treated lateritic soil: (A) **UCS test**and (B) **splitting tensile strength test.**

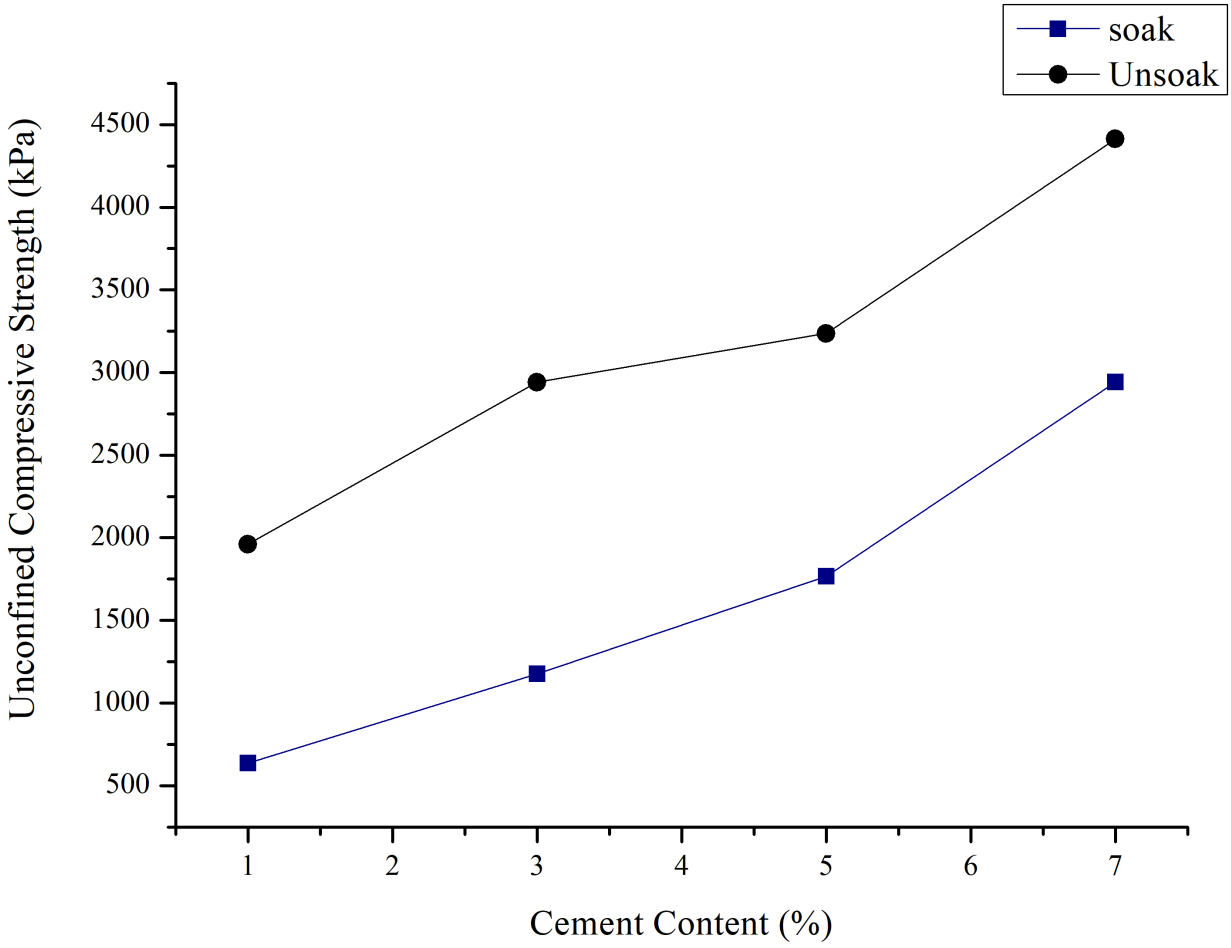


Figure 5

Variation in the unconfined compressive strength of cement-treated lateritic soil with cement content under soaked and unsoaked conditions.

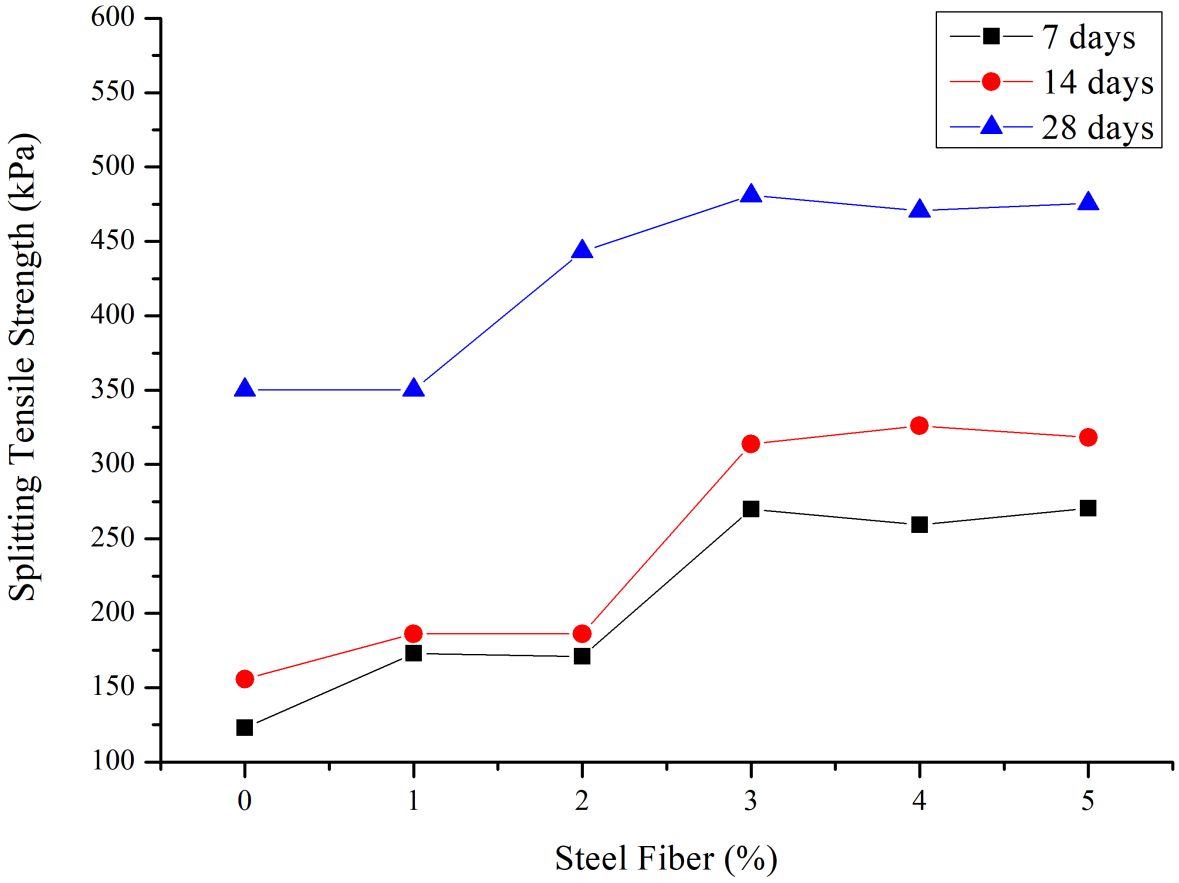


Figure 6

Effect of steel fiber content on the splitting tensile strength of lateritic cement soil at different curing ages.

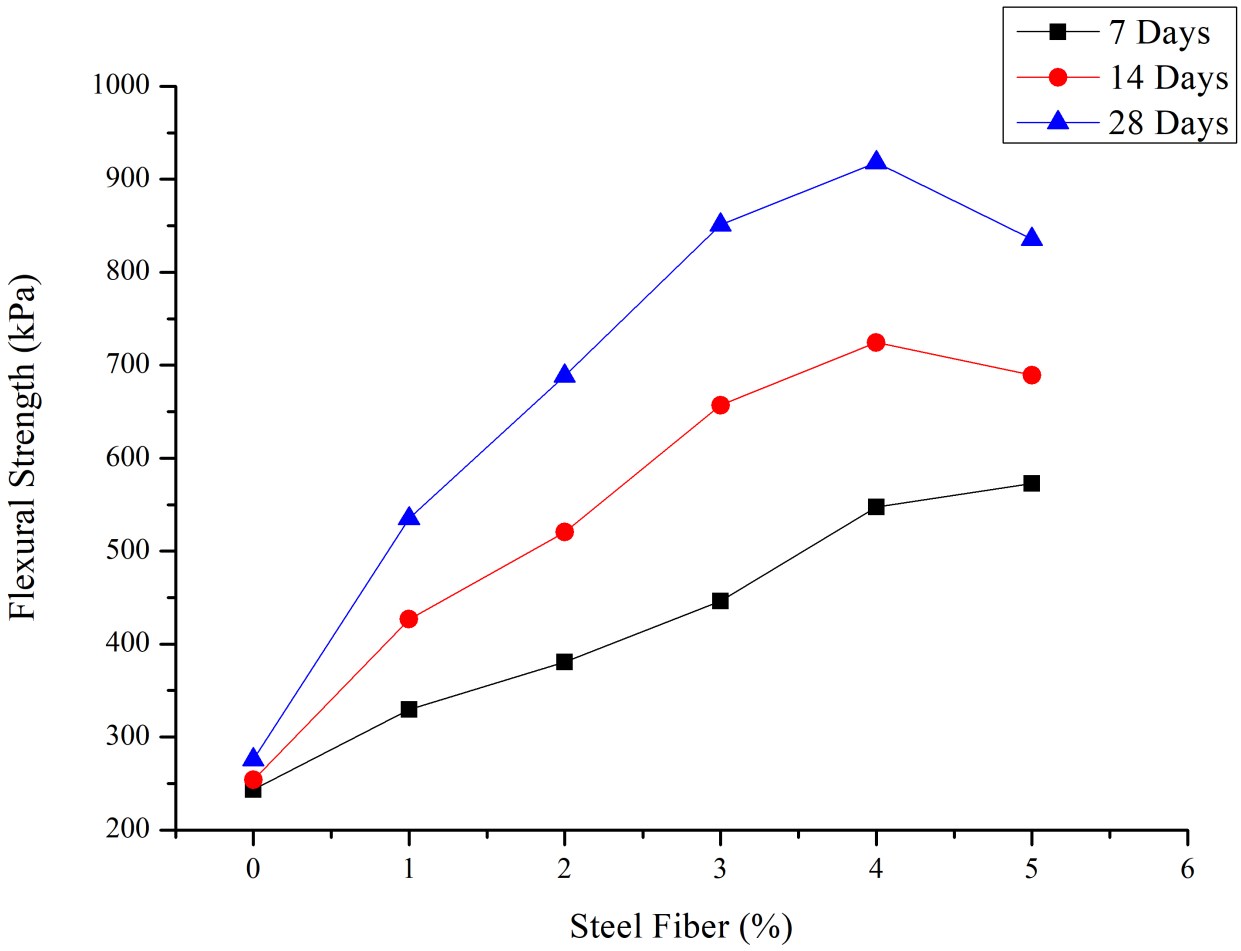


Figure 7

Variation in the flexural strength of steel fiber-reinforced cement-treated lateritic soil as a function of fiber content and curing age.

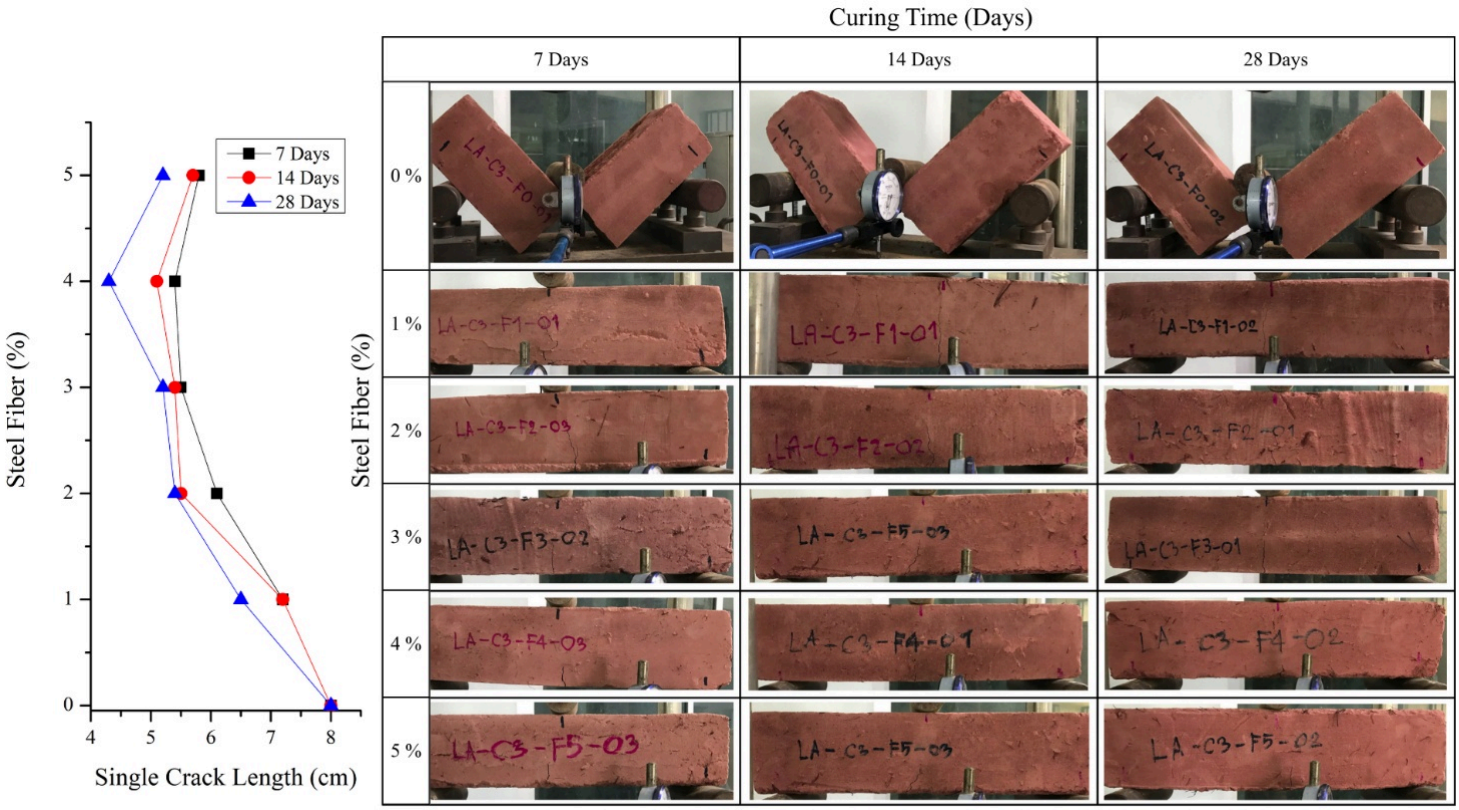


Figure 8

Crack patterns and measured single-crack lengths of steel fiber-reinforced cement-treated lateritic soil beams after flexural testing at different fiber contents and curing ages.

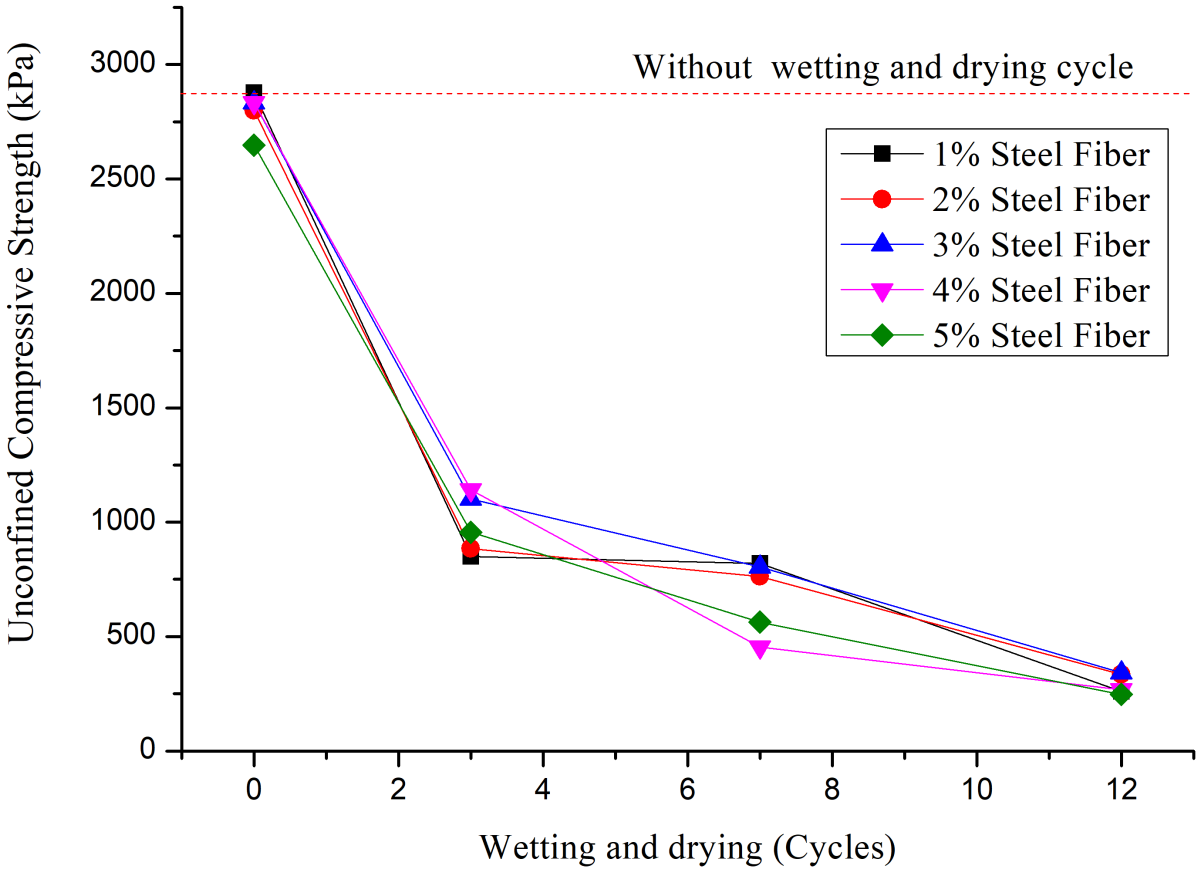


Figure 9

Variation in the unconfined compressive strength of fiber-reinforced cement-treated lateritic soil subjected to wetting–drying cycles.