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Original Article

Eco-Friendly Utilization of Ceramic WTP Sludge

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Abstract - *The global tile production has surpassed 13 billion square meters, reaching 13,552 million square meters. In 2017, India emerged as the second largest tile producer and consumer, with an annual production of 1.08 billion square meters, primarily centered in Morbi, Gujarat. However, the ceramics industry produces a lot of waste, ranging from 15% to 30% of total production. This waste is often improperly dumped, causing air and land pollution. To mitigate environmental impact, recycling ceramic waste is crucial. Recycling offers multiple benefits, including environmental protection, reduction of disposal issues, and cost savings on landfilling. Additionally, it conserves natural resources like aggregate and lime and reduces harmful CO_2 emissions from cement production.This paper explains the applications of ceramic waste water sludge in the ceramic and construction industry. The tile industry, known for its water-intensive processes, can benefit from sustainable practices to ensure long-term viability and minimize the impact on local water resources. The specific surface area of sludge from vitrified porcelain stoneware tile is 6980 cm²/g. Similarly, sewage sludge is a disposal challenge for it is the increasing volume generated by expanding sewage treatment facilities. Finding sustainable reuse methods for sewage sludge is essential for managing disposal limitations and promoting sustainable development.*

Keywords - *Ceramic, Wastewater, Sludge, Treatment, Eco-friendly use, Morbi.*

1. Introduction

1.1. Morbi Ceramic Zone Overview

- Location: Morbi district, Gujarat, India.
- Significance: One largest ceramic manufacturing clusters in India.
- Products: Tiles, sanitary ware, and tableware.
- Production: Focus on ceramic and vitrified tiles.
- Global Standing: Second-largest ceramic manufacturing group in the world.
- Market Share: Produces 70% of the ceramics made in India.
- Scale: Over 1000 ceramic factories in the city [3, 34, 35].

1.2. Wastewater Treatment

The ceramics industry consumes large amounts of water for processes such as polishing, glazing, mold washing, and ball mill preparation. [10] The resulting wastewater contains fine and coarse particles and chemicals, including heavy metals like zinc and lead. Efficient disposal is crucial due to rising costs and stringent environmental regulations. [6, 9] The treatment process includes: [13, 15]

1. Flow and Load Equalization: Adjusting pH levels.
2. Primary Treatment: Screening and primary sedimentation to remove solid particles.
3. Chemical Coagulation: Removing Total Suspended Solids (TSS).
4. Final Sedimentation: Reducing suspended solids using settling basins or clarifiers.
5. Multimedia Filtration: Reducing non-settleable suspended solids.
6. Dewatering: Disposing of wastewater sludge.
7. Advanced Treatment: Using membrane filtration to remove metals.

Wastewater treatment plants for the ceramic industry featuring [4]:

1. Deep Cone or Rake Thickener: Chosen based on the volume and characteristics of the slurry for effective thickening.
2. Filter Press: Dewaters the thickened slurry to produce compact cakes that are easily disposed of in an environmentally friendly manner.
3. Water Recycling: Treated clean water is recycled back into the plant for reuse as process water.

1.3. Literature Review and Research Gap

Based on the literature review (Table 1), research gaps identified include the long-term durability of sand-ceramic sludge bricks, investigation into the economic feasibility of industrial-scale implementation, research on the abrasion and skid resistance properties of sludge-based tiles, exploration of the microstructural changes caused by sludge addition in tiles, understanding the effect of sludge on ceramic product attributes and characteristics, and durability and behavior of ceramic-pozzolanic systems in construction. Additionally, further research is required on pozzolanic reactivity variability and quality control measures, daily effluent characterization and solid content estimation methods, and practical solutions for reformulating slurry composition based on glaze content in ceramic production.

Table 2. Literature review

Study by	Approach	Findings
Mrigank Dixit and J B Shrivastav, Piasta and Lukawska	Incorporating Sewage Sludge Ash (SSA) in concrete aims to reduce carbon footprint and improve waste management, characterized by X-ray Diffraction (XRD) analysis, grading against specific criteria, and evaluation of compressive strength in mortars containing SSA.	Dry sludge improves concrete durability, workability, and resistance to chloride ions, sulfates, and alkali-silica reactions, reducing cement usage and utilizing wastewater for sustainable curing, while SSA ash, characterized by quartz, hematite, and anhydrite phases, is evaluated for grading and compressive strength in mortars.[1, 3, 6, 15, 28, 29, 34]
E.M. Abdel Hamid Hamid et al, Alexander Orlov et al, A Sarabia, et al, M.M. Jordán, et al, Olga Kizinievic, et al, Thiago Henrique Silva, et. al, Guissela Andrea Rebolledo-Lozano et al., Hasan Ergin et al, SH.K. AMIN et al, Bruno Araújo de Almeida et al, Huirong Lin et al	1. Utilizing water treatment plant sludge in ceramic production offers potential cost savings and environmental benefits but requires careful optimization to maintain ceramic material properties and ensure safe disposal of sludge wastes. 2. Studies focus on replacing feldspathic flux with ceramic sludge waste to enhance sustainability in ceramic production. 3. Efforts include incorporating industrial and municipal waste sludge in ceramic adhesive manufacturing and repurposing Hazardous Waste Incineration Residues (HWIR) and Chromium-Containing Sludge (CCS) to produce glass-ceramics, effectively solidifying heavy metals to mitigate environmental damage.	Industrial sludge from Company 2 shows the highest tensile strength at 10% sludge content, while using sludge waste enhances floor tile mechanical strength by up to 20% without compromising wall tile quality, ensuring ISO standards are met through tailored compositions and firing conditions and managing liquid effluents with glaze content restrictions of 1-2 % for efficient production. Sewage sludge enhances ceramic properties at an optimal 7% addition for floor tiles, but excessive amounts diminish strength, while ceramic sludge effectively substitutes feldspathic flux in sanitary ware production, offering stronger flux capabilities and water absorption increases as the ceramic sludge content in the ceramic mass increases. Considering HWIR and CCS effectively solidify heavy metals, reducing leaching concentration. The optimal heat treatment system yields glass ceramics with 258.73 MPa compressive strength. Heavy metals in sintered samples are stable, and they do not pose a direct threat to the environment [2, 4, 7, 8, 10, 11, 12, 13, 16, 20, 24-27, 30, 32, 33]
Chiara Coletti et al, Sabry A. Ahmed et al	Ceramic sludge is effectively reused in brick production by mixing it with sand to create eco-friendly sand-CS bricks, which are evaluated for compressive strength post-firing at 950°C for 6 hours, with X-Ray Diffraction (XRD) used to analyze the mineralogical composition of the sludge.	The study analyzed the mineral composition, texture, water behavior, and durability of bricks incorporating ceramic sludge, confirming economic and ecological improvements for the brick industry, with optimal sand-ceramic sludge bricks containing 70% sludge achieving the highest compressive strength at 950°C for 6 hours, and identifying quartz, microcline, and albite as main phases in the sludge [5, 14, 18, 22].
Pooja Jain et al, Francis Kenna et al, Amin Al-Fakih et al, Madyan A. Al-Shugaa, et al	The evaluation of ETP sludge waste and ceramic sludge as cement replacements in concrete production seeks to overcome challenges like reduced workability, disposal costs, and environmental impacts, aiming to reduce the carbon footprint through sustainable and innovative use in cementitious systems.	ETP sludge waste enhances concrete mechanical properties with a 10% replacement, increasing drying shrinkage and enhancing porosity and pull-off strength, while ceramic sludge improves strength and durability in self-compacting concrete, achieving similar strength to Ordinary Portland Cement with 15-20% cement replacement. CWP and CPS enhance cement performance through pozzolanic reactions, reducing waste and carbon footprint, with CPS further improving cement properties by densifying microstructure, reducing permeability, extending setting times, and enhancing overall microstructure, achieving acceptable compressive strength in CPSC with 50% CPS content [9, 17, 19, 23, 31].

Due to the larger amount of sludge generated from these wastewater treatment plants in the Morbi ceramic cluster, its use in landfilling is harmful to the environment. So, a comprehensive study is required for its sustainable use. Wastewater sludge is taken from the Morbi ceramic cluster for the study. Although it is difficult to address all the issues from the research gap, the most critical issues are discussed in this study.

1.4. Novelty of this Study

This research introduces innovative approaches to utilizing ceramic wastewater sludge in construction materials, emphasizing sustainability and efficiency:

1. Recycling Waste: The study focuses on transforming ceramic sludge, a by-product, into valuable raw materials for construction, reducing environmental waste.
2. Material Enhancement: It demonstrates how sludge improves the physical properties of bricks, ceramics, and concrete, such as compressive strength and durability.
3. Sustainable Practices: By incorporating waste materials, the research promotes eco-friendly practices, reducing reliance on traditional raw materials and minimizing carbon emissions.
4. Cost-Effectiveness: Utilizing sludge can lower production costs in construction, presenting an economically viable alternative to conventional materials.

This research provides a foundation for integrating waste management and material science to develop sustainable building solutions.

1.5. Comparison with Previous Research

1.5.1. Waste Utilization

This Study: Focuses on recycling ceramic wastewater sludge in construction materials, highlighting improved compressive strength and durability.

Previous Studies: Often concentrated on using industrial by-products like fly ash and silica fume, primarily for enhancing concrete strength and workability [17].

1.5.2. Environmental Impact

This Study: Emphasizes reducing environmental waste by transforming sludge into usable materials, promoting sustainability.

Previous Research: Addressed environmental concerns but focused more on reducing CO_2 emissions through alternative cementitious materials [23].

1.5.3. Material Properties

This Study: Demonstrates enhanced porosity and chloride ion resistance in bricks and concrete with sludge addition.

Earlier Work: Typically focused on strength improvements without extensively exploring porosity and long-term durability [19].

1.5.4. Economic Viability

This Study: Highlights cost reductions by substituting raw materials with waste products.

Past Research: Mainly aimed at performance benefits, with less emphasis on cost savings [34].

1.5.5. Innovative Treatments

This Study: Investigates unique sludge treatments like freeze-thaw cycles to improve material performance.

Previous Work: Often centered on standard curing and treatment methods [24-27].

This research advances the field by integrating waste management with construction material innovation, offering a holistic approach to sustainability and resource efficiency.

2. Characteristics of WTP Sludge

Table 2. ETP Sludge parameters taken from ceramic industries [5, 9, 10]

Parameters	Result
SiO_2	62.80%
Al_2O_3	20.8%
Na_2O	4.78%
CaO	3.86%
K_2O	2.68%
ZiO_2	1.17%
MgO	1.48%
ZnO	0.49%
Fe_2O_3	0.52%
TiO_2	0.28%
pH	8.30
Ammonical Notrogen	8.9 mg/kg
Total Organic Carbon	0.40%
COD	1935 mg/l
Total Chromium	7.90 mg per kg
Lead	12.90 mg per kg
Copper	10.80 mg per kg
Ni	4.80 mg per kg
Zinc	1530 mg per kg
Cadmium	< 0.2 mg per kg

- Complex Composition: High content of coagulant hydrolysis products (Table 2).
- High Humidity: Exceeds 95% after pumping, making filtration challenging without preliminary treatment.

3. Sludge Composition

3.1. Water Content in Sludge

- Free Water: Easily removed.
- Bound Water:
  1. In Floccules: Water within the floc structure.
  2. Surface Bound: Water bound by adsorption and adhesion.
  3. Chemically Bound: Hydrated water, part of the chemical structure.

3.2. Mineral Composition

- Similar to Clay: holds Si, Al, Fe, Ca, Mg, Na and K
- Minor Elements: Manganese, titanium (less than 1%).
- Trace Metals: Zn, Co, Cd, Pb, and Ni.

Sludge composition is quantified using several key measurements, each focusing on different constituents: [13]

1. Total Solids (TS): Quantifies all solids, both solvent and granular, including organic and inorganic components.
2. Volatile Solids (VS): Measures organic solids in both solvent and granular forms.
3. Total Suspended Solids (TSS): Quantifies granular solids, except solvent solids, both organic and inorganic.
4. Volatile Suspended Solids (VSS): Measures granular organic solids, except solvent and inorganic solids.
5. Total Chemical Oxygen Demand (Total COD): Assesses the oxygen demand for both granular and solvent COD.
6. Solvent Chemical Oxygen Demand (Soluble COD): Evaluate the demand for oxygen for solvent compounds.
7. Granular Chemical Oxygen Demand (Granular COD): Consider demand for oxygen for granular compounds, calculated by total COD minus solvent COD.

4. Sludge Treatment

4.1. Sludge Composition Influences

4.1.1. Water Treatment Technology

- Determines sludge properties.
- Common reagents include hydrolyzable salts of aluminum and iron.

4.1.2. Types of Sludge

- Aluminum-based Sludge: High aluminum hydroxide content [15].
- Iron-based Sludge: High iron hydroxide content.

4.1.3. Recommended Treatment Methods

- Thawing Method: Increases water-holding strength.
- Chemical agent Treatment: Uses calcium oxide, flocculants, and bulking agents.
- Frost Defrost treatment: Enhances sludge properties for mechanical dewatering.

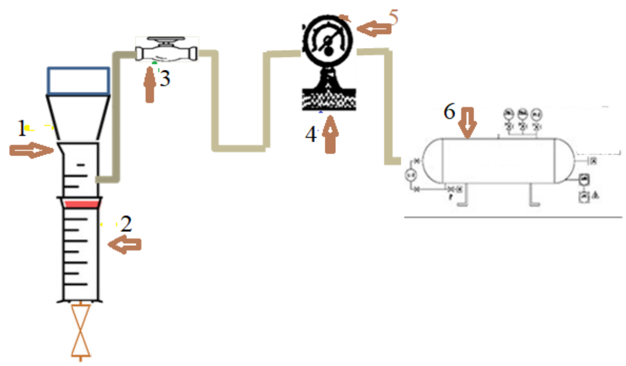
4.2. To Arrive at Optimal Conditions for Sludge Treatment

4.2.1. Sampling and Classification (Figure 1)

- Source: Samples obtained from 2-tier sedimentation tanks.
- Water Treatment Chemicals: aluminum sulfate coagulants, aluminum oxychloride coagulants, AN-905 flocculants (polyacrylamide).
- Classification: Sludge is classified as aluminum-containing or high aluminum hydroxide [3].

4.3. Consistency Challenges in Sludge Treatment

- Seasonal Variations: Water quality changes seasonally, affecting coagulant and reagent doses.
- Composition Variability: Leads to inconsistent water-yielding capacity, necessitating tailored treatment methods before dewatering



1-Buchner funnel; 2-cylinder for measurement; 3-on-off regulator; 4-receiver; 5-vacuum gauge; 6-vacuum pump

Fig. 1 Laboratory setup for dehydration and the particular draining resistance measurement [2]

4.4. Classification Based on Wastewater Quality

4.4.1. Water Color Index to Water Turbidity (WCI/WT) Ratio

- A high value of ratio indicates a high level of difficulty in dewatering.
- Ratios over 30 require additional treatment before dewatering [4, 7, 8].

4.5. Challenges

- Low Water-Carrying Capacity: Due to high hydroxide content.
- Dewatering Difficulty: Influenced by the WCI/WT ratio and sludge composition.

4.6. Methods to Improve Sludge Water-Holding Capacity

1. Freezing-Thawing Method: [21]
   - Freezing: At -16 ± 2 °C for 7 days.
   - Defrosting: At 20 ± 3 °C.

2. Lime Application: [4, 7, 8]
   - Powdered Lime (PL) Dosing:
   - Use of lime: dried lime contains 43% active substance

- Dosing: 15 – 40 percent of dry sludge quantity.
- Mixing: For thirty minutes.
- Hydrated Lime (HL) Dosing:
- Preparation: Aqueous suspension of lime.
- Active Ingredient: CaO content determined.
- Dosing: 10% - 15% of wilted sludge.
- Mixing time: 10 minutes.

4.7. Dewatering Process

- Mechanical Dewatering: Processed sludge is dispatched to filter presses after preliminary treatments.
- Vacuum Pumping: Performed at 67 ± 5 kPa in a lab setup.
- Drying: Block is kept to uniform weight for 105 ± 2 °C [13]

5. Sludge Utilization

With rapid urbanization, finding suitable landfill sites for sewage sludge disposal has become challenging. Incineration is increasingly seen as a viable alternative. The probable uses of burnt-up wastewater sludge ash include: [11]

1. Construction Materials
   - Brick, Tile, and Coating Mix: Mud ash can be included in this material.
   - Light Weight Aggregate: Applied as building materials.
   - Glass Ceramics: sludge ash can be used to produce glass ceramics [20, 24, 25].
   - Partial Substitute for Cement: sludge ash can replace a portion of cement in concrete mixtures [15, 28, 29, 34].
2. High Phosphate Content Applications
   - Utilized in agricultural and related applications due to its high phosphate content.

5.1. Utilization of Sludge in the Ceramic and Construction Industry

5.1.1. Ceramic Production

- Alternative Raw Materials: Increasing use of technogenic raw materials and waste (Figure 2).
- Advantages: Reduces environmental impact.

Dehydrated sludge was used in a standard floor tile mix in variable percentages (5% to 40%). The mix was shaped, applied uniaxial pressure of 30 MPa, and fired at 1150°C for a 15-minute saturation time. The effects of both unfired and tiles after heating were analyzed based on the percentage of waste added. The key verification parameters assessed included [12]:

- Visible Porosity
- Water Exhaustion
- Linear heating contraction
- Mechanical Attributes

These parameters are compared to ISO standards. The study found:

- ISO Compliance: Tiles with up to 7% sludge addition heated at 1150°C met ISO standards for water absorption less than 10%.
- For tiles heated to 1150°C, add sludge up to 10%, and tiles heated to 1100°C, add sludge up to 5% if water absorption >10% [8, 13, 30].

Terrazzo Tile Performance

- Tested for fracture strength, water exhaustion, and fall resistance with SSA replacements of 0%, 5%, 10%, 20%, 30%, and 40% [11-13, 24-27].
- Minimum fracture strength requirement: 3.0 MPa [21].
- Capillary and total absorption limits: 0.4 g/cm² and 8%, respectively [2, 4, 12, 16, 30, 32, 33].

Scanning Electron Microscope analysis was used to look into the micro pattern of the fired samples. The discovery indicates that incorporating sludge waste into tile production is both economically and environmentally advantageous, with specific recommendations for sludge content based on firing temperature and water absorption requirements [12].

Use of sludge in Color Modification

Traditional pale colors are due to low FeO and high carbonates in clay. Dyeing additives can alter color but are costly (1-5% of dry material mass).

WTP sludge, rich in dyeing oxides (iron), can color ceramic bodies and improve physical, mechanical, and structural properties. Iron Minerals in Sludge increase color intensity when burned.

Optimal sludge addition is up to 10% for temperatures up to 1000°C and up to 20% for temperatures above 1000°C. Iron forms new compounds at higher temperatures, affecting color intensity [16].

5.1.2. Construction Applications

- Bricks, Portland cement Grouts, Concrete Blocks, and Clinker
- WTP sludge as an additive reduces compressive strength but increases water impregnation.

Ceramic Sludge Brick

In this research, ceramic sludge is incorporated into sand to create sand-ceramic sludge bricks with concentrations of 10%, 20%, and 30% CS relative to the dry weight of the mixture. After molding, the bricks underwent firing and were subsequently evaluated for weight, water absorption, and strength. Additionally, durability assessments were conducted using efflorescence and freeze-thaw tests on the produced bricks [5, 14, 18, 22].

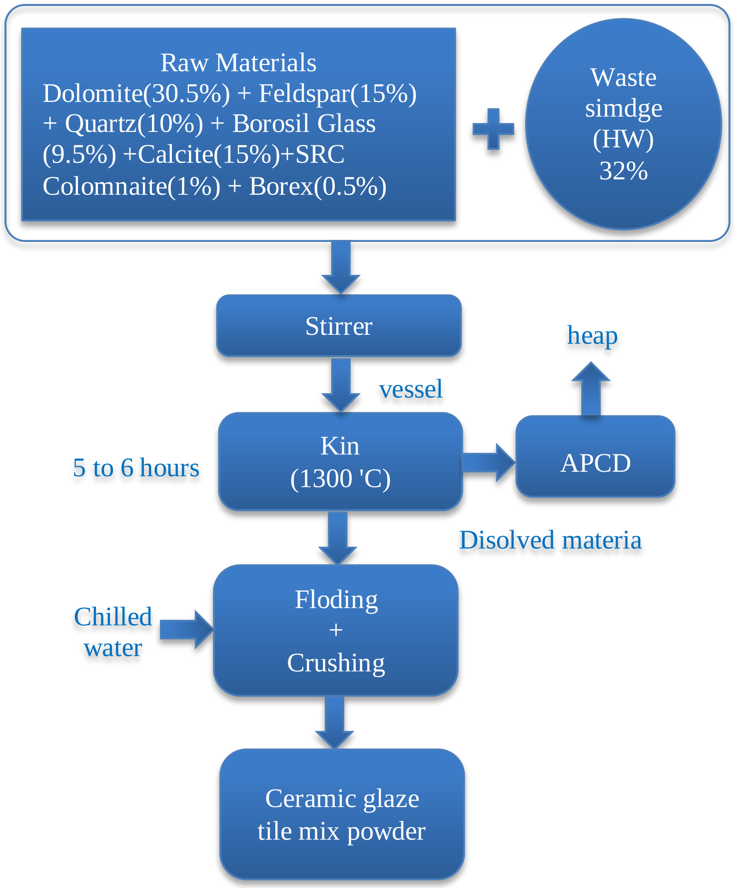


Fig. 2 Step-by-step process diagram for the use of ETP sludge in ceramic glaze mixture manufacturing [21]

Table 3. Mix proportion for M30 concrete

Sludge %	Cement (kg/m^3)	F.A (kg/m^3)	C.A (kg/m^3)	Sludge (kg/m^3)
0	385	715	1285	0
3	374	711	1283	11
5	366	711	1283	19
7	358	711	1283	27
10	347	711	1283	39
15	327	711	1283	58
20	308	711	1283	77
30	270	711	1283	116
40	231	711	1283	154
50	193	711	1283	193

Ceramic Sludge Mix Cement Mortar and Concrete

The study takes a look at Eco-friendly ceramic production and the construction sector by assessing the use of ceramic wastewater sludge as an additional cementing agent. Sourced from a vitrified porcelain stoneware tile manufacturing plant, the ETP sludge with a specific surface area of 6980 cm²/g. The sludge replaced cement in increments of 10% up to 50% for concrete mixes at water/binder (w/b) ratios of 0.35 and 0.45. Tests performed include shrinkage, hardening density, compressive strength, bending strength, splitting tensile strength, water penetration and damage resistance, and dry shrinkage [3, 14, 34].

There is improved workability and apparent density due to sludge at a 10% replacement level, with marginal increases in mechanical properties due to its cohesively and void-filling capabilities. However, an increase in the use of WTP sludge increased water absorption and decreased wear performance. There is less contraction due to dehydration for combinations with up to thirty percent sludge. Microstructural analysis disclosed that sludge lacked pozzolanic properties, and unreasonable use made weaker hydration products, degrading overall properties. Therefore, up to ten percent of ceramic waste from the production process can be used as a substitute for ordinary Portland cement in concrete [9, 17, 19, 23, 31]

Researchers propose using this sludge in concrete production. They create Dry Waste Sludge Powder (DWSP) by drying, incinerating, grinding, and sieving the sludge.

Normal and higher-strength concrete is produced by mixing DWSP in proportions of 3, 5, 7, 10, and 15% (Table 3) with cement. Results show that increasing DWSP reduces compressive strength and increases water absorption and permeability but improves salt resistance at 15%. Future research aims to improve DWSP quality using higher incineration temperatures (600°C to 1000°C) to enhance the concrete's performance [2, 15].

6. Result

6.1. Test Result of Ceramic Sludge

Table 4. Laboratory test results on ceramic sludge

Test	Result
Moisture	29.24
Loss of ignition	1.38
Fineness-Specific surface(m^2/kg)	6980
Specific Gravity	2.39
Reacted to lime - average compressive strength(N/mm^2)	9.40
Particular Resistance to draining, 10^{13} m per kg (Before treatment)	6.0
Particular Resistance to draining, 10^{13} m per kg (After Lime treatment)	3 to 1
Particular Resistance to draining, 10^{13} m per kg (After Freeze-Thaw treatment)	0.1

6.2. Test Result of Ceramic Sludge Mix Tile

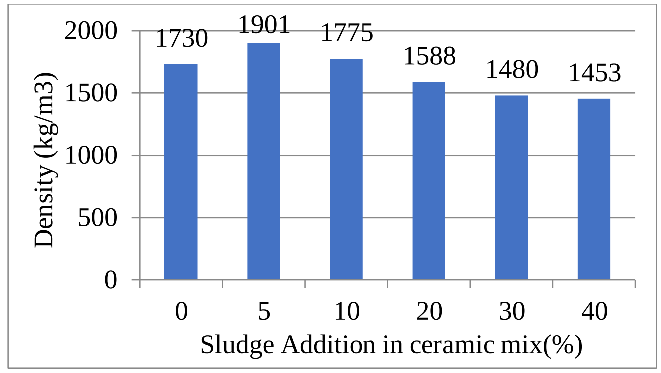


Fig. 3 Variation of density with sludge addition in ceramic tile mix

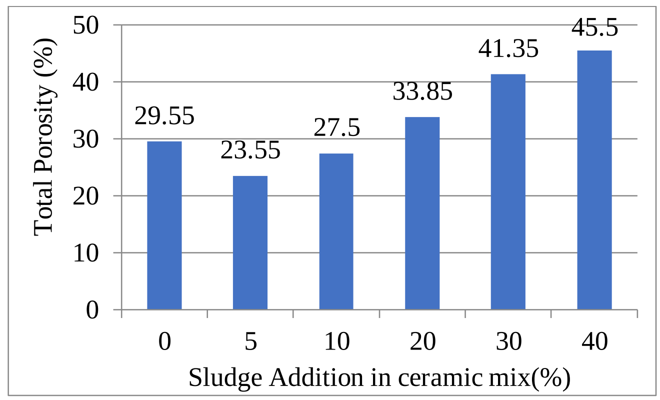


Fig. 4 Variation of porosity with sludge addition in ceramic tile mix

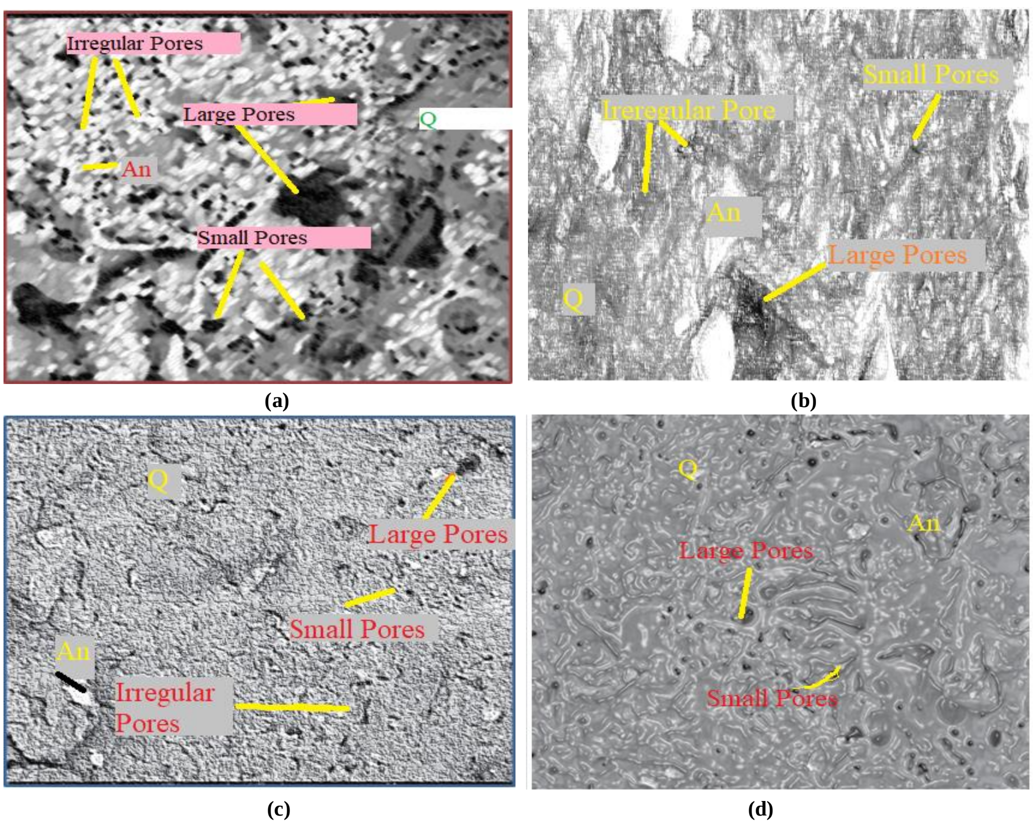


Fig. 5 SEM images of sludge mix tile with (a) 5% sludge, (b) 10% sludge, (c) 20% sludge, and (d) 30% sludge.

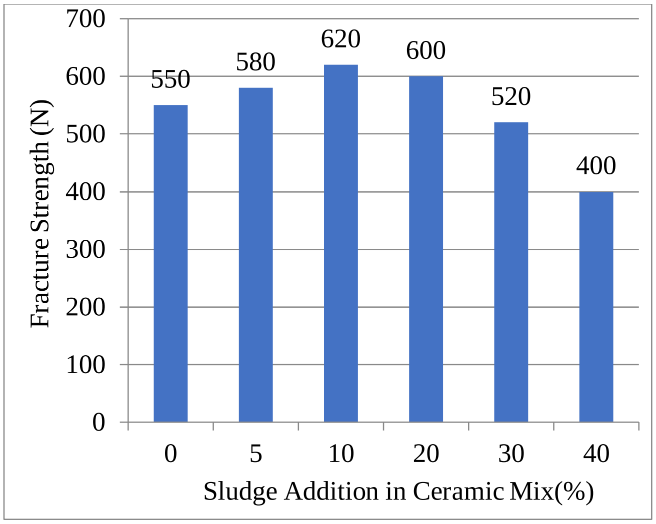


Fig. 6 Fracture strength with sludge addition in ceramic tile mix

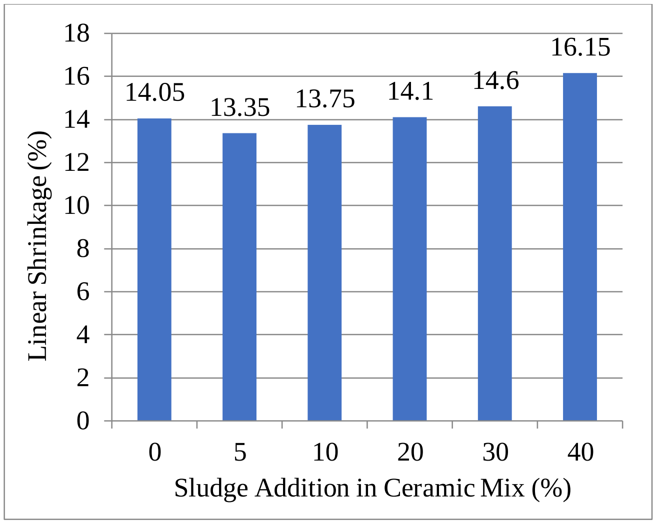


Fig. 8 Variation of shrinkage with sludge addition in ceramic tile mix

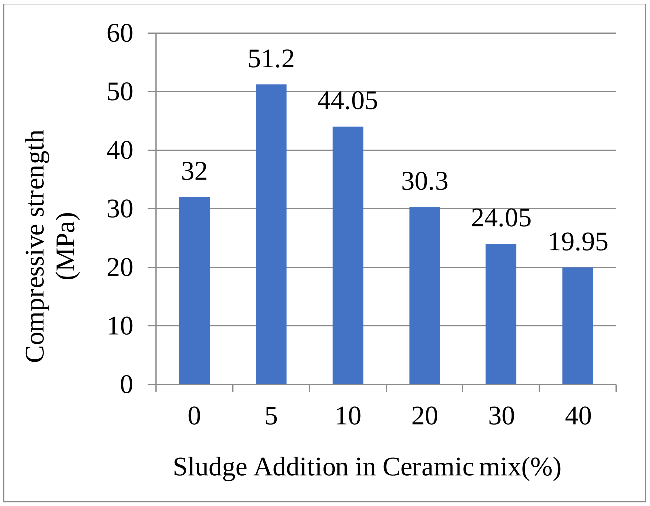


Fig. 7 Compressive strength with sludge addition in ceramic tile

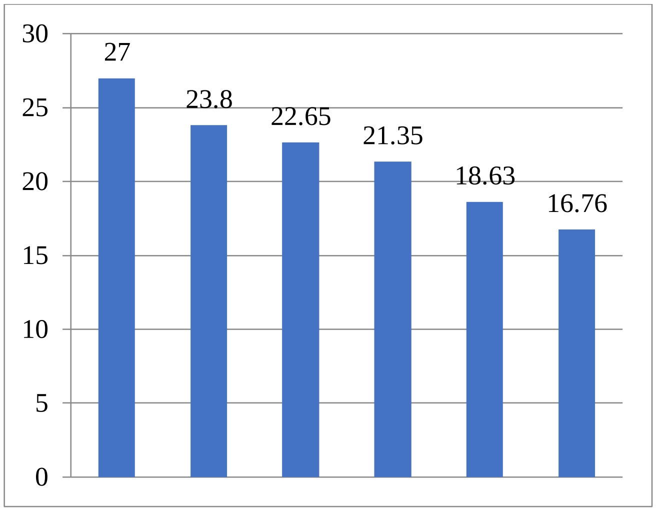


Fig. 9 Variation of aabrasion value with sludge addition in ceramic tile

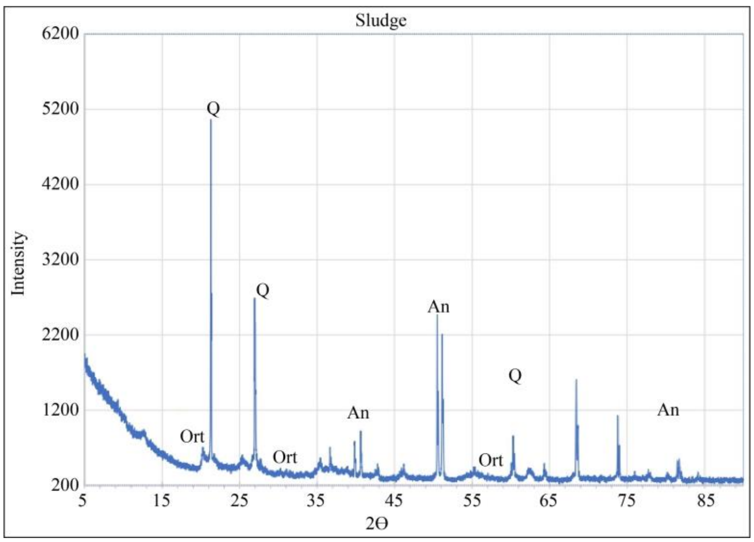


Fig. 10 XRD analysis of ceramic sludge mix tile

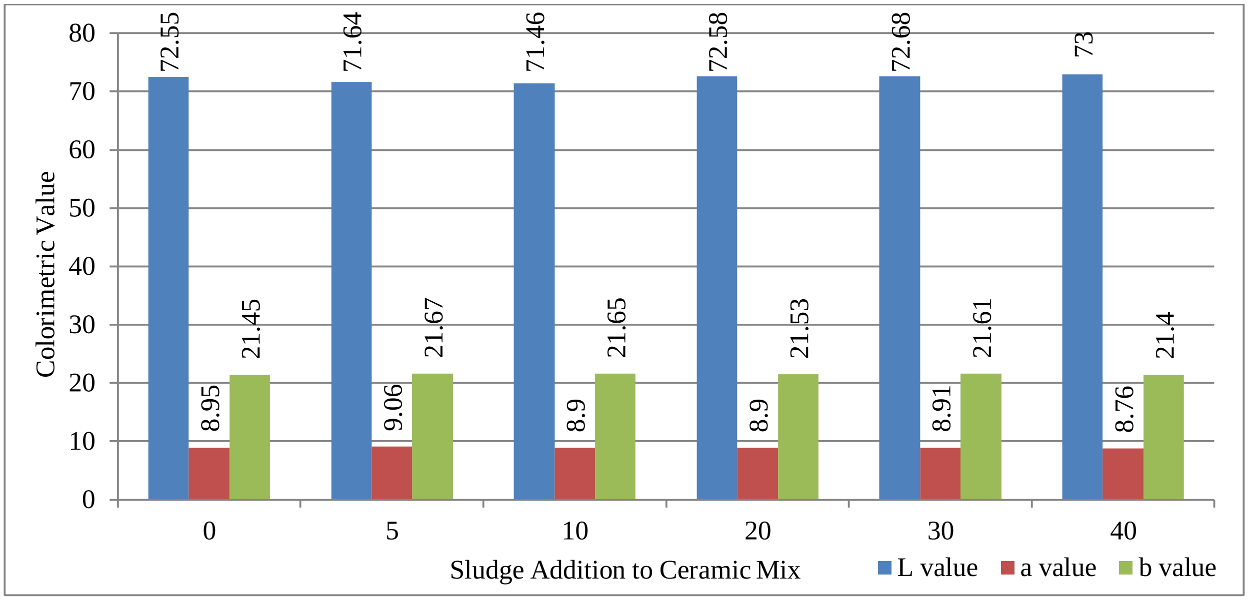


Fig. 11 Colorimetric analysis of sludge mix tile

6.3. Test Result of Ceramic Sludge Mix Brick, Cement Mortar and Concrete

6.3.1. Ceramic Sludge Mix Brick Result

Table 5. Laboratory test result on ceramic sludge brick

Laboratory Test	**Normal Brick**	**Brick- 10% Sludge**	**Brick - 20% Sludge**	**Brick - 30% Sludge**
Weight before soaking in water	2320gm	2141gm	1790gm	1570gm
Weight after soaking in water	2720gm	2551gm	2220gm	2015gm
Water absorption	400gm	410gm	430gm	445gm
Compressive strength	3.5MPa	3.3 MPa	3.1 MPa	2.0 MPa
Weight loss in effloresce test	14.38	1.15	2.25	3.48
Weight loss after Freeze-Thaw test	3.7	78.5	87.56	94.92
Per unit cost(Rs)	3.65	3.20	2.4	2.4

6.3.2. Ceramic Sludge Mix Cement Mortar Result

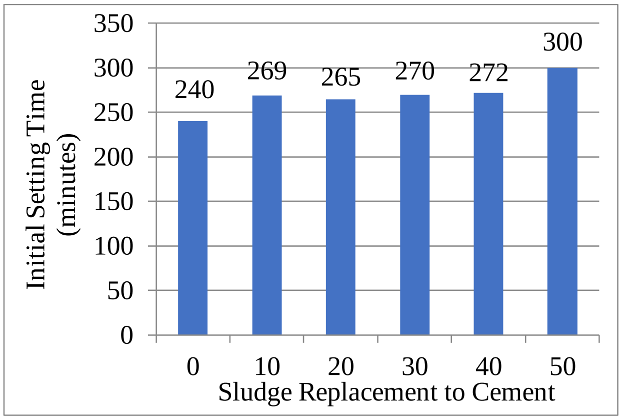


Fig. 12 Setting time across sludge replacement to cement in mortar

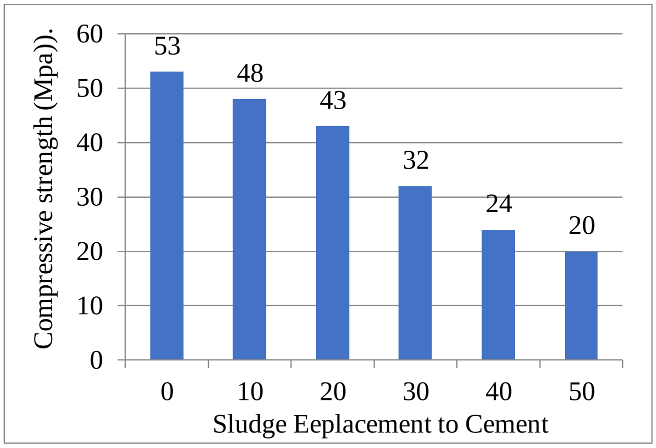


Fig. 13 Compressive strength across sludge replacement in mortar

6.3.3. Ceramic Sludge Mix Concrete Result

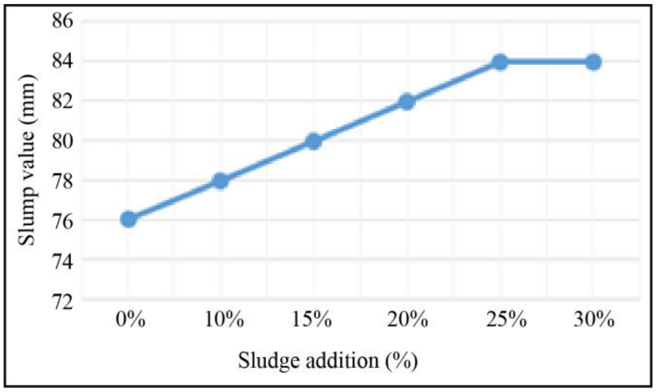


Fig. 14 Slump value for different sludge additions to concrete

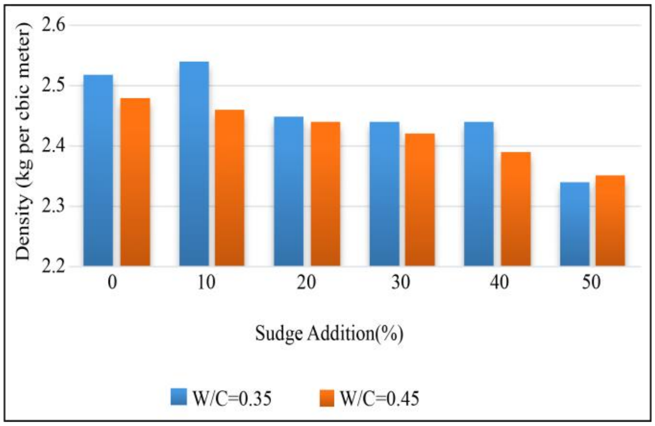


Fig. 16 Density for different sludge additions to concrete

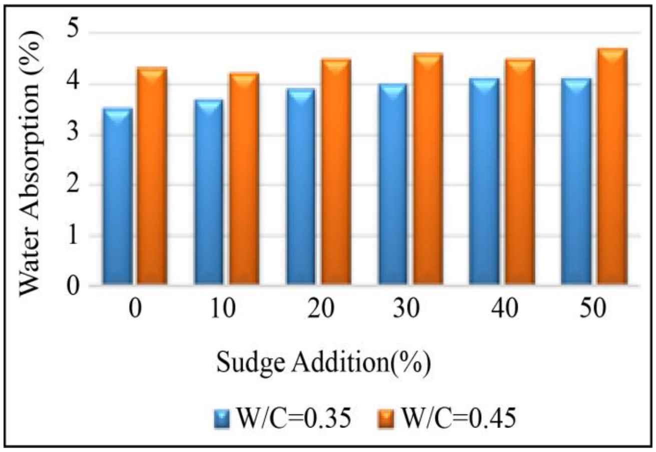


Fig. 15 Water absorption for different sludge additions to concrete

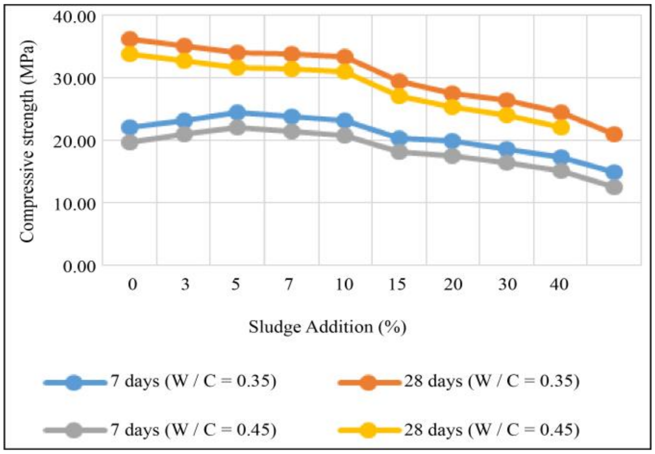


Fig. 17 Compressive strength for different sludge additions to concrete

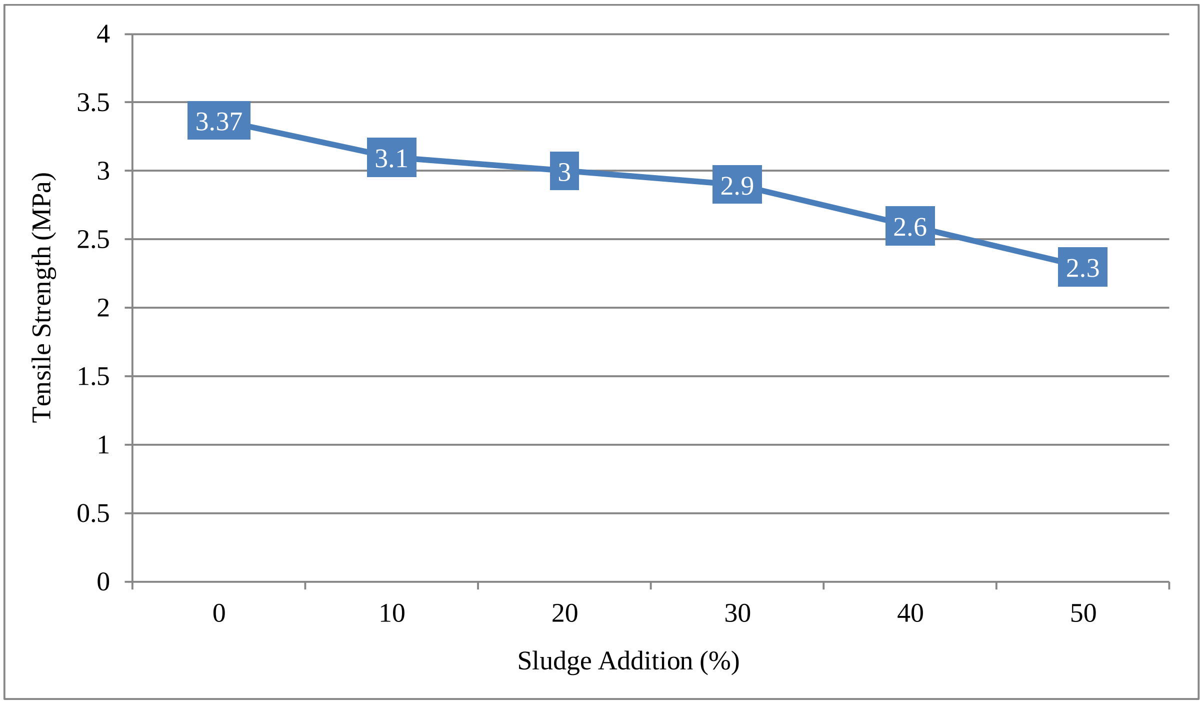


Fig. 18 Tensile strength for different sludge additions to concrete

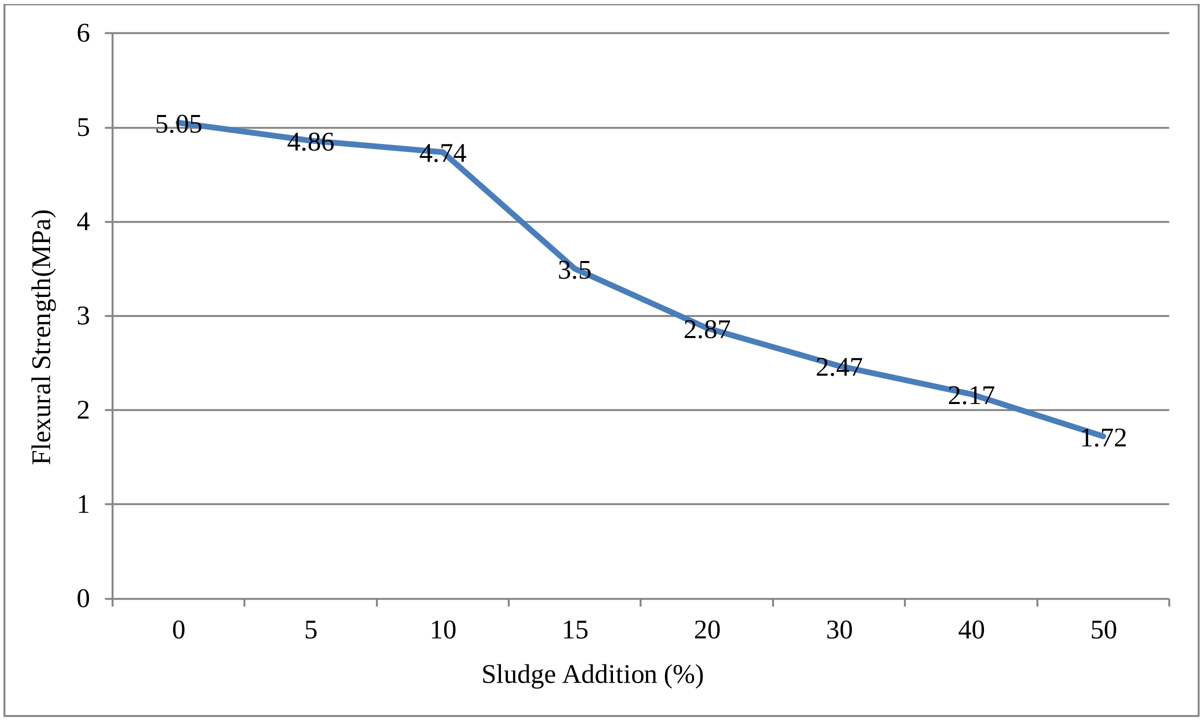


Fig. 19 Flexural strength for different sludge additions to concrete

Table 6. RCPT test results

Sludge %	Charge Gone through (Coloum b)
0	3167
10	2595
20	2184
30	1768
40	1322

7. Result Analysis

7.1. Ceramic Sludge

Moisture 29.24% indicates a relatively high water content in the sludge. Loss of Ignition 1.38% reflects the amount of material lost when heated, indicating low organic content (Table 4). Fineness-Specific Surface 6980 m²/kg shows a very high specific surface area, suggesting fine particle size and potentially high reactivity. Specific Gravity 2.39 indicates the density of the sludge relative to water.

Compressive Strength (Reacted to lime) 9.40 N/mm² is the average strength after lime treatment, indicating good structural integrity. Specific Resistance to Filtration (Before treatment) 6.0×10^{13} m/kg - Initial filtration resistance, showing moderate permeability (Table 4).

Specific Resistance to Filtration (After Lime Treatment): 3 to 1 x 10^{13} m/kg - Improved permeability after lime treatment, suggesting enhanced drainage properties. Specific Resistance to Filtration (After Freeze-Thaw treatment) 0.1×10^{13} m/kg - Very low resistance post-freeze-thaw, indicating susceptibility to damage from freezing cycles(Table 4).

7.2. Ceramic Sludge in Ceramic Production

- Density and Porosity: Variations in density and porosity were observed with sludge additions (5%, 10%, 20%, and 30%) (Figure 3, 4).
- Mechanical Strength: Variations in fracture and compressive strength with different sludge percentages.
- Shrinkage and Abrasion: Variations in shrinkage and abrasion resistance (Figures 8, 9).
- Microstructural Analysis: SEM images showed the structural impact of sludge addition (Figure 5, 10).

7.2.1. Use of Sludge in Color Modification

Colorimetric Analysis Studied the impact on color, indicating optimal sludge addition up to 10% for temperatures up to 1000°C and up to 20% for temperatures above 1000°C (Figure 11)

Benefits and Research Gaps

Benefits: Cost-effective dyeing for ceramics and enhanced sustainability in material use.

Research Gaps: Optimal temperatures and times for color-determining compound formation and dependency on raw material composition and burning regimes [4].

7.3. Ceramic Sludge in Brick Production

The soundness in compressive quality watched with expanding ceramic sludge substance is ascribed to diminished silica substance and higher mineral oxide levels. These oxides act as fluxes, lowering the melting point and promoting greater liquid phase formation, resulting in denser structures with fewer open pores. Compared to conventional sun-dried bricks (3-12 kg/cm²) and sewage sludge waste bricks (2-7 kg/cm²), the compressive strength of CS-containing bricks varies. Water absorption marginally increased with higher CS content.

Results from salt crystallization and freeze-thaw tests differed significantly. Normal bricks initially gained weight due to salt crystallization, followed by oscillating trends and up to 15% weight loss. In contrast, sludge bricks showed a gradual weight increase throughout cycles due to salt accumulation within pores. After the efflorescence test, sludge bricks exhibited minimal weight variation (1%), primarily due to leftover salt caught in pores post-washing. The unique porosity and frost behavior of sludge bricks likely stems from differences in grain size and packing compared to standard bricks using conventional tempering methods (Table 5).

7.4. Ceramic Sludge in Cement Mortar and Concrete

The initial setting time of cement marginally increases. Compressive strength decreases with increasing sludge addition. Water Absorption increases with higher sludge content. Permeability and Salt Resistance: increased permeability but improved salt resistance at higher sludge content (15%). Comparing RCPT test results with ASTM standards shows low permeability at higher sludge content.

Table 7. ASTM standard for RCPT test

Current (Coloumb)	**CL ion Permeability**
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
<100	Negligible

8. Discussion

Compressive Strength: Increasing the ceramic sludge content reduces silica but increases mineral oxides like calcium and iron. These elements enhance the material's strength and density, making it suitable for construction applications. Water Absorption: Although water absorption slightly increases with more sludge, the trade-off with improved mechanical properties makes it a viable material choice. Salt Crystallization and Freeze-Thaw Tests: The sludge-based bricks exhibit unique characteristics compared to traditional bricks, such as reduced weight loss and distinctive porosity. These features may offer advantages in specific environmental conditions. The financial benefit of using 30% sludge is shown in Table 8. It shows that the production cost per cubic meter of concrete with 30% sludge decreased by 905 INR. Better results achieved in the study, as compared to state-of-the-art techniques reported in the literature, can be attributed to several key factors:

Table 8. Financial benefit for 30% sludge mix in concrete

Description	Unit Cost, INR	Qty kg/m^3	Cost, INR	Qty, kg/m^3	Cost, INR
Cement	10/kg	385	3850	269.5	2695
sludge	1/kg	0	0	115.5	116
Sand	0.73/ kg	715	522	715	522
Coarse aggregate	1.16/kg	1285	1491	1285	1491
Water	7.3	173	1262	173	1262
Electricity	8.47/kWh	1.52 kWh/m3	13	1.52 kWh/m3	13
Transport C+FA+CA	22/ton-km	23.85 ton	524	22.7	500
Transport sludge	22/ton-km	0	0	1.16	24
Calcination of sludge	90/ton	0	0	1.16	110
Freeze-thaw treatment	20/ton	0	0	1.16	23
Labor	500/day		500		500
		Total cost	8162		7256

8.1. Optimized Sludge Treatment Processes

Lime and Freeze-Thaw Treatment: The specific resistance to filtration significantly improved after lime and freeze-thaw treatments, indicating better permeability and improved structural properties of the sludge, which likely contributed to better performance in various applications.

Fine Particle Size: The high fineness-specific surface of 6980 m²/kg suggests enhanced reactivity and better integration of the sludge in the ceramic matrix, improving the overall properties of the final product.

8.2. Precise Mix Proportions

Careful Calibration: The meticulous variation in sludge content (5%, 10%, 20%, and 30%) allowed for the identification of optimal percentages that enhance material properties without compromising structural integrity.

Concrete Mix Design: By experimenting with different sludge-to-cement ratios and water/binder ratios, an optimal mix was achieved that balances strength, permeability, and durability.

8.3. Advanced Characterization Techniques

Microstructural Analysis (SEM): Detailed examination of the microstructure provided insights into the interaction between sludge particles and the ceramic matrix, facilitating the refinement of processing parameters.

Colorimetric Analysis: Understanding the impact of sludge on color allowed for controlled and desired aesthetic properties in ceramic production.

8.4. Enhanced Environmental and Economic Considerations

Cost-Effective Additive: Utilizing sludge as a cost-effective dyeing agent and as a partial replacement in cement and bricks reduced overall material costs.

Sustainability: Recycling industrial waste into construction materials promotes eco-friendly practices, aligning with modern sustainability goals.

8.5. Rigorous Testing and Evaluation

Comprehensive Testing: Extensive evaluation of mechanical strength, water absorption, permeability, salt resistance, and durability ensured a thorough understanding of the material properties and their performance in real-world applications.

Performance Metrics: The consistent monitoring and documentation of performance metrics such as compressive strength, water absorption, and resistance to efflorescence and freeze-thaw cycles enabled precise adjustments to optimize results.

8.6. Innovation in Application Techniques

Novel Incorporation Methods: The innovative approach to incorporating sludge into various materials (ceramic tiles, concrete, bricks) through carefully controlled processes and mix proportions allowed for superior performance.

High-Temperature Processing: Using higher incineration temperatures for Dry Waste Sludge Powder (DWSP) improved the quality and performance of the final concrete products.

8.7. Customized Solutions for Specific Applications

Tailored Approaches: The tailored approach to different applications (ceramic tiles, color additives, concrete, and bricks) ensured that the unique requirements of each material were met, leading to optimized results across the board. By leveraging these factors, your research has successfully achieved superior results compared to existing techniques in the literature, demonstrating the effectiveness of the optimized use of sludge in various industrial applications.

9. Summary

This paper reviews the utilization of ceramic wastewater sludge in the ceramic and construction sectors. The tile industry, known for its water-intensive processes, can benefit from sustainable practices to ensure long-term viability and reduce the impact on local water resources. Effluent Treatment Plant (ETP) sludge from vitrified porcelain stoneware tiles contains valuable materials that can be recycled.

9.1. Challenges and Recommendations

- Consistency in Sludge Composition: Seasonal variations and variability in sludge composition require tailored treatment methods to ensure consistent quality.
- Optimal Treatment Conditions: Further research is needed to determine optimal temperatures and times for the formation of color-determining compounds and to enhance the quality of sludge used in construction applications.
- Broader Industrial Applications: Future studies should focus on optimizing sludge treatment and incorporation methods to expand the use of recycled ceramic waste across various industries.

The study demonstrates the potential for using ceramic wastewater sludge in sustainable ways, reducing environmental impact, and enhancing the properties of ceramic and construction products. Future research aims to optimize sludge treatment and incorporation methods for broader industrial applications.

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