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EVALUATING THE MECHANICAL PROPERTIES OF CONCRETE CONTAINING TEXTILE AND TANNERY SLUDGE AS PARTIAL CEMENT REPLACEMENT

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ABSTRACT

Background: Concrete production is heavily dependent on cement, whose manufacturing contributes (7–8)% of global anthropogenic CO_2 emissions. Simultaneously, the textile and tannery industries generate vast quantities of hazardous sludge, creating serious environmental disposal challenges in Cameroon where landfilling and incineration remain the primary management strategies. There is consequently a growing need for sustainable valorization alternatives for these industrial waste streams. **Objective**: This study investigates the technical feasibility of using textile sludge, tannery sludge, and their binary combination as partial cement replacements in concrete production. **Methods:** Loss-on-ignition, colorimetric, and liquid-liquid extraction methods have been used to assess the physicochemical properties (pH, organic matter, and organic compound profiles) of the sludge samples collected in a clean non-reactive plastic containers. Sieve analysis, moisture content, specific gravity technologies are designed to evaluate the specific gravity, the grain size distribution, water content, apparent density and the volumetric mass of the aggregates. The Dreux–Gorisse formulation approach was used to produce three categories of concrete specimens incorporating 0%, 5%, 10%, 15%, and 20% cement replacement by sludge (textile only, tannery only, and combined textile + tannery), cured at 22°C over 3, 7, and 28 days. Compressive strength, water absorption, and workability were evaluated. **Results:** Compressive strength decreased with increasing sludge substitution but remained within acceptable limits for non-load-bearing applications at (10–15)% replacement. Water absorption increased progressively with sludge dosage, ranging from (6.7–7.3)% at 5% replacement to (15.7–16.3)% at 20%. Workability declined slightly with increasing sludge content. The best mechanical performance was recorded at (10–15)% substitution for all three sludge categories. **Conclusion**: Textile and tannery sludge can substitute up to (10–15)% of cement in concrete without compromising suitability for non-structural and low-load applications, including agricultural facilities. This approach reduces industrial waste disposal burdens and lowers cement consumption, contributing to sustainable construction in Cameroon.

Keywords*: tannery sludge; textile sludge; concrete production; compressive strength; cementitious material.*

1. INTRODUCTION

Concrete is the most widely used construction material globally, valued for its compressive strength, durability, and adaptability to a broad range of structural and non-structural applications, from masonry bonding and plastering to column construction and the fabrication of precast elements (Neville, 2011). Its primary binding agent, Portland cement, accounts for approximately (7–8)% of global anthropogenic CO_2 emissions, ranking cement manufacturing among the largest single industrial contributors to greenhouse gas accumulation (Barbhuiya et al., 2024; Andrew, 2019). This environmental burden is compounded by the intrinsically energy-intensive nature of clinker production, which requires limestone calcination at temperatures exceeding 1400°C (Barbhuiya et al., 2024). Decarbonizing this process without fundamental technological shifts is extremely difficult; consequently, the partial substitution of cement with supplementary cementitious materials (SCMs) derived from industrial by-products has emerged as one of the most scientifically robust strategies for simultaneously reducing cement consumption and valorizing otherwise problematic waste streams (Scrivener et al., 2018; Junaid et al., 2022). In Cameroon, rapid urbanization and population growth have driven exceptional demand for construction materials; particularly cement mortar, a composite of cement, sand, and water extensively used in masonry, plastering, and structural applications. Concurrently, the textile and tannery industries, which process cotton, wool, silk, and animal hides through operations including desizing, scouring, bleaching, dyeing, and finishing, generate substantial solid and liquid waste. According to the United Nations Industrial Development Organization (UNIDO, 1998), the processing of one metric ton of animal hides produces approximately 100–150 kg of sludge enriched in inorganic compounds (chromium, sulfides, sulfates, chlorides, and ammonium) and elevated concentrations of organic matter. The volumes of water involved are considerable: between 25 and 60 m^3 per ton of fresh leather processed, with approximately 400 kg of chemicals used per ton, generating effluents with very high pollutant loads (UNIDO, 1998). In Cameroon, sludge management relies primarily on landfilling and incineration, of which is neither technically adequate nor economically viable, given the country's resource constraints and the severe environmental risks associated with heavy metal leaching and toxic emissions (Veronica et al., 2008).

The potential of industrial sludge as a partial cement replacement has been thoroughly documented across multiple material systems and geographies. Balasubramanian et al. (2006) demonstrated that textile effluent treatment plant

(ETP) sludge could substitute up to 30% of cement in non-structural building materials, flooring tiles, hollow bricks, and solid bricks, without significantly compromising compliance with material standards. Zhan and Poon (2015) confirmed the technical viability of reutilizing textile ETP sludge in concrete blocks, while Pandey et al. (2012) reported a progressive strength decline with increasing sludge dosage in cement blocks, attributed to the high organic content and variable physicochemical composition of the sludge. Das et al. (2022) highlighted multiple pathways for textile ETP sludge valorization into value-added construction and agricultural products, while Rahman et al. (2014) provided systematic physicochemical characterization of textile ETP sludge and evaluated its performance as a building material constituent. Goyal et al. (2019) studied textile sludge in cement mortar and paste formulations, observing negligible performance loss at up to 5% cement replacement but progressive strength deterioration at higher dosages, attributed to increased porosity and reduced calcium hydrosilicate (C-S-H) gel formation.

With respect to tannery sludge specifically, Malaiškienė et al. (2019) reported that 6% cement substitution improved both flexural and compressive strength of mortar and reduced water absorption, effects attributed to a denser C-S-H microstructure, while dosages exceeding 6% produced the opposite effect. Basegio et al. (2002) established the environmental and technical feasibility of incorporating up to 10% tannery sludge in ceramic clay products. Jothilingam et al. (2023) produced sustainable bricks using tannery sludge as a principal additive with satisfactory compressive performance, and Juel et al. (2017) confirmed the sustainable application of tannery sludge in Bangladeshi brick manufacturing. More recently, Chowdhury et al. (2024) conducted a comprehensive comparative evaluation of textile ETP and tannery sludges in cement mortar, both individually and in binary combination, at 5–20% replacement by weight, finding that up to 10% substitution yielded mortar meeting S-type classification, while 20% textile ETP sludge was compatible with N-type applications. Sunmathi et al. (2025) further validated tannery sludge in M20–M30 grade concrete, confirming adequate mechanical performance at optimized replacement levels.

Beyond sludge-specific studies, there is a broader consensus that industrial by-product valorization in cementitious matrices generates co-benefits: reduced raw material extraction, lower embodied carbon, and mitigation of disposal-related environmental impacts (Junaid et al., 2022; Scrivener et al., 2018). Arisiketty and Vijayarengan (2024) synthesized the state of knowledge on valorization of tannery, water treatment plant, and textile sludges across cement, concrete, and brick production, underscoring the multi-sectoral relevance of this approach. Zhan et al. (2020) provided mechanistic insight into physicochemical interactions between textile ETP sludge and cement paste, revealing the retarding effects of organic compounds and chromium species on hydration kinetics. Patil et al. (2022) reviewed the state of the art on sustainable building materials using textile ETP sludge, emphasizing that leachability, heavy metal stabilization, and long-term durability require systematic characterization before field deployment. Nayak et al. (2022) provide a useful performance benchmark through their review of fly ash concrete, offering comparative insights into SCM behavior in cementitious matrices. Despite this growing evidence base, a significant research gap persists regarding the specific behavior of textile and tannery sludges generated in Cameroon. Sludge physicochemical properties vary considerably as a function of local raw materials, process chemicals, and effluent treatment practices, meaning that findings from South Asian or European industrial contexts cannot be directly extrapolated to Central African conditions. Furthermore, the combined use of textile and tannery sludge in a single concrete mix, which could leverage complementary chemical profiles and increase material availability in scenarios where one sludge type is scarce, has not been comprehensively investigated. The present study therefore addresses this gap by evaluating the workability, compressive strength, and water absorption of concrete specimens incorporating locally sourced textile sludge, tannery sludge, and their binary combination as partial cement replacements at 0%, 5%, 10%, 15%, and 20% by weight, cured at 22°C over 3, 7, and 28 days, using materials from industrial facilities in Cameroon.

2. MATERIELS AND METHODES

2.1 Materials

The Textile and tannery sludge samples were collected from industrial facilities in Bamenda using clean, non-reactive plastic containers where generated from the processing of hides and cottons and constitutes both solid and wastewater. Water used in the processing of leather is between 25 to 60 cubic liters per ton of fresh leather. Generally, about 400 Kg of chemicals is being used per ton of leather, and these chemicals are dissolved in process water which generates effluent with a high concentration of organic matter and inorganic mater (sulfides, sulfate, chromium, chloride and ammonium). Solid waste from these industries, consist of salt, tanned leather shavings and trimming, shredded cotton, remains of chemical products and their containers. Samples were homogenized for consistency by removing contaminants like plastics and metal debris before transported to the lab for analysis. The cement and sand used in the mortar mixes were subjected to standard preliminary tests, including normal consistency of cement and sieve analysis of sand. Three types of sludge-based cement mortars. To evaluate the quality of the cement-sludge mortar, tests for initial and final setting time, compressive strength, tensile strength, and water absorption were conducted in accordance with relevant standards. Aggregate samples were similarly collected using clean equipment and labeled bags. The aggregates and sludge were characterized to evaluate their suitability for concrete, focusing on chemical and physical properties that affect workability, strength, and setting time.

2.2 Methodology

Figure 1 below outline the methodology adopted to study the physiochemical properties of both tannery and textile sludge, evaluate the properties of concrete, and determine the maximum optimal proportion of cement, sand, water, and sludge to be combined without compromising the quality of concrete mixed. Finally, to evaluate the physical and mechanical properties of the sludge-concrete specimens for real time exploitation in the construction industry in Cameroon.

2.2.1 Collection of samples

Sludge collection: the textile and tannery sludge was obtained from local facilities that generate this waste within Bamenda municipality. The samples were collected using clean non-reactive plastic containers from different areas of the sludge storage to ensure a representative composition. Once the samples are collected, visible contaminants such as plastics, metal debris should be removed before transported to laboratory for analysis.
Aggregate collection: trowels and bags where the non-contaminant equipment's used in collecting the aggregate samples were washed to eliminate contaminants. Meanwhile, a label was added to each of the bags for identification purpose before transported to the laboratory for further analysis.

2.2.2 Characterization of Materials

Understanding the physicochemical properties of the aggregates to be used for concrete production is an important step in ensuring the quality and the performance of the resulting concrete. These may influence the workability, strength and setting time of the resultant sludge mixed concrete. To characterize the aggregates a few set of tests are to be carried out.

Textile and Tannery dry sludge:

To estimate the moisture content, the weight of a clean and dry container was taken, and recorded as W_1, a portion of the sludge sample was transferred into the pre-weighted plate, and the weight of the plate + sludge recorded as W_2, oven dry for 105ºC for a duration for 24 hours. After the drying and cooling of the samples, a new W_3 is recorded. The process is repeated for both samples in order to eliminate errors. Equation 1 below is an extract that showcase the experimental model used to estimate the moisture content. Table 1 also outlines the characterization of the sludge used as 20% replacement of cement in concrete production as shown in figure 2.

$$\textbf{Moisture content (\%)} = (W2 - W3)/(W2 - W1)\times 100 \qquad (1)$$

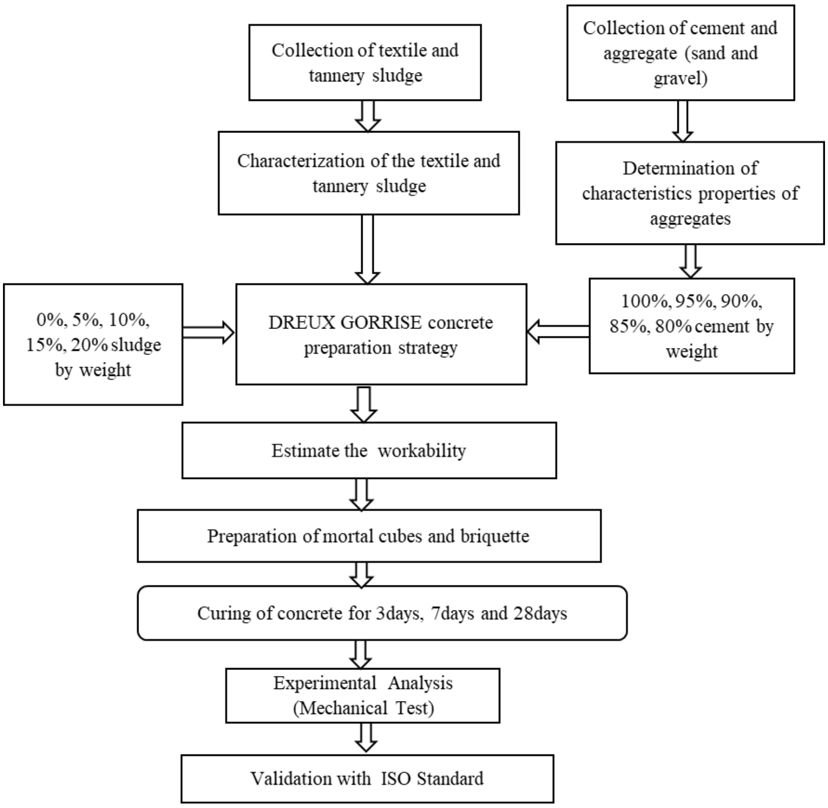

Figure 1: Flow diagram of the methodology adopted for the study.

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Table 1: Characterization of Textile and Tannery Sludge

No.	Parameter	% in textile sludge	% in tannery sludge
1	Ketone	30	23
2	Benzene	11	14
3	Ethylbenzene	6	10
4	Tannins (Phenol)	-	11
5	Dispersed dyes	30	27
6	Solvent (aceton)	6	7
7	Aldehydes	2	9
8	Triglycerides	5	5
9	Tannins polyphenol	4	7
10	Organic Content	58.22	62.08
11	pH	6.02	8.88

Figure 2: An eye shot of oven dried-textile sludge.

The pH of the textile and tannery sludge samples was determined using a simple colorimetric method with litmus paper. Small amounts of sludge were placed on a clean ceramic plate, and both red and blue litmus papers were immersed in the samples. After removal, the color changes were compared to a standard chart. The test was repeated with fresh strips to confirm the results. The study used the Loss-on-Ignition (LOI) method to determine the organic content of textile and tannery sludge. Sludge samples were first oven-dried at 70°C (to prevent organic loss), weighed (W1), and then ignited at 600°C for 3 hours. After cooling, the remaining weight (W2) was measured, and organic content was calculated using equation 2.

$$\text{Organic content (\%)} = (W1 - W2) / W1 \times 100 \qquad (2)$$

For organic compound analysis, samples underwent liquid-liquid extraction and were analyzed using gas chromatography (GC) with a flame ionization detector (FID). The GC was calibrated, and appropriate columns were selected based on compound properties. The temperature was gradually increased to separate compounds by volatility, and their concentrations were detected during elution. The Natural Moisture Content Test was conducted to determine the moisture content of the aggregates and assess whether additional water would be required during concrete mixing. Aggregates were first weighed in their natural state, then oven-dried at 105°C for 24 hours, and weighed again. The moisture content was calculated based on the weight difference.

Aggregates (Sand and Gravel):

The characterization of aggregates plays a vital role in concrete formulation as they account for approximately 60-80 % of the total volume of the concrete material. The specific density and the rate of water absorption of the sand and gravel were estimated because the nature of the environment as it varies their increase/decrease in weight (figure 2). Also, the extern of absorption varies from one aggregate to another, depending on the nature of the material. The granulometric analysis of the aggregates (sand and gravel) was done following the Dreux and Fester in 1998 method, this method consists of dividing the aggregate into several categories base on particle sizes. Table 2, 3 and 5 are extracts that portrays the granulometric nature of the various aggregate.

Figure 3: Aggregate density measurement.

Table 2: Sieve size analysis for gravel (5/15).

No.	Sieve size (mm)	mass retained (g)	Cumulative retained (%)	Cumulative sieveage (%)
1	20	0	0	100
2	16	34.3	1.2	98.8
3	14	138.5	4.8	95.2
4	12.5	182.4	6.3	93.7
5	10	966.5	33.3	66.7
6	8	170.2	58.7	41.3
7	6.3	224.0	77.3	22.7
8	5	255.4	88.1	11.9
9	4	283.4	97.8	2.2
10	2.5	286.3	98.8	1.2
11	2	286.5	98.9	1.1

Table 3: Sieve size analysis for gravel (15/25).

No.	Sieve size (mm)	mass retained (g)	Cumulative retained (%)	Cumulative sieveage (%)
1	50	0	0	100
2	40	1331.5	8	92
3	31.5	1884.6	35	65
4	25	4900	75	25
5	20	15312.5	92	8
6	16	15312.7	99.2	0.8

Table 4: Sieve analysis on sand.

No.	Sieve size (mm)	Cumulative retained (%)	Cumulative sieveage (%)
1	8	0	100
2	6.3	1	99
3	3.15	3	97
4	2.5	8	92
5	2	12	88
6	1.6	119	81
7	1	43	57
8	0.63	72	28
9	0.5	80	20
10	0.4	92	8
11	0.315	94	6
12	0.25	98	2
13	0.06	99	1

With the above information on the particle size distribution:

Fineness modulus (M_f) = cumulative % of retained /100 **(1)**

Giving an M_f value of 3.53, the following observations to estimate the specific and the apparent densities are obtained after analysing the characteristics component of the aggregates (table 5 and 6).

Table 5: Specific density of aggregate.

No.	Aggregate type	Observation
1	Sand (Wum sand)	2.474
2	Aggregate (5/15)	2.821
3	Aggregate (15/25)	2.772

Table 6: Apparent density of aggregate.

No,	Aggregate type	Observation
1	Sand	1.44
2	Gravel (5/15)	1.85
3	Gravel (15/25)	1.82

2.2.3 Formulation of Concrete Specimen

Water/Cement Ratio

To determine the water/cement ratio of concrete, knowledge of the targeted compressive strength of the concrete, the quality and the maximum grain size of the aggregates, and the true class of the cement is used. Since the distribution of the compressive strength of concrete follows the natural, the targeted resistance is 25MPa with an

average coefficient of variation of about 15%, the average resistance of our concrete material produced will be calculated (equation **3**):
Where:

G: *is the granular coefficient of the aggregate,*
F_{ce} *: is the cement class, label on the cement,*
F_{cm} *:is the average targeted resistance of the concrete after 28 days.*

$$C/E = F_{cm} / (G * F_{ce}) + 0.5 \qquad (3)$$

$$F_{cm} = f_c(28) \times 1.15$$

Cement/Water Dosing

The cement and water dosage was deduced from the C/E graph as a function of the slum Dreux and fester 1998. Our objective is to obtain ordinary plastic concrete of class S2 with a consistency between 50mm and 90mm, for this studies a slump of 80mm was chosen which leads to a cement dosage of C = 275kg/m3. This quantity was corrected taking into consideration the influence of the specific surface of the aggregate (rolled or crushed).

Aggregate and Sludge Dosage

Using the C/E slump graph from Dreux and Fester, an 80 mm slump was chosen, corresponding to S2 class plastic concrete. This yielded a cement dosage of 275 kg/m³, adjusted based on whether the aggregates were rolled or crushed. The fineness modulus (Mf) was then used to further characterize the aggregate mix (equation 4). Based on the cumulative percentage retained, a graph was plotted to determine the AOB point, which helped in assigning the proportion of each aggregate fraction. To explore the use of sludge as a partial cement replacement, five mix variations were prepared with sludge replacing cement by weight at 0%, 5%, 10%, 15%, and 20% (table 6). The selection of sludge proportions was based on its physical characteristics, the targeted concrete performance, and applicable standards. Concrete mixing involved first combining the dry aggregates and cement (or cement-sludge mix), followed by the addition of water (CEN, 2011). The resulting mix was placed into lubricated molds, compacted in layers, and leveled off. Samples were cured at a controlled temperature of 22°C for 3, 7, 14, and 28 days. For testing, (2×2×2) inch concrete cubes and triangular specimens (10 cm × 5 cm) were cast. In total, approximately 10 cement-only cubes and 40 sludge-modified concrete specimens were prepared for compressive strength evaluation.

$$M_f = \text{sum of cumulative \% retained} / 100 \qquad (4)$$

2.2.4 Concrete Testing

To assess workability, a slump test was performed. Concrete was placed in a slump cone in three layers, each tamped 25 times (figure 4a). After striking off the excess and lifting the cone vertically, the slump (the reduction in height) was measured. This test was done on mixes with varying sludge content (textile, tannery, and combinations). Being the primary goal of structural properties of concrete, the Compressive strength of the specimens made with varying sludge proportions were cured for 3, 7, and 28 days. After curing, the specimens were wiped clean and tested using a compressive strength machine (figure 4a). Load was applied gradually until failure, and strength was calculated using: Prepare 10cm X 5cm cubes were tested in a compression test machine and the compressive strength was calculated by using following equation **5**:

$$\sigma = P/A \qquad (5)$$

With:
Σ: *Maximum compressive strength,*
P: *Maximum load carried by the cube before failure and A Cross sectional area of cube.*

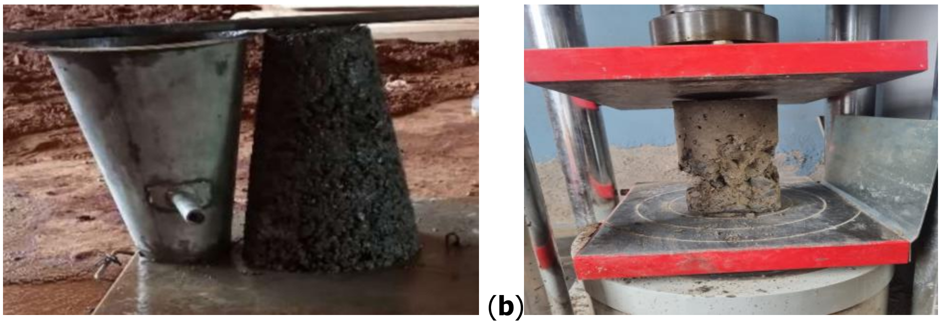
(**a**) (**b**)

Figure 4: setup for a-Abram slump cone spacemen; b- concrete strength test machine.

Table 6: Composition of sludge concrete mix.

No.	Sample	Sludge used	0% replacement by weight	5% replacement by weight	10% replacement by weight	15% replacement by weight	20% replacement by weight
1	Category 1	Textile sludge	0% sludge + 100% cement and aggregates	5% sludge + 95% cement and aggregates	10% sludge + 90% cement and aggregates	15% sludge + 85% cement	20% sludge + 80% cement
2	Category 2	Tannery sludge	0% sludge + 100% cement	5% sludge + 95% cement	10% sludge + 90% cement	15% sludge + 85% cement	20% sludge + 80% cement
3	Category 3	Textile and tannery sludge	0% sludge + 100% cement	2.5% tannery sludge +2.5% textile sludge + 95% cement	5% tannery sludge + 5% textile sludge + 90% cement	7.5% tannery sludge +7.5% textile sludge + 85% cement	10% tannery sludge + 10% textile sludge + 80% cement

Water absorption indicates concrete's porosity and durability. Specimens (10 cm × 5 cm) were oven-dried for 24 hours (figure 5), cooled for 90 minutes, and weighed (W1). They were then submerged in water for 72 hours, surface-dried, and weighed again (W2). Water absorption was calculated using equation 6. These tests were carried out for all three concrete categories: textile sludge, tannery sludge, and a mix of both, at sludge replacement levels of 0%, 5%, 10%, 15%, and 20%.

$$\textbf{Water Absorption (\%)} = [(W2 - W1) / W1] \times 100 \qquad (6)$$

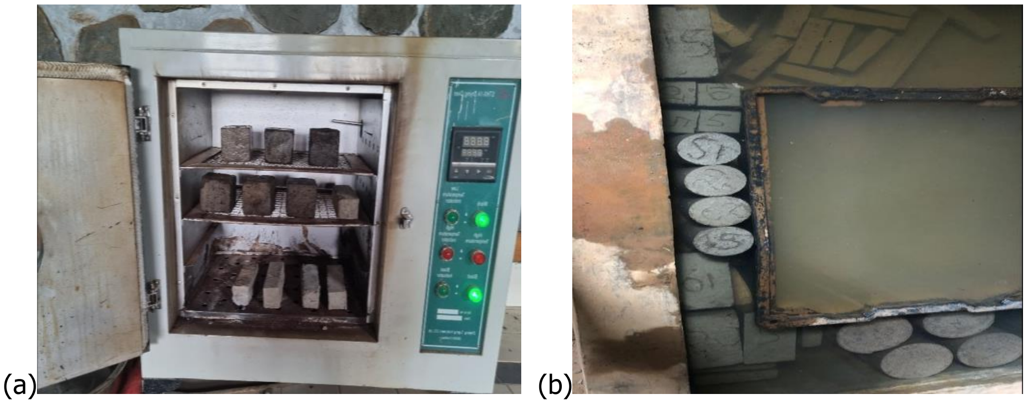

Figure 5: a-Specimen in oven; b-Specimen immersed in water.

3. RESULTS

The result obtained after preparing the concrete mix and allowing it to cure for 3, 7, and 28 days, the workability, compressive strength, and water absorption nature of the sludge concrete specimens are the respective mechanical properties assessed for future valorization of the used of these materials in the construction of agricultural and other building facilities.

3.1 Workability

Since the effortlessly nature of the concrete to be worked in a required shape relies on the attitude at which the concrete is mixed, maneuver, placement and compacted without any mismatch towards inhomogeneity, the slump value targeted for all the batches of concrete is 70 mm. Figure 6 below is an extract that expresses how the workability for the dosage of 1% to 20% of sludge to cement ratio are obtained. However, the workability parameter was observed to decrease slightly with increased sludge content, indicating the need for possible admixture use or water adjustment in future studies. This is in line with the study of Mottakin et al. (2023) who investigated on the utilization of Textile Effluent Treatment Plant Sludge as Supplementary Cementitious Material in Concrete with a slump test results observing that workability decreases with increasing sludge content, and strength remains comparable up to 10% replacement. Inclusively, we can also see that the textile sludge showcase a huge significant workability value as contrast to that of textile and tannery combine, and/or tannery sludge.

3.2 Compressive Strength

Assisting as one of the most important valued added parameter that expresses the capability of a concrete material to resist efforts without rapture, the compressive strength gain after 3, 7 and 28 days of curing for the different percentages of sludge inclusion is being outline in pounds per square inch units (psi) below (figure 7 to 9). The conducted ccompressive strength and adsorption tests were conducted on the produced cubes using fine aggregate partially replaced by textile and tannery sludge.

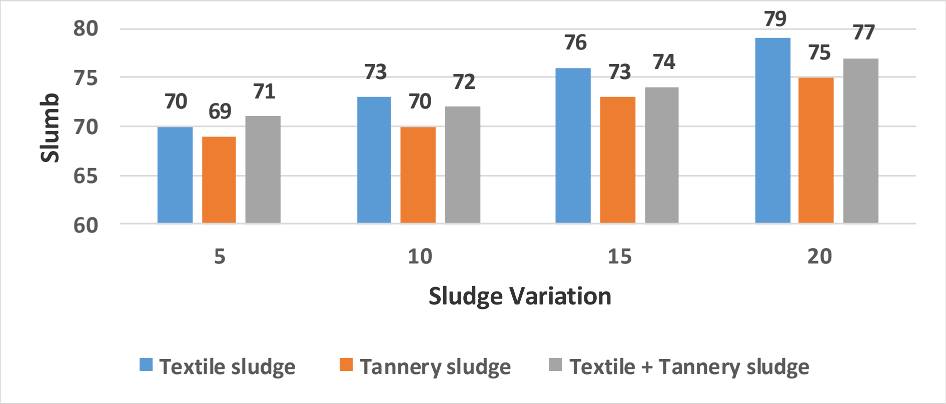

Figure 6: Workability of sludge concrete mix.

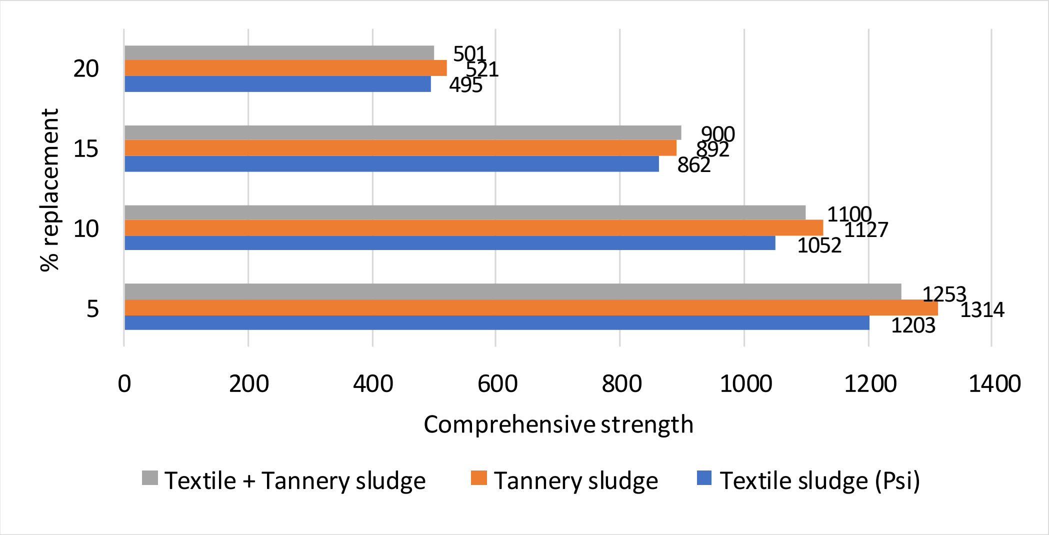

Figure7: Compressive strength of sludge-concrete specimen on the 3rd day

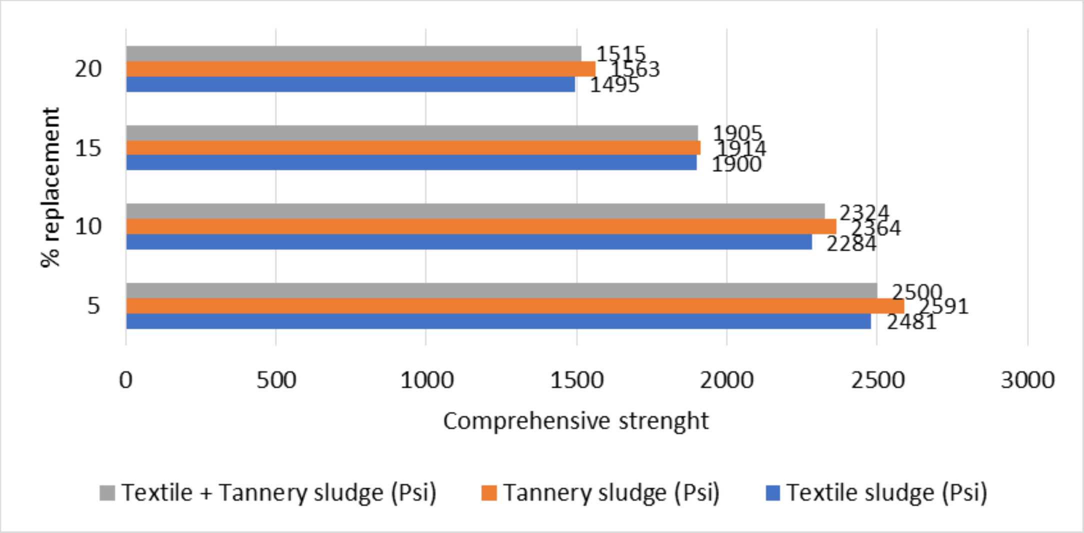

Figure 8: Compressive strength of sludge-concrete specimens on the 7th day

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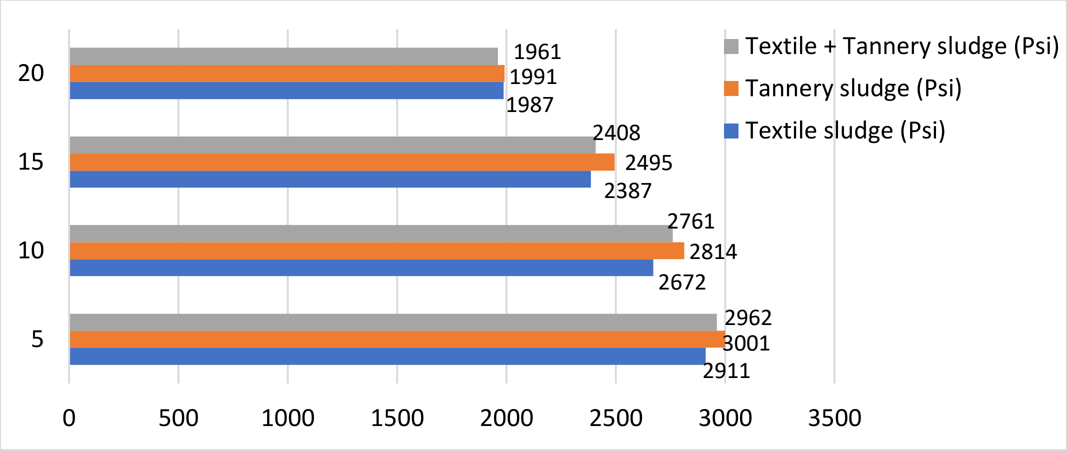

Figure 9: Compressive strength of sludge-concrete specimens in the 28th day.

3.3 Water Absorption and Density

To appraise ability of the suggested concrete material, experimental results indicate a consistent increase in water absorption with rising sludge dosage (figure 10-11). At 5% replacement, absorption ranges from 6.7%–7.3%, while at 20% dosage, absorption rises to 15.7%–16.3%. This trend shows that higher sludge incorporation increases porosity, thereby facilitating greater water ingress into the concrete matrix.

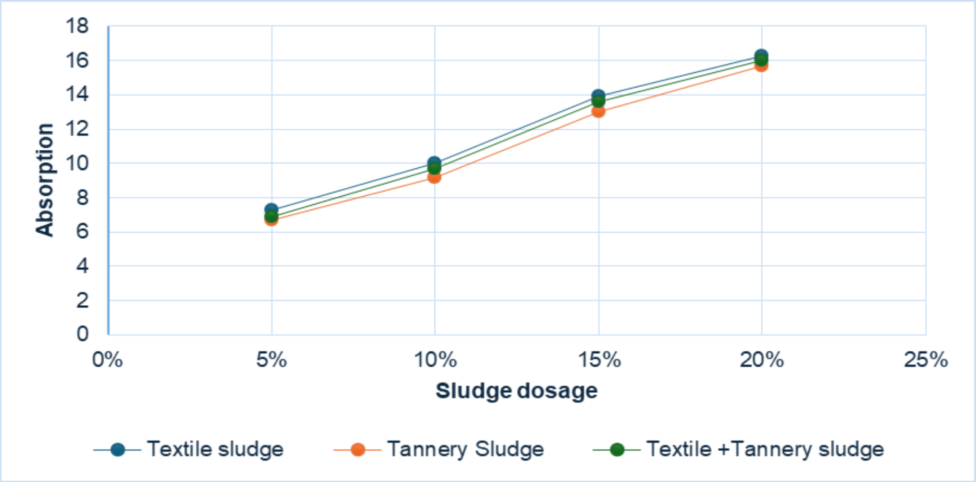

Figure 10: Water Absorption of Specimens after 7 days.

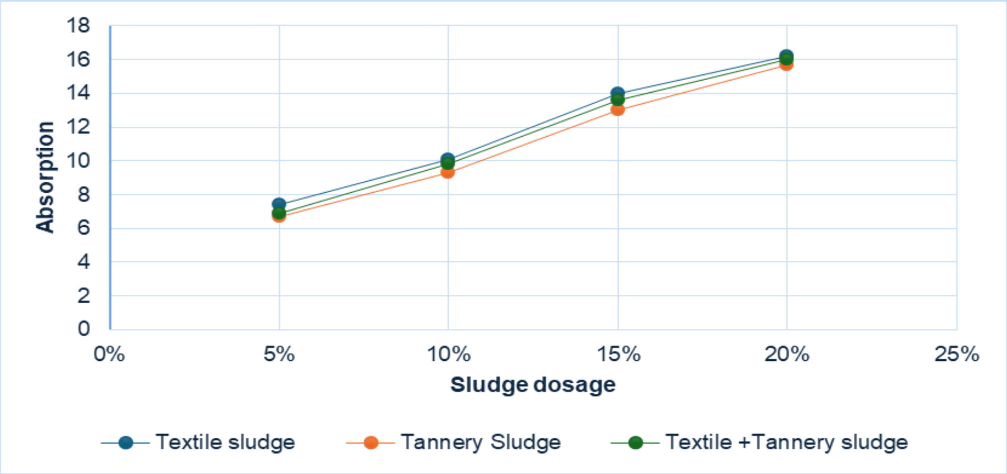

Figure 11: Water Absorption of Specimens after 10 days

4. DISCUSSION

This study demonstrates that partially substituting cement with locally sourced textile sludge, tannery sludge, and their binary combination is technically feasible in concrete production at replacement levels of up to 10–15% by weight, without compromising suitability for non-load-bearing and low-load structural applications. These findings extend the existing evidence base by providing, for the first time, systematic mechanical performance data for Cameroonian industrial sludges in cementitious matrices and by evaluating the combined use of two sludge types within a single concrete mix, a configuration previously unexamined. Three principal domains warrant discussion: (i) mechanical performance outcomes and their underlying mechanisms, (ii) water absorption and durability implications, and (iii) the practical and environmental significance of these findings for the Cameroonian construction context.

4.1 Compressive Strength: Mechanisms Underlying Sludge-Induced Strength Reduction

The progressive decrease in compressive strength with increasing sludge substitution is consistent with mechanistic trends reported widely in the literature. At 28 days, mixes incorporating 5–15% sludge remained close to the target comprehensive strength and within the performance envelope for lightweight concrete blocks (1500–4000 psi), whereas 20% substitution lowered strength below 2500 psi—below acceptable limits for most non-structural applications. This dose–response behavior is attributable to four interacting mechanisms.

First, the high moisture content of sludge modifies the effective water-to-cement ratio. Industrial sludge retains residual water even after oven-drying at 105°C, meaning that when added to a mix formulated at a fixed water-to-cement ratio, the actual free water in the system is higher than designed, diluting the hydration products and increasing porosity (Zhan et al., 2020). Second, the elevated organic content of both sludge types, 58.22% for textile sludge and 62.08% for tannery sludge, as determined by loss-on-ignition, interferes with cement hydration kinetics. Organic compounds, particularly ketones, aldehydes, tannins, and dispersed dyes identified in the GC-FID analysis, are known to retard the formation of calcium silicate hydrate (C-S-H) gel, the principal strength-contributing phase in hydrated cement paste (Goyal et al., 2019; Zhan et al., 2020). Third, poor particle packing resulting from the irregular morphology and broad particle size distribution of the sludge creates interstitial voids that cannot be filled by hydration products, reducing the bulk density of the cementitious matrix. Fourth, the chemical heterogeneity of the sludge, including sulfate-bearing compounds from tannery processing, may generate expansive ettringite formation during later hydration stages, destabilizing the microstructure at higher replacement levels (Malaiškienė et al., 2019; Chowdhury et al., 2024).

Early-age strength (3 and 7 days) was particularly sensitive to sludge incorporation, consistent with the strong retarding action of organic compounds during the acceleration phase of hydration (Goyal et al., 2019). By 28 days, this effect partially dissipated as the cement fraction completed hydration, explaining the relatively higher later-age strengths. This age-dependent recovery has practical implications: concrete containing sludge should not be remolded or loaded at early ages, and a minimum 28-day curing period is recommended before assessment or service loading.

Comparing the three sludge categories, the combined textile–tannery binary mix performed comparably to single-sludge mixes, with no systematic synergistic or antagonistic effect on compressive strength. This finding is of practical significance: it confirms that operators in Cameroon can use whatever sludge combination is available at a given facility without major performance trade-offs, as long as the total substitution level is maintained within the 10–15% envelope. The absence of a synergistic effect also suggests that the mechanisms governing strength reduction in each sludge type are independent and additive rather than chemically interactive, a hypothesis that merits future confirmation by microstructural analysis (SEM/XRD) and isothermal calorimetry. These results align with Chowdhury et al., (2024), who found that textile ETP and tannery sludges in cement mortar could substitute up to 10% of cement without compromising S-type mortar performance, and with Sunmathi et al., (2025), who confirmed adequate mechanical behaviour of tannery sludge-modified M20–M30 grade concrete at optimized replacement ratios. They also corroborate the findings of Goyal et al. (2019), who identified 5% as the optimal replacement threshold in mortar systems, and of Mottakin et al., (2023), who reported comparable strength at up to 10% replacement in concrete. The slightly higher optimal threshold observed in the present study (10–15% versus 5–10% in mortar-based studies) likely reflects differences in the aggregate matrix: in concrete, the heterogeneous aggregate structure provides additional mechanical interlocking that partially compensates for the weakened cementitious paste phase, a phenomenon consistent with established composite mechanics theory (Neville, 2011).

4.2 Workability: Implications for Mix Design and Field Application

The decline in workability with increasing sludge content, reflected in the progressive reduction in slump from 77 mm at 0% to lower values at higher replacement levels, is attributable to the fine-particle nature of the sludge and its significant water absorption capacity. Sludge particles, particularly those derived from textile dyeing processes, contain hydrophilic dyes, organic fibres, and surfactant residues that compete with cement paste for available free water, reducing the lubrication effect of the paste phase and increasing the viscosity of the fresh mix (Goyal et al., 2019; Patil et al., 2022). The lower workability of tannery sludge mixes relative to textile sludge mixes is consistent with the higher chromium and sulfide content of tannery sludge, which may promote faster partial stiffening of the paste. From a practical standpoint, all mixes in this study remained within workability ranges compatible with normal reinforced concrete (slump > 50 mm), suggesting that sludge-amended concrete can be placed and compacted using standard construction equipment, particularly under light to moderate reinforcement densities. However, at 20% substitution, the proximity to the lower workability limit suggests that admixture use, specifically plasticizers or superplasticizers, may be required to maintain constructability in field conditions, particularly in Cameroon's hot-season temperatures where evaporative water loss during transport and placement is significant. This recommendation is consistent with Mottakin et al., (2023) and Chowdhury et al., (2024), both of whom noted that chemical admixtures could extend the viable replacement range without strength penalty.

4.3 Water Absorption and Durability: Critical Assessment

The consistent and dose-dependent increase in water absorption, from 6.7–7.3% at 5% replacement to 15.7–16.3% at 20%, is among the most clinically relevant findings of this study from a long-term durability perspective. Water absorption is the primary indicator of concrete porosity, and elevated porosity accelerates every major deterioration mechanism, including carbonation-induced corrosion of reinforcement, sulfate and chloride ion ingress, alkali–silica reaction, and freeze–thaw damage (Neville, 2011; Zhan et al., 2020).

The higher absorption of textile sludge mixes relative to tannery sludge mixes at equivalent replacement levels is mechanistically explicable by the finer particle distribution and higher organic fibre content of textile sludge. Organic fibres act as water-retaining agents within the hardened matrix, creating capillary pore networks that facilitate water ingress after specimen drying (Goyal et al., 2019; Patel & Pandey, 2012). The intermediate absorption values of the combined binary mix, recorded at 13.6% at 15% dosage, between the textile (13.9%) and tannery (13.0%) values, suggest that mixing the two sludge types achieves a balanced compromise in pore structure, offering the operator a degree of predictability in durability performance. The attainment of absorption saturation by day 7, evidenced by the negligible difference between 7-day and 10-day absorption measurements, indicates that the pore network is relatively rapidly accessible to water. This is a characteristic feature of highly porous, poorly interconnected capillary matrices and confirms the importance of restricting sludge dosage to ≤10% in applications where durability is a primary concern. At this threshold, absorption values of 6.7–8.5% are consistent with the performance range documented for non-structural concrete blocks in tropical and semi-acid environments (Balasubramanian et al., 2006; Jothilingam et al., 2023).

The durability implications of these results are directly applicable to the target applications identified in this study, agricultural and low-rise building structures in Cameroon. In this context, exposure to cyclic wetting and drying, moderate biological attack, and occasional chemical exposure from agricultural fertilizers and pesticides represent the primary durability challenges. For these applications, a water absorption ceiling of ≤10% is recommended, corresponding to sludge replacement levels of ≤10% based on the present data. Above this threshold, the risk of accelerated deterioration, particularly at structural connections and reinforcement cover zones, increases substantially.

4.4 Environmental and Socioeconomic Significance

The environmental benefits of this valorization pathway extend well beyond mechanical performance. Textile and tannery industries in Cameroon produce tens of thousands of tonnes of sludge annually in major centers such as Bamenda, Douala, and Garoua (Veronica et al., 2008). This sludge is typically landfilled without engineered containment, posing serious risks due to heavy metal leaching particularly carcinogenic Cr(VI) from tannery waste (Patel & Pandey, 2012; Zhan et al., 2020). Incorporating sludge into concrete encapsulates heavy metals within a stable matrix, providing simultaneous waste immobilization and resource recovery, benefits particularly valuable where enforcement of waste treatment regulations is limited (Das et al., 2022; Patil et al., 2022). Economically, cement is costly in Cameroon, heavily influencing project affordability. A 10–15% reduction in cement consumption represents a meaningful cost saving for small contractors, with benefits for affordable housing and agricultural infrastructure (Arisiketty & Vijayarengan, 2024; Junaid et al., 2022). Additionally, reduced cement demand and reduced landfill dependency contribute to Cameroon’s National Development Strategy 2030 and Paris Agreement commitments. That said, carbon benefits must be assessed against the energy required for sludge drying and transport; a full life-cycle assessment is needed to quantify net gains.

4.5 Limitations and Directions for Future Research

Several limitations of the present study must be acknowledged to contextualize the findings appropriately. First, the study does not include microstructural characterization by scanning electron microscopy (SEM) or X-ray diffraction

(XRD), which would have provided direct mechanistic evidence for the pore structure changes and hydration product modifications inferred from macroscopic performance data. Future studies should incorporate these techniques to validate the proposed mechanistic explanations (Malaiškienė et al., 2019; Zhan et al., 2020). Second, leachability testing, particularly for hexavalent chromium, arsenic, and lead from the tannery sludge fraction, was not conducted. This is an important omission given that heavy metal mobilization from sludge-amended concrete during its service life and at end-of-life represents a potential environmental and public health risk (Patel & Pandey, 2012; UNIDO, 2018). Third, the study evaluated only short-term mechanical performance (up to 28 days); long-term durability under conditions representative of Cameroonian service environments, including elevated temperature, humidity cycling, and chemical exposure from agricultural activities, remains uninvestigated. Fourth, tensile strength, flexural strength, and elastic modulus were not evaluated, limiting the scope of mechanical characterization (ASTM C496, 2007). Fifth, the influence of chemical admixtures such as plasticizers, pozzolanic activators, or nano-SiO_2 was not studied; existing research suggests these could significantly extend viable replacement levels (Rao et al., 2023; Mottakin et al., 2023). Sixth, although the Dreux–Gorisse method is suitable in Cameroon, the absence of ISO/ASTM reference mixes limits international comparability. Future work should therefore include parallel EN 206 or ASTM C39 reference designs.

Based on these limitations, the following research priorities are identified: (i) systematic leachability and eco-toxicological assessment of sludge-amended concrete, including column leaching tests and Toxicity Characteristic Leaching Procedure (TCLP); (ii) microstructural and mineralogical characterization by SEM-EDX and XRD at multiple replacement levels; (iii) long-term durability assessment under accelerated carbonation, sulfate immersion, and freeze–thaw cycling conditions; (iv) LCA of the full valorization pathway from sludge generation to concrete production and end-of-life; and (v) pilot-scale field trials in agricultural and low-rise residential construction in Bamenda and other Cameroonian industrial centres, incorporating real-time performance monitoring.

5. CONCLUSION

This study confirms that textile sludge, tannery sludge, and their binary combination can serve as technically viable partial replacements for cement in concrete at substitution levels of 10–15% by weight, without compromising suitability for non-load-bearing applications, agricultural structures, and low-rise wall construction. At these dosages, 28-day compressive strength remains within the performance range for lightweight concrete blocks (1500–2500 psi), water absorption is maintained below 14%, and workability remains adequate for standard construction practices. At 20% substitution, however, both mechanical and durability performance decline markedly, and this level is therefore not recommended for structural or semi-structural applications.

The binary combination of textile and tannery sludge performs comparably to the single-sludge mixes, demonstrating the operational flexibility of the approach in contexts where one sludge type may be intermittently available or produced in limited quantities. The environmental significance of this valorization pathway is multi-faceted: it reduces cement consumption and associated CO_2 emissions, provides a technically robust alternative to landfilling or incinerating hazardous industrial sludge, and supports the development of sustainable, locally adapted construction materials within Cameroon.

The study highlights several priority areas for future research, including comprehensive leachability testing, detailed microstructural analysis, long-term durability evaluation under representative exposure conditions, life-cycle assessment, and pilot-scale field demonstrations. Further investigation into the use of chemical admixtures to expand the performance window of sludge-amended concrete is also warranted. Successful large-scale implementation of this valorization strategy will require coordinated efforts among industrial waste producers, construction-material manufacturers, and regulatory authorities to establish appropriate technical standards and certification frameworks suited to the Cameroonian regulatory environment.

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