

A Comprehensive Study on Elemental Analysis and Sustainable Integration of CETP (Common Effluent Treatment Plant) Sludge as A Substitute to Sand in Concrete

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Abstract

This study examines the utilization of sludge from common effluent treatment plants (CETP) as a fractional substitute for sand in M₂₀ concrete mixtures. Its aim is to address disposal challenges associated with CETP sludge while promoting sustainable use of natural resources. The research assesses the structural and microstructural attributes of concrete mixes containing varying percentages of CETP sludge (0%, 10%, 20%, 30%, 40%, and 50%). Tests conducted include compressive, flexural, and split tensile strength, alongside durability assessments like dry and wet durability, sulphate resistance, and chloride penetration. Energy dispersive x-ray analysis (EDAX) identifies significant elements in CETP sludge, such as chromium, zinc, nickel, copper, iron, sodium, lead, cadmium, and potassium, influencing properties from improved corrosion resistance to potential structural reinforcement. Findings indicate that replacing 10% of sand with CETP sludge optimizes compressive strength, achieving an average of 21.01 N/mm² after 28 days, compared to 26.58 N/mm² for conventional concrete. Tensile strength at 10% replacement measures 2.40 N/mm², slightly lower than the control's 2.90 N/mm², and flexural strength is 1.61 N/mm² after 28 days, compared to 2.11 N/mm² for the control mix. The slump test confirms good workability, with a slump value of 100 mm for the mix containing 10% CETP sludge replacement. This study validates the technical feasibility and economic viability of incorporating CETP sludge into concrete, potentially reducing fine aggregate costs by 10%. To further enhance the performance and safety of CETP sludge concrete, future research could explore the integration of geopolymer encapsulation techniques. Such encapsulation could effectively immobilize heavy metals, mitigating potential environmental and health risks associated with CETP sludge. This aligns with the journal's focus on advanced materials and sustainable practices, offering a pathway for innovative, eco-friendly building materials and supporting sustainable development goals through improved waste management and resource conservation.

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Received Date: July 26, 2024

Accepted Date: November 05, 2024

Published Date: November 11, 2024

Citation: Sandeep Kumar. C, Usha. S, Shivaraju. G. D. A Comprehensive Study on Elemental Analysis and Sustainable Integration of CETP (Common Effluent Treatment Plant) Sludge as A Substitute to Sand in Concrete. Journal of Polymer & Composites. 2025; 13(Special Issue 1): S49–S59p.

Keywords: CETP sludge, concrete strength, durability, EDAX, sustainable construction, waste management

INTRODUCTION

This study investigates the potential of using common effluent treatment plant (CETP) sludge as a partial substitute for sand in M₂₀ grade concrete. Given the substantial disposal challenges posed by CETP sludge, this research seeks to provide a sustainable solution by repurposing the sludge in concrete production. Prior studies indicate that incorporating industrial waste into concrete can enhance various properties while also addressing

waste disposal concerns [1, 2]. CETP sludge has previously been considered viable for construction materials, exhibiting promising results in mechanical and durability assessments [3, 4].

In this study, concrete mixes with varying CETP sludge replacement levels of 0%, 10%, 20%, 30%, 40%, and 50% were prepared, and their mechanical properties were evaluated. Compressive, flexural, and split tensile strengths were tested, along with durability assessments, including dry and wet durability, sulphate resistance, and chloride penetration tests [5, 6]. Additionally, the presence of heavy metals and minerals in CETP sludge, such as chromium, zinc, nickel, and copper, identified through energy dispersive x-ray analysis (EDAX), could contribute to enhanced corrosion resistance and structural reinforcement [7, 8].

The findings reveal that a 10% replacement of sand with CETP sludge optimized compressive strength, achieving an average of 21.01 N/mm² after 28 days, which, while slightly lower than the conventional concrete's 26.58 N/mm², still demonstrates sufficient strength for certain structural applications [9].

Similarly, tensile strength at 10% replacement was recorded at 2.40 N/mm², just slightly below the control's 2.90 N/mm², while flexural strength measured 1.61 N/mm² after 28 days, compared to 2.11 N/mm² for the control [10, 11]. Sustainable construction materials like CETP sludge-based concrete align with global sustainable development goals by promoting efficient waste management and reducing the reliance on natural resources [12, 13]. Furthermore, the economic advantages of CETP sludge inclusion, particularly a reduction in fine aggregate costs by up to 10%, highlight the financial viability of this approach, underscoring its relevance in the construction industry [14, 15].

Life cycle assessment studies have shown the potential of CETP sludge applications in concrete to reduce environmental impacts associated with waste disposal, providing an eco-friendly alternative to traditional sand aggregates [16]. Previous research on industrial sludge in concrete, including textile and municipal waste sludge, supports the effectiveness of such sludge in enhancing concrete properties [17, 18, 19]. This study thus contributes to a growing body of knowledge on the use of waste materials in construction, helping to alleviate environmental impacts and improve concrete performance in line with contemporary sustainability targets [20, 21, 22].

Studies show that incorporating industrial waste, such as CETP sludge, into concrete can improve its properties while helping to solve disposal issues [23, 24]. CETP sludge, along with other waste, has been found to enhance concrete's mechanical and durability characteristics, including resistance to sulphates and chlorides [25, 26]. EDAX analysis indicates that the heavy metals in CETP sludge could contribute to better corrosion resistance and structural integrity [27, 28]. These findings support sustainable construction practices by improving concrete performance and addressing environmental concerns [23, 28].

LITERATURE REVIEW

The utilization of various waste materials in concrete has garnered considerable interest in recent years, highlighting both environmental and performance advantages.

In a study by Jianguo Lu et al. (2024), the incorporation of municipal solid waste incinerator bottom ash (MSWIBA) as a partial replacement for fine aggregate resulted in reduced water absorption, indicating effective pore filling. The optimal replacement ratio was identified to range between 24.8% and 57.8%, leading to improved compressive strength, albeit still lower than that of concrete made with ordinary portland cement (OPC). Similarly, Prashanth Janardhan et al. (2023) investigated the use of incinerated solid waste (ISW) and recycled plastic waste (RPW) as partial substitutes for cement and fine aggregate. Their results showed that replacing up to 20% of fine aggregate and 15% of cement with ISW enhanced the strength of the concrete. However, higher percentages of cement replacement resulted in decreased strength due to the reduced formation of calcium silicate hydrates.

Maria C. A. Feitosa et al. (2023) explored the potential of using sewage sludge as a fine aggregate replacement. They concluded that an optimal replacement level of 5% improved both compressive strength and capillary water absorption, positioning sewage sludge as a viable alternative. Research by Skanda Kumar B N et al. (2023) examined the use of common effluent treatment plant (CETP) sludge, revealing that it exhibited good flowability and unconfined compressive strength (UCS) values for controlled low-strength materials (CLSM). This finding suggests its potential for various applications while contributing to the reduction of soil and groundwater pollution.

A.B.M.A. Kaish et al. (2021) investigated various industrial wastes and found that optimal replacement levels of 10% for alum sludge and 15% for quarry and limestone dust enhanced both the density and mechanical properties of concrete.

This indicates the promise of industrial waste materials as sustainable substitutes for conventional fine aggregates. Lastly, Yue Liu et al. (2020) focused on water treatment sludge, revealing that replacement ratios exceeding 10% negatively impacted compressive strength and sulphate resistance. Their microstructural analyses highlighted the formation of ettringite and a more porous interfacial transition zone (ITZ), underscoring the importance of carefully considering replacement levels to balance performance with the benefits of utilizing waste materials.

OBJECTIVES

Research aims: exploring CETP sludge as a sustainable substitute for fine aggregate in concrete applications:

- To investigate the physical properties and elemental composition of CETP sludge using energy dispersive x-ray analysis (EDAX)
- To explore the substitution of fine aggregate with CETP sludge at varying percentages 10%,20%,30%,40% and 50%
- To evaluate the mechanical and durable parameters of concrete incorporated with CETP sludge at varying proportions of fine aggregate
- To study the optimum mix ratio of CETP sludge as a replacement with fine aggregate and analysing the suitability of usage of CETP sludge in concrete

METHODOLOGY

This research begins with the collection of representative CETP sludge samples from a common effluent treatment plant. The sludge is dried to remove excess moisture and sieved to achieve a uniform particle size suitable for concrete mixing. Elemental composition analysis is conducted using energy dispersive x-ray analysis (EDAX). In addition, the physical properties of the CETP sludge, such as water absorption, specific gravity, and bulk density, are evaluated and compared with conventional fine aggregate. Concrete mixes are then prepared with varying levels of CETP sludge replacement (0%, 10%, 20%, 30%, 40%, and 50%) for fine aggregate, adhering to M₂₀ grade concrete specifications and maintaining a consistent water-cement ratio. The mechanical properties, including compressive, tensile, and flexural strength, are measured at 7, 21, and 28-day intervals through standard testing on concrete cubes. Durability tests, such as sulphate resistance, chloride penetration, and alternating wetting and drying cycles, are also conducted to assess the long-term performance of the concrete. Based on these findings, practical recommendations for incorporating CETP sludge into concrete production are developed.

RESULTS AND DISCUSSION

Elemental Composition Analysis

Energy dispersive x-ray analysis for CETP sludge.

Table 1 summarizes the impact of specific elements on concrete properties, while Figure 1.a illustrates the elemental analysis. Elements like chromium, zinc, nickel, and iron enhance concrete's durability and resistance, contributing to its structural strength. Conversely, elevated levels of sodium, lead, cadmium, and potassium may compromise structural integrity and reduce lifespan. Figure 1.b presents the microstructure of CETP sludge.

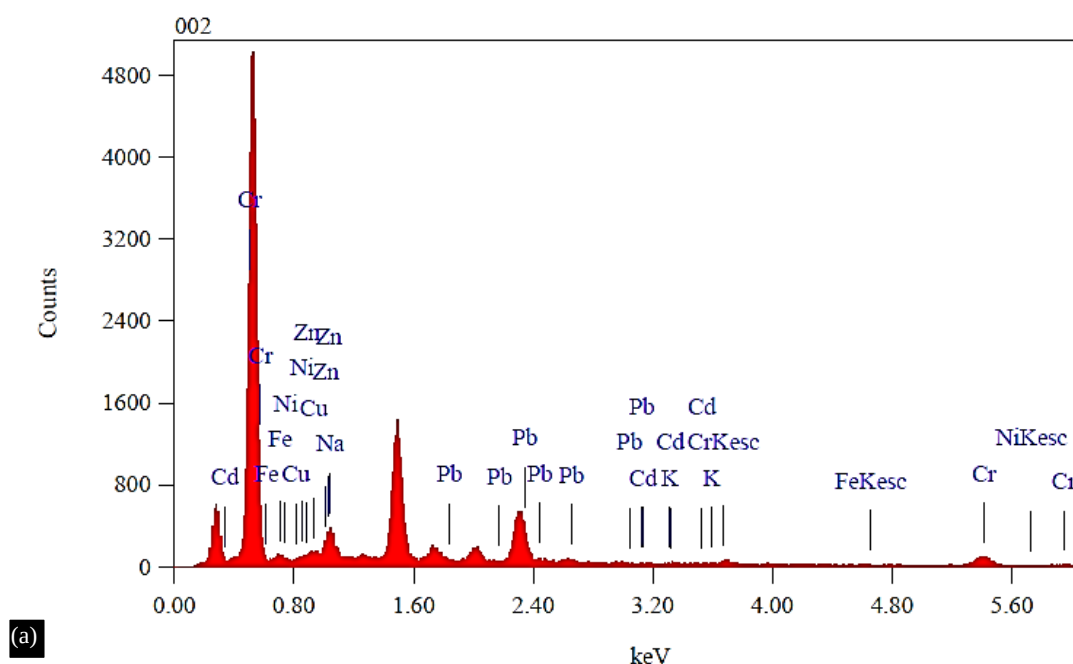


Figure 1. a. Elemental analysis.

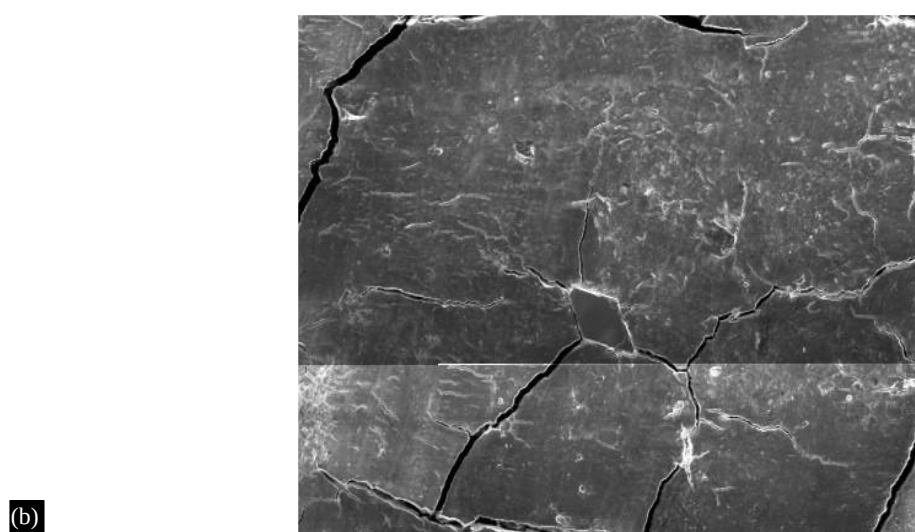


Figure 1. b Microstructure image of CETP sludge

Table 1. Elemental influences on concrete: enhancing strength and durability.

S. N.	Element	Impact on concrete properties
1.	Cr (Chromium)	Enhances corrosion resistance, improving the longevity of concrete structures.
2.	Zn (Zinc)	Improves corrosion resistance, contributing to the durability of reinforced concrete.
3.	Ni (Nickel)	Improves durability and strength, making concrete more resistant to wear and tear.
4.	Cu (Copper)	Small amounts improve strength, enhancing the mechanical properties of concrete.
5.	Fe (Iron)	Iron contributes to the overall strength and durability of concrete. It can improve hardness and resistance to wear.
6.	Na (Sodium)	Structural damage and reduced durability of concrete.
7.	Pb (Lead)	Concrete can reduce compressive strength and durability.
8.	Cd (Cadmium)	Cadmium in concrete can weaken the material and reduce its durability.
9.	K (Potassium)	High levels can contribute to alkali-silica reaction (ASR), causing expansion and cracking, leading to structural damage.

A Comparative Analysis

The comparative analysis highlights key differences between fine aggregate and CETP sludge, indicating the potential for partial replacement in concrete. CETP sludge has a much higher water absorption (3.05% vs. 1.01%), reflecting its greater porosity. Its significantly lower bulk density (675 g/cc loose, 750 g/cc compacted) compared to fine aggregate (1580 g/cc loose, 1800 g/cc compacted) suggests that CETP sludge is lighter and less dense. With a lower specific gravity (1.49 vs. 2.65) and finer particle size (4.05 vs. 2.69), CETP sludge offers a more lightweight, finer material option. These characteristics make CETP sludge suitable for partial replacement of fine aggregate in concrete, at levels ranging from 10% to 50%, potentially improving material efficiency and performance. These values are presented in Table 2.

Table 2. Attributes of fine aggregate and CETP sludge.

S.N.	Tests	Fine aggregate	CETP sludge
1.	Absorption of water	1.01%	3.05%
2.	Bulk density (loose)	1580 g/cc	675 g/cc
3.	Bulk density (compacted)	1800 g/cc	750 g/cc
4.	Specific gravity	2.65	1.49
5.	Particle fineness	2.69	4.05

Table 3. Quantity estimation of raw materials per meter cube.

S.N.	Sludge percentage	CETP sludge	Fine aggregate in kg	Cement in kg	Coarse aggregate in kg
1.	0%	0	672	403.2	1512
2.	10%	67.2	604.8	403.2	1512
3.	20%	134.44	537.56	403.2	1512
4.	30%	201.6	470.4	403.2	1512
5.	40%	268.8	403.2	403.2	1512
6.	50%	336	403.2	403.2	1512

Table 3 presents the quantity estimation of raw materials required per cubic meter of concrete with varying percentages of CETP sludge as a replacement for fine aggregate. At 0% replacement, the concrete mix includes fine aggregate, cement, and coarse aggregate in their standard proportions. With a 10% replacement level, a portion of the fine aggregate is substituted with CETP sludge, while the amounts of cement and coarse aggregate remain consistent. As the replacement percentage increases to 20%, 30%, 40%, and finally 50%, the quantity of CETP sludge gradually increases, with a corresponding reduction in the fine aggregate portion. Throughout all replacement levels, the quantities of cement and coarse aggregate are kept constant, allowing for a systematic substitution of fine aggregate with CETP sludge to explore the impact on concrete performance.

Table 4. A slump cone test was conducted on the concrete mixture.

S.N.	Sludge %	Water/ Cement ratio	Slump in mm
1.	0%	0.40	105
2.	10%	0.40	100
3.	20%	0.50	98
4.	30%	0.50	96
5.	40%	0.60	98
6.	50%	0.60	95

The slump cone test shows that as CETP sludge content increases, more water is needed to maintain workability due to its higher absorption. At 0% sludge with a 0.40 water-cement ratio, the slump is 105 mm, but with 10% sludge, it drops to 100 mm. As sludge content rises to 20% and 30%, the water-

cement ratio increases to 0.50, yet the slump continues to fall to 98 mm and 96 mm. At 40% and 50% sludge, with a 0.60 water-cement ratio, the slump stabilizes around 95-98 mm. This trend suggests that while more water is required as sludge content increases, the overall workability decreases due to the stiffer nature of the mix. The results are summarized in table 4, and the graphical representation of the slump measurements is shown in Figure 2.

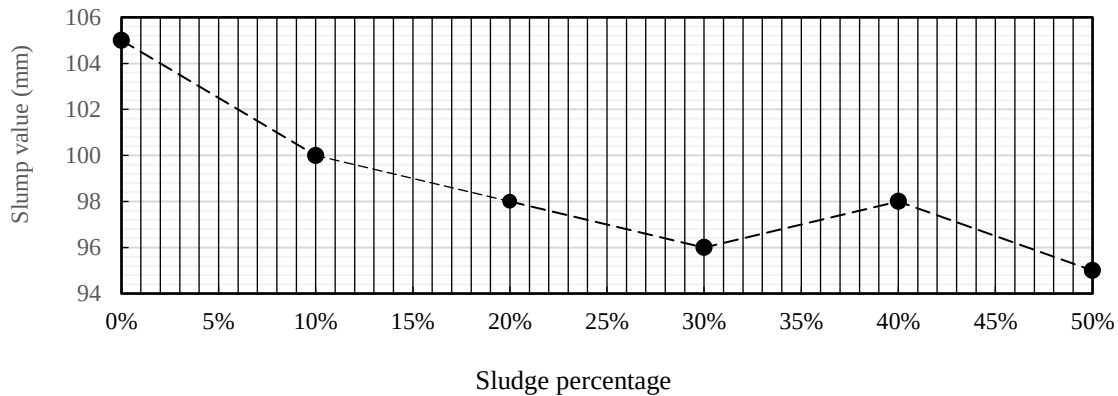


Figure 2. Concrete slump measurement in millimeters.

Mechanical properties of Concrete with Varying CETP Sludge Percentages.

Table 5. Compression tests were conducted on concrete specimens cured for durations of 7, 21, and 28 days.

S.N.	Sludge percentage	Compression strength in N/ mm ² after 7, 21 and 28 days					
		7	Average days	21	Average days	28	Average days
1.	0%	16.01	16.23	24.99	25.38	27.11	26.58
		16.44		25.77		26.04	
2.	10%	9.77	9.81	18.22	17.78	20.25	21.01
		9.85		17.33		21.77	
3.	20%	7.0	7.25	11.55	11.78	12.24	12.39
		7.55		12.0		12.54	
4.	30%	2.99	3.05	5.11	4.95	6.01	5.62
		3.11		4.78		5.23	
5.	40%	2.22	2.44	2.22	2.23	4.0	3.78
		2.66		2.23		3.55	
6.	50%	2.50	2.55	2.25	2.68	2.23	2.63
		2.60		3.11		3.03	

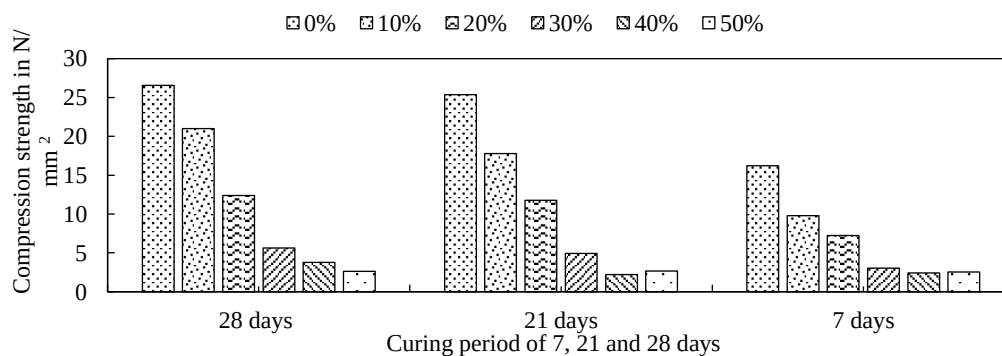


Figure 3. Compressive strength of concrete samples (MPa).

The compression test results reveal that incorporating up to 10% CETP sludge as a fine aggregate replacement preserves sufficient compressive strength, achieving 21.01 N/mm² after 28 days. However, exceeding this percentage leads to a significant decline in strength, highlighting the optimal use of CETP sludge at a 10% replacement level to ensure concrete performance remains effective while promoting sustainability. The findings are presented in Table 5, with a graphical representation of the compressive strength in MPa illustrated in Figure 3.

Table 6. Tensile strength tests were conducted on concrete specimens cured for durations of 7, 21, and 28 days.

S.N.	Sludge percentage	Tensile strength in N/ mm ² after 7, 21 and 28 days					
		7	Average days	21	Average days	28	Average days
1.	0%	1.83	1.83	2.12	2.40	2.97	2.90
		2.06		2.68		2.82	
2.	10%	1.55	1.48	2.40	2.33	2.43	2.40
		1.41		2.26		2.36	
3.	20%	1.13	1.19	1.41	1.55	1.37	1.42
		1.24		1.69		1.46	
4.	30%	1.07	1.03	1.12	1.01	1.32	1.26
		0.98		0.90		1.20	
5.	40%	0.70	1.28	0.68	0.63	0.52	0.58
		0.58		0.58		0.64	
6.	50%	0.40	0.39	0.42	0.41	0.50	0.53
		0.38		0.40		0.56	

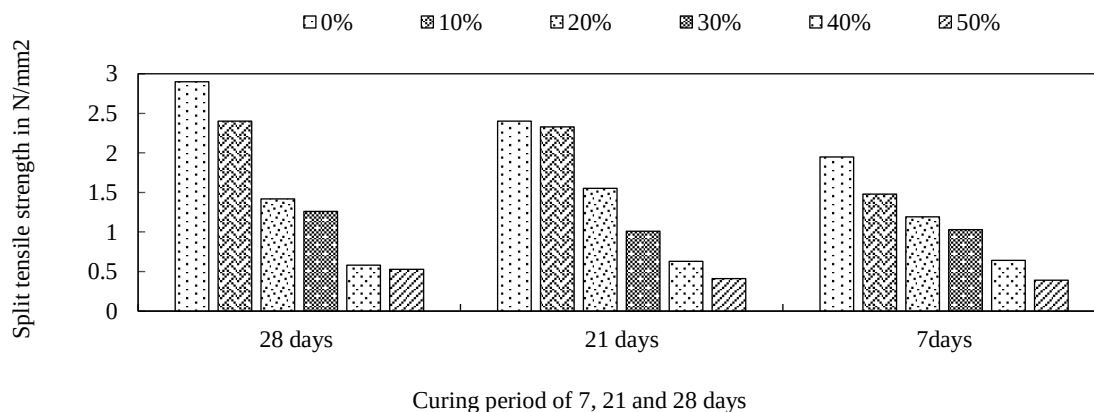
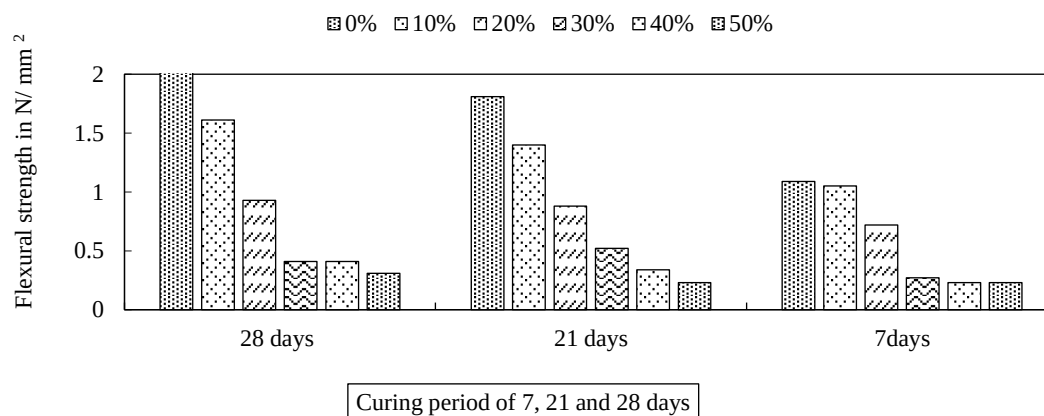


Figure 4. Tensile strength analysis of concrete with CETP sludge (MPa).

Table 6 presents the tensile strength test results for concrete specimens cured for 7, 21, and 28 days, demonstrating the impact of CETP sludge on concrete's tensile properties. At 0% sludge, the tensile strength after 28 days is 2.90 N/mm², reflecting strong performance. With a 10% replacement of fine aggregate, the tensile strength slightly decreases to 2.40 N/mm², but it remains within an acceptable range for construction. However, as the sludge content increases to 20%, 30%, 40%, and 50%, the tensile strength declines sharply to 1.42 N/mm², 1.26 N/mm², 0.64 N/mm², and 0.56 N/mm², respectively. These findings indicate that while up to 10% CETP sludge can maintain suitable tensile strength, higher replacement levels lead to a significant reduction in structural integrity. Therefore, limiting the sludge content to 10% is recommended to balance sustainability and mechanical performance. A graphical representation of the tensile strength in MPa is shown in Figure 4.

Table 7. Flexural strength tests were conducted on concrete specimens cured for durations of 7, 21, and 28 days.

S.N.	Sludge percentage	Flexural strength in N/ mm ² after 7, 21 and 28 days					
		7	Average days	21	Average days	28	Average days
1.	0%	1.07	1.09	1.88	1.81	2.18	2.11
		1.11		1.73		2.03	
2.	10%	1.07	1.05	1.53	1.40	1.64	1.61
		1.03		1.26		1.57	
3.	20%	0.72	0.72	0.73	0.88	0.97	0.93
		0.71		1.02		0.89	
4.	30%	0.26	0.27	0.56	0.52	0.38	0.41
		0.27		0.48		0.44	
5.	40%	0.21	0.23	0.33	0.34	0.43	0.41
		0.24		0.34		0.38	
6.	50%	0.24	0.23	0.23	0.23	0.29	0.31
		0.22		0.22		0.32	

**Figure 5.** Flexural strength of concrete samples (MPa) for curing periods of 7, 21, and 28 days

The flexural strength test results show that incorporating CETP sludge significantly impacts concrete performance. As shown in Table 7, tests were conducted on concrete specimens, revealing that at 0% sludge, the average flexural strength after 28 days is 2.11 N/mm², indicating strong structural capacity. With a 10% replacement of fine aggregate, the flexural strength decreases to 1.61 N/mm², which remains within an acceptable range. These results highlight the importance of limiting CETP sludge content to 10% to ensure sufficient flexural strength while supporting sustainable concrete practices. The graphical representation of flexural strength in MPa is illustrated in Figure 5.

Durability Parameter

Table.8. Results of compression strength and durability tests for concrete with CETP sludge.

S. N.	Sludge percentage	Compression strength in Mpa	Alternative wetting and drying test	Sulphate attack test	Chloride attack test
1.	0%	26.58	24.5	23.42	23.44
2.	10%	21.01	20.77	25.33	24.44
3.	20%	12.39	13	18.66	16.14
4.	30%	5.62	5.66	7.55	5.33
5.	40%	3.72	2.43	4.44	4.0
6.	50%	2.63	2.2	2.66	2.55

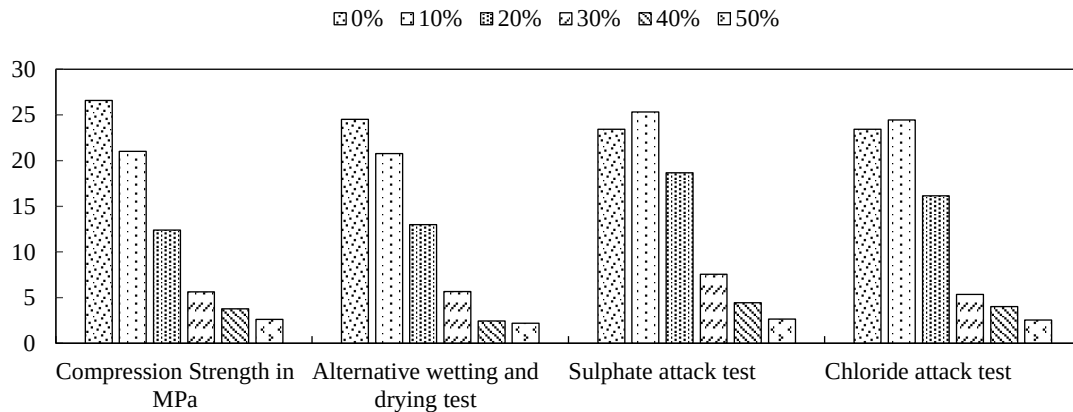


Figure 6. Concrete durability testing: wetting & drying, sulphate attack, and chloride resistance.

The experimental results, presented in Table 8, indicate a significant decline in the durability parameters of concrete as the percentage of CETP sludge increases. At 0% sludge, the concrete exhibits the highest compressive strength and strong performance in alternative wetting and drying, sulphate attack, and chloride attack tests. Incorporating 10% sludge shows a noticeable reduction in compressive strength, but the performance in durability tests remains relatively stable. However, at higher replacement levels, a drastic decrease in compressive strength is observed, alongside significant diminishment in the alternative wetting and drying, sulphate attack, and chloride attack test results. These findings suggest that while incorporating CETP sludge up to 10% is viable, excessive replacement negatively impacts the mechanical properties and durability of concrete. This highlights the need for optimizing the sludge replacement ratio to maintain the structural integrity and longevity of concrete applications. A graphical representation of the durability parameters is shown in Figure 6.

CONCLUSION

Comprehensive conclusions and recommendations for advancing future research:

- The presence of Chromium in CETP sludge, while enhancing hardness and corrosion resistance in concrete, necessitates careful balance to avoid potential drawbacks such as increased brittleness and internal stresses.
- CETP sludge demonstrates potential for partial replacement of fine aggregate in concrete, exhibiting higher water absorption, lower bulk density, lower specific gravity, and finer particle size, making it a lightweight alternative.
- The slump cone test indicates that increasing CETP sludge content necessitates higher water-cement ratios to maintain workability, yet the overall workability declines due to the stiffer nature of the mix.
- Incorporating up to 10% CETP sludge as a fine aggregate replacement preserves sufficient compressive strength, while exceeding this percentage results in significant declines, highlighting the optimal use at 10%.
- The tensile strength test shows that while up to 10% sludge maintains acceptable strength, higher replacements lead to reduced structural integrity, underscoring the need to limit sludge content for mechanical performance.
- The addition of CETP sludge negatively impacts flexural strength a maximum of 10% replacement is essential to ensure adequate performance in structural applications.
- Exploring geopolymers encapsulation as a future research direction could further enhance the safety and performance of CETP sludge in concrete. Encapsulation may help prevent the release of heavy metals and improve overall durability, aligning with advanced materials and sustainable construction practices.
- The innovation of this study is the use of CETP sludge as a partial replacement for fine aggregate in concrete, while assessing its durability parameters, addressing waste management challenges and enhancing sustainability in construction.

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