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Utilizing Recycled Rubber and Municipal Waste Incineration Fly Ash in Cement-Stabilized Clayey Soils

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Abstract

This study explores an innovative approach combining municipal solid waste incinerator fly ash (MSWIFA), cement, and recycled rubber to enhance soil properties. The research fills a research gap by exploring the synergistic effects of these materials, striving to strike a balance between strength and flexibility in soil stabilization. A total of 123 tests, comprising Proctor compaction and unconfined compression tests, were performed on clayey soil samples treated with varying stabilizer proportions: 10%, 20%, and 30% MSWIFA; 10%, 15%, and 20% cement; and 0%, 5%, and 10% rubber by dry weight. The tests revealed that the ideal blend of 5% rubber, 10% MSWIFA, and 20% cement resulted in a notable 294% increase in unconfined compressive strength and a significant enhancement in soil ductility, presenting a stark contrast to traditional cement-stabilized soils recognized for their brittleness and limited flexibility. This approach not only enhances soil characteristics but also promotes environmental sustainability by utilizing waste materials in the stabilization process.

Keywords: Cement; MSWIFA; Rubber; Soil Stabilization; Shear Behavior.

1. Introduction

Soil stabilization is a critical engineering practice employed to enhance the geotechnical properties of soil, thereby improving its suitability for various construction applications. While traditional methods like compaction and drainage are commonly used, they often prove insufficient for weak and unstable soils. To address these limitations, chemical stabilization techniques, such as cement-based stabilization have emerged as an effective alternative [1-5].

It has been widely utilized due to its ability to substantially increase soil strength. The addition of cement initiates chemical reactions that form hydrates, effectively binding soil particles and leading to increased compressive strength, shear strength, and durability [6-9]. However, this method can also introduce brittleness, restricting its application in certain engineering scenarios [10-12]. In a recent study, Okonkwo & Kennedy (2023) [13] demonstrated that cement effectively lowers the optimum moisture content (OMC) of black cotton soil, thereby enhancing its workability. Their research also highlighted that combining cement with lime improved various soil properties, including maximum dry density, California Bearing Ratio (CBR), and unconfined compressive strength (UCS). Nevertheless, they observed a reduction in plasticity, which can limit the use of cement-stabilized soil in specific construction applications.

In addition to the decreased flexibility and increased susceptibility to cracking over time exhibited by cement-treated soils, which limit their long-term performance and sustainability, the application of cement can lead to higher project expenses and raise environmental concerns due to the significant energy consumption in its production and potential CO_2 emissions. Researchers have tackled these challenges by investigating the utilization of industrial by-products as

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economical and eco-conscious soil stabilizers [14, 15]. Fly ash, with its significant pozzolanic properties, stands out as a promising soil stabilizer. Through its reaction with lime, it forms cementitious compounds that bolster soil strength and longevity. Moreover, incorporating fly ash in soil stabilization not only aids sustainability endeavors but also offers a practical application for this industrial by-product, thereby mitigating the environmental consequences linked to cement manufacturing [16-18].

Similarly, municipal solid waste incineration fly ash (MSWIFA) has emerged as an effective solution in waste management, providing energy recovery while significantly reducing waste volume in landfills [19, 20]. Studies suggest that MSWIFA can also improve the mechanical properties of subgrade soils, offering dual benefits for geotechnical performance and waste management. Varaprasad et al. (2020) [21] demonstrated that incorporating up to 25% MSWIFA into soil increased UCS by 80% and California Bearing Ratio (CBR) by 4.5 times. Beyond these initial enhancements, further MSWIFA additions reduced soil density and optimum moisture content, and decreased soil plasticity, swelling, and water absorption by up to 70%. Research by Liu et al. [22] further supports the effectiveness of MSWIFA in soil reinforcement. Their study on cement-stabilized soil in Guangxi, China, found that MSWIFA enhanced sandy soil strength. While the addition of certain chemical agents caused a slight reduction in strength, increasing MSWIFA content to 12% ultimately resulted in a strength improvement of up to 49%. This indicates the potential for MSWIFA to partially replace cement in soil stabilization, leading to cost savings and environmental benefits. In a related study, Aouf et al. [23] examined the effects of cement and MSWIFA on unstable soils and found that MSWIFA additions increased maximum dry density by 20%. The highest strength gain was achieved at 30% MSWIFA, with a remarkable 196% increase in unconfined compressive strength. These results highlight the efficacy of MSWIFA in enhancing soil performance, offering a sustainable and economically feasible option for soil stabilization.

Exploring novel avenues for soil enhancement, researchers delved into the use of rubber, particularly derived from recycled tires, as a cost-effective and resilient alternative, offering promising solutions for sustainable soil stabilization practices. Rubber exhibits excellent elastic properties and mitigates the brittleness commonly associated with cement-based stabilization [24]. When rubber particles are added to soil, they act as stress-relief agents, absorbing and dissipating energy during loading, resulting in a more ductile and resilient soil capable of withstanding deformation without fracturing.

Extensive studies underscore the advantages of incorporating shredded rubber tires into soil to enhance its properties and reduce environmental pollution [25-28]. Research has demonstrated that by varying the proportion of shredded rubber tires mixed with soil, significant improvements in specific gravity, liquid limit, and plastic limit can be achieved. According to Sidek et al. (2023) [29], the use of shredded rubber tires as a soil stabilizer has yielded promising results, enhancing soil strength while decreasing construction costs and providing an environmentally friendly solution for tire disposal. Nazaruddin et al. (2023) [30] conducted a series of experiments to determine the optimal proportion of shredded rubber tires for stabilizing clayey soil, finding that a 2% concentration was ideal. These findings highlight the practicality and benefits of repurposing discarded rubber tires for soil stabilization. In their study, Haranatti et al. (2023) [31] reported that incorporating 6% tire chips into soil leads to substantial improvements in soil properties, specifically achieving a 1.5-fold increase in the CBR compared to untreated soil. Tire chips can serve as a valuable resource in road construction, contributing to waste reduction and promoting sustainability within civil engineering.

Further research indicates that integrating scrap rubber tires with cement may enhance the strength and durability of stabilized soil. Marathe et al. (2015) [32] demonstrated that soil treated with varying proportions of shredded tires can be used as a subgrade, achieving optimal UCS with a composition of 4% rubber and 2% cement. Naseem et al. (2019) [33] found that a blend of 5% tire rubber powder and 10% cement kiln dust significantly enhanced the strength of expansive soil while reducing its plasticity, improving characteristics such as UCS and maximum dry density. Wang et al. (2019) [34] explored the incorporation of discarded tire fibers into cement-stabilized clay, observing improvements in flexibility and reduced swelling at concentrations up to 7.5%. Although this incorporation slightly decreases compressive and tensile strength, it enhances resistance to repeated wet-dry cycles, making this modified clay suitable for a range of applications, including filling, backfilling, road sub-bases, and canal slopes, provided the cement concentration is maintained at a minimum of 6%. Bekhiti (2019) [35] investigated the effects of adding 0.5%, 1%, and 2% waste tire rubber fibers to clay soil stabilized with 5%, 7.5%, or 10% cement, finding that while the swelling potential of the soil was reduced, its compressibility increased due to the rubber's properties. Recently, He et al. (2023) reported that cemented soil treated with rubber presents an economical and environmentally friendly lightweight filler with significant engineering potential. Their study indicates that strength increases with higher cement content but decreases with greater rubber content, achieving optimal performance at 5-10% rubber. Additionally, the strength enhancement correlates positively with curing age, indicating that longer curing periods contribute to improved soil strength [36].

While the individual benefits of cement, MSWIFA, and rubber as soil stabilizers are well-documented, further research is essential to optimize their combined application and evaluate their long-term performance. Currently, there is a notable gap in comprehensive studies examining the synergistic effects of these materials when utilized together as stabilizing agents. The integration of cement, rubber, and fly ash in soil stabilization strategies presents a synergistic solution that combines the strength of cement, flexibility of rubber, and sustainability of fly ash to comprehensively address soil enhancement challenges. By leveraging the unique properties of each material, this combined approach aims to optimize soil performance while mitigating issues such as brittleness, enhancing resilience, promoting environmental sustainability through waste reduction, and ensuring cost-effectiveness.

This research aims to investigate these synergistic effects to enhance the geotechnical properties of clayey soil. By systematically varying the dosages of cement, MSWIFA, and rubber, the optimal combination that balances strength, ductility, and environmental sustainability is identified. The primary objectives include evaluating the impact of varying dosages of cement, rubber, and MSWIFA on the geotechnical properties of the target soil, such as density, optimum moisture content, and shear strength. By fulfilling these objectives, this research aspires to advance sustainable and effective soil stabilization techniques that can address the challenges associated with weak and unstable soils.

2. Material and Methods

2.1. Soil Characteristics

A locally sourced soil sample from Abi Samra, Tripoli, Lebanon, was investigated in this study, as detailed by Aouf et al. (2023) [23]. According to the Unified Soil Classification System (USCS), the soil is classified as lean clay with sand. Figure 1 shows the results of the sieve analysis, conducted using the wet sieving method due to the high fines content in the soil, which is 82.5%. In addition, Table 1 presents the properties of the natural soil, determined in accordance with ASTM standards, including Atterberg limits (ASTM D4318), compaction characteristics (ASTM D1557-78), and unconfined compressive strength (ASTM D2166).

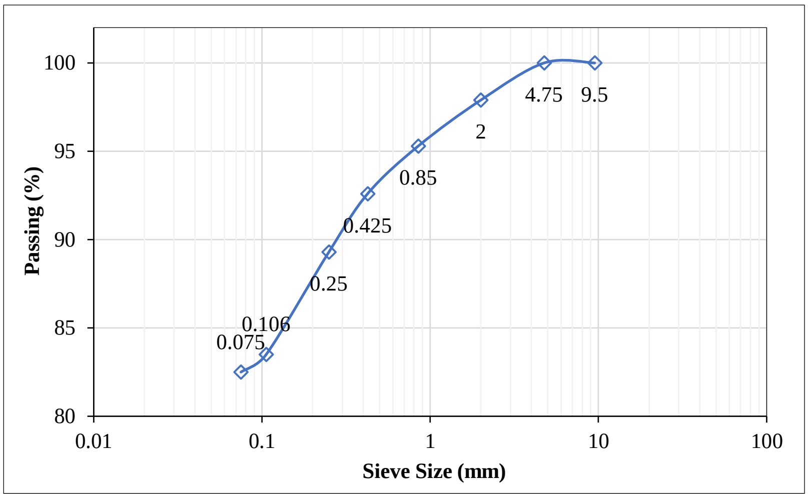

Figure 1. Grain Size Distribution curve

Table 1. Soil Properties [23]

Parameters	Natural Soil
Sieve analysis	
Gravel, %	0
Sand, %	17.5
Fines, %	82.5
Atterberg's Limits	
Liquid Limit, %	46
Plastic Limit, %	12
Plasticity Index, %	34
Soil Classification	CL
Specific gravity, KN/m^2	2.65
Compaction	
Maximum dry density, KN/m^2	17.8
Optimum moisture content, %	14.5
UCS	
qu, kN/m^2	78.85

2.2. Chemical Additives

2.2.1. Ordinary Portland Cement

In accordance with the Lebanese requirements LIBNOR (NL 53:1999) for the cement PA-L, 42.5, the ordinary Portland cement (OPC) that is used is produced by Holcim (Lebanon) S.A.L. It has a specific gravity of 3.15 and a density of 1551 kilograms per cubic meter. Tables 2 and 3 provide an illustration of the chemical components of cement, as well as the physical properties of cement.

Table 2. Cement's Chemical Composition

Component	%
LOI	9.66
SiO_2	16.33
Al_2O_3	3.79
Fe_2O_3	2.81
CaO	61.15
MgO	1.34
SO_3	2.89
K_2O	0.23
Na_2O	0.21
TiO_2	0.42
Mn_2O_3	0.04
P_2O_5	0.24
CI	0
Total	**99.11**

Table 3. Cement's Physical Properties

Blaine (cm^2/g)	5372		3000 Minimum
Expansion (mm) the Chatelier	0.1		10 Maximum
Initial setting Time (minutes) (Vicat)	145		75 Minimum
Compression Resistance (N/mm^2)	2 Days	18.6	Min 46-Max 50
	7 Days	33.3	
	28 Days	49.1	

2.2.2. MSWIFA

The fly ash utilized in this study was sourced from the filtration unit at the Municipal Solid Waste Incineration (MSWI) plant operated by SCCOMO in Bar-Elias, Lebanon, as shown in Figure 2 [37].

Figure 2. Municipal Solid Waste Incineration Fly Ash collected by Jumbo Bags [37]

The plant features a dual combustion system designed to enhance combustion efficiency and reduce harmful emissions. Before collection, sodium bicarbonate and activated carbon are added to absorb acids and heavy metals. The ash sample was dried at 105°C until a constant mass was achieved, with a recorded moisture content of 1.89%. A portion of the dried sample was subjected to high-temperature fusion, while the loss on ignition (LOI) test was conducted on another sample by heating it to 950°C until the mass stabilized. The chemical composition of the MSWIFA is detailed in Table 4, revealing a high CaO content (26.32%), indicative of its potential cementitious properties for soil stabilization. The MSWIFA has a density of 2.6 g/cm³ and is classified as a natural pozzolan due to its fineness. The percentage retained on sieve No. 325 in a wet sieve analysis exceeded the allowable limit, with 13% retention.

Table 4. Chemical Composition of Fly Ash [37]

Chemical Composition	% by weight	Chemical Composition	% by weight
SIO_2	14.68	Na_2O	5.94
AL_2O_3	12.74	TiO_2	1.91
Fe_2O_3	4.35	MnO	0.05
CaO	26.32	P_2O_5	0.57
MgO	2.25	Cr_2O_3	0.026
SO_3	3.05	Cl	11.77
K_2O	4.30	LOI	12.01

2.3. Rubber

In the present study, shredded rubber tire granulate was incorporated into the MSWIFA-cement-clay mix at various percentages. The shredded rubber has a particle size of 2 mm, a specific gravity of 1.1, and its primary components, Styrene-butadiene copolymer and carbon block, are detailed in Table 5, as provided by the supplier.

Table 5. Chemical Composition and Components of Rubber

Chemical Composition	% by weight	Chemical Composition	% by weight	Component	%	Component	%
SIO_2	33.8	Na_2O	1.4	Styrene-butadiene copolymer	62	Sulfure	1.1
AL_2O_3	7.8	TiO_2	1.00	Carbon block	31	Accelerator	0.7
Fe_2O_3	11.4	LOI	12.5	Extender oil	1.9		
CaO	13. 3	SO_3	1.6	Zinc oxide	1.9		
MgO	6.4	K_2O	1.1	Stearic acid	1.2		

3. Research Methodology

The percentages of additives utilized in this study, including cement, MSWIFA, and recycled rubber, were determined based on previous research findings. Specifically, cement was incorporated in the range of 10% to 20% [38-40], while MSWIFA was added at 10%, 20%, and 30% [21, 22, 41]. The inclusion of rubber was also assessed, with contents ranging from 5% to 10%, as supported by relevant literature [33, 42, 43].

MSWIFA was mixed into the soil at varying proportions of 10%, 20%, and 30% by dry weight of the soil. Portland cement was then added to the MSWIFA-soil mixture at rates of 10%, 15%, and 20% by dry weight of the blend. Additionally, shredded rubber was incorporated at 5% and 10% by dry weight of the specimen. The soil and incorporated additives are illustrated in Figure 3.

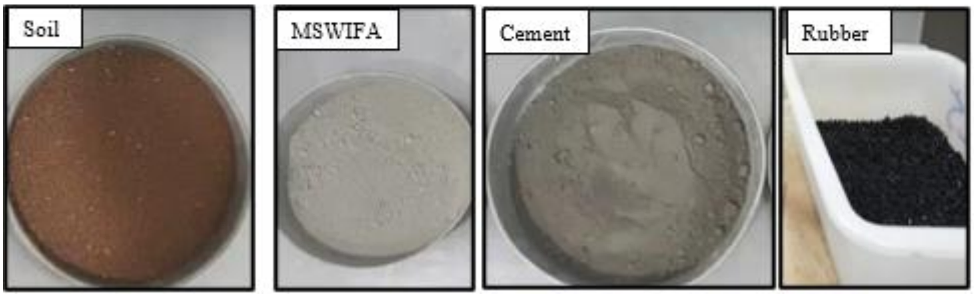

Figure 3. Selected Materials

A total of 123 tests were performed to evaluate the effects of MSWIFA, cement, and rubber on the compaction and shear strength characteristics of the soil. The Modified Proctor and Unconfined Compression Tests were performed on the various soil specimens, as detailed in Figure 4.

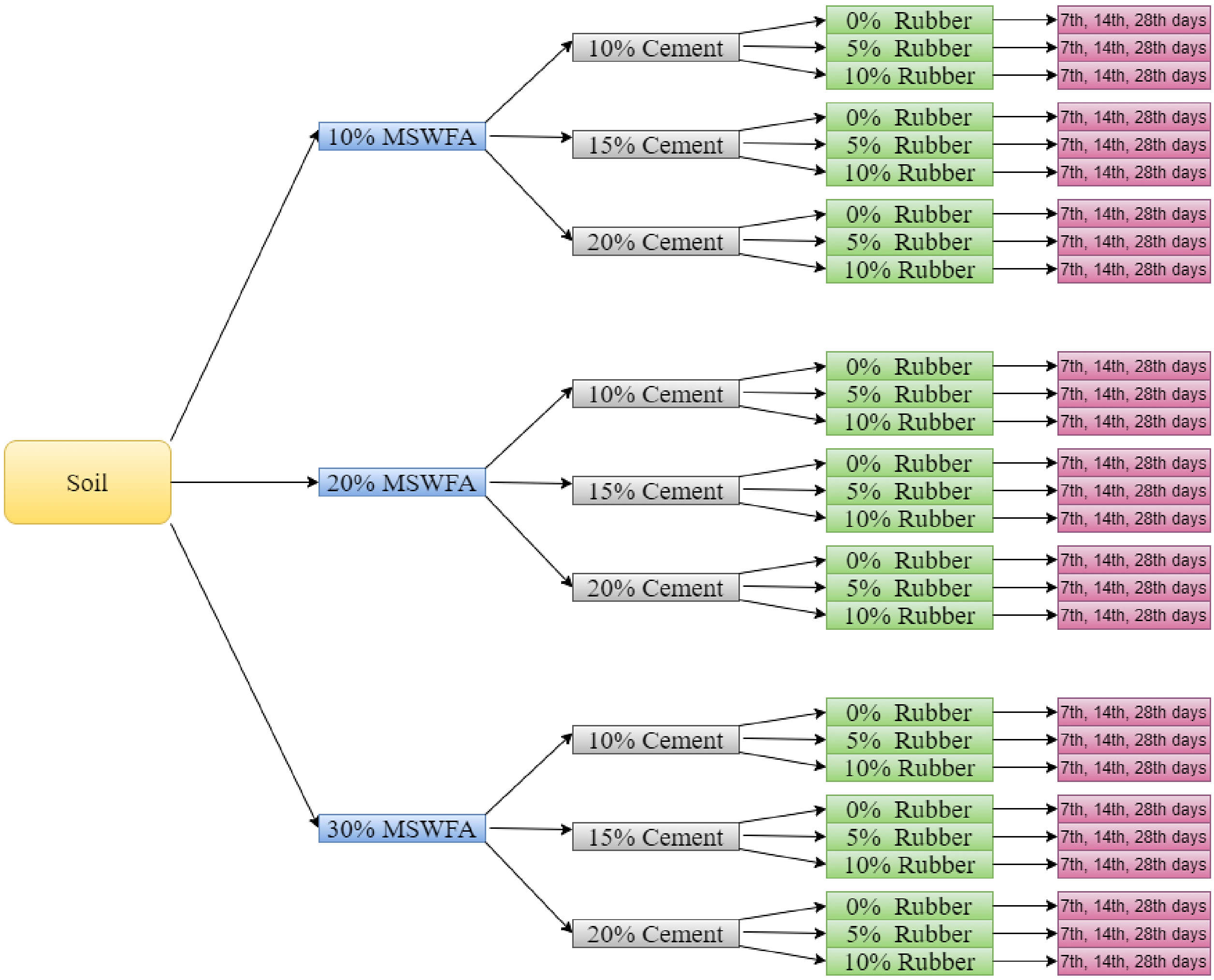

Figure 4. Mixing Percentages

To maintain consistency, the soil and MSWIFA were oven-dried at 105°C and sieved through a 0.425 mm sieve. Different water contents were used and thoroughly mixed with the materials to ensure homogeneity. The compaction tests were carried out to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the specimens, following the ASTM D1557-78 standard, as illustrated in Figure 5. Based on these results, the samples were prepared at their respective OMC to perform the Unconfined Compression Test (UCS) in accordance with ASTM D2166.

The prepared soil samples were placed in PVC molds of 76 mm height and 38 mm diameter and cured at room temperature with 100% humidity for 7, 14, and 28 days as illustrated in Figures 6 and 7. The same procedure was applied to both MSWIFA-soil-cement mixtures with and without rubber. A flowchart of the research methodology is provided in Figure 8.

(a) (b) (c) (d)

Figure 5. Proctor test a) Mold b) Hammer c) Compacted Soil d) Extruding the Mold

Figure 6. Specimens in room temperature covered in plastic bags

(a) (b) (c)

Figure 7. a) Specimen b) Sample at the beginning of UCS test c) Sample after the UCS test

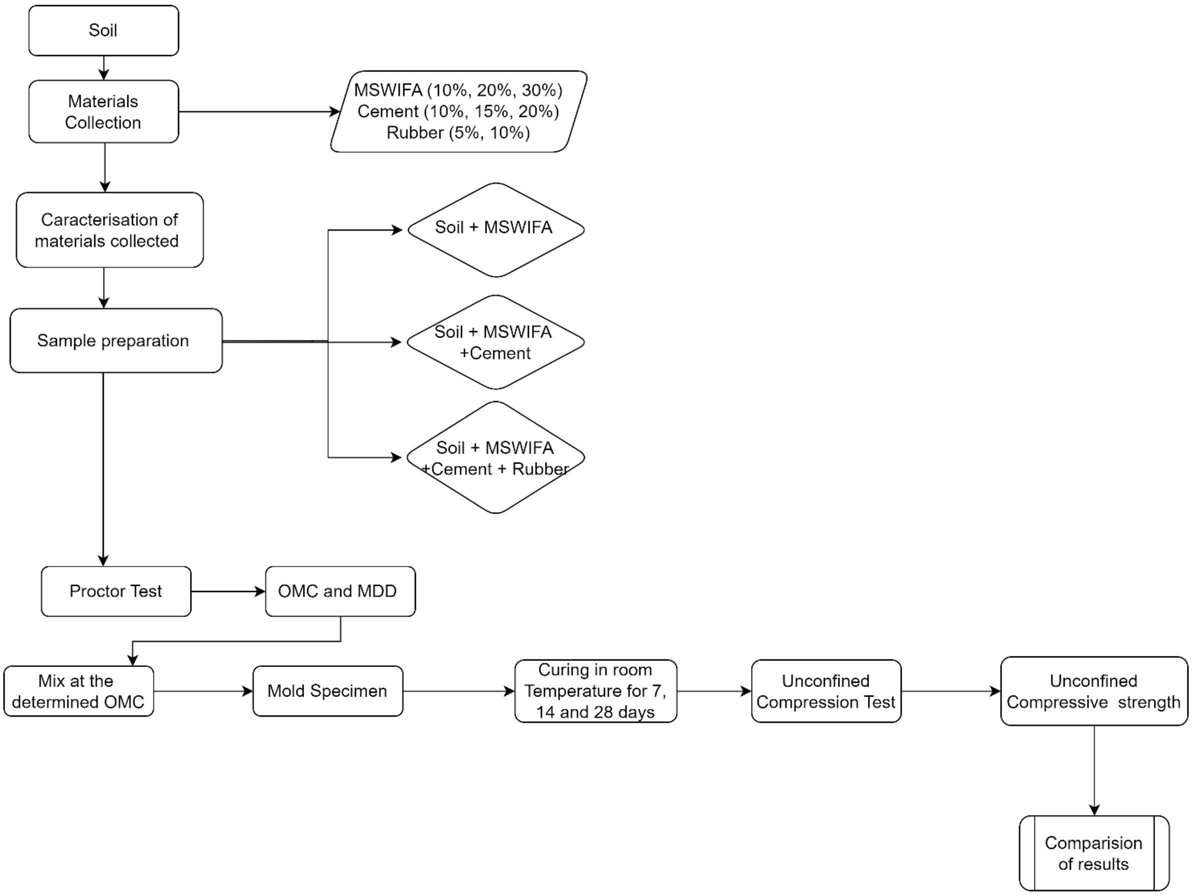

Figure 8. Procedure flow chart

4. Results & Discussion

4.1. Effect of MSWIFA and MSWIFA-Cement on Soil Properties

4.1.1.Compaction Characteristics of MSWIFA Treated Soil

Aouf et al. [23] examined the effects of various stabilizing materials on the compaction characteristics of the clay under consideration. A total of 33 Proctor tests were conducted on different soil specimens with varying percentages of stabilizing materials. Figure 9 illustrates the Proctor Compaction curves, depicting the relationship between moisture content and dry density for the different soil-MSWIFA mixtures.

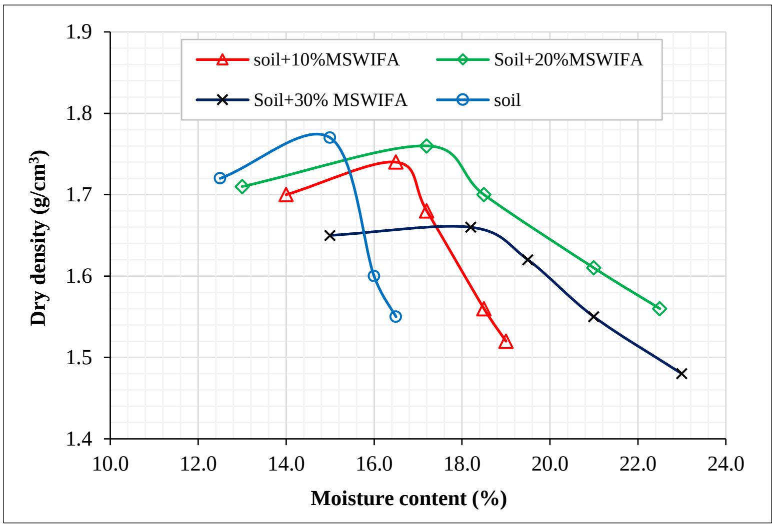

Figure 9. Variation of MDD and OMC function of MSWIFA content

As illustrated in Figure 9, the MDD of the untreated soil was measured at 1.78 g/cm³. This value decreased to 1.66 g/cm³ with an increase in MSWIFA content from 0% to 30%. It is important to highlight that the reduction in MDD is minimal at lower MSWIFA contents, becoming more pronounced at higher concentrations, particularly at 30% MSWIFA. Conversely, the gradual addition of MSWIFA resulted in an increase in the OMC of the soil, rising from 14.5% to 18.2%.

This reduction in MDD can be attributed to several interrelated factors. The fine and irregular shape of fly ash particles can impede effective packing with clay particles during the compaction process, leading to a lower bulk density and, consequently, a reduced MDD. Furthermore, fly ash lacks the cohesive properties inherent in clay, which can disrupt the natural binding forces between clay particles and contribute to a decrease in overall density. Additionally, the water absorbed by fly ash may not be available for effective compaction, further reducing the achievable density. Many pozzolanic materials, including fly ash, possess high water absorption capacities. This elevated absorption can be linked to both the physical and chemical characteristics of MSWIFA. Its non-uniform particle structure, characterized by numerous hollow spaces, facilitates significant water retention. Moreover, certain hygroscopic oxides present in the ash actively attract and retain water molecules, resulting in an increased OMC. These findings align with the research conducted by Varaprasad et al. (2020) [21], Karim et al (2020) [44], Khan et al (2021) [45] and Turan et al. (2022) [46].

In line with these findings, the introduction of a cementitious material becomes imperative to elevate the MDD, enhance the general stability of the compacted soil, and lower the OMC. This approach not only optimizes the efficiency of the compaction process but also ensures a more robust and sustainable soil stabilization strategy.

4.1.2. Compaction Characteristics of MSWIFA-Cement Treated Soil

Figure 10 illustrates the effects of cement incorporation on the compaction characteristics of the MSWIFA-soil mixture. Specifically, an increase in MSWIFA content to 20% in a soil-cement mixture containing 10% cement results in an increase of MDD from 1.81 g/cm³ to 1.91 g/cm³. However, as the proportion of MSWIFA in the soil-cement mixture continues to rise, the MDD progressively declines. This trend is similarly observed with mixtures containing 15% and 20% cement.

While the addition of fly ash generally leads to a decrease in the MDD of soil, the opposite effect is observed when it is combined with cemented soil mixtures. In all concentrations tested, the addition of cement markedly increases the MDD of the MSWIFA-treated soil. Notably, the incorporation of 10% cement resulted in the highest MDD compared to mixtures containing 15% or 20% cement content, yet the differences among these values were minimal. The introduction of cement modifies the soil structure by binding the soil particles together and filling voids.

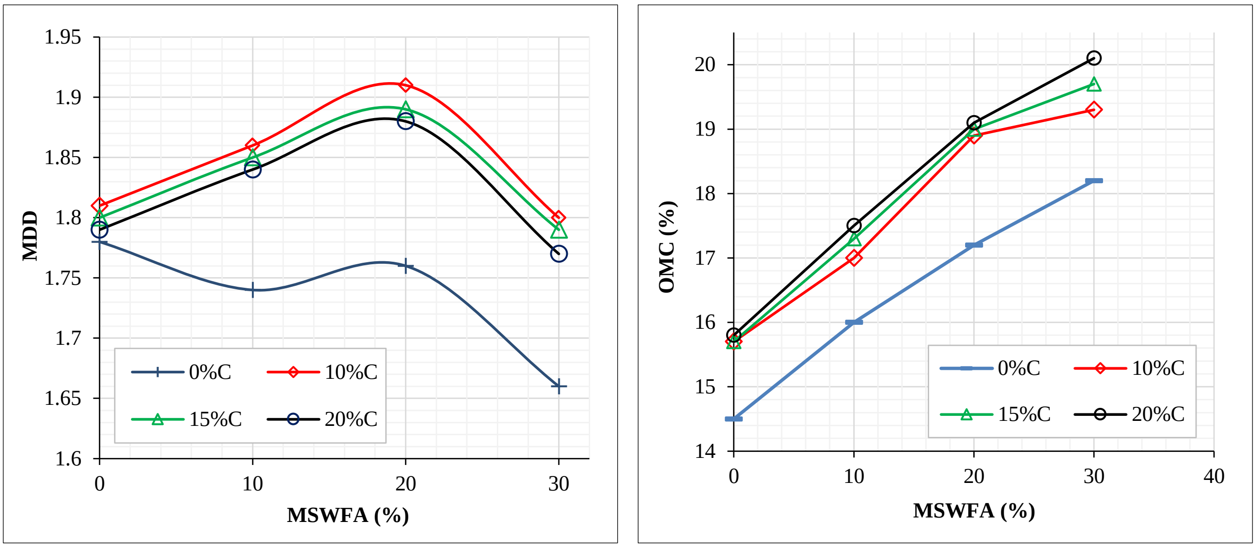

Figure 10. Effect of Cement on the MDD and OMC of Soil-MSWIFA Mix

It was also remarkable that the improvement in the MDD of the soil-MSWIFA mixture is initially observed with the addition of cement; however, this increase has a threshold beyond which the MDD reduces. Further additions can lead to a reduction in MDD. This phenomenon occurs because higher MSWIFA concentrations can disrupt effective particle packing, necessitating additional water and resulting in decreased MDD and elevated OMC, as noted by Yadav et al. (2017) [47]. It is also evident that all mixtures with varying cement contents achieve optimal performance at a MSWIFA content of 20%.

On the other hand, as the content of MSWIFA augmented, the OMC of the cemented mixtures exhibited a nearly linear rise. These mixtures contain fly ash, which serves as a pozzolanic material, and cement, both of which require water for their hydration and chemical reactions. The effect of fly ash on both soil and cemented mixtures was comparable. However, the addition of cement further elevated the OMC of the MSWIFA-treated specimens. When cement is added to the MSWIFA-soil mixture, it undergoes hydration, forming calcium silicate hydrates (C-S-H) and other compounds that contribute to the overall strength and stability of the mixture. The hydration process requires water, which can lead to an increase in the OMC due to the additional moisture needed for the chemical reactions to occur. These findings are in good agreement with other studies [48-50].

4.1.3. Shear Behavior

Figure 11 presents the stress-strain relationship of cement-MSWIFA-treated specimens, while Figure 12 illustrates the UCS values for soil-MSWIFA samples with varying cement content at 28 days curing time. An analysis of these results reveals that, with 10% cement, the UCS increases by 2%, 4%, and 47% for 10%, 20%, and 30% MSWIFA content, respectively. For specimens with 10%, 20%, and 30% MSWIFA, the addition of 15% cement enhances UCS by 95%, 89%, and 113%, respectively. Similarly, introducing 20% cement improves the UCS by 179%, 149%, and 196% for 10%, 20%, and 30% MSWIFA, respectively. These findings indicate that the compressive strength of the stabilized soil increases with higher cement content, reaching optimal strength in specimens with 30% MSWIFA and 20% cement.

This enhancement likely results from the formation of calcium silicate hydrate (CSH) during cement hydration, which acts as a binding agent, bonding with soil particles and interacting with the active silica in MSWIFA to produce additional cementitious compounds. Cement content up to 15% notably enhanced the soil's properties, though increasing it beyond this threshold resulted in reduced ductility and a more brittle material.

In conclusion, cement proves to be an effective binder, significantly enhancing UCS even at higher concentrations. MSWIFA also contributes to strength improvements by filling voids and promoting pozzolanic reactions with cement. Thus, optimal cement and MSWIFA levels (20% and 30%, respectively) yield a substantial UCS increase due to their synergistic interaction with the soil. Several studies have extensively documented the improvement of soil strength through the addition of cement and fly ash [51, 52].

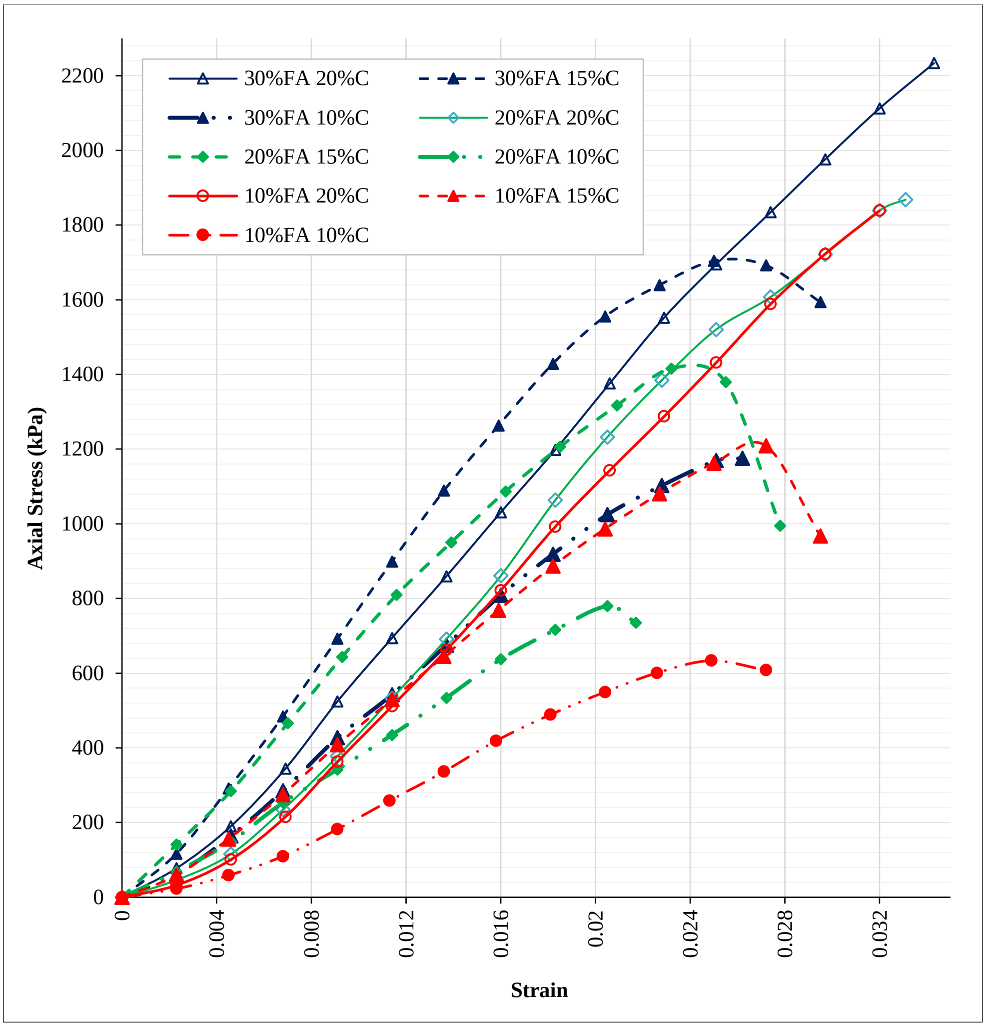

Figure 11. Stress-Strain behavior for Soil mixed with different percentages of MSWIFA and Cement contents at 28 days

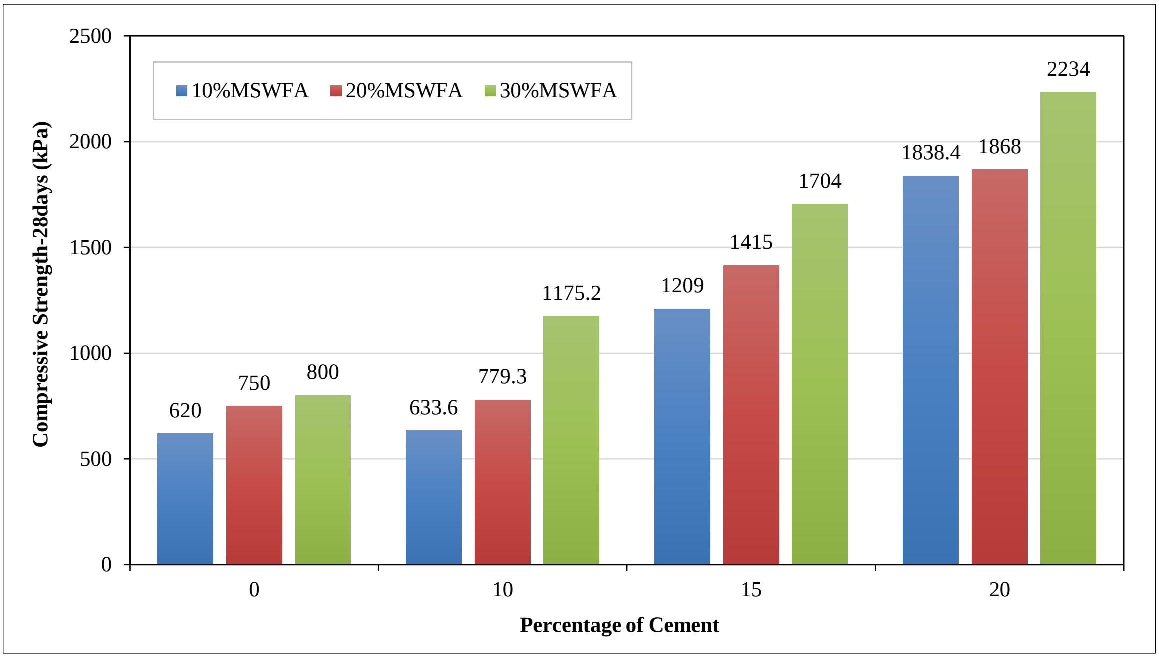

Figure 12. Compressive strength (28 days) of mixtures versus MSWIFA content for different percentages of Cement

The failure mode revealed that cracks developed and extended with minimal warning signs. The cracks were characterized by their length, width, and sparse distribution. These cracks propagated along the shear surface, and due to the brittle nature of the shear failure, the failure surface appeared smooth as shown in Figure 13-b.

(a) (b)

Figure 13. Failure mode of soil cement MSWIFA mix a) just before failure, b) after failure

Using cement and fly ash substantially strengthens soils with inherently low strength, yet it often renders the stabilized material more brittle. This trade-off between maximizing strength and retaining flexibility limits the potential applications for these stabilized soils. To address this limitation, the present study explored incorporating a plastic material, specifically rubber, into the mixture. The inherent elasticity of rubber shows potential for enhancing the flexibility of stabilized soil, while retaining much of the strength contributed by cement and ash.

4.2. Effect of Rubber MSWIFA-Cement Mixtures on Soil Properties

4.2.1. Compaction Characteristics

Figure 14 illustrates the variation in MDD of soil treated with different proportions of MSWIFA, cement, and rubber. The data shows a noticeable decrease in MDD with the addition of rubber to the soil-MSWIFA-cement mix, particularly at 10% rubber content. For instance, in samples with 20% MSWIFA and 20% cement, the MDD decreased from 1.88 g/cc to 1.67 g/cc as the rubber content increased from 0% to 10%. However, incorporating 5% rubber into the MSWIFA-cement-treated samples resulted in a higher MDD compared to the untreated soil. This finding suggests that, at lower level of rubber content, the effects of the MSWIFA-cement additives are more significant than those of the rubber. In fact, the cement and fly ash can effectively fill the voids between the rubber and soil particles. Nevertheless, this advantageous effect is reversed at higher rubber content of 10 % in this case.

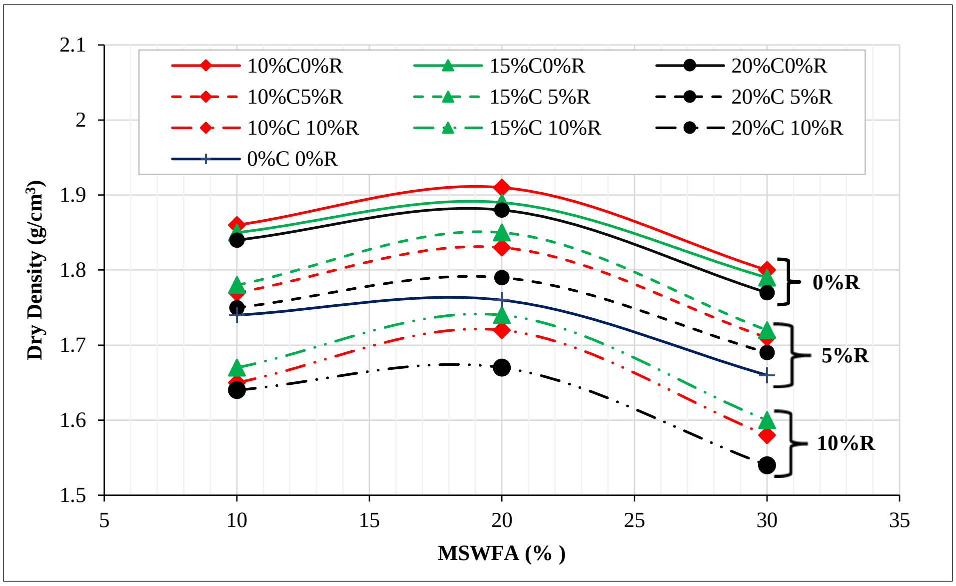

Figure 14. Effect of varying % of Cement, ash, and Rubber on the MDD of soil

Besides, for soil containing 15% cement and 5% rubber, increasing MSWIFA content from 10% to 20% raised the MDD from 1.78 g/cc to 1.85 g/cc. However, further increases in MSWIFA content subsequently lowered the MDD. Results also indicate that a 15% cement content achieves a higher MDD than both 10% and 20% cement levels when rubber is included in the mix.

The decrease in MDD with rubber incorporation is attributed to several key factors. First, rubber has a significantly lower density than both soil and additive particles, so when incorporated, it replaces denser material, lowering the overall mass of the compacted volume. Additionally, rubber particles of 2 mm dimension are larger and less rigid than soil grains, which disrupts the packing efficiency and creates additional void spaces within the soil matrix, thus decreasing achievable density even with maximum compaction. Furthermore, the elasticity of rubber particles absorbs part of the compaction energy, reducing the extent to which soil particles can densely pack together. These combined factors contribute to the overall reduction in MDD in the MSWIFA-rubber-cement soil mixtures. The effect of rubber on increasing the OMC and reducing the MDD of soil has also been documented in previous studies [33, 35, 36].

Figure 15 presents the variation in OMC for soil specimens treated with different proportions of cement, MSWIFA, and rubber. The data indicate that adding rubber slightly reduced the OMC of the cement-MSWIFA treated samples. For example, at fixed levels of 10% cement and 30% MSWIFA, the OMC decreases from 19.4% to 19% and further to 18.6% with the addition of 0%, 5%, and 10% rubber, respectively. It is also notable that the MSWIFA content is the primary factor influencing OMC changes. By increasing the ash content, the OMC considerably augmented, while increases in cement content result in only a slight OMC increase.

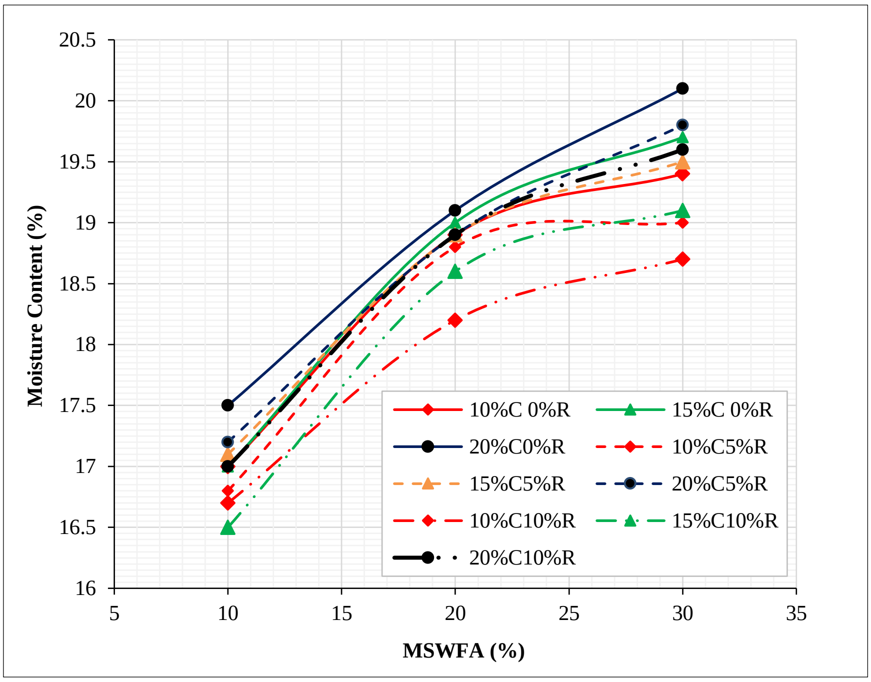

Figure 15. Effect of varying % of Cement, ash, and Rubber on the OMC of soil

Rubber particles, with their low water absorption capacity and hydrophobic nature, reduce the total surface area available for moisture retention in soil-cement-MSWIFA mixtures. This property minimizes the amount of water required to reach optimal compaction. Additionally, as rubber does not participate in hydration reactions, it limits bonding interactions with cement and MSWIFA particles, further decreasing the moisture needed for effective compaction. The effect of rubber on reducing the OMC and MDD of soil has also been documented in previous studies [35, 36].

4.2.2. Shear Behavior

The stress-strain behavior of the soil-MSWIFA-rubber mixtures stabilized with different cement contents of 10%, 15%, and 20% is presented in Figure 16. The incorporation of rubber into the soil-cement-MSWIFA mixture generally results in a reduction in compressive strength while significantly increasing ductility, as observed. Notably, a specific blend containing 5% rubber, 20% cement, and 10% MSWIFA demonstrated an exception to this trend, as illustrated in Figure 16-c. This particular mixture exhibited substantial increases in both compressive strength and ductility, outperforming the control mix that did not include rubber. When compared to the control mix with 20% cement and 30% MSWIFA, the rubber-enhanced performance showed an approximate 30% improvement in strength and better ductility. These findings are in good agreement with past investigations. These results align with findings by Al-Subari et al. (2021) [53], who investigated the impact of tire rubber powder (TRP) in soil-cement blends. Using TRP contents of 2.5%, 5%, 10%, and 20% with cement dosages of 7%, 10%, and 13%, they observed that rubber inclusion up to 10% enhanced ductility, while higher levels produced diminishing effects. Similarly, Yadav et al. (2020) [47] found that adding rubber fibers up to an optimum 5% improved ductility in cemented clayey soil, enhancing strain hardening under compressive loads. Rubber granulates, effective up to an optimum 2.5%, also increased ductility though they were less effective than fibers in reducing the soil's brittleness under tensile loads.

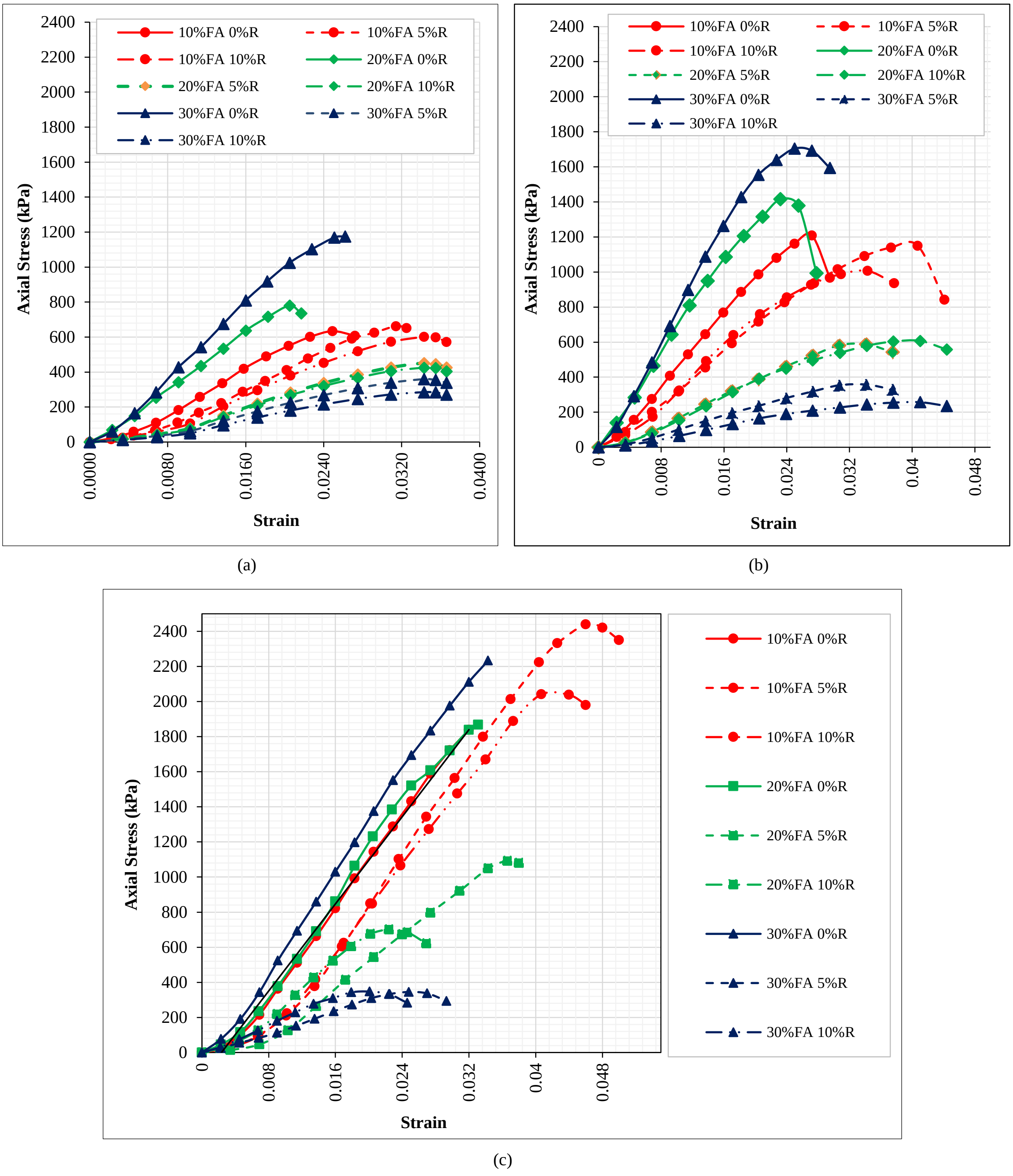

Figure 16. Stress-strain behavior for MSWIFA treated Soil with and without Rubber for varying Cement Contents of (a) 10%, (b) 15%, and (c) 20%

Rubber enhances soil ductility primarily due to its elastic properties, which allow it to deform significantly under stress without breaking. This elasticity contributes to the material's ability to stretch and absorb energy, reducing the likelihood of sudden failure. Additionally, incorporating rubber creates voids within the soil matrix, facilitating greater flexibility in particle movement and enabling the soil to adjust and deform more easily under load. Furthermore, rubber's elasticity allows for effective stress redistribution throughout the soil matrix, spreading the load over a wider area and minimizing the risk of localized failure. However, when the rubber content was increased to 10%, both strength and strain decreased, although this mix maintained greater flexibility than the original soil, such flexibility could be beneficial in applications requiring some yielding or resistance to failure under load.

Figure 17 presents the variation of UCS with MSWIFA content for different proportions of cement and rubber after 28 days of curing time. For all the samples, the UCS significantly improved by increasing the cement content, with the highest enhancement observed at 30% cement. It is noteworthy that, for mixes without rubber, the UCS increased with higher MSWIFA content at a constant cement level. In contrast, an opposing trend was observed in rubber-cement mixes, where the UCS reached its maximum at 10% MSWIFA content. Moreover, at 10% MSWIFA content, the incorporation of rubber increased the UCS up to 5% content, beyond which the UCS began to decline with further rubber inclusion. At low rubber content, the shredded particles effectively interact with the soil, MSWIFA, and cement matrix, enhancing cohesion and improving the overall mechanical properties of the mixture. However, as the rubber content increases beyond 5%, the voids may become too pronounced, leading to a reduction in the effective contact area between soil and cement particles.

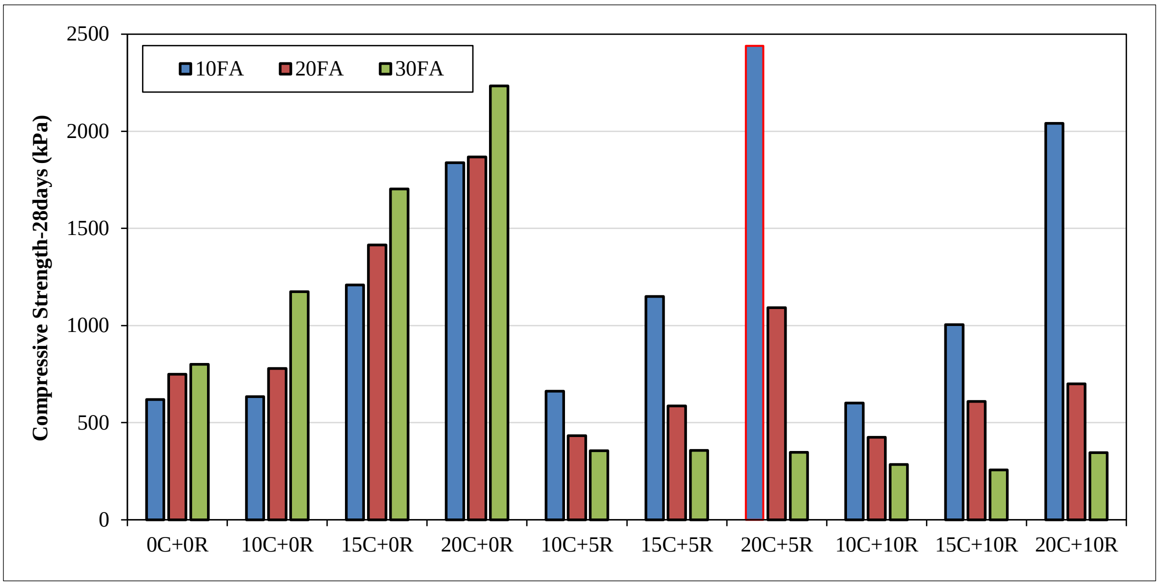

Figure 17. Compressive strength (28 days) of the mix compared to MSWIFA content for various Cement and Rubber percentages

Overall, the addition of 5% rubber to the cement and MSWIFA mixture not only enhances strength but also improves ductility, particularly at 10% MSWIFA content. This allows the soil to absorb more stress and elongate without fracturing. The increased flexibility is particularly advantageous in constructions on soft or unstable soils, where ground movements from loads, traffic, or climatic changes, such as freeze-thaw cycles, can lead to cracking or failure in traditional stiff soil-cement composites. In practical applications, such as road construction and foundation stabilization, the rubber-enhanced soil mixture reduces the likelihood of brittle failure, offering a more durable solution to issues of cracking and ground movement. Specifically, a mixture consisting of 10% MSWIFA, 20% cement, and 5% rubber has been identified as optimal for maximizing strength improvement while preserving flexibility. This suggests that incorporating rubber, along with suitable ratios of cement and MSWIFA, can enhance the overall performance of the material.

5. Conclusions

This research examined the potential of an innovative combination of materials, namely rubber, cement, and municipal solid waste incineration fly ash (MSWIFA), for enhancing the mechanical behavior of clayey soil. Proctor Compaction and UCS tests were conducted to assess the effects of varying percentages of cement (10%, 15%, and 20%), MSWIFA (10%, 20%, and 30%), and rubber (0%, 5%, and 10%) on soil properties. The findings demonstrate the effectiveness of this approach in achieving a favorable balance between strength and ductility, overcoming a significant limitation inherent in traditional cement-based stabilization techniques.

The combination of cement and MSWIFA resulted in a marked enhancement in soil strength, as indicated by UCS Test results. However, this method often rendered the soil more susceptible to damage. The introduction of rubber into the mixture successfully mitigated this issue; specifically, the inclusion of 5% rubber preserved substantial strength improvements while significantly increasing the flexibility of the soil compared to mixtures containing only cement and MSWIFA. Notably, higher rubber content beyond 5% led to a decrease in strength gain, highlighting the necessity of optimizing proportions for specific applications. This novel methodology offers a promising alternative for soil stabilization projects requiring both high strength and adequate flexibility. It is particularly well-suited for applications such as foundations for structures exposed to movement or vibration, road bases in regions subject to freeze-thaw cycles or heavy traffic loads, and slope stabilization efforts where some degree of deformability is advantageous.

In conclusion, it can be definitively stated that rubber waste and MSWIFA can effectively enhance weak soils, thereby improving their mechanical and physical properties. By utilizing these recycled materials, we can not only increase soil stability but also address environmental concerns associated with the accumulation of used tires and solid waste.

5.1. Future Recommendation

The results of this study indicate several areas for further investigation. Initially, greater research into the optimum rubber content for various soil types would provide a more customized method of stabilizing soil under varied geotechnical circumstances. It is advised to conduct long-term performance experiments, such as freeze-thaw and wetting-drying cycles, to evaluate the rubber-cement-MSWIFA mix's durability in actual environmental settings. Furthermore, a life-cycle evaluation of the environmental effect that emphasizes the benefits of waste management and a decrease in carbon footprint might draw attention to the method's sustainability advantages. Investigating other industrial byproducts, such as bio-based additions, might improve stabilized soils' mechanical and environmental performance even further. Finally, studies on the behavior of the mix under dynamic loads and the development of prediction models would increase the mix's applicability in a variety of construction projects.

6. Declarations

6.1. Author Contributions

Conceptualization, G.Ao. and L.J.; methodology, G.Ao. and L.J.; formal analysis, G.Ao., G.Al., and L.J.; investigation, G.Ao.; resources, G.Ao.; data curation, G.Ao.; writing—original draft preparation, G.Ao.; writing—review and editing, G.Ao., G.Al., and L.J.; visualization, G.Ao., G.Al., and L.J.; supervision, G.Ao., G.Al., and L.J.; project administration, G.Ao. and L.J. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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