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ENHANCED SOIL PILES WITH PORTLAND CEMENT-RHA-MWCNT MIX FOR DEEP MIXING METHODS IN LOW-RISE BUILDING AND BRIDGE FOUNDATIONS

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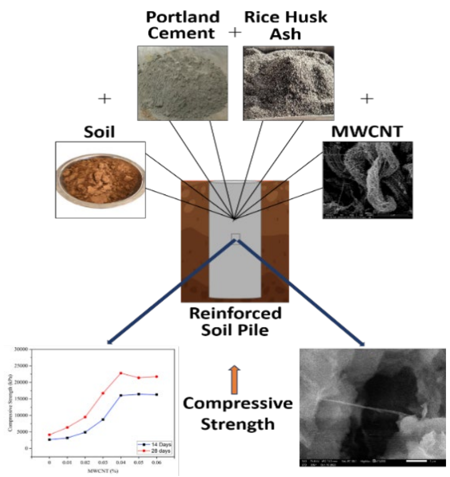
Graphical abstract



Abstract

Soft soil's low strength and high deformation characteristics pose significant challenges in low-rise building and bridge constructions. This research introduces an innovative method to fortify soft soil using Portland cement (PC), rice husk ash (RHA), and multi-walled carbon nanotubes (MWCNTs) as additives for reinforced soil pile (RSP) development through a deep mixing technique. The physico-mechanical characterization result reveals a remarkable 83% (1075 to 1962 kg/m^3) increase in average density and a significant 405% (4.14 to 20.92 MPa) enhancement in compressive strength after 28 days of curing, achieved with the addition of only 0.04 wt% MWCNT to the soil-PC-RHA mixture. Furthermore, a large-scale static load test was conducted to assess its translational efficiency in a real-world scenario. The result revealed a comparable compressive strength between the laboratory-scale and large-scale implementation (20.9 MPa vs. 23.4 MPa). This substantial improvement, attributed to the synergistic effects of MWCNT, surpasses the performance of traditional soil-PC-RHA blends in the literature. By leveraging the distinctive attributes of PC, RHA, and MWCNT, this eco-friendly technology offers a promising alternative for high-strength low-rise construction, addressing the inherent limitations of soft soils and presenting transformative potential with far-reaching implications for geotechnical engineering and sustainable infrastructure development.

Keywords: Deep foundation, soil piles, soil stabilization, rice husk ash, and multi-walled carbon nanotube

1.0 INTRODUCTION

Soft soils, including alluvial soil, loose clay, and silt deposits, pose significant geotechnical challenges in many major cities throughout the Philippines, as emphasized by the previous reports on lowland soils [1,2]. These soil types often exhibit inadequate bearing capacity, compromised shear strength, and excessive settlement, posing threats to the stability and performance of medium-rise buildings and bridges in urban areas [3–5]. In regions characterized by such soft and silt soils, traditional construction methods like reinforced concrete piles or bored piles may fall short in providing the necessary skin friction and bearing capacity required to support structures adequately [6,7]. Moreover, the economic implications of these conventional methods raise concerns for both practitioners and clients, highlighting the need for alternative, cost-effective solutions [8–10].

To address the challenges posed by soft soils, chemical stabilization has emerged as an innovative approach. Portland cement (PC), a hydraulic cement produced by calcining a blend of limestone and clay, has garnered significant attention as a stabilizing agent due to its unique ability to enhance soil properties regardless of inherent characteristics independently [11–14]. The hydration process of PC, triggered by water addition, promotes the formation of a cohesive matrix within the soil, thereby improving its mechanical attributes [15]. However, the escalating cost of PC raises economic concerns, necessitating the exploration of alternative, cost-effective stabilizing agents that can effectively improve soil properties.

Rice Husk Ash (RHA), a byproduct of rice milling and combustion, presents another promising additive [16,17]. Rich in amorphous silica and other reactive compounds, RHA enhances the workability and durability of the composite material [18]. Its pozzolanic nature facilitates reactions with calcium hydroxide produced during cement hydration, leading to the creation of additional cementitious compounds that enhance cohesion and reduce permeability, ultimately augmenting environmental resistance [16,19].

In addition to PC and RHA, the inclusion of multi-walled carbon nanotubes (MWCNTs) shows great potential for achieving enhanced soil pile stabilization [20,21]. MWCNT is primarily composed of graphite layers wrapped with each other forming a tube-shaped structure [21] as shown in Figure 1. Possessing exceptional mechanical, thermal, and electrical properties, MWCNTs hold promise in significantly strengthening and stabilizing the composite. Their high aspect ratio and load-bearing capabilities pose great potential to the improvement of the structural integrity of the soil-cement matrix, operating at the nanoscale [20]. In light of these considerations, this research study aims to explore the development and application of reinforced soil piles (RSP), utilizing a composite mixture comprising PC, RHA, and MWCNT. The primary objective is to assess the feasibility and effectiveness of this composite material in enhancing the deep mixing method for foundation applications in the context of both low-rise building and bridge construction.

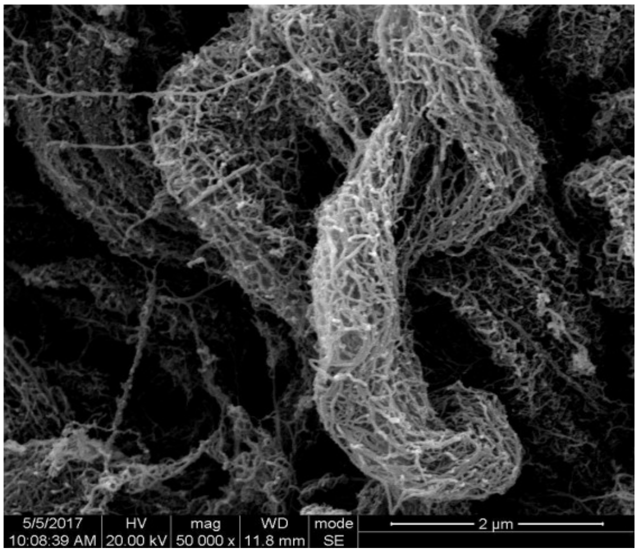


Figure 1 Microphotograph of multi-walled carbon nanotube used as an additive in this study.

This combined strategy presents a comprehensive approach to enhance the performance of RSP. Cement stabilization offers advantages due to its versatility in transforming the mechanical behavior of soils, making it suitable for various applications, including the stabilization of soft clay soils for structures such as single-story buildings, bridge approaches, and elevated road embankments.

By incorporating environmentally sustainable additives such as rice husk ash and advanced materials like multi-walled carbon nanotubes, the study seeks to augment the bearing capacity and settlement characteristics of soft soils. This research contributes to the ongoing efforts to develop sustainable and cost-effective solutions for geotechnical challenges in construction, with potential implications for the broader fields of geotechnical engineering and infrastructure development.

2.0 METHODOLOGY

The materials employed in this study encompassed undisturbed soil samples extracted at a 10-meter depth from the shoreline area of Davao City, Philippines, serving as the foundational component of the investigation. Type-I PC, acting as the primary binder, was sourced from Holcim Philippines, Inc., located in Lugait, Misamis Oriental, Philippines. The RHA, a vital component in the composite mixture, was supplied by DOLE Philippines in Polomolok, South Cotabato, with its chemical composition provided in Table 1. MWCNT, pivotal for enhancing the structural integrity at the nanoscale, was procured from US Research Nanomaterials, Inc., and their specifications are meticulously outlined in Table 2. Additionally, a polycarboxylate-based surfactant, crucial for enhancing workability and dispersion, was acquired from Changsha Jianglong Chemical Technology Co., Ltd., ensuring a comprehensive and meticulously chosen set of materials for the experimental investigations.

The RSP samples for this study were meticulously prepared using a formulation outlined in Table 3, where the concentration of each component was expressed in parts per hundred (php) of soil. The mixtures were created using soil extracted from a depth of 10 meters, incorporating Rice Husk Ash (RHA), PC, and Multi-Walled Carbon Nanotubes (MWCNT),

Table 1 X-ray fluorescence analysis of the rice husk ash used in the preparation of reinforced soil piles as provided by DOLE Philippines

Element (%)	Composition, %
Si	94.09
Mg	4.15
P	1.13
Fe	0.27
Mn	0.11
Sb	0.09
Ca	0.06
Zr	0.06
Zn	0.02
Cu	0.01

Table 2 Specifications of the multi-walled carbon nanotubes soil pile reinforcement as provided by the US Research Nanomaterials, Inc.

Properties	Specifications
Outside Diameter	20-30 nm
Inside Diameter	5-10 nm
Ash	<1.5 wt.%
Purity	>95 wt.%
Length	10-30 µm
Specific Surface Area	110 m^2/g
Electrical Conductivity	>100 S/cm
Bulk Density	0.28 g/cm^3
True Density	~2.1 g/cm^3

as specified in the formulation. The study employed a fixed ratio of PC, RHA, and soil, maintaining a consistent water-cementitious ratio by setting the water weight at 0.5:1 to the dried soil sample's weight, aligning with the saturated water content of the original soil as per ASTM D2216 standards. The investigation also delved into the influence of MWCNT additive concentration on soil pile properties with each batch yielding three samples subjected to 15 blows per H/3 following ASTM D698 batch sampling guidelines. The physico-mechanical properties of the produced RSP samples were characterized, including unit density, and subsequent sealing and curing for 14, 28, 42, and 56 days, in adherence to ASTM 1632-96 protocols, before undergoing compressive testing. The morphological features of the samples were examined via Scanning Electron Microscopy (SEM) using JEOL JSM-IT200 (JEOL, Ltd, Tokyo, Japan). Compressive testing involved applying axial loads to molded cylinders or cores following ASTM D2938 specifications, maintaining a prescribed rate until failure. The unconfined compressive strength (UCS) test followed ASTM D1143 procedures, measuring axial deflection under static axial compression 28 days after pouring. This multifaceted methodological approach ensures a thorough investigation into the properties and behavior of the developed RSP samples.

The large-scale RSP preparation and testing in this study involved the manual excavation of two holes at a depth of 1.7 meters, using a pick shovel (Figure 2a). An auger, larger than the hole diameter, was inserted to create a bulb at the bottom, and a casing was installed to protect the excavated soil. The holes were filled with a wet soil pile mixture (Figure 2b) comprising PC, Rice Husk Ash (RHA), and Multi-Walled Carbon Nanotubes (MWCNT), followed by covering and curing for 28 days before subjecting them to triaxial testing. The static pile load test, conducted according to ASTM D1143/ASTM D1143M-07, measured the axial deflection of the foundation elements loaded in static axial compression (Figures 2c and 2d). The excavation surrounding the soil pile at a depth of 100mm preceded the installation of the loading cell system. Using a total station with a prismless function, the elevation of the soil pile top was measured, and a pressure of 68.95MPa (10,000psi) was applied through a hydraulic pump, observing settlement over intervals. The process was repeated with varying intervals and readings. The second soil pile was excavated mechanically, and cylindrical samples were extracted and tested for compression at a universal testing machine following ASTM C39, determining stress and strain values (Figures 2e and 2f).

Table 3 Formulation used for the preparation of reinforced soil piles at different multiwalled carbon nanotubes concentration

	Concentration, php of soil[a]						
Formulation	SP-0.00%	SP-0.00%	SP-0.00%	SP-0.00%	SP-0.00%	SP-0.00%	SP-0.00%
Soil	100	100	100	100	100	100	100
Portland Cement	20	20	20	20	20	20	20
RHA	20	20	20	20	20	20	20
MWCNT	0.00	0.01	0.02	0.03	0.04	0.05	0.06
Water	70	70	70	70	70	70	70

[a] Concentrations of each ingredient are expressed in parts per hundred parts (php) of soil.

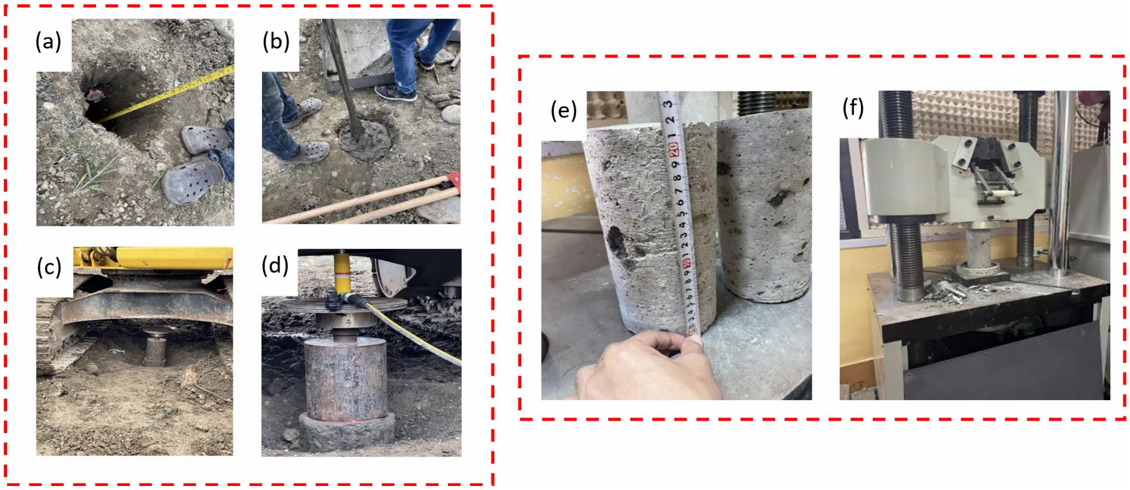


Figure 2 Actual images of the preparation and testing the large-scale reinforced soil piles

3.0 RESULTS AND DISCUSSION

Figure 3 presents a comprehensive depiction of the soil profile in the shoreline area of Davao City, providing crucial insights into the geological characteristics of the region. The soil sampling strategy, conducted at intervals of 1.0 meters for the initial 3.0 meters and subsequently at 1.5-meter intervals, captures a nuanced representation of the subsurface composition. The geological profile reveals a predominant characterization of the soil as medium stiff to olive brown, interspersed with very dark gray layers. The inorganic composition is chiefly constituted by clays and sands, classifying the soil as loose to medium dense, with a notable layer of coralline limestone at depths ranging from 3.0 to 4.5 meters, measured from the ground surface following ASTM D 1586-67.

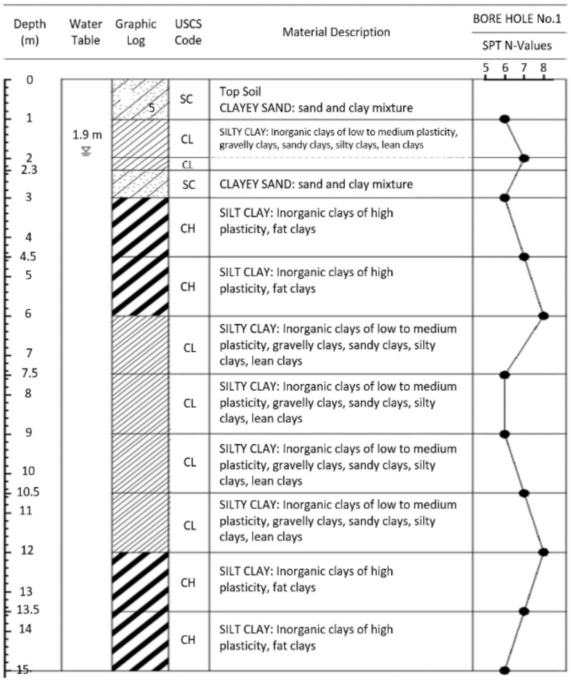


Figure 3 The soil subsurface classification and conditions for the determination of physical characteristics of the soil according to ASTM D 1586-67 (Shoreline area in Davao City, Philippines)

The original soil exhibits noteworthy shear strength parameters, with an unconfined compressive strength of 31.47 kPa and an undrained shear strength of 37.52 kPa, as detailed in Table 4. These values serve as the foundational reference for subsequent analyses and discussions related to soil pile property enhancement through the incorporation of PC, RHA, and MWCNT. The detailed characterization of the soil profile, coupled with the initial shear strength parameters, establishes a crucial baseline for understanding the inherent properties of the soil and forms the basis for assessing the efficacy of the proposed soil improvement techniques.

Table 4 Mechanical properties of the soil samples extracted at 10 meters below the ground 10 meters below the ground

Properties	Soil Samples
Unconfined Compressive Strength, kPa	31.47 ± 2.5
Undrained Shear Strength, kPa	37.52 ± 2.5

The density variations in the soil mixture containing PC and RHA at different concentrations of MWCNT are presented in Figure 4. The observed trend reveals a proportional increase in density with higher MWCNT content, suggesting an effective mitigation of air voids by MWCNTs [21,22]. This phenomenon indicates successful bonding among soil, PC, and RHA, resulting in denser samples. The notable impact can be attributed to the nano-scale dimensions of MWCNTs, which adeptly fill the relatively larger void spaces within the soil-cement matrix [23]. Consequently, this yields a denser material which is typically associated with higher mechanical performance, as corroborated by previous research [24,25]. It is worth noting that the density at 14 days surpasses that at 28 days, primarily attributed to the initial water presence, which subsequently evaporates during the succeeding days up to 56 days, as visually depicted in Figure 4. Additionally, it can be observed the significant density enhancement with the incorporation of PC-RHA-MWCNT additives. These findings underscore the promising potential of MWCNTs in enhancing the structural characteristics of the soil-cement-RHA composite, offering valuable insights for the optimization of soil improvement strategies in geotechnical engineering applications.

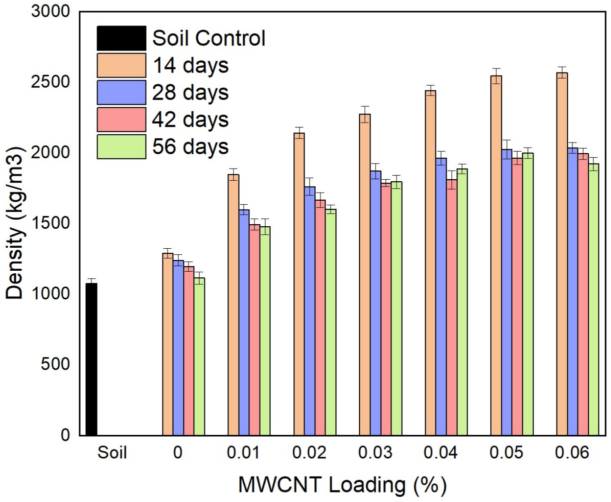


Figure 4 The density profile of the reinforced soil piles at different multiwalled carbon nanotube (MWCNT) loading in a constant soil-PC-RHA mixture at 14 to 56 days curing

The bearing capacity of the prepared soil pile samples was measured according to its compressive strength as outlined in Figure 5. This includes the compressive strength variations of the soil mixture incorporating PC and RHA at different concentrations of MWCNT during the curing process. The figure distinctly illustrates a significant enhancement in compressive strength with increasing MWCNT concentration, a phenomenon observed at both the 14-, 28-, 42-, and 56-day curing intervals. This observed trend aligns with the findings of prior research, reinforcing the notion that higher MWCNT quantities in the cement paste contribute to increased compressive strength [26]. It can be observed that there is no significant increase in compressive strengths beyond 0.04% MWCNT loading, indicating that this is the optimum MWCNT loading in a constant soil-PC-RHA mixture. Notably, a substantial increase of 13.4 MPa at the 14-day mark expanded further to 16.8 MPa after 28 days, surpassing the compressive strength of the soil-PC-RHA mixture by 502% at 14 days and 405% at 28 days. Furthermore, no significant increase can be observed beyond 28 days of curing time. The introduction of MWCNT thus significantly enhances the early-age strength of the soil mixture, concurrently elevating its overall compressive strengths.

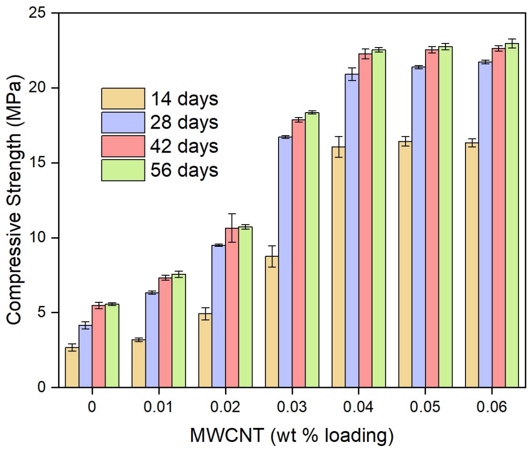


Figure 5 Compressive strengths of the reinforced soil piles at different multiwalled carbon nanotube (MWCNT) loading in a constant soil-PC-RHA mixture at 14 to 56 days of curing

Table 5 presents the crucial findings from the comprehensive evaluation of the large-scale soil pile, shedding light on its performance in terms of load-bearing capacity, settlement behavior, and mechanical strength. The static pile load test conducted at 28 days yielded an average pile capacity of 126.8 kN, accompanied by a maximum settlement of 9 mm. This assessment provides valuable insights into the soil pile's response to applied loads, crucial for ensuring stability and safety in real-world applications. The observed deviation in the settlement, attributed to the incorporation of a bottom valve in the pile construction, serves as a strategic measure to prevent sliding and encourage controlled pile failure, highlighting the meticulous engineering considerations involved in the construction process.

Table 5 Mechanical performance of large-scale reinforced soil piles comprising soil, Portland cement, rice husk ash, and 0.04 wt% multiwalled carbon nanotubes

Reinforced Soil Pile Mixture	Load-bearing Capacity, kN	Settlement, mm	Compressive Strength, MPa
Soil-PC-RHA-0.04% MWCNT	126.8 ± 15.0	9.0 ± 0.8	23.4 ± 1.5

In conjunction with the load test, compressive strength tests were performed on three cylindrical samples extracted from the in-situ reinforced soil pile. The results underscored an impressive average compressive strength of 23.4 MPa for the soil-PC-RHA-0.04% MWCNT mixture. This outcome not only surpassed the laboratory compressive strength of samples with 0.04% MWCNT content but also validated the achievement of the anticipated compressive strength target of 21 MPa, based on the lab-scale RSP samples. These results attest to the efficacy of the innovative approach, combining PC, RHA, and MWCNT, in significantly enhancing the mechanical strength of the in-situ soil pile. The collective enhancement in the RSP's mechanical properties is attributed to the increased density achieved through the novel composite mixture. This observation aligns with established correlations between composite density and bearing capacity, confirming that the improved performance is intricately linked to the optimized density of the soil-cement-RHA-0.04% MWCNT mixture. These findings contribute valuable insights into the feasibility and success of the proposed approach, holding implications for the advancement of sustainable and high-strength solutions in geotechnical engineering applications.

The SEM figures presented in Figure 5 provide valuable insights into the morphological features of RSP samples prepared with various components. The figures capture distinct stages of the experimental setup, allowing for a qualitative and quantitative assessment of the impact of MWCNTs on the microstructure of soil-PC-RHA composites. Figure 5a offers the SEM images of a soil pile containing PC and RHA. At 30 µm magnification, the figure reveals a textured surface with a noticeable roughness. This texture suggests the presence of aggregates and voids within the composite material [21,27]. The rough surface may indicate a less compact structure, potentially leading to increased porosity. In Figure 5b, the SEM image showcases a soil pile with the same composition as Figure 5a but with the addition of 0.04% MWCNT. The microphotograph exhibits a smoother surface compared to Figure 6a, indicating a potential improvement in the overall compactness of the composite [27,28]. The reduction in surface roughness suggests that the inclusion of MWCNT may contribute to a more homogeneous distribution of components, resulting in a denser structure [21,22]. The findings presented in the SEM figures align with previous studies that observed MWCNTs enveloped by a C-S-H layer [29–31]. This phenomenon supports the idea that MWCNTs establish effective connections with hydration products, leading to improved mechanical properties [24,25]. The high aspect ratio and significant specific surface area of MWCNTs enable them to interact with the cement matrix, resulting in enhanced density and reduced porosity [23]. Moreover, Figures 6c and 6d delve into the microstructure of RSP with PC, RHA, and MWCNT, specifically highlighting the mechanism by which carbon nanotubes bridge micro-cracks within the concrete composites. The images provide visual evidence of MWCNTs acting as bridges across micro-cracks, reinforcing the structure and enhancing its mechanical properties. This bridging phenomenon is crucial for preventing crack propagation and improving the durability of the composite material [21,24,32,33].

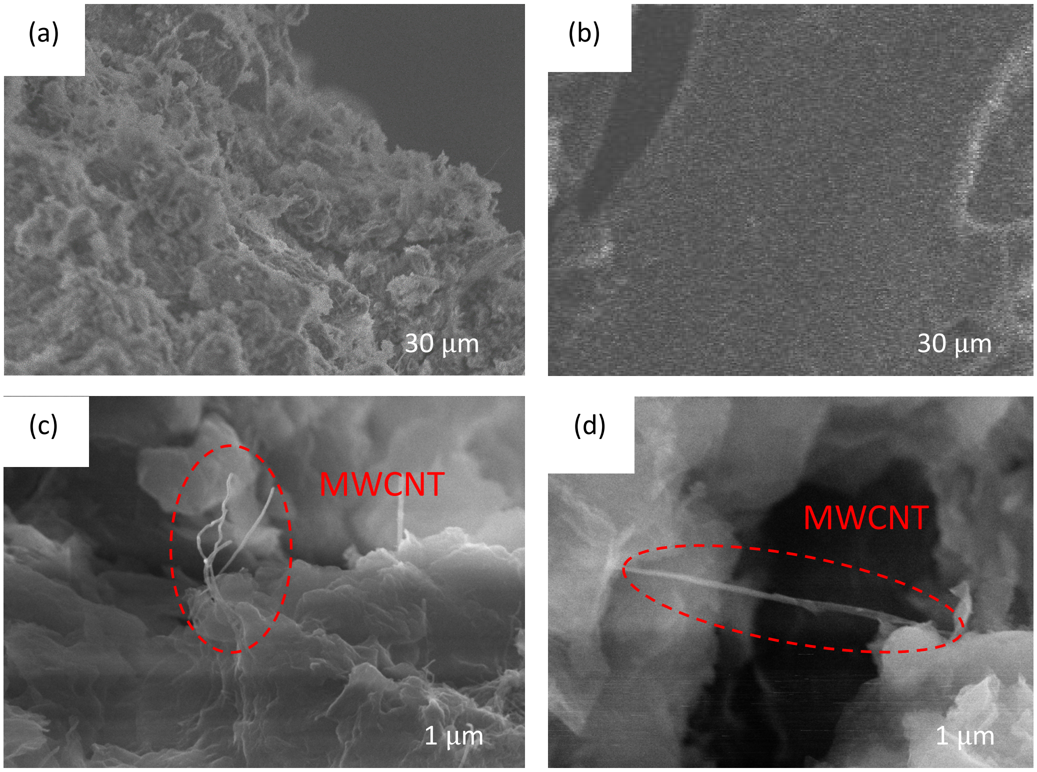


Figure 6 Morphological images of the prepared reinforced soil piles comprising soil, portland cement (PC), rice husk ash (RHA), and 0.04 wt% multiwalled carbon nanotube (MWCNT); (a) soil-PC-RHA at 30 µm, (b) soil-PC-RHA-MWCNT at 30 µm, (c) soil-PC-RHA-MWCNT(unbridged) at 1 µm, and (d) soil-PC-RHA-MWCNT(bridged) at 1 µm

4.0 CONCLUSION

The present study unveils the transformative impact of the novel PC–RHA–MWCNT mixture on soil properties, presenting a groundbreaking approach for enhancing soil stability. The substantial improvement in compressive strength, with a remarkable 55,633% and 405% increase over original soil and soil-PC-RHA, respectively, at 28 days, underscores the efficacy of incorporating 0.04% MWCNT into the soil mixture. The optimization of MWCNT content is further supported by an enhanced packing density within the mixture by 83%. Notably, the achieved pile load-bearing capacity of 126.8 kN aligns closely with practical static load test results, demonstrating the reliability of the developed solution despite minor settlement variations. The successful integration of RHA and MWCNT emerges as a practical and cost-effective alternative for stabilizing soil, particularly in soft clay conditions, presenting a promising avenue for medium-rise construction structures. This research not only advances geotechnical engineering but also underscores the potential for sustainable infrastructure development, highlighting the role of innovative materials and methodologies in shaping the future of construction practices.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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