Research Article

Journal of
Environmental
Nanotechnology

Balancing Sustainability and Strength: Analyzing the Effects of Textile, Tannery, and Water Treatment Sludge on Brick Performance

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Received: 27.06.2024 Accepted: 12.09.2024 Published: 30.09.2024
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ABSTRACT

This study investigates the feasibility of incorporating various industrial waste materials, specifically textile sludge, tannery sludge, and water treatment plant sludge, in brick production as a sustainable construction practice. The research analyses the impact of varying sludge proportions on the compressive strength of fired clay bricks. Results indicate an inverse relationship between increasing sludge content and compressive strength across all types. Bricks incorporating higher proportions of textile sludge exhibited a linear decrease in compressive strength, ranging from 0.1 MPa to a low of 0.005 MPa. Similarly, increasing the ratio of tannery sludge to fly ash Class C and Ground Granulated Blast-furnace Slag within the brick mixture consistently corresponded with reduced compressive strength, with a 5:70:25 mix yielding 0.8 MPa and a 40:30:30 proportion resulting in 0.17 MPa. Water treatment plant sludge exhibited a similar trend. A mix proportion of 5:70:25 (sludge: fly ash class C: GGBS) yielded a compressive strength of 1.87 MPa while increasing the sludge proportion to 40:50:10 resulted in a lower compressive strength of 1.20 MPa. These findings underscore the importance of a balanced approach when incorporating industrial sledges in brick production. While beneficial from a sustainability perspective, the observed reduction in compressive strength, particularly compared to conventional clay bricks exceeding 2.5 MPa, necessitates careful consideration. Future research should focus on optimizing mix designs, incorporating performance-enhancing additives, or identifying applications where lower compressive strengths are acceptable to fully realize the potential of these waste materials in sustainable construction.

Keywords: Industrial waste utilization; Sustainable construction; Textile sludge; Tannery sludge; Brick production.

1. INTRODUCTION

The global construction industry, a colossal engine driving economic growth and societal development, faces a critical juncture. While it stands as a pillar of modern civilization, responsible for shaping our built environment and providing essential infrastructure, the industry grapples with a complex web of challenges (Benachio *et al.* 2020). Foremost among these is the environmental impact of its activities, demanding a paradigm shift towards sustainable practices. Traditional construction methods rely heavily on resource-intensive materials and processes, contributing significantly to energy consumption, greenhouse gas emissions, and waste generation (Bilal *et al.* 2020). The extraction, manufacturing, and transportation of conventional building materials, such as concrete and steel, carry a substantial environmental burden (Chamasemani *et al.* 2023; Keerthana *et al.* 2024). Moreover, the industry's reliance on finite natural resources raises concerns about resource depletion and ecosystem degradation (Al-Numan *et al.* 2024). In response to these mounting concerns, sustainable construction has emerged as a guiding principle for the industry's future (Rajesh *et al.* 2024). Sustainable construction advocates for a holistic approach that minimizes the environmental footprint of buildings throughout their entire lifecycle, from material sourcing and construction to operation and eventual demolition (Al-Numan *et al.* 2024).

Central to this paradigm shift is the adoption of circular economy principles. Unlike the traditional linear model of "take-make-dispose," a circular economy promotes a closed-loop system that prioritizes resource efficiency, waste reduction, and material reuse. In construction, this translates to minimizing virgin material consumption, maximizing the lifespan of buildings and components, and diverting waste from landfills through reuse and recycling (Kandpal *et al.* 2024).

One promising avenue for advancing sustainable construction practices is using industrial byproducts as alternative construction materials. Industries worldwide generate vast quantities of byproducts, many of which hold untapped potential as valuable resources in construction applications. These byproducts, often treated as waste and destined for landfills, can substitute conventional building materials, reducing the demand for virgin resources and mitigating the environmental impact of their extraction and processing. Among the numerous industrial byproducts with potential applications in construction, textile sludge, tannery sludge, and water treatment plant sludge have garnered significant attention. These byproducts, generated in substantial quantities by their respective industries, pose significant environmental challenges if not managed responsibly. Finding the optimal proportions of materials in mixtures for applications like the sludge-based bricks described can be complex and time-consuming. The complexity is influenced by the number of variables and desired performance criteria. However, statistically designed experiments and analysis methods can help simplify this process and make it more efficient (Srinivasan *et al.* 2024).

The textile industry, a significant contributor to the global economy, generates substantial amounts of wastewater during its various processing stages. Textile sludge, a byproduct of textile wastewater treatment, comprises a complex mixture of organic and inorganic components, including fibres, dyes, chemicals, and heavy metals (Testolin *et al.* 2021). The improper disposal of textile sludge can contaminate soil and water resources, posing risks to human health and ecosystems. However, textile sludge also presents an opportunity for resource recovery. Its composition, rich in organic matter and fibres, suggests potential applications as a sustainable alternative to conventional building materials. Researchers have explored its incorporation into bricks, concrete, and other construction materials, aiming to reduce the environmental footprint of these materials while providing a viable disposal solution for textile waste (Jamshaid *et al.* 2024).

The leather tanning industry, essential for producing leather goods, generates significant amounts of tannery sludge during its processing operations. Tannery sludge, a complex mixture of organic and inorganic compounds, including chromium, tannins, and proteins, poses significant environmental risks if not managed appropriately (John Louis *et al.* 2024). Its disposal in landfills can lead to soil and water contamination, threatening human health and ecosystems (Sampathkumar *et al.* 2024). Recognizing the environmental challenges associated with tannery sludge disposal, researchers have investigated its potential as a resource for sustainable construction (Sunmathi *et al.* 2023). Studies have explored its incorporation into bricks, concrete, and other building materials, aiming to reduce the environmental impact of these materials while providing a beneficial use for this industrial byproduct. Water treatment plants, essential for safe drinking water, generate substantial amounts of sludge as a byproduct of their treatment processes. Water treatment plant sludge, a complex mixture of organic matter, inorganic compounds, and microorganisms, requires careful management to prevent environmental pollution (Ahmad *et al.* 2017). Traditionally, it has been disposed of in landfills, but this practice raises concerns about landfilling capacity and potential environmental risks (Siddiqua *et al.* 2022). However, water treatment plant sludge also presents an opportunity for resource recovery. Its composition, rich in organic matter and inorganic compounds, suggests potential applications as a sustainable alternative to conventional building materials. Researchers have explored its incorporation into bricks, concrete, and other construction materials, aiming to reduce the environmental footprint of these materials while providing a viable disposal solution for water treatment plant sludge (Davydov *et al.* 2023).

This research focuses on the comparative analysis of textile, tannery, and water treatment plant sludge as alternative materials in brick production. The present research addresses these knowledge gaps by conducting a comprehensive comparative analysis of textile, tannery, and water treatment plant sludge in brick production. The study will investigate:

- Analyze each sludge type's physical and chemical properties, identifying key parameters influencing brick properties and potential environmental concerns.
- Evaluate the individual impact of each sludge type (at various replacement levels) on the mechanical (compressive strength) and physical (water absorption, efflorescence) properties of fired bricks.
- Determine optimal combinations and proportions of the three sludge types to achieve desired brick properties while minimizing potential drawbacks (e.g., heavy metal leaching).
- Evaluate the environmental impact of using these sludge-based bricks compared to conventional bricks, considering factors like embodied energy and leaching potential.
- The research addresses a significant gap in the existing literature by conducting a comprehensive comparative analysis of these three sludge types in brick manufacturing.

2. MATERIALS AND METHODOLOGY

2.1 Textile Sludge

Textile sludge, a byproduct of textile manufacturing, often contains fibres, organic matter, and potential chemical residues. The fibers can act as reinforcement within the brick, potentially enhancing its tensile and flexural strength, making it more resistant to cracking under bending or pulling forces (Guo *et al.* 2024). The organic matter can increase the brick's porosity, which can be beneficial for insulation as the trapped air pockets help regulate temperature (Koçyiğit, 2022). The textile sludge used in this study (Fig. 1) is collected from a textile industry in Chennai. Table 1 shows the physio-chemical properties of textile sludge.

Fig. 1: Textile sludge

Table 1. Physio–chemical properties of textile sludge (Velumani *et al.* 2016)

Property	Value	Property	Value
Colour	Brown	Copper	87.35 mg/kg
pH	9.16	Chromium	34.36 mg/kg
Specific gravity	2.4	Zinc	82.65 mg/kg
Total solids	97.22	Nickel	30.80 mg/kg
Total volatile solids	7.78	Lead	101.13 mg/kg
Cadmium	Below determination level (BDL)		

2.2. Tannery Sludge

Tannery sludge, generated during leather processing, typically contains organic matter, chromium compounds, and potentially other minerals. The organic matter, similar to textile sludge, can influence the brick's porosity and insulation properties. However, managing the potential for shrinkage or uneven burning during firing is crucial due to the decomposition of organic matter. While chromium compounds present potential environmental concerns, in controlled amounts and with proper treatment, they might contribute to the brick's colour and potentially enhance its durability. The tannery sludge utilized for this study, collected from a leather industry located in Chennai, is shown in Fig. 2. Table 2 shows the physio-chemical properties of tannery sludge.

Table 2. Physio–chemical properties of tannery sludge

Property	Value	Property	Value
pH	7.23	Potassium	261.22 mg/kg
Dried matter	40.21%	Chromium	11723.84 mg/kg
Organic matter	36.69%	Zinc	3412.94 mg/kg
Phosphorus	51.33 mg/kg	lead	40.21 mg/kg
Nitrogen	2597.32 mg/kg		

Fig. 2: Tannery Sludge

2.3 Water Treatment Plant Sludge

Water treatment plant sludge, a result of water softening processes, often contains aluminum, lime, iron compounds, organic matter, and potentially sand or silt. The aluminum, lime, and iron compounds contribute to the brick's strength and durability. Organic matter, with other sludge types, influences porosity and insulation properties. Table 3 illustrates the physio-chemical properties of water treatment plant sludge, as shown in Fig. 3, which was collected from a water treatment plant in Chennai for this study.

Fig. 3: Water treatment plant sludge

Table 3. Physio–chemical properties of water treatment plant sludge (Andrade *et al.* 2019)

Property	Value	Property	Value
Volatile matter	43.5%	Fluorine	0.101 mg/L
Total Suspended solids	<2%	Mercury	0.0022 mg/L
Density	0.858g/cm^3	Silver	<0.002 mg/L
Arsenic	0.006 mg/L	Copper	< 0.006 mg/L
Aluminium	102 mg/L	Zinc	0.039 mg/L
Barium	0.202 mg/L	Lead	<0.004 mg/L
Cadmium	<0.0006 mg/L	Chromium	0.066 mg/L

2.4. Fly Ash Class C

Fly ash, a by-product of coal combustion, has become a valuable resource in the construction industry, particularly in enhancing brick properties. Fly ash. Specifically, Class C is known for its high calcium oxide content, which gives it cementitious properties (Balasubramaniam *et al.* 2021).

These properties play a crucial role in improving the mechanical characteristics of bricks, such as strength and durability (Arif Kamal *et al.* 2016). Fly ash acts as a pozzolanic material, reacting with calcium hydroxide to form additional calcium silicate hydrate gel, enhancing the brick's overall strength and stability (Meyer, 2009). Furthermore, incorporating fly ash can reduce water demand, improve workability, and reduce shrinkage during drying (Hossain *et al.* 2008). Fly ash class C, available in the local market, is used for this purpose, as shown in Fig.4. Table 4 gives the physio-chemical properties of fly ash class C.

Fig. 4: Fly ash class C

Table 4. Physio–chemical Properties of Fly Ash Class C

Property	Value	Property	Value
Specific gravity	2.58	Calcium oxide	28.9%
Fineness	15.9	Magnesium oxide	4.8%
Silicon oxide	32.9%	Potassium oxide	0.3%
Aluminium oxide	19.4%	Moisture content	0.8
Iron oxide	5.4%	Loss on ignition	0.6
Sulfur trioxide	3.8%		

2.5 Ground Granulated Blast Furnace Slag (GGBS)

Ground granulated blast furnace slag is a by-product of the iron and steel industry that has gained significant attention in construction (Bijen *et al.* 1996). This material possesses unique properties that can enhance the performance of various construction materials, including bricks. GGBS is known to improve the early-age strength of bricks, as the calcium oxide content in the slag acts as an effective activator (Jamil *et al.* 2022).

Additionally, GGBS can contribute to the long-term durability of bricks by enhancing their resistance to weathering and chemical attack (Rajesh *et al.* 2021). Fig. 5 shows ground granulated blast furnace slag (GGBS), which was collected from the local market for this study. The physicochemical properties of GGBS are depicted in Table 5.

Table 5. Physio–chemical properties of ground granulated blast furnace slag

Property	Value	Property	Value
Specific gravity	2.9	Lime	34.48%
Fineness	400 m^2/Kg	Magnesia	6.79%
Silica	30.61%	Titanium Oxide	Nil
Alumina	16.24%	Sulphur Trioxide	1.85%
Iron Oxide	0.584%	Loss on Ignition	2.1

Fig. 5: Ground Granulated Blast Furnace Slag (GGBS)

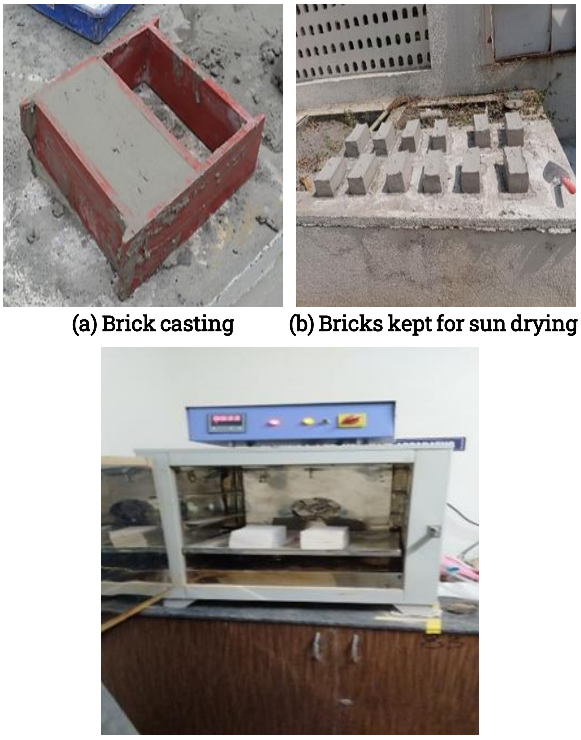
3. METHODOLOGY

3.1 Sample Preparation

This study investigates the feasibility of incorporating industrial waste in brick manufacturing by evaluating the impact of varying sludge concentrations on brick properties. Ten distinct mix proportions were designed, incorporating sludge contents ranging from 2% to 50% in increments of 2% to 15%, followed by 20%, 30%, 40%, and 50%. Textile, tannery, and water treatment plant sludges were selected as representative industrial sludges. To ensure homogeneity and consistency, each sludge type, along with the supplementary binders, fly ash class C, and ground granulated blast-furnace slag, underwent a rigorous preparation process involving drying to eliminate excess moisture and sieving to achieve a uniform particle size distribution.

The dried and sieved materials were then combined in proportions and thoroughly mixed to achieve a homogenous mixture. The specific mixing method and duration should be documented to ensure experimental reproducibility. This mixture was then poured into standard brick molds, measuring 190 mm x 90 mm x 90 mm, fabricated from a non-reactive material that facilitates easy demolding. (Refer to Fig 6)

A two-stage drying process was implemented to remove moisture from the molded bricks. The bricks were sun-dried for 24 hours for gradual moisture evaporation and minimizing cracking. The bricks underwent further drying in an 110^{0} C oven temperature for an additional 24 hours (Refer to Fig. 6).



(a) Brick casting (b) Bricks kept for sun drying

(c) Oven drying of bricks

Fig. 6: Manufacturing of sludge into-operated bricks

4. RESULTS

4.1. Compressive Strength Test of Proposed Bricks

Ten representative specimens are subjected to a standardized compression test to determine the compressive strength of bricks. Following a 24-hour saturation period, each brick is carefully positioned on the lower plate of a compression testing machine, as shown in Fig. 7. A controlled compressive load is then applied until failure, with the failure load meticulously recorded. The compressive strength of each brick is calculated by dividing the recorded failure load by the brick's bearing area. Subsequently, the average compressive strength is determined from the individual strength values of the tested samples.

4.1.1 Bricks with Textile Sludge

Table 6 shows an analysis of brick samples incorporating varying proportions of textile Sludge, fly ash class C, and Ground Granulated Blast-furnace Slag (GGBS), revealing a correlation between mix proportions and compressive strength. Samples ranged from a 2:70:28 to a 50:40:10 ratio of Textile Sludge: Fly ash Class C: GGBS, marked sequentially from 1 to 10, respectively. Compressive strength, measured in MPa, was inverse to textile sludge content. As the proportion of textile sludge increased, compressive strength decreased linearly from a high of 0.1 MPa to a low of 0.005 MPa. This suggests that higher concentrations of textile sludge negatively impact the structural integrity of the bricks. This observed trend suggests that incorporating higher percentages of textile sludge negatively impacts the structural integrity of the bricks, resulting in significantly lower compressive strength than conventional clay bricks, which typically exhibit strengths exceeding 2.5 MPa (Dang *et al.* 2018).

Fig. 7: Compressive strength test

It summarizes studies that looked into replacing some clay in bricks with tannery waste. According to the studies, adding tannery waste may affect the compressive strength of the bricks and save energy during the brick-burning process because the sludge's organic composition acts as a fuel source.

Table 6. Compressive strength of bricks with textile sludge

Mix Proportions (TS: FL: GGBS)	Marking on bricks	Compressive strength (MPa)		
Trials		1	2	3
2:70:28	1	0.1	0.08	0.11
5:70:25	2	0.08	0.09	0.10
8:52:40	3	0.05	0.048	0.052
10:60:30	4	0.03	0.033	0.029
12:48:30	5	0.02	0.018	0.023
15:60:25	6	0.017	0.019	0.015
20: 30:50	7	0.015	0.0148	0.0153
30:50:20	8	0.012	0.015	0.010
40:30:30	9	0.008	0.006	0.0075
50:40:10	10	0.005	0.0047	0.0053

*TS – Textile Sludge, FL – Fly ash Class C, GGBS - Ground Granulated Blast-furnace Slag

4.1.2 Bricks with Tannery Sludge

Table 7 presents a distinct inverse relationship between the proportion of tannery sludge incorporated into brick composites and the resultant compressive strength. Increasing the ratio of tannery sludge to fly ash Class C and GGBS within the mixture consistently corresponds with a reduction in compressive strength. This trend is exemplified by a mix proportion of 5:70:25, which yields a compressive strength of 0.8 MPa, while a

40:30:30 proportion, reflecting a significantly higher tannery sludge content, results in a compressive strength of 0.17 MPa. This finding highlights the critical need for builders and material scientists to carefully evaluate the implications of utilizing tannery sludge in brick production. While potential benefits may exist, the observed reduction in compressive strength, particularly in comparison to conventional clay bricks, which frequently exhibit strengths exceeding 2.5 MPa (Dang *et al.* 2018), necessitates a reasonable approach to maximize resource efficiency and the structural integrity of the final product.

Table 7. Compressive strength of bricks with tannery sludge

Mix Proportions (TAS: FL: GGBS)	Marking on bricks	Compressive Strength (MPa)		
Trials		1	2	3
2:70:28	1	0.5	0.49	0.47
5:70:25	2	0.48	0.50	0.46
8:52:40	3	0.40	0.42	0.38
10:60:30	4	0.35	0.32	0.30
12:48:30	5	0.30	0.28	0.33
15:60:25	6	0.27	0.30	0.25
20: 30:50	7	0.24	0.26	0.25
30:50:20	8	0.20	0.18	0.22
40:30:30	9	0.17	0.15	0.20
50:40:10	10	0.09	0.10	0.07

*TAS - Tannery Sludge, FL – Fly ash Class C, GGBS - Ground Granulated Blast-furnace Slag

4.1.3. Bricks with Water Treatment Plant Sludge

Table 8 illustrates a significant relationship between the proportion of water treatment plant sludge incorporated into brick mixtures and the resulting compressive strength. As the ratio of Water Treatment Plant Sludge: Fly ash class C: GGBS skews towards a higher water treatment plant sludge content, a corresponding decrease in compressive strength is observed. For instance, a mix proportion of 5:70:25 yields a compressive strength of 1.87 MPa, while increasing the water treatment plant sludge proportion to 40:50:10 results in a lower compressive strength of 1.20 MPa. This trend highlights the need for builders and engineers to consider the implications of incorporating water treatment plant sludge into brick manufacturing. While it may offer particular advantages, the potential reduction in compressive strength, particularly in comparison to conventional clay bricks, which typically exhibit strengths exceeding 2.5 MPa (Dang *et al.* 2018), necessitates a balanced approach to ensure material efficiency and structural integrity in construction projects.

4.2. Water Absorption Test of Proposed Bricks

The water absorption capacity of bricks is evaluated by submerging a set of representative specimens in water for a predetermined duration, typically 24 hours, as shown in Fig. 8. After the submersion period, the bricks are removed, excess surface water is carefully wiped away, and the saturated weight of each brick is recorded. This standardized test provides valuable insights into the porosity and potential durability of the tested bricks.

$$\% \; of \; water \; absorbed \; by \; the \; bricks = \frac{(saturated \; dry \; weight - intial \; dry \; weight)}{Dry \; weight} * 100$$

Table 8. Compressive Strength of Bricks with Water Treatment Plant Sludge

Mix Proportions (WTS: FL: GGBS)	Marking on bricks	Compressive Strength (MPa)		
Trials		1	2	3
2:70:28	1	1.93	1.90	2.02
5:70:25	2	1.87	1.91	1.89
8:52:40	3	1.80	1.78	1.83
10:60:30	4	1.77	1.79	1.75
12:48:30	5	1.73	1.70	1.74
15:60:25	6	1.69	1.72	1.70
20: 30:50	7	1.59	1.63	1.57
30:60:10	8	1.57	1.55	1.60
40:50:10	9	1.20	1.22	1.18
50:45:5	10	1.09	1.10	1.07

*WTS – Water Treatment Plant Sludge, FL – Fly ash Class C, GGBS - Ground Granulated Blast-furnace Slag

Table 9. Water Absorption Test Results of Proposed Brick Samples

Bricks with	Mix proportions	% of water absorbed by the bricks
Textile Sludge	2:70:28	50
Tannery Sludge		40
Water Treatment Plant Sludge		25

Fig. 8: Water Absorption Test

Table 9 shows the water absorption tests conducted on the proposed brick samples, incorporating various industrial sludges, revealed significant variations in their capacity to absorb water. Textile sludge bricks exhibited the highest water absorption at 50%, indicating a highly porous structure. Tannery sludge bricks, with a mix proportion of 2:70:28 (sludge: fly ash: GGBS), demonstrated slightly lower absorption at 40%. Notably, water treatment plant sludge bricks exhibited the lowest water absorption at 25%. These values significantly exceed the maximum water absorption limit of 20% stipulated by IS 3495:1992 for standard burnt clay building bricks. This suggests that incorporating textile, tannery, and water treatment plant sludge in the tested proportions could lead to bricks with compromised durability and lower resistance to freeze-thaw cycles, potentially limiting their structural applications.

Fig. 9: Water absorption test

4.3. Efflorescence Test of Proposed Bricks

The efflorescence potential of bricks is assessed by partially submerging representative brick specimens in distilled water within a controlled environment for seven days. Following the submersion period, the bricks are removed and allowed to dry naturally at room temperature, as shown in Fig. 9. The extent of efflorescence is then visually evaluated, and a rating is assigned based on standardized scales, ASTM C67, which categorizes the severity and characteristics of any observed salt deposits. This method qualitatively assesses the potential for unsightly salt formations on brick surfaces.

Table 10 illustrates the efflorescence analysis of the proposed brick samples, incorporating textile, tannery, and water treatment plant sludge, revealing concerning levels of salt deposition. Both textile and tannery sludge bricks exhibited severe efflorescence, indicating a substantial presence of soluble salts migrating to the surface. While water treatment plant sludge bricks showed a slightly lesser degree of efflorescence and were categorized as heavy, they still signified a considerable presence of salt deposits. These findings raise significant concerns regarding these bricks' aesthetic acceptability and long-term durability. IS 3495:1992 emphasizes its undesirability in building bricks while not providing specific limits for efflorescence. The observed high levels of efflorescence suggest potential issues with salt leaching, which leads to unsightly staining, weakens mortar joints, and potentially compromises the structural integrity of the bricks over time.

Table 10. Efflorescence Results of Proposed Brick Samples

Bricks with	Mix proportions	% of deposits observed on the bricks	Level of efflorescence
Textile Sludge	2:70:28	More than 50%	severe
Tannery Sludge		More than 50%	severe
Water Treatment Plant Sludge		10 % - 50%	heavy

5. DISCUSSION

This paper investigated the feasibility of utilizing textile, tannery, and water treatment plant sludge as alternative raw materials in brick production. The results revealed crucial insights into the mechanical and physical properties of the manufactured bricks.

The compressive strength, a critical parameter for building materials, was significantly influenced by the type and proportion of sludge incorporated. As seen in Table 8, bricks with higher water treatment plant sludge content exhibited a decrease in compressive strength. This aligns with previous studies indicating the potential for reduced strength when incorporating inevitable industrial byproducts (Guo *et al.* 2022). However, it is noteworthy that some compositions, particularly those with sludge proportion varying from 2-50% along with fly ash class C and GGBS, achieved lower compressive strengths comparable to conventional clay bricks, highlighting the potential for optimizing these materials for structural applications (Ganapathy *et al.* 2024).

Water absorption analysis revealed that incorporating all three sludge types resulted in higher water absorption rates than standard clay bricks. This is likely attributed to the porous nature of the sludges (Ahmadi *et al.* 2023). Notably, textile sludge bricks exhibited the highest absorption rate, 50%, exceeding the acceptable limit for building bricks stipulated by IS

3495:1992. This suggests that while textile sludge holds promise, its proportion needs careful optimization to mitigate potential durability issues associated with high water absorption. Further research could explore incorporating high-strength reinforcement materials to enhance the mechanical properties of the sludge-based bricks. For instance, a study demonstrated the effectiveness of Fiber Reinforced Polymer composites in improving the strength of concrete beams (Navaneethan *et al.* 2024). A similar approach could be investigated for the sludge bricks, potentially mitigating the reduced compressive strength with increased sludge proportions. This could lead to the development of a more robust and sustainable construction material. Further research could also investigate the impact of additional stabilizing agents, such as Bentonite nano clay, on the properties of the sludge-incorporated bricks. As Ganapathy *et al.* 2024 demonstrated, incorporating Bentonite nano clay with fly ash and other additives could effectively enhance the strength and stability of expansive soils (Sampathkumar *et al.* 2024). Investigating similar combinations within the brick matrix could improve performance characteristics and expand the potential applications of these sustainable building materials.

6. KEY FINDINGS AND FUTURE OUTLOOK

- Incorporating textile, tannery, and water treatment plant sludge in brick production presents a promising avenue for sustainable construction but necessitates careful consideration of material proportions to ensure structural integrity.

- While higher proportions of water treatment plant sludge reduced strength, optimised mixes (2-50% sludge with fly ash and GGBS) showed comparable strength to standard bricks.

- Increasing concentrations of textile, tannery, and water treatment plant sludge in brick composites correspond with a reduction in compressive strength, highlighting a potential trade-off between sustainability and structural performance.

- Significant efflorescence observed in bricks incorporating these industrial wastes, particularly those with higher textile sludge content, raises concerns regarding long-term durability and aesthetic acceptability.

- Further research is warranted to optimise mix designs, investigate the efficacy of mitigating additives, and conduct comprehensive life cycle assessments to evaluate this approach's environmental impact and viability fully.

- This research primarily focused on the mechanical properties of sludge-incorporated bricks. However, further investigation into the thermal properties, particularly their combustion characteristics, could be valuable. Their study highlights the importance of analyzing combustion behaviour when utilizing waste materials as fuel sources. A similar analysis for the sludge-based bricks, especially if they are proposed for applications involving exposure to heat or fire, could provide a comprehensive understanding of their performance and safety aspects.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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