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Investigating the utilization of oxidized textile residue as a strengthening substance in the composition of subgrade soil for pavement construction

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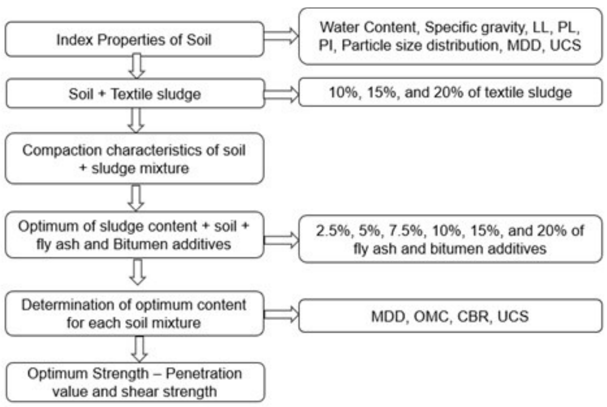
Graphical abstract



Abstract

The textile industry, vital in the country's industrialization and playing a crucial role in the national economy, generates solid byproducts known as textile sludge. Integrating waste into stabilized soils, along with textile sludge (TS), fly ash (FA), and asphalt additives, offers scientific, economic and sustainability benefits. This study aimed to examine the subsurface solidification technique employing sludge and two supplement additives (asphalt and fly ash additive) implemented on pavement groundwork and supporting layers. The research involved characterization tests and physical soil stabilization with TS and stabilizers (fly ash, and asphalt) at proportions of 2.5%, 5%, 7.5%, 10%, 15%, and 20% as soil additives, which were carried out experimentally. The test results highlighted the potential application of soil-textile sludge mixtures in pavement strata (support and subgrade). The inclusion of fly ash has been proven to be the most effective method for chemically stabilizing the sludge. The maximum dry density was achieved with soil containing 10% textile sludge, supplemented with 15% fly ash. This resulted in a notable increase in UCS value from 235 kN/m^2 to 242 kN/m^2 and an improvement in CBR value from 4.1% to 9.12%. Furthermore, the addition of 5% bitumen further enhanced the UCS value, reaching 451 kN/m^2 and significantly increased the CBR value to 21.6%. Stabilizing textile sludge offers significant environmental benefits by mitigating issues associated with improper waste disposal.

Keywords: Textile sludge, fly ash, asphalt, stabilization, OMC, MDD, UCS, CBR

1. Introduction

The global challenge involves an increasing recognition of the problem of solid waste generation and the quest for appropriate disposal methods. Residues produced as by-products in any industrial operation can lead to significant environmental consequences when their final destination is unsuitable (Karthikeyan & Vinothkumar 2017). Annually, the worldwide textile industry produces approximately 113.8 million tons of fabric, contributing to the social and economic development of numerous emerging nations (Cheng *et al.* 2020). Despite its economic benefits, the industry generates 92 million tons of textile waste residues, posing challenges in terms of recycling (Karthikeyan & Vinothkumar 2017).

Each million tons of textile-contaminated water results in approximately 25m^3 of sludge, with the greater part of this waste being released into the ecological system (Patil *et al.* 2021). The composition of textile waste sludge is variable (Cheng *et al.* 2020), typically containing elements such as organic matter (Gardete *et al.* 2019), nitrogen, phosphorous, and micronutrients (Karthikeyan & Vinothkumar 2017). Proper disposal of this residue is essential due to the presence of toxic substances such as polymers (Abdulrahman *et al.* 2021), caustic soda, aluminum sulfate, iron (Sarli *et al.* 2020), lime, and other products used in the dyeing operation and effluent treatment (Khodabandeh *et al.* 2023). Industries must manage the removal of this material responsibly to prevent harm to both the environment (Varthini &

Palanikumar 2021; Johari *et al.* 2021) and public health (Behnood 2018; Cheng *et al.* 2020). However, even when deposited in landfills (Varthini & Palanikumar 2021), a significant environmental impact persists (Gardete *et al.* 2019), affecting both soil and groundwater due to the presence of metal pollutants in the sediment sludge (Karthikeyan & Vinothkumar 2017).

Various studies have explored the utilization of textile sludge (Cheng *et al.* 2020) in alternative applications (Khodabandeh *et al.* 2023; Behnood 2018). Suggestions include its application as fertilizer in agriculture, as a chemical component in various industries (such as cement production) (Varthini & Palanikumar 2021), in energy generation (such as biogas) (Gardete *et al.* 2019), and as an enhancer for bricks, tiles, and concrete (Peng *et al.* 2020). Researchers like Niyomukiza *et al.* (2023) and Karthikeyan & Vinothkumar (2017), propose incineration as a potential method for the ultimate disposal of the sludge. However, it's noted that the resulting ash could also be contaminated residue.

As per Cheng *et al.* (2020), despite the potential of textile sludge for applications in the energy sector (Varthini & Palanikumar 2021), it typically undergoes landfill disposal without any reutilization (Sarli *et al.* 2020). Currently, advocating for biomass-based electricity and heat production is considered a significant alternative for developing countries (Khodabandeh *et al.* 2023; Johari *et al.* 2021). However, its adoption is limited due to the relatively low efficiency of power generation from solid fuel, with conversion rates rarely exceed 10% (Patil *et al.* 2021).

Integrating textile sludge into traditional materials in civil engineering (Nazir *et al.* 2021), such as aggregates and ceramic blocks, has demonstrated a practical and effective solution for appropriately managing this type of waste. Cheng *et al.* (2020) suggested that the chemical correlation between the composition of textile sediments and the chemical characteristics of cement clinker could explain the favorable performance of the sludge (Karthikeyan & Vinothkumar 2017). However, the authors emphasize that the focus of the study was on the application of clay based building blocks (Cheng *et al.* 2020), where different conditions of exposure at the destination are anticipated in relation to laboratory conditions.

The research was conducted in Tirupur, India, where sludge production reached 100 tons per day, and concrete elements were augmented with textile sludge (Patil *et al.* 2021). The findings suggest the feasibility of using this substance in non-structural elements, considering that textile sludge may induce corrosion in steel bars. Investigations carried out by Gardete *et al.* (2019) established that a lime pretreatment process, designed to eliminating ammonia, can effectively address corrosion issues (Khodabandeh *et al.* 2023).

Pavement construction, involving the mobilization of substantial soil volumes, emerges as an alternative for repurposing residues, especially when considering stabilization (Gardete *et al.* 2019; Daraei *et al.* 2019). This approach, blending soil stabilization with the reuse of industrial byproducts, holds promise for executing pavement layers. (Khodabandeh *et al.* 2023; Cheng *et al.* 2020) The process of soil stabilization entails enhancing soil properties by incorporating various materials, such as fly ash (Puspita *et al.* 2023), GGBS, cement, lime, and asphalt emulsion (Behnood 2018). It effectively diminishes soil permeability and compressibility while bolstering shear strength (Abdulrahman *et al.* 2021; Patil *et al.* 2021). Adopting a stabilization technique utilizing waste materials prevents the disposal of these substances in landfills, thus conserving valuable landfill space (Behnood 2018; Beshah *et al.* 2021). Consequently, employing soil solidification with industrial byproducts yields scientific, sustainable, and economic benefits (Gardete *et al.* 2019).

Various authors explored options for incorporating different types of sludge into soils, including wastewater sludge (Karthikeyan & Vinothkumar 2017), sewage sludge (Cheng *et al.* 2020; Patil *et al.* 2021), bentonite sludge (Beshah *et al.* 2021), granite sludge (Sarli *et al.* 2020), and waste paper sludge (Khodabandeh *et al.* 2023; Mohammed *et al.* 2021). In these investigations, chemical additives like fly ash and asphalt additives played a role in promoting the stabilization of residues (Behnood 2018; Abdulrahman *et al.* 2021).

Utilizing such materials allows countries with natural or industrial residues that lack a final disposal point to find a solution in construction materials (Cheng *et al.* 2020). Consequently, employing the stabilization method on sludge for pavement layer applications can enhance the desired properties of stabilized soils.

Previous studies have primarily focused on the disposal and treatment of textile sludge, overlooking its potential as a construction material. By characterizing the physical and mechanical properties of soi-textile sludge mixtures with fly ash and asphalt additives, this study sheds light on a novel approach to sustainable pavement construction. The investigation of various proportions of textile performance while minimizing environmental impact. Through an examination of the subsurface stabilization technique involving textile sludge and supplementary additives, this research addresses a significant research gap in the field of pavement engineering and waste management.

2. Materials and methods

2.1. Materials

This research involved textile sediment sludge obtained from a fabric industry situated in Tiruppur city, Tamilnadu, India. Soil samples were taken from treatment plants within the textile industry in Tiruppur town, Tamilnadu, India. Both the soil and sediment samples were placed in PE bags and subsequently air-dried. The residue was pre-dried in open air on trays at a typical temperature of 30°C for 7 days (Karthikeyan & Vinothkumar 2017). Following this phase, it underwent additional drying in an oven set at 110°C to eliminate any remaining moisture (Cheng *et al.* 2020). Notably, the sludge was not subjected to milling to minimize associated treatment costs. The characteristics and compositions are detailed in Table 1. Chemical additives like fly ash and asphalt were incorporated to enhance the stabilization of mixture (Cheng *et al.* 2020). Based on the test results, the soil is classified as CH according to the BIS classification. Figure 1 shows the methodology of the proposed study.

Table 1. Clay soil and textile sludge characteristics

Properties	Values	
	Clay soil	Textile sludge
Specific Gravity	2.68	1.89
Natural moisture content (%)	4.38	198.00
Max. dry density (g/cc)	1.66	-
Optimum moisture content (%)	13.20	-
Plastic limit (%)	20.00	Non-Plastic
Liquid limit (%)	48.00	Non-Plastic
Plastic limit (%)	28.00	Non-Plastic
Gravel (%)	1.03	-
Sand (%)	19.25	96.26
Silt & Clay (%)	79.72	3.74
Silica (SiO_2)	61.52	58.25
Alumina (Al_2O_3)	24.33	4.62
Iron Oxide (Fe_2O_3)	5.02	0.98
Other Oxides	6.15	24.57
Loss of Ignition	2.98	11.58

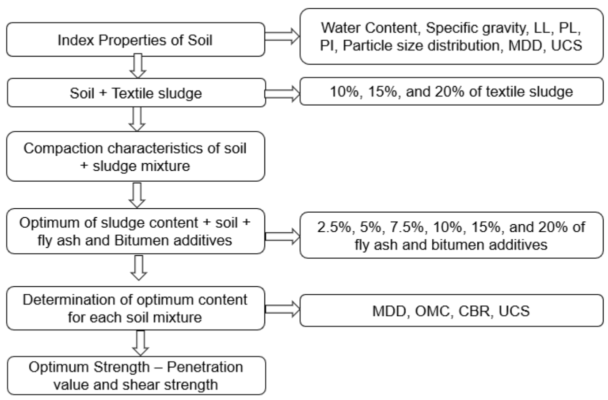


Figure 1. Methodology flow diagram

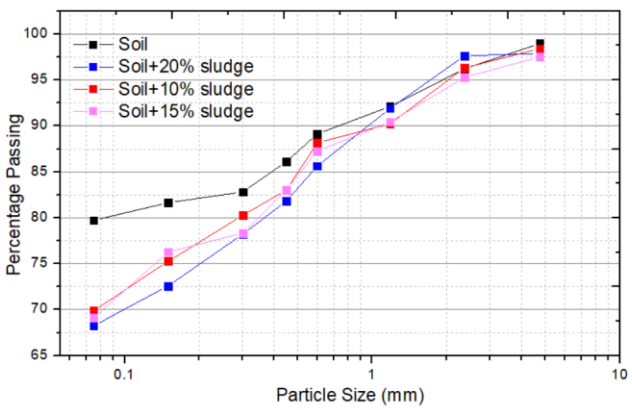


Figure 2. Particle size distribution curves for soil + sludge

2.2. Mechanical stabilization

The objective of soil stabilization was to explore the effect of textile sludge on the mechanical characteristics of the soil. Sludge additions of 10%, 15%, and 20%, all without lumps, were implemented (Patil *et al.* 2021). A series of tests, including densification tests, California bearing ratio (CBR) tests (Mohammed *et al.* 2021), and unconfined compressive strength (UCS) tests (Cheng *et al.* 2020), were carried out on both pure soil samples and mixed samples (soil + sludge) to identify the optimal sludge content for improved mechanical behavior (Patil *et al.* 2021).

Based on the physical properties listed in Table 1, clay soil particles are finer than textile sludge particles. Clay particles are known for their extremely small size, typically less than 0.002 millimeters. On the other hand, textile sludge particles can vary in size (Mohammed *et al.* 2021) but are generally coarser compared to clay particles (Patil *et al.* 2021). Therefore, when textile sludge, with its relatively larger particles, is mixed with clay soil, it can lead to a decrease in the percentage passing (Patil *et al.* 2021). The percentage passing curves are shown in Figure 2.

2.3. Chemical stabilization

The optimal percentage of sediments, as identified through mechanical stabilization results, was chosen for chemical stabilization (Cheng *et al.* 2020). In the mix comprising soil and the previously determined 10% sludge, fly ash, and asphalt additives were introduced in varying proportions: 2.5%, 5%, 7.5%, 10%, 15%, and 20% by weight (Behnood 2018). The additives employed for chemical stabilization were identical to those traditionally used in pavement roads (Liu & Hung 2023).

Modified soil specimens underwent compaction and were subsequently assessed for the following parameters: CBR and UCS (Cheng *et al.* 2020; Liu & Hung 2023). The optimal mix design was determined using mechanical tests. For each investigated additive, three samples were prepared based on the densification constraints established in the light compaction test at the OMC.

2.4. Compaction test

For every sample (pure clay soil and sludge mixtures), compaction tests were conducted by compacting a range of soil samples at varying moisture levels. A moisture density curve was then plotted with dry density and moisture content as axes (Liu & Hung 2023). The maximum dry density (MDD) was observed at the optimum water content (OMC) and the outcomes were extracted from the curve. The CBR was assessed for blends consisting of soil, soil-blended additive and the investigated textile sludge, following the BIS method. The specimens were maintained in a dry condition, and subsequently, the penetration test was conducted. The BIS procedure was also employed for the compressive strength test (Umair *et al.* 2023). The quantity of water incorporated into the blend of mixes (soil, soil-sludge mixture and additive) was determined based on the results of densification tests (Patil *et al.* 2021). The specimens were conditioned at room temperature, and subsequently, the sample underwent testing in an unconfined medium under applied axial loads.

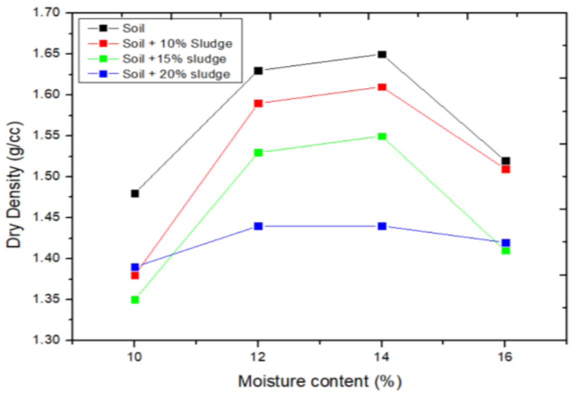


Figure 3. Standard Proctor's compaction curves

3. Results and discussion

3.1. Mechanical stabilization

3.1.1. Standard Proctor compaction test

The moisture density curves for various combinations of blended soil-sludge tests are plotted and shown in Figure 3, while the light compaction optimum values are plotted in Figure 4. The addition of sludge reduces the maximum dry density without changing the moisture level. The moisture density curves for mixtures with 20% sludge inclusion exhibit varying behavior without a distinct peak (Umair *et al.* 2023), potentially due to the denser fraction of the soil affecting intermolecular bonds (Patil *et al.* 2021). In contrast, the addition of 10% sludge provides results closer to the baseline compared to the 15% and 20% additions (Patil *et al.* 2021). Based on these experimental results, the 10% sludge addition is chosen to further study of shear strength.

Textile sludge typically contains organic matter and fine particles, which tend to increase the porosity of the soil mixture (Umair *et al.* 2023). As a result, there is more air space between particles, leading to a reduction in density of soil (Liu & Hung 2023). Additionally, the organic content in textile sludge may promote decomposition and microbial activity, causing further void formation as the organic matter breaks down (Liu & Hung 2023). Moreover, the physical characteristics of textile sludge particles (Umair *et al.* 2023), such as their irregular shape and relatively low specific gravity compared to soil particles (Liu & Hung 2023), contribute to a decrease in compactness and dry density (Umair *et al.* 2023).

Textile sludge typically contains moisture, which can offset any changes in moisture content caused by the addition of dry soil (Liu & Hung 2023). Additionally, the absorption capacity of the soil may reach its limit with the available moisture in the textile sludge, preventing further changes in moisture content. Furthermore, the physical properties of textile sludge (Liu & Hung 2023), such as its fine particle size and organic composition (Umair *et al.* 2023), may contribute to maintaining moisture equilibrium within the soil mixture, resulting in no significant change despite the addition of textile sludge (Liu & Hung 2023).

3.1.2. Unconfined Compressive Strength and CBR

The inclusion of sludge into the soil did not result in a notable alteration of the CBR results; however, decrease in UCS results were noted with its inclusion (Behnood 2018). This outcome was anticipated, given that both the soil and sludge exhibit finer characteristics, resulting in the soil-sludge mixture possessing a reduced density compared to pure clay soil (Patil *et al.* 2021).

Table 2 Shear strength properties of soil sludge mixture with additives

Soil Mixture	UCS strength (kN/m²)	CBR (%)
Soil	235.00	4.10
Soil+10% Sludge	191.00	4.90
Soil + 10% Sludge +2.5% FA	198.00	5.40
Soil + 10% Sludge +5% FA	204.00	6.75
Soil + 10% Sludge + 7.5% FA	218.00	7.15
Soil + 10% Sludge + 10% FA	231.00	7.55
Soil + 10% Sludge + 15% FA	242.00	8.92
Soil + 10% Sludge + 20% FA	238.00	9.12
Soil + 10% Sludge + 2.5% Asp	328.00	12.90
Soil + 10% Sludge + 5% Asp	451.00	21.60
Soil + 10% Sludge + 7.5% Asp	421.00	19.80
Soil + 10% Sludge + 10% Asp	311.00	19.10
Soil + 10% Sludge + 15% Asp	289.00	16.20
Soil + 10% Sludge + 20% Asp	186.00	15.60

The soil sample was mixed with additives such as fly ash or bitumen and compacted in layers using standard compaction energy (Liu & Hung 2023). The sample was thoroughly mixed with additives to ensure uniform distribution and compaction (Umair *et al.* 2023). This standardized approach ensures consistent compaction and allows for accurate evaluation of CBR values with additives (Umair *et al.* 2023).

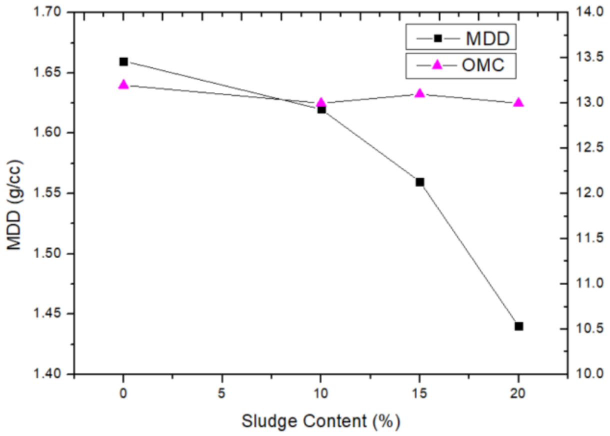


Figure 4. Behaviour of MDD and OMC with addition of sludge

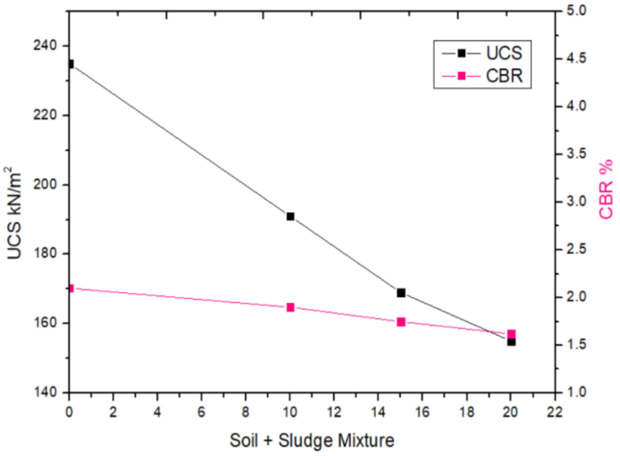


Figure 5. Behaviour of UCS and CBR with addition of sludge

Based on the findings from mechanical stabilization, it was confirmed that the 10% sludge content yielded the most favorable results (Patil *et al.* 2021). Integrating higher quantities of residues into the soil could enhance residue management more effectively; however, this could potentially diminish the mechanical strength of the soil (Bagriacik and Guner 2021). Despite the observed UCS and CBR value for the sludge content, granularity stabilization should not be employed without additives, as the outcomes fall under the specified standards for pavement bases and subbases (Amrani *et al.* 2021). Consequently, chemical bonding is essential to enhance soil-sludge mixture stabilization (Behnood 2018).

3.2. Chemical stabilization

Compaction curves illustrate variations in soil-textile sludge mixture characteristics with the addition of different proportions of fly ash (Patil *et al.* 2021; Khodabandeh *et al.* 2020) and asphalt additives, as shown in Figures 6 and 7. The maximum dry density results showed a notable increase in samples incorporating fly ash and asphalt compared to those achieved with pure clay soil (Khodabandeh *et al.* 2020) and a soil mixture containing sludge (Behnood 2018). This increase is attributed to the higher specific mass of the additives compared to the soil and the blended soil-sludge mixture (Khodabandeh *et al.* 2020). The Figure 6 clearly shows that the dry density of the soil mixture improves with the inclusion of 10% of fly ash, and beyond this limit, there is no significant increase in dry density (Sagar *et al.* 2021). Similarly, from the Figure 7, it is observed that the addition of asphalt increases the dry density up to 15%; thereafter, the increment marginally decreases (Patil *et al.* 2021). A slight fluctuation (2% to 3%) in optimum moisture content (OMC) values is observed with an increase in fly ash and asphalt additives (Sagar *et al.* 2021). The OMC decreases with higher additive content in the mixture.

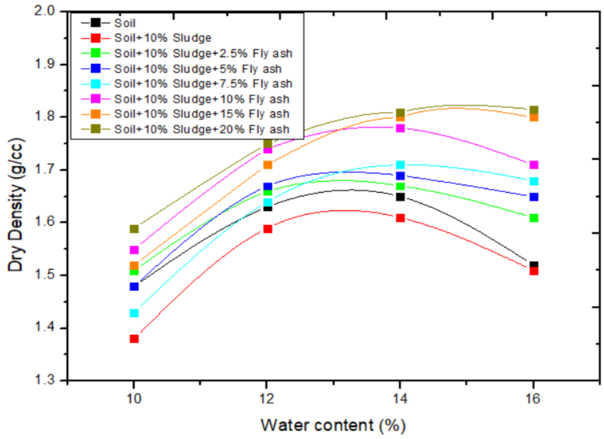


Figure 6. Compaction behaviour of soil + 10% of Sludge + Fly ash

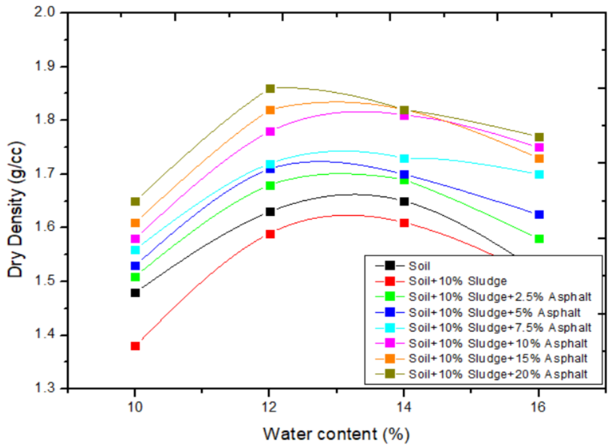


Figure 7. Compaction behaviour of soil + 10% of Sludge + Asphalt

The obtained results align with findings from previous literature studies that investigated the chemical stabilization of sewage sludge (Amrani *et al.* 2021; Patil *et al.* 2021; Sagar *et al.* 2021) and water sludge, respectively.

Fly ash, a byproduct of coal combustion in power plants, typically contains fine particles with a high surface area (Amrani *et al.* 2021). When fly ash is added to soil, it fills in the void spaces between soil particles and effectively increasing the density of the soil mixture (Sagar *et al.* 2021). This densification results in a greater ability of the soil to hold water, thus requiring more moisture to achieve the same level of compaction. Additionally, fly ash particles may exhibit some degree of water absorption (Amrani *et al.* 2021), further contributing to the increase (2% to 3%) in OMC, as shown in Figure 6 (Amrani *et al.* 2021).

Bitumen, being a hydrophobic material, tends to repel water and reduces the soil's ability to absorb moisture (Sagar *et al.* 2021). This action results in a decreased demand for water to achieve optimum compaction (Amrani *et al.* 2021), as shown in Figure 7. Moreover, bitumen's adhesive properties can lead to better particle bonding and increased soil stability, further reducing the need for additional moisture content to achieve desired compaction levels (Sagar *et al.* 2021).

3.3. Shear strength parameters

3.3.1. Unconfined compressive strength

Table 2 displays the UCS and CBR values. Notably high UCS values are observed with the incorporation of fly ash, observed peak at 15%, but declining beyond this threshold when combined with a soil-sludge mixture (Sagar *et al.* 2021). This could be attributed to the pozzolanic binding nature, enhancing the soil's shear strength (Amrani *et al.* 2021; Khodabandeh *et al.* 2020). In the case of asphalt addition, substantial changes are noted with 5% addition, followed by decrease with higher asphalt content (Patil *et al.* 2021). Figure 8 shows the UCS value for soil-sludge mixture with additives.

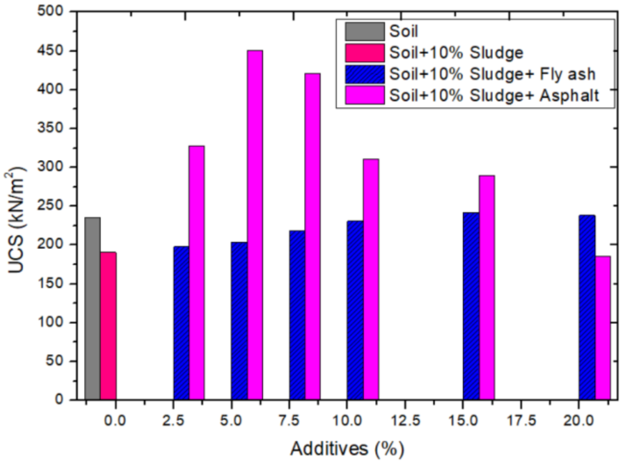


Figure 8. UCS values for soil-sludge mixture with additives

In Figure 9, the CBR results are presented. With soil-sludge and fly ash incorporation, a gradual increase is observed with higher stabilizer contents (Amrani *et al.* 2021). The percentages of additives yield higher values than the soil and soil-sludge mixture (Sagar *et al.* 2021), indicating a beneficial enhancement for pavement bases (Khodabandeh *et al.* 2020). However, for soil-sludge with asphalt (Asp) inclusion, there is a nominal improvement observed for 5%, 7.5%, and 10% content, but beyond this range, a reduction is noted.

Previous literature studies also support this, suggesting that the addition of asphalt and sludge (Sagar *et al.* 2021) including water sludge and sewage sludge, does not lead to CBR improvements (Khodabandeh *et al.* 2020). The authors clarify that as CBR tests are conducted with saturated samples (Umair *et al.* 2023), the asphalt functions as a hydrophobic substance and may not necessarily increase bearing capacity. Consequently, this inclusion is not recommended for pavement surfaces subjected to saturation (Amrani *et al.* 2021).

4. Conclusion

It was noted that introducing 10% sludge yielded improved mechanical outcomes during the physical stabilization stage. Nonetheless, for the infusion of byproducts into pavement layers (support and subbase), chemical stabilization is essential. Incorporating fly ash and asphalt met the CBR criteria for various pavement layers and enhance mechanical parameters compared to pure soil. The introduction of 15% fly ash yielded superior results in maximum dry density and UCS values, while a 5% asphalt content achieved a higher value. Consequently, drawing from the outcomes of this study, it is recommended that the combination of soil and stabilized textile sludge is suitable for application in the base layers of low-volume roads. However, a substantial incorporation of additives (such as fly ash and asphalt) may be deemed a costly input in the manufacturing process. Leveraging textile sludge stabilization offers significant environmental advantages, mitigating potential malfunctions and issues associated with improper waste disposal. There is an ongoing need to establish a connection between laboratory test outcomes and the real-world performance of this sludge. Prior to integrating textile sludge into pavements, it is imperative to assess the following aspects: the design challenges and corresponding solutions that consultants may encounter in novel projects, and the apprehension regarding potential pollution when utilizing calcined textile sludge.

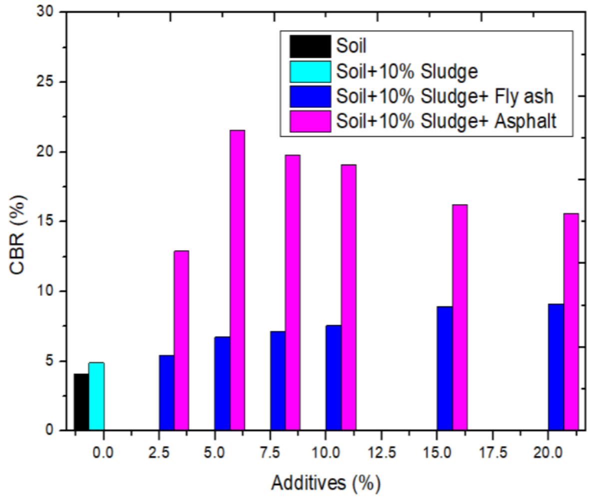


Figure 9. CBR values for soil-sludge mixture with additives

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