Exploring the Use of Common Effluent Treatment Plant (CETP) Sludge as an Eco-Friendly Substitute for Fine Aggregates in Advanced Concrete Paver Blocks

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Abstract

Concrete remains a pivotal material in infrastructure development but poses significant environmental challenges due to high demand for natural aggregates and energy-intensive cement production. Concurrently, the rising volume of industrial wastes, notably Common Effluent Treatment Plant (CETP) sludge rich in heavy metals, presents disposal and pollution hazards. This study investigates the feasibility of repurposing CETP sludge as a partial substitute for natural fine aggregates (river sand) in M30 grade hexagonal concrete paver blocks. Comprehensive laboratory experiments characterize sludge chemistry, mechanical strength, durability under aggressive environments, workability, and environmental safety through leaching tests. The results indicate that a 5% sludge replacement optimizes mechanical and durability performance, aligns with environmental safety standards, and delivers up to 8% cost savings. This work supports circular economy principles by turning industrial waste into a resource, thereby promoting sustainable construction and waste management practices at scale.

keywords: *CETP sludge, Cementitious matrix immobilization, Toxic heavy metals in sludge, Waste valorization, Sulfate attack resistance*

1. Introduction

Concrete's global ubiquity arises from its strength, affordability, and adaptability. Nonetheless, these benefits are counterbalanced by substantial environmental costs associated with the extraction of natural aggregates—especially river sand, leading to ecosystem degradation such as riverbank erosion, habitat loss, and sedimentation issues. Additionally, cement manufacture emits a significant fraction of anthropogenic CO2, contributing to climate change.

Simultaneous industrial growth generates vast amounts of hazardous wastes. CETP sludge, a concentrated byproduct of wastewater treatment from clusters of small-medium industries, contains toxic heavy metals (chromium, lead, cadmium) that pose serious disposal challenges. Inappropriate handling risks soil and groundwater contamination.

The dual imperative to conserve rapidly depleting river sand and responsibly manage toxic sludge motivates this study, which hypothesizes that partial replacement of fine aggregates in concrete paver blocks with CETP sludge can address both challenges synergistically, providing a sustainable material with adequate mechanical and durability performance.

2.Literature Review

Industrial Waste in Concrete: Previous research demonstrates the feasibility of using industrial byproducts (fly ash, slag, marble dust, sewage sludge) as cement or aggregate replacements. Such additions often improve durability and mechanical properties while reducing carbon footprint.

CETP Sludge as Construction Material: Studies reveal that CETP sludge incorporated in fired bricks and concrete can enhance durability under certain conditions. However, beyond 10-15% sludge content, mechanical properties typically degrade due to increased porosity and weaker matrix bonding. Proper pre-treatment and optimization of mix design are critical.

Chemical Composition & Environmental Impact: The effectiveness of sludge in construction material depends on elemental composition and leachate behavior. Chromium, iron, zinc improve corrosion resistance, whereas lead and cadmium pose leaching risks. Cementitious encapsulation significantly reduces leachability and environmental hazards.

Mechanical Performance: Recommended sludge replacement levels range between 5-10% to balance strength and workability. Higher sludge content increases brittleness and reduces tensile and flexural strengths.

Durability Considerations: Resistance to water absorption, sulfate and chloride attacks, and freeze-thaw cycles is vital. Low sludge content projects generally demonstrate good durability; high content adversely affects it due to permeability increases.

Regulatory and Safety Context: Reuse must comply with Central Pollution Control Board (CPCB) and international environmental safety guidelines. Rigorous laboratory testing using SEM and XRD analysis assists in understanding microstructure and phase stability.

Paver Block Applications: As pedestrian pavements and driveways demand moderate-to-high strength (minimum 30 MPa as per IS 15658:2006), sludge use is viable only if this criterion consistently satisfies.

3. Objectives and Scope

Primary Objectives:

- Characterize CETP sludge chemically and physically using EDAX and leaching tests.
- Prepare and evaluate M30 concrete mixes with incremental sludge replacements (0 to 25%).
- Investigate workability, compressive, tensile, flexural strength, and durability including wet-dry, sulfate, and chloride exposure.
- Conduct leachate analysis for environmental safety.
- Determine optimal sludge content balancing performance and safety.

Secondary Objectives:

- Promote green building practices via waste valorization.
- Perform cost-benefit analysis showing economic viability.
- Frame guidelines for industry adoption and regulatory compliance.

Scope:

- Laboratory investigation limited to paver blocks (non-structural).
- Single sludge source (Eco Green Solutions); variations between sludge sources remain for future study.
- SEM and XRD analyses planned as further work.

4. Materials and Methods

Table No.1: Materials Used

Material	Water Absorp.	Bulk Density (Loose)	Bulk Density (Compacted)	Specific Gravity	Sieve Analysis
Cement	–	1500 g/cc	1550 g/cc	3.15	<90 µm
Fine Aggregate	1.01%	1580 g/cc	1800 g/cc	2.65	2.69 mm
CETP Sludge	3.05%	675 g/cc	750 g/cc	1.49	4.05 mm
Coarse Aggregate	1.25%	1500 g/cc	1680 g/cc	2.65	6.5 mm

4.1 Chemical Composition of CETP Sludge (EDAX)

Table No.2: Chemical Composition of CETP Sludge

Element	% by Weight	Effect
Chromium	85.57	Hardness, corrosion resistance
Iron	4.99	Strength, abrasion resistance
Sodium	5.58	Durability concerns if too high
Nickel	1.23	Durability, wear resistance
Lead	0.92	Low durability, environmental risk
Copper	0.74	Mechanical enhancement
Zinc	0.59	Corrosion resistance
Cadmium	0.18	Reduces longevity, environmental risk

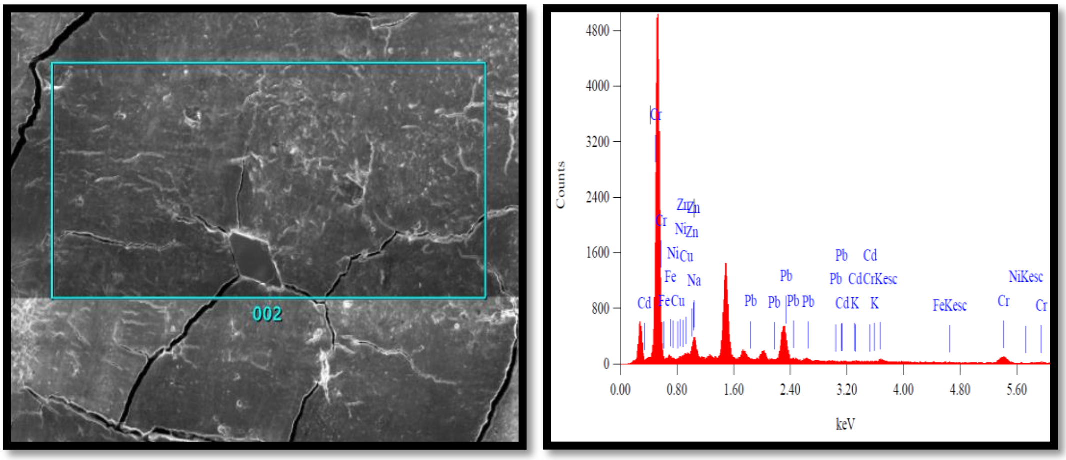

Fig1: EDAX Result

Chemical Composition Impact

Elemental composition of sludge influences mechanical and durability behavior. Chromium and iron can enhance hardness and abrasion resistance, improving durability. However, sodium and heavy metals like lead and cadmium may negatively affect durability and pose risks of leaching.

Physical Properties of Aggregates and Sludge

The bulk density, specific gravity, and water absorption are key parameters that affect mix design and fresh concrete properties. Lower specific gravity and higher porosity of sludge compared to natural sand result in increased water demand, which can impair workability unless adjusted with admixtures. The size distribution and texture affect packing density and compaction.

Mix Design and Procedures

- **Concrete Grade:** M30, with mix ratio 1:0.75:1.5 (cement: fine agg.: coarse agg.), w/c = 0.45–0.55.paper-ajith.pdf
- **Sludge Replacements:** 0%, 5%, 10%, 15%, 20%, 25% (by weight of fine aggregate)
- **Specimens:** 150mm cubes (compression), 100x100x500mm beams (flexural), 150x300mm cylinders (tensile), hexagonal paver blocks for durability.

All specimens were cured in water at 27 ±2°C for 7, 14, 28 days and tested as per IS standards.

5. Results and Discussion

5.1 Workability (Slump Test)

Workability Theory

Workability indicates ease of mixing, placing, and compacting. Replacement of fine aggregates with porous sludge particles increases water absorption, reducing free water and decreasing slump. Higher sludge contents thus demand increased water or superplasticizers to maintain workability.

Table No.3: Slump Test

Sludge %	Water/Cement Ratio	Slump (mm)
0%	0.45	105
5%	0.45	100
10%	0.50	98
15%	0.50	96
20%	0.55	98
25%	0.55	95

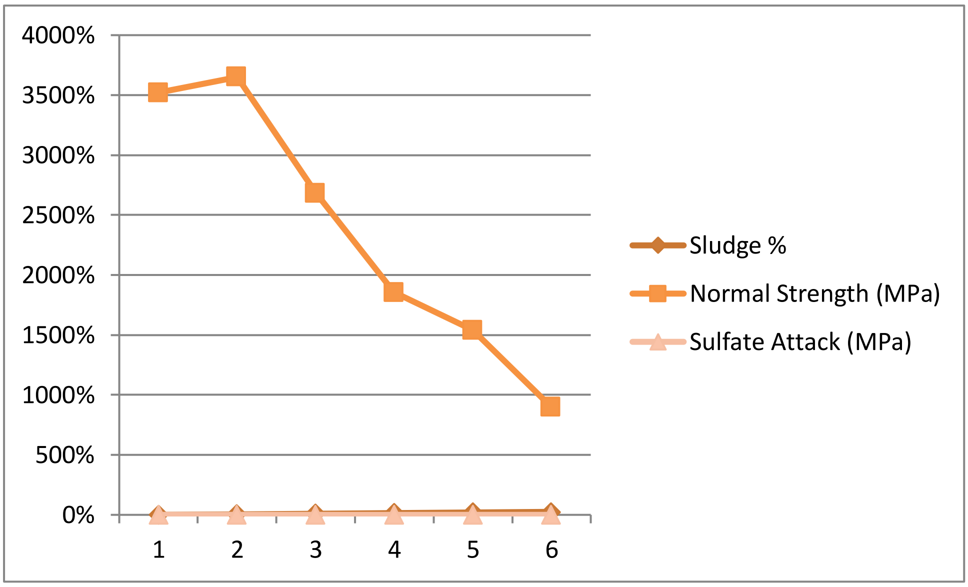

Fig 2: **Slump Test**

- Higher sludge content caused lower slump and increased water demand, requiring superplasticizer for workability above 5%.

5.2 Mechanical Properties

Mechanical Strength

Compressive, tensile, and flexural strengths depend on the concrete matrix's ability to resist different stresses. Optimal sludge content offers beneficial filler effects and possibly chemical contributions (e.g., chromium enhancing matrix bonding), improving strength. Excessive sludge increases porosity and weakens binding interfaces, reducing strength and ductility.

Table No.4: Mechanical Properties

Sludge %	Comp. Strength (N/mm²) 7d	21d	28d	Tensile Strength (N/mm²) 7d	21d	28d	Flexural Strength (N/mm²) 7d	21d	28d
0%	22.88	31.68	35.20	2.06	2.85	3.17	2.97	4.12	4.58
5%	23.73	32.85	36.50	2.14	2.96	3.28	3.08	4.27	4.75
10%	17.43	24.13	26.81	1.57	2.17	2.41	2.27	3.14	3.49
15%	12.06	16.70	18.56	1.09	1.50	1.67	1.57	2.17	2.41
20%	10.00	13.85	15.39	0.90	1.25	1.39	1.30	1.80	2.00
25%	5.84	8.08	8.98	0.53	0.73	0.81	0.76	1.05	1.17

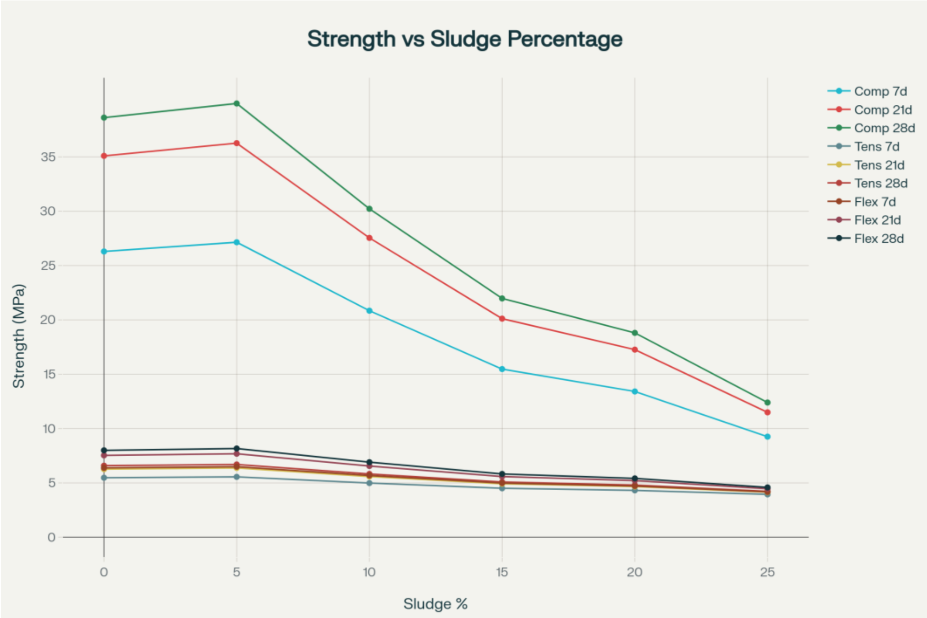

Fig 3: Mechanical Properties

- **5% sludge yielded peak strengths** in all parameters.
- **>10% replacement** caused pronounced loss in both strength and ductility.

5.3 Durability Assessment

Concrete's durability against sulfate and chloride attacks relies on its permeability and chemical stability. The addition of sludge influences pore structure and may alter ion transport. Low sludge content may enhance sulfate resistance due to chromium's corrosion resistance properties, while high sludge content increases permeability and susceptibility to chemical attack and freeze-thaw damage.

Table No.5: Durability Assessment

Sludge %	Normal Strength (MPa)	Sulfate Attack (MPa)	Chloride Attack (MPa)	Wet-Dry Cycles (MPa)
0%	35.20	33.50 (-4.8%)	34.00 (-3.4%)	34.20 (-2.8%)
5%	36.50	36.80 (+0.8%)	37.00 (+1.4%)	36.90 (+1.1%)
10%	26.81	27.30 (+1.8%)	27.40 (+2.2%)	27.20 (+1.5%)
15%	18.56	19.20 (+3.4%)	19.50 (+5.1%)	19.10 (+2.9%)
20%	15.39	16.10 (+4.6%)	16.40 (+6.6%)	15.90 (+3.3%)
25%	8.98	9.60 (+6.9%)	10.00 (+11.3%)	9.40 (+4.7%)

- **5% sludge pavers** excelled in chemical/durability exposure; higher values suffered from surface degradation and internal cracking.

5.4 Water Absorption

- Increased with sludge content (from ~1% at 0% to >3% at 25%), confirming greater porosity in higher sludge mixes.paper-ajith.pdf+1

5.5 Leaching (Environmental Safety)

Heavy Metal Immobilization in Cementitious Matrices

Cement hydration generates calcium silicate hydrates that can physically encapsulate and chemically bind heavy metals, reducing leachability. The toxic elements in CETP sludge, when immobilized in the concrete matrix, are prevented from environmental release under normal conditions, confirming environmental safety

Table No.6: Leaching test

Sludge %	Cr (mg/L)	Na (mg/L)	Pb (mg/L)	Cu (mg/L)	Cd (mg/L)	K (mg/L)	Fe (mg/L)
5%	0.066	0.179	0.283	0.486	0.667	2.842	1.803
10%	0.057	0.681	0.174	2.148	0.722	3.158	0.859
15%	0.046	1.894	0.043	0.216	0.741	0.789	0.575
20%	0.037	3.140	1.043	1.581	0.694	2.368	0.391
25%	0.041	2.798	0.861	1.378	0.867	3.158	0.351

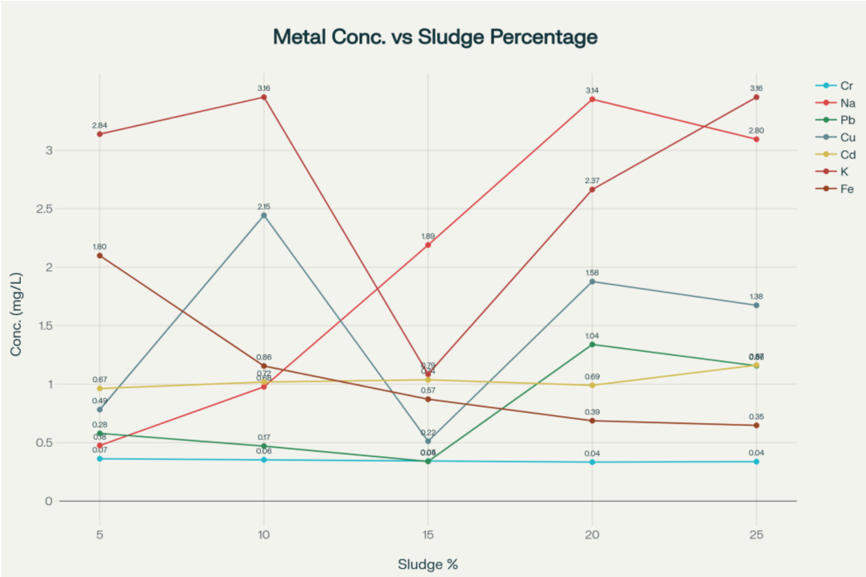

Fig 4: : Leaching test

- All mixes met regulatory safety limits in leaching tests; concrete matrix effectively immobilized heavy metals.

Economic Impact

- **Material cost saving up to 8%** for 5% replacement, due to reduced need for sand and lower waste disposal costs.repor-1.pdf+1
- No process changes required for adoption in existing ready-mix or paver manufacturing plants.

6. Conclusions

- **5% CETP sludge as fine aggregate** in M30 paver blocks offers optimum mechanical strength, durability, and environmental compliance.
- Using more than 10% sludge compromises physical and environmental performance due to increased porosity, reduced bonding, and water demand.
- The solution yields economic and ecological benefits—reduced natural sand consumption, safe waste valorization, and meaningful cost savings.

7: Recommendations and Future Scope

- **Pre-treatment and Advanced Testing:** Research pre-treatment (e.g., calcination) of sludge to increase feasible replacement ratio. SEM/XRD studies recommended for micromechanical insights.
- **Field Trials:** Pilot projects for real-life performance monitoring and lifecycle assessment.
- **Collaboration:** Industry (ready-mix), regulatory, and academic partnerships to support scale-up, standard updates, and commercial deployment.
- **IPR:** Patent methodology and formulation for competitive and responsible use.

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