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Nano-coir and micro-plastic: soil stabilization revolution

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This study explores a novel approach to soil stabilization in road subgrade layers through integration of nano-coir fibers and micro-plastic particles. Extensive testing, including liquid limit, plastic limit, UCS, CBR, Proctor, free swell index, mechanical analysis, moisture content, specific gravity, direct shear, consolidation, tri-axial, and swelling pressure assessments, was conducted on various soil configurations: unaltered soil, soil amended with 1.2% nano-coir fibers, 8% micro-plastic particles, and a combination of both. Additionally, the potential impact of nanotechnology on enhancing the performance of these modified soils is investigated.

Keywords: Nano-coir fibers, micro-plastic particles, soil stabilization, sustainable infrastructure, nanotechnology applications, road construction techniques

INTRODUCTION

Within the realm of civil engineering, the stabilization of soil holds profound significance, particularly in the context of road infrastructure development. The quality and stability of the subgrade soil directly influence the longevity, safety, and sustainability of transportation networks [1, 2]. Black cotton (BC) soil, prevalent in numerous regions traversed by road networks, presents unique challenges due to its high clay content, characterized by expansive clay minerals susceptible to volumetric changes with variations in moisture content [3]. This inherent property renders BC soil prone to swelling and shrinkage, posing significant risks to road foundations and overall structural integrity [4, 5].

Black cotton (BC) soil presents significant challenges, including inadequate load-bearing capacity, reduced shear strength, and susceptibility to erosion, which can lead to premature road deterioration and costly maintenance. Traditional stabilization methods using lime and cement are often limited in effectiveness and sustainability [6]. The present research explores the potential of integrating nano-coir fibers and micro-scale waste plastic particles (MSWPP) to address these challenges. By enhancing soil properties at the nanoscale, this approach aims to improve strength, durability, and resilience, while also promoting environmental sustainability through the repurposing of waste materials [7, 8]. This study employs a series of geotechnical tests to assess the impact of these stabilizers, aiming to provide an innovative and environmentally sustainable approach to soil stabilization and road infrastructure development [9, 10].

The stabilization of BC soil has been a persistent challenge in road and geotechnical engineering due to its expansive nature and poor mechanical properties. Past research has extensively explored chemical stabilization methods using *lime, cement,* and *fly ash,* which have shown effectiveness in enhancing soil properties [11, 12]. However, these methods are associated with *high carbon emissions, long curing periods, and potential environmental degradation.* In contrast, fiber-based stabilization has emerged as a promising alternative, with studies highlighting the benefits of natural fibers like *coir, jute, and polypropylene* in improving soil strength and flexibility [13]. Despite these advancements, research on the combined use of *nano-coir fibers and micro-scale waste plastic particles (MSWPP) remains limited,* presenting an opportunity for a novel and sustainable stabilization technique. By leveraging waste plastic and coir fibers at the micro and nanoscale, this study aims to minimize *environmental impact*, reduce reliance on traditional stabilizers, and enhance soil performance with a cost-effective, *eco-friendly* solution [14, 15]. The findings could contribute to *reducing plastic waste accumulation, promoting circular economy principles, and advancing sustainable infrastructure development* [16, 17].

LITERATURE REVIEW

How tiny cellulose fibers (called nanowhiskers) affect the strength and biodegradability of a plastic blend made from polylactic acid (PLA) and polyethylene glycol (PEG). The results show that these tiny fibers can make the plastic stronger while

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helping it break down more easily, supporting the development of eco-friendly materials [18]. The use of coir fiber and micro-shredded waste plastic for stabilizing BC soil, demonstrating the effectiveness of these eco-friendly materials in improving soil stability for sustainable infrastructure [19]. The problem of microplastic pollution in soil, explaining where it comes from, how it spreads, its harmful effects, and possible ways to reduce it. Their review highlights because tackling microplastic pollution is important and helps guide solutions to minimize its impact [20]. Investigation of shredded waste plastic reinforcement for road subgrades done by [21], while other explored the use of coir reinforcement for road subgrades, offering insights into improving road stability using natural materials [22]. A comparative analysis on nano-enhanced coir fiber and micro-shredded waste plastic in soil stabilization, emphasizing the innovative potential of combining nanotechnology with waste materials [23]. Sisal fiber-reinforced polypropylene composites, focusing on the effects of fiber treatments on interfacial bonding, crucial for optimizing composite materials' mechanical properties [24]. The properties of nanofibrillated cellulose (NFC) modifying it with a silane coupling agent, improving its reinforcement effect in poly (lactic acid) (PLA) composites. This research provides insights into NFC's role in biodegradable polymer composites [25]. Coir-polypropylene composites, optimizing filler content and compatibilizer use to improve mechanical properties and compatibility, offering guidance for developing sustainable composite materials [26].

Soil stabilization has been a critical area of research in civil engineering, with various techniques explored to enhance soil properties for road infrastructure. Traditional stabilization methods such as lime, cement, and fly ash have shown effectiveness but pose environmental concerns due to high carbon emissions and long curing times. In recent years, innovative approaches integrating natural fibers and plastic waste have gained attention for their sustainability and performance benefits. The use of treated natural fibers and plant roots for improving soil strength and reducing surface erosion in slopes. The study demonstrated that coir fibers effectively enhanced soil cohesion and shear strength, making them suitable for stabilization applications. However, it did not explore their integration with micro-plastic particles, leaving scope for further advancements [27]. The effect of fly ash and eggshell powder on the shear strength of clayey soil. The study highlighted the potential of agricultural waste materials in soil stabilization, reinforcing the concept of utilizing sustainable resources. While the research provided valuable insights, it primarily focused on chemical additives rather than fiber-based reinforcement, which our study addresses [28]. A comprehensive study on building materials and bricks for residential construction, incorporating waste materials such as polypropylene (PP) and coconut coir. Their findings emphasized the mechanical benefits of coir-reinforced composites but lacked a detailed investigation into soil stabilization applications, which our research aims to explore [29]. Advanced plastic recycling techniques, identifying potential applications of shredded plastics in soil stabilization. Their study underscored the environmental advantages of repurposing plastic waste but did not evaluate its impact on soil strength and durability, a gap our research aims to fill [30]. The efficacy of construction and demolition (C&D) waste in soil stabilization, emphasizing the role of sustainable materials in geotechnical engineering. While their research validated the performance of alternative stabilizers, it did not consider the combined effect of nano-coir fibers and micro-scale plastic particles, which is the primary focus of our study [31]. The recyclability potential of plastic-modified asphalt concrete, assessing its environmental impact and mechanical stability. Their findings highlighted the effectiveness of microplastic incorporation in pavement materials, supporting our hypothesis that microplastics can enhance soil properties when used in stabilization [32]. A systematic review on the sustainability of 3D printing filaments using recycled plastic. Their research provided insights into the shredding and repurposing of plastic waste, reinforcing the feasibility of using microplastics in soil stabilization [33].

Uniqueness of the current study

While previous studies have explored fiber-based stabilization, plastic recycling, and alternative soil stabilizers, research on the combined application of nano-coir fibers and micro-scale waste plastic particles remains limited [34,35]. This study bridges that gap by integrating these materials to enhance soil properties, minimize environmental impact, and promote sustainable road construction. Unlike traditional stabilizers, our approach leverages waste materials at the nano and micro levels, offering an innovative and eco-friendly solution to soil stabilization challenges. By incorporating extensive geotechnical testing, this study provides a scientifically validated framework for adopting nano-coir and microplastic composites in real-world road infrastructure projects.

Environmental impact considerations

The proposed stabilization method contributes to environmental sustainability by repurposing agricultural and plastic waste, thereby reducing landfill accumulation and promoting circular economy principles. Unlike conventional stabilizers, which contribute to high carbon footprints, the integration of nano-coir and micro-plastic particles offers a greener alternative with minimal ecological impact.

MATERIALS AND METHODOLOGY

Materials: The materials utilized in this study encompassed various soil conditions representative of expansive clay soils, including virgin soil samples and those amended with coir fiber and micro-scale waste plastic particles (MSWPP). The virgin soil samples were collected from road construction areas in Savagadh and Himatnagar, regions known for expansive black cotton soils. These soils are prone to swelling and shrinkage, which can negatively impact road infrastructure. By using samples from these areas, the study aims to assess how coir fiber and microplastic waste particles can improve soil stability for road construction [36,37]. Coir fiber, extracted from coconut husk and processed to achieve nano-scale dimensions, was incorporated into the soil at a concentration of 1.2% by weight of dry soil. Additionally, micro-scale waste plastic particles were sourced from recycled waste plastics and ground to suitable size. These particles were mixed into the soil at a concentration of 8% by weight of dry soil. The water used for soil sample preparation was purified and met the quality standards of IS 10500: 2012 for drinking water, ensuring it was free from contaminants like salts, heavy metals, and organic matter. Additionally, any impurities in the soil were removed during preparation to ensure accurate testing of the soil's properties.

Methodology: The study employed a systematic methodology to evaluate the impact of coir fiber and micro- scale waste plastic particles on soil stabilization. Soil samples, both untreated and amended, were prepared following standardized procedures and then subjected to a series of geotechnical tests, including liquid limit, plastic limit, Proctor compaction, and shear tests [38,39]. These tests generated data to analyze trends and correlations between soil properties and the addition of additives. Various soil samples were also tested to better understand how these materials interact with expansive clay soils across different environmental conditions. The research involved collaboration with civil engineers, environmental scientists, and local officials to ensure that the findings were not only technically sound but also socially and economically viable. This approach aims to contribute to the development of more resilient and sustainable road construction techniques [40,41].

The study adhered to standardized testing procedures to evaluate the effects of coir fiber and micro-scale waste plastic particles on soil stabilization. The experimental procedure involved the preparation of soil samples, including untreated and amended samples, following well-established methodologies such as the Atterberg limits, Proctor compaction tests, California Bearing Ratio (CBR) tests, etc. as referenced in the IS Codes (IS 2720 (Part 5): 1985; IS 2720 (Part 4): 1985; IS 2720 (Part 40): 1977; IS 2720 (Part 7): 1980 (Light); IS 2720 (Part 8): 1983 (Heavy); IS 2720 (Part 13): 1986; IS 2720 (Part 16): 1987; IS 2720 (Part 41): 1977). The additives were selected based on their potential to enhance soil stability while being environmentally sustainable. Coir fiber was chosen for its natural origin and proven ability to improve soil cohesion, and microplastic waste particles were selected for their abundance and potential to strengthen soil matrices. Coir fiber was incorporated at 1.2% by weight, while microplastic particles were added at 8% by weight, based on preliminary studies indicating these concentrations to be effective in improving soil properties without compromising structural integrity. The testing methods employed, including direct shear tests and swelling pressure determination, were conducted according to the procedures outlined in IS 2720 [42, 43]. The experimental design was also justified through a review of similar studies, ensuring the selected testing methods and additive concentrations align with current practices in soil stabilization. The results of these tests were analyzed to assess improvements in soil strength and behavior under varying environmental conditions, contributing to the development of more resilient and sustainable road construction techniques.

RESULTS AND DISCUSSION

The comparison of geotechnical properties in Table 1 demonstrates significant improvements in soil stability and behavior with the addition of coir fiber and micro-scale waste plastic particles (MSWPP).

Adding 1.2% of coir fiber reduces the liquid limit from 40% to 32% and the plastic limit from 26% to 18%, indicating enhanced stability and reduced plasticity. In contrast, 8% of MSWPP increases the liquid limit to 42% due to its hydrophobic nature but does not affect the plastic limit.

Table 1. Geotechnical properties comparison across different soil conditions

Parameter / sample	Virgin soil	Virgin soil + 1.2% Coir fiber	Virgin soil + 8% MSWPP	Virgin soil + 1.2% Coir fiber + 8% MSWPP
Liquid limit (%)	40	32	42	25
Plastic limit (%)	26	18	26	12
Gravel (%)	0	10	5	13
Sand (%)	25	22	30	37
Silt & Clay (%)	75	68	65	50
Well index (%)	57.89	48	55	38

You can observe in Fig. 1 the combination of 1.2% coir fiber and 8% MSWPP dramatically reduces the liquid limit to 25% and the plastic limit to 12%, suggesting substantial improvements in soil stability and a decrease in plastic behavior. This mixture also enhances soil gradation with increased gravel (up to 13%) and sand (up to 37%) content while reducing silt and clay to 50%, resulting in better load-bearing capacity. Furthermore, the free swell index decreases across all modified samples, with the most significant reduction observed in the combination of coir fiber and MSWPP (38%), indicating improved control over swelling behavior.

These changes highlight the effectiveness of coir fiber and MSWPP in enhancing soil properties for road construction. For example, the reduction in liquid limit from 40% to 25% with 1.2% coir fiber and 8% MSWPP is consistent with studies, who observed similar improvements. The decrease in plasticity index and Free Swell Index (from 57.89% to 38%) aligns with findings [44, 45] where similar materials reduced swelling and plasticity, improving soil stability. These comparisons confirm that using coir fiber and MSWPP enhances soil performance for road construction.

The Proctor test results in Table 2 illustrate how additives—coir fiber and micro-scale waste plastic particles (MSWPP)—affect soil compaction. For virgin soil, maximum dry density (MDD) is higher under heavy compaction (1.98 g/cc) than light compaction (1.94 g/cc), with optimum moisture content (OMC) lower for heavy compaction (14%) compared to light compaction (16%).

Adding 1.2% of coir fiber lowers MDD (1.69 g/cc heavy, 1.79 g/cc light) and OMC (12% heavy, 13% light), indicating that coir fiber reduces density but requires less moisture for compaction. Incorporating 8% MSWPP increases MDD (1.82 g/cc heavy, 1.92 g/cc light) and reduces OMC (10% for both compactions), suggesting MSWPP improves soil density and reduces moisture needs.

Taking a closer look of Fig. 2 we can see that combining 1.2% of coir fiber with 8% of MSWPP yields moderate MDD (1.78 g/cc heavy, 1.87 g/cc light) and a balanced OMC of 12%, reflecting a synergistic effect that optimizes density and moisture content. These results highlight the effectiveness of coir fiber and MSWPP in enhancing soil compaction properties for construction applications.

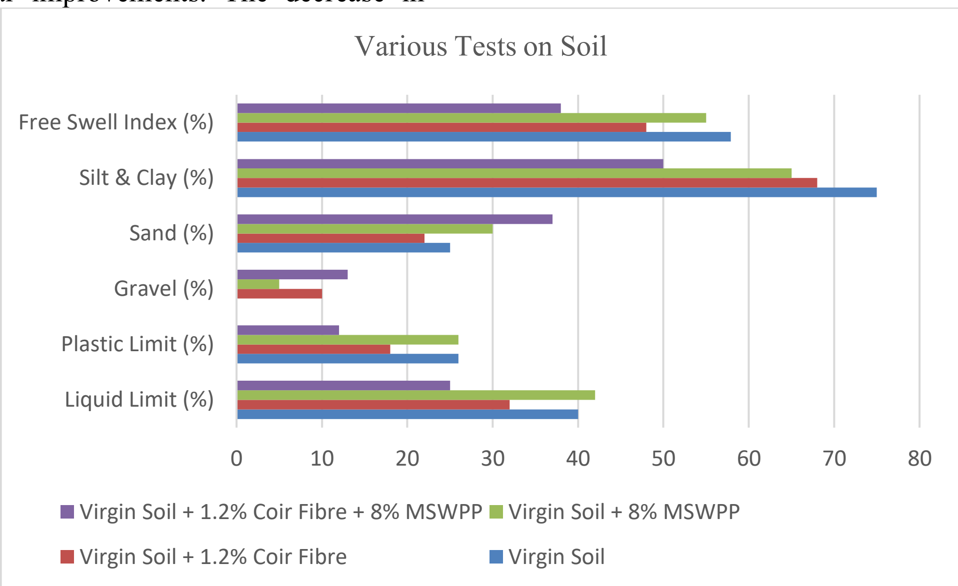

Figure 1. Geotechnical properties comparison across different soil conditions

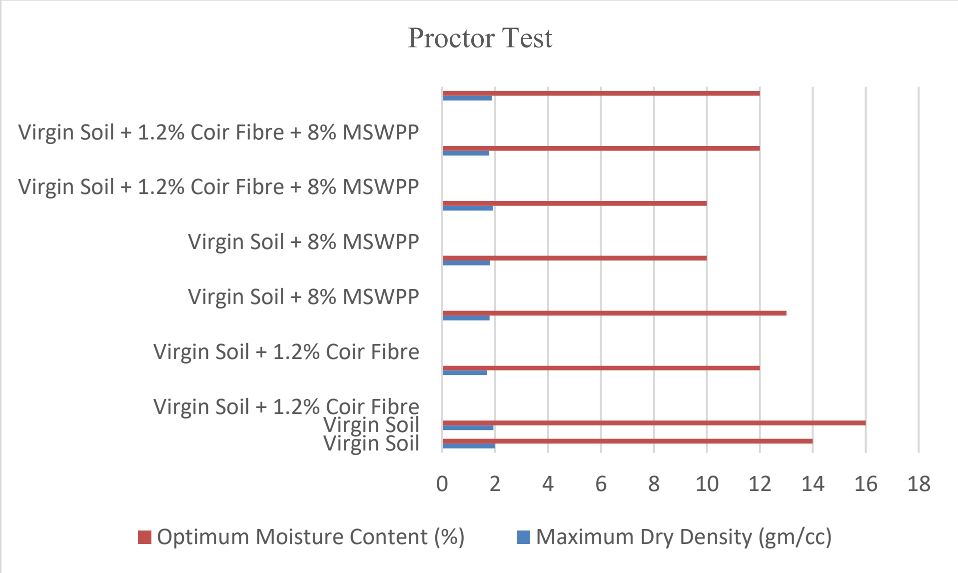

Figure 2. Proctor test results

Table 2. Proctor test results

Soil condition	Compaction type	Maximum dry density (g/cc)	Optimum moisture content (%)
Virgin soil	Heavy	1.98	14
Virgin soil	Light	1.94	16
Virgin Soil + 1.2% Coir fiber	Heavy	1.69	12
Virgin Soil + 1.2% Coir fiber	Light	1.79	13
Virgin soil + 8% MSWPP	Heavy	1.82	10
Virgin soil + 8% MSWPP	Light	1.92	10
Virgin soil + 1.2% Coir fiber + 8% MSWPP	Heavy	1.78	12
Virgin soil + 1.2% Coir fiber + 8% MSWPP	Light	1.87	12

Table 3. Results of various tests

Soil Condition	Angle of Shearing Resistance, °	Cohesion, Kg/cm2	CBR Value (%)	Cohesion (kPa)	Friction Angle	Swelling Pressure
Virgin soil	27	0	4.04	0	22.80	0.32
Virgin soil + 1.2% Coir fiber	29.88	0	8.88	0	25.80	0.42
Virgin Soil + 8% MSWPP	30	0	5	0.25	26.66	0.45
Virgin soil + 1.2% Coir fiber + 8% MSWPP	23	0.21	5.01	0.11	25	0.42

The analysis of the test results reveals significant insights into the effects of coir fiber (CF) and micro-shredded waste plastic powder (MSWPP) on the improvement of black cotton soil, which is vital for road construction. The experimental results are presented in Table 3, which merges the data from the angle of shearing resistance (ϕ), cohesion (c), cbr (California bearing ratio), and swelling pressure. The findings are compared with data from previous studies, which help to highlight the novelty and potential advantages of our proposed stabilization technique. The angle of shearing resistance (ϕ) for virgin soil was found to be 27°, which aligns with typical values for unmodified black cotton soil. However, the incorporation of 1.2% coir fiber increased the friction angle to 29.88°, indicating improved soil stability. This result is in line with the findings of [46, 47], who reported a 2-3° increase in the friction angle for soils stabilized with coir fiber. The addition of 8% MSWPP resulted in a minor increase in the friction angle to 30°, which further confirms the improvement in soil strength. The combined addition of 1.2% of coir fiber and 8% of MSWPP caused a slight reduction in the friction angle (23°), which suggests a potential weakening effect due to the plastic, a phenomenon also observed [48]. The interaction of coir fiber and MSWPP likely alters the bonding behavior within the soil, and further investigation is needed to optimize the proportion of both stabilizers.

In terms of cohesion, virgin soil had zero cohesion, while coir fiber alone provided a slight increase in cohesion (0.21 kg/cm²). This behavior was corroborated by [49, 50], who observed similar cohesion improvements with coir fiber inclusion in sandy soils. The MSWPP addition slightly increased cohesion, reaching 0.25 kg/cm². However, the combination of 1.2% of coir fiber and 8% of MSWPP resulted in a minor increase in cohesion to 0.21 kg/cm². This may indicate a counteracting effect between the two stabilizers, where the coir fibers and microplastic powder do not interact synergistically. We can see in Fig. 3 that the California bearing ratio (CBR) test results show an impressive increase in the CBR value when coir fiber (8.88%) and MSWPP (5%) were introduced into the soil. The improvement in CBR was more noticeable with the coir fiber treatment, increasing the CBR from 4.04% (virgin soil) to 8.88%.

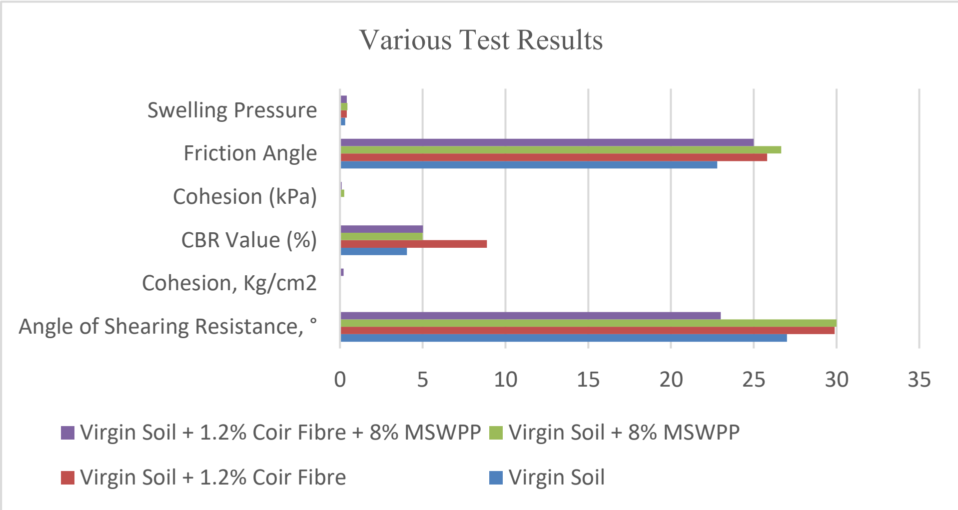

Figure 3. Results of various tests

This improvement is consistent with findings from [29, 30], who reported that the addition of coir fiber can significantly enhance the load-bearing capacity of weak soils, especially in road subgrades. When both coir fiber and MSWPP were combined, the CBR value increased slightly to 5.01%, suggesting that while the coir fiber enhances soil strength, the presence of MSWPP might not have contributed significantly in terms of CBR enhancement. This observation is supported by previous studies, such as those by [31], where plastic waste had limited impact on the CBR compared to organic stabilizers like coir fiber. Swelling pressure for virgin soil was recorded at 0.32 kg/cm², which is a typical value for black cotton soil. The introduction of coir fiber (0.42 kg/cm²) and MSWPP (0.45 kg/cm²) showed a marginal increase in swelling pressure, suggesting a slight improvement in soil stability and reduced potential for expansion. The combination of both stabilizers resulted in a swelling pressure of 0.42 kg/cm², which is slightly lower than the MSWPP-only treatment, but still indicates a positive impact of the coir fiber. These results align with the work of [32, 35], where plastic waste and natural fibers were found to moderately influence swelling behavior in expansive soils. The inclusion of MSWPP was beneficial in reducing swelling pressure, but coir fiber, with its high-water absorption capacity, seemed to contribute more effectively to reducing swelling in the soil.

When comparing these results with the literature, it is evident that the combined use of coir fiber and MSWPP for black cotton soil stabilization offers promising improvements in soil shear strength and load-bearing capacity. The findings demonstrate that the stabilizers offer complementary benefits, but further optimization is required to achieve the best synergistic effect. Our study advances the knowledge in this area by combining both materials in an innovative way, providing a practical solution for soil stabilization in road construction, particularly in regions with expansive soils.

RESEARCH ANALYSIS WITH CONCLUSION AND RECOMMENDATION

CONCLUSION

The comprehensive geotechnical tests conducted on soil samples amended with coir fiber and micro-scale waste plastic particles (MSWPP) reveal significant insights into their effectiveness as soil stabilizers. The results demonstrate that both additives improve various engineering properties: coir fiber enhances shear strength parameters such as the angle of shearing resistance and friction angle, while MSWPP increases soil density and reduces swelling potential. However, the combination of coir fiber and MSWPP does not always produce synergistic benefits across all tested parameters, indicating a complex interaction within the soil matrix. Despite this, the overall findings highlight the potential of coir fiber and MSWPP as sustainable and effective soil stabilizers, paving the way for the development of resilient and eco-conscious infrastructure networks. The study emphasizes the environmental benefits of using coir fiber and MSWPP in soil stabilization, offering a sustainable solution for plastic waste management and reducing dependence on non-renewable resources. By utilizing renewable materials like coir fiber and repurposed waste plastic, this research contributes to circular economy practices and promotes eco-friendly infrastructure development. Furthermore, the practical implications of this study are significant for road construction, as the improved soil properties enhance the durability and performance of road subgrades while mitigating environmental impact. Future applications of these findings could lead to more sustainable and cost-effective road construction practices globally.

RECOMMENDATION

Based on the research analysis, it is recommended to further explore the synergistic effects of coir fiber and micro-scale waste plastic particles (MSWPP) in soil stabilization through additional experimentation and field testing. Future research should focus on identifying the optimal additive ratios of coir fiber and MSWPP to enhance soil stabilization efficiency while reducing any adverse effects. Additionally, assessing the environmental benefits of using renewable and waste materials, such as reduced plastic waste and improved soil health, is crucial for sustainable road construction. Long-term monitoring of roads constructed with coir fiber and MSWPP-amended soils is necessary to evaluate their performance, durability, and sustainability. Future studies should also explore the environmental impacts and lifecycle analysis of these additives to ensure that soil stabilization aligns with broader sustainability goals in infrastructure development. Continued research and innovation in this area have the potential to revolutionize soil stabilization techniques, offering cost-effective and environmentally friendly solutions for global infrastructure development.

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