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Harnessing hazardous wastes: the production, characterization, and performance of controlled low strength materials using common effluent treatment plant sludge

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Abstract
India's rapid industrialization has led to an increase in waste generation, necessitating efficient disposal methods. This research addresses this challenge by exploring the use of Common Effluent Treatment Plant (CETP) sludge, a hazardous waste, in the production of Controlled Low-Strength Materials (CLSM). The study aims to mitigate the environmental impacts associated with CETP sludge disposal while providing a sustainable solution. To assess the feasibility of this approach, an experimental program was conducted with variations in the mix ratio of CETP sludge and slag sand, a byproduct of steel production. The properties of the produced CLSM, such as flowability and unconfined compressive strength (UCS), were thoroughly examined using Scanning Electron Microscopy, X-ray Diffraction, and X-ray Fluorescence analyses. The results reveal that the CLSM produced with CETP sludge and slag sand exhibits promising performance, with excellent flowability and UCS values ranging from 1.8 to 5.5 MPa. This research underscores the potential of waste materials in creating sustainable and environmentally friendly construction materials, contributing to effective waste management practices and sustainable industrial growth.

Keywords Common effluent treatment plant sludge, Fly ash, Processed slag sand, Controlled low-strength material, Flowability, Unconfined compressive strength, Micro structural analysis, Sustainability

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1 Introduction

Effective disposal of domestic and industrial waste poses a significant challenge, necessitating the utilization of appropriate technical methods and means. Industrial processes, such as treatment units and thermal plants, generate substantial quantities of sludge and cinders as waste products. The management and utilization of such hazardous industrial waste has become a critical concern. In this study, the focus is on the utilization of waste materials from a Common Effluent Treatment Plant (CETP) sludge, which is an industrial waste, in producing Controlled Low Strength Materials (CLSM), commonly known as granular or flowable fills. Materials like these possess extensive applicability in various non-structural constructions, which includes backfills for retaining walls, bridge abutments, and other applications requiring filling [1]. CLSM is preferred for non-structural applications due to its high permeability, shear strength, and flowability, provided that its compressive strength remains below 8.3 MPa [1]. Few of the key constituents used in CLSM production are fly ash; an industrial residue obtained from thermal power generation, ground granulated blast furnace slag; a by-product obtained by processing the waste slag developed during the manufacturing of steel in blast furnaces [2], ternary mixtures of cement, waste gypsum board, blast furnaces, and incinerated sewage sludge ash, which have been productively utilized reducing the energy as well as facilitating an effective method of sustainable disposal of these solid wastes [3, 4]. The utilization of industrial waste materials, including CETP sludge and fly ash, not only provides a sustainable approach but also helps to reduce carbon footprints [5]. Improper disposal of large volumes of sludge not only diminishes the function of surface soil but also contaminates surface water resources and groundwater [3]. Therefore, finding suitable methods to incorporate such waste materials into beneficial applications like CLSM is essential for sustainable waste management and environmental protection. CLSM offers several advantages, including good flowability, excavatability, ease of mixing and placement [6], low shrinkage, and compressibility characteristics. Moreover, CLSM is not labor-intensive and is influenced by varying moisture conditions [7]. Ongoing developments in CLSM technology focus on novel production systems and the incorporation of new materials to reduce material density and enhance thermal insulating properties [8, 9]. The research proposed in this study aims to evaluate the fresh and hardened properties of CLSM mixtures incorporating CETP sludge, class-F fly ash, and processed slag sand, in accordance with relevant Bureau of Indian Standards Indian Standards/American Society for Testing and Materials (ASTM) specifications [10, 11]. Various compositions and percentages of CETP sludge are considered to develop CLSM for numerous applications, addressing the need for sustainable waste management and resource utilization.

2 Research significance

This research offers innovative solutions for sustainable waste management and construction practices by repurposing waste materials, particularly in the production of sustainable construction materials. It addresses the pressing global priority of environmental sustainability.

2.1 Sustainable waste management – a new paradigm

Managing CETP sludge, a hazardous waste byproduct from wastewater treatment, presents significant environmental challenges. Traditional disposal methods, such as landfilling, pose risks of soil and groundwater contamination. This research proposes a novel approach by integrating CETP sludge into CLSM production, which is sustainable and, it not only reduces environmental hazards, but also aligns with waste minimization principles.

2.2 Endorsing sustainable construction practices

The construction industry's increasing demand for sustainable materials is met by utilizing CETP sludge and Processed Slag Sand (PSS) in CLSM. This approach showcases the feasibility of using waste materials as alternatives to conventional construction resources, supporting the principles of the circular economy. The CLSM produced demonstrates promising performance, highlighting its viability, and contributing to sustainability in construction.

2.3 Implications for policy and practice

The research findings have significant implications for waste management and construction sectors. Demonstrating the utility of CETP sludge and slag sand in CLSM can influence waste management policies towards repurposing of waste materials. Additionally, these insights offer practical examples for the construction industry to adopt sustainable materials, promoting environmental-friendly practices.

3 Materials

3.1 CETP sludge

The CETP sludge is obtained from an effluent treatment plant located at the outskirts of the city of Bengaluru, near Bidadi Industrial Area. Being one of the fastest growing metropolitans in India. Approximately 35 t of CETP sludge is produced per month from this unit. The sludge was then examined for its physical and chemical characteristics.

In this study, the focus is on the sludge produced at the CETP. The CETP process begins with the collection of effluents in separate tanks, categorized based on their characteristics such as acid/alkali content, high frequency rinse, chrome presence, and Total Dissolved Solids levels. After initial testing and treatment in respective reactors and neutralizers, the effluent undergoes blending and further treatment stages, including the addition of polyelectrolytes in a flash mixer for effective settling in a clarifier. The resultant sludge, after dewatering through a filter press or decanter, is then classified, treated, and disposed of according to its hazardous nature. This streamlined overview, complemented by Fig. 1, encapsulates the critical stages of the CETP process relevant to the generation and handling of the sludge, which is the primary subject of this study.

The morphology of the CETP sludge has been illustrated in Fig. 2. The SEM image showing morphology reveals the presence of irregular CETP sludge flakes consisting of angular irregularly shaped particles of various sizes, with porous structure. The samples are collected from corner and central regions of the unit and were later considered for experimental studies. Physical properties of the CETP sludge are evaluated to ascertain its applicability in the development of CLSM mix.

3.2 Fly ash

The class F fly ash used was obtained from Raichuru Thermal Power Corporation, Raichur, Karnataka, tested as per IS3812:2013 [12]. The properties of fly ash are given in Table 1. It also displays the chemical composition and physical parameters of Class-F fly ash, as determined by X-ray Fluorescence (XRF) analysis. These values provide important insights into the properties of the fly ash and its suitability for the development of CLSM.

As delineated in Table 1, the chemical constituents of CETP sludge are distinctively outlined. Notably, the fundamental constituents of cementitious materials, specifically silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3), collectively constitute a mere 27.9% of the sludge. This is significantly lower than the typical composition of these elements in conventional cementitious materials, which generally exceed 50%. As a residual byproduct of wastewater treatment processes, the CETP sludge inherently possesses a composition that diverges from traditional cementitious materials. Despite the lower concentration of SiO_2, Al_2O_3, and Fe_2O_3, the CETP sludge nonetheless exhibits cementitious properties. This is attributable to the presence of these components, albeit in diminished proportions. Furthermore, it is crucial to note that the cumulative percentages (99.97%) presented in Table 1 do not equate to 100%. This is due to the presence of other constituents within the sludge that have not been itemized in the Table 1. These unlisted constituents, which include water and organic matter among others, contribute to the remaining percentage, thereby accounting for the total composition of the sludge.

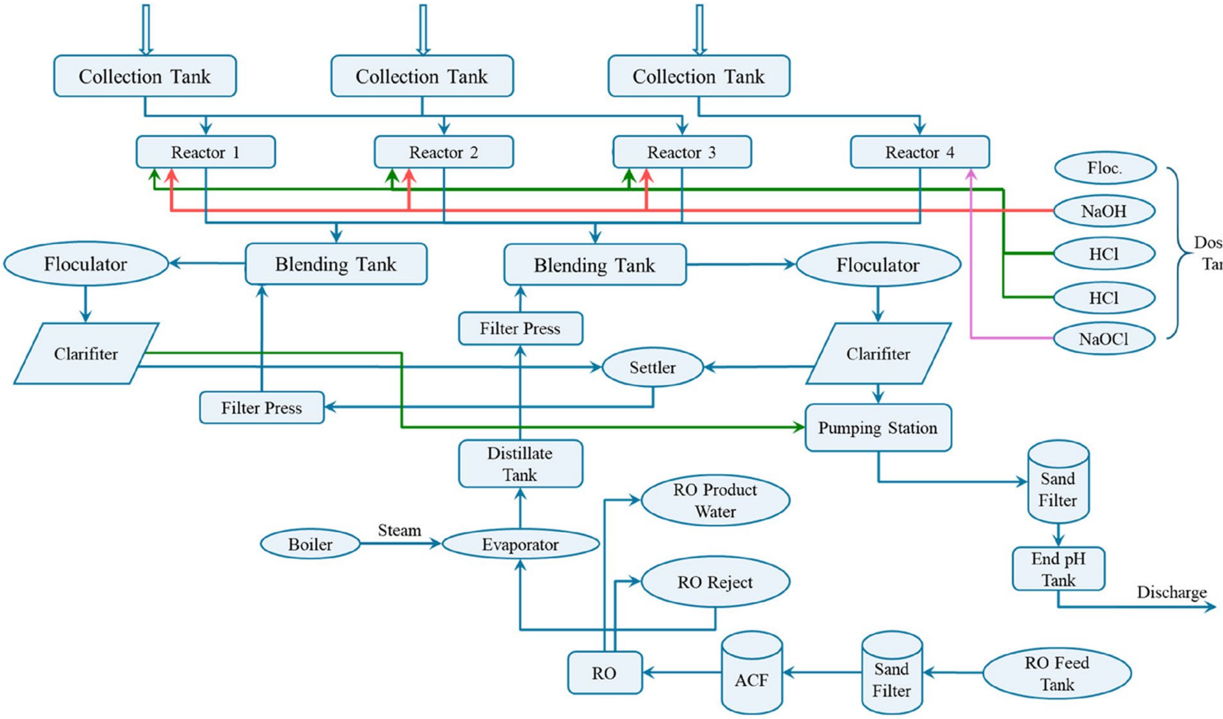


Fig. 1 Flowchart of effluent treatment

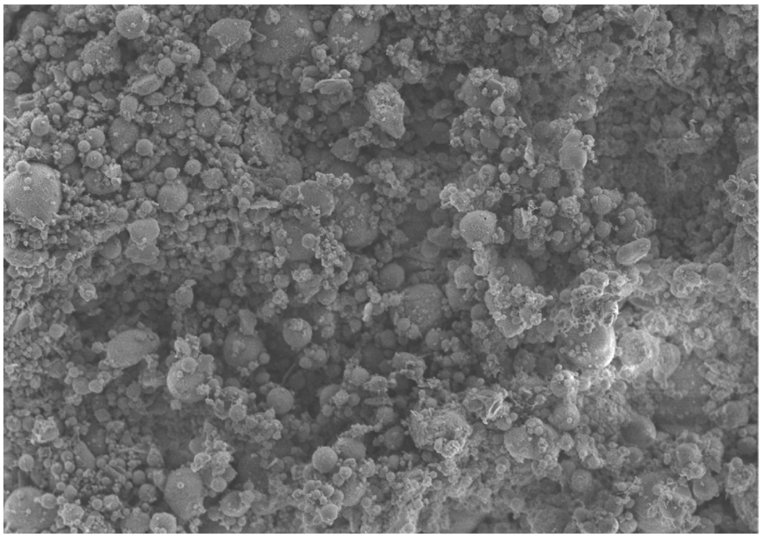


Fig. 2 SEM image of CETP sludge sample

While the chemical composition of the CETP sludge might ostensibly suggest its aptitude as a filler material, it is imperative to underscore that the sludge retains constituents that impart cementitious properties. Despite the relatively diminished percentages of SiO_2, Al_2O_3, and Fe_2O_3 in comparison to conventional cementitious materials, these components persist within the sludge and contribute significantly to the cementitious attributes of the CLSM. Moreover, the incorporation of CETP sludge as a filler material can substantially augment the overall properties of the CLSM. The sludge serves a dual purpose in this context. On one hand, it fills voids within the material, thereby enhancing its density and strength. On the other hand, it contributes to the sustainability of the material by repurposing a waste product, thereby aligning with the principles of circular economy and sustainable waste management. This innovative approach not only challenges the conventional understanding of cementitious materials but also paves the way for the development of sustainable construction materials that leverage waste products.

3.3 Processed slag sand

PSS is one of the alternatives to river sand and M-sand (Fig. 3). This raw material for PSS manufacture is the byproduct of steel industry. It has been tested for all the properties pertaining to equivalent to Zone-II sand as per IS-383:2016 [13]. Physical properties of PSS and M-sand are given in Table 2. The sieve analysis (Fig. 4) of PSS and M-sand is carried out as per IS: 383–2016 [13].

In the context of this investigation, PSS has been selected as a critical constituent in the formulation of CLSM utilizing CETP sludge. The incorporation of PSS is not merely a serendipitous choice but a scientifically grounded decision, driven by its inherent physicochemical attributes. Characterized by its granulometric configuration and latent hydraulicity, PSS augments the rheological properties of the CLSM, enhancing both flowability and unconfined compressive strength (UCS). This synergistic interaction with CETP sludge enables the attainment of specific mechanical benchmarks, aligning with the engineering requirements of sustainable construction materials. Moreover, the repurposing of PSS, as an industrial byproduct, resonates with the ecological ethos of the research, transforming potential waste into a valuable engineering resource. This innovative approach underscores the dual objectives of the study: the development of performance-oriented construction materials and the promotion of environmentally responsible practices. The integration of slag sand into the CLSM

Table 1 Properties of class-F fly ash

Constituents	**CaO**	**Al_2O_3**	**SiO_2**	**SO_3**	**K_2O**	**TiO_2**	**MnO_2**	**Fe_2O_3**	**P_2O_5**	**Cr_2O_3**	**Na_2O**	**MgO**	**Cumulative**
Test results (%)	1.21	26.72	63.78	0.47	1.21	2.21	0.04	4.29	–	0.04	–	–	99.97
Physical parameter	**Specific gravity**		**Fineness -Blaine's fineness ($m^2\ kg^{-1}$)**			**Particles retained on 45 µm sieve in %**				**pH of fly ash**			
Obtained values	2.23		523.9			12.2				8.6			

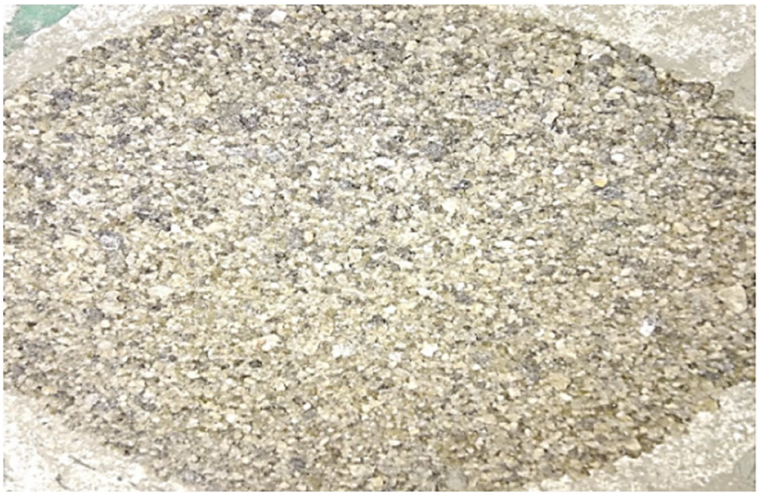


Fig. 3 Processed slag sand sample

Table 2 Physical properties of PSS and M-sand

Parameter	Obtained Results	
	Processed slag sand	**M-sand**
Specific gravity	2.80	2.7
Water absorption (%)	1.01	0.8
Fineness modulus	2.62	2.77
Zone	II	II

matrix, therefore, represents a judicious and multifaceted strategy, reflecting a confluence of engineering acumen and environmental prudence. A comparison was made between PSS sand and the widely used M-sand for their particle size distributions after conducting sieve analysis test shown in Fig. 4. In this study, instead of river sand, M-sand was compared as in the state of Karnataka, the mining of river sand has been prohibited as per National Mineral Policy – 2008 [14] which has rendered the use of M-sand for construction inevitable.

4 Methodology

4.1 General

The CETP sludge and class-F fly are used to produce CLSM. The specimen preparation and methodology for this study were designed to ensure accuracy and replicability. For specimen preparation, PSS and M-sand

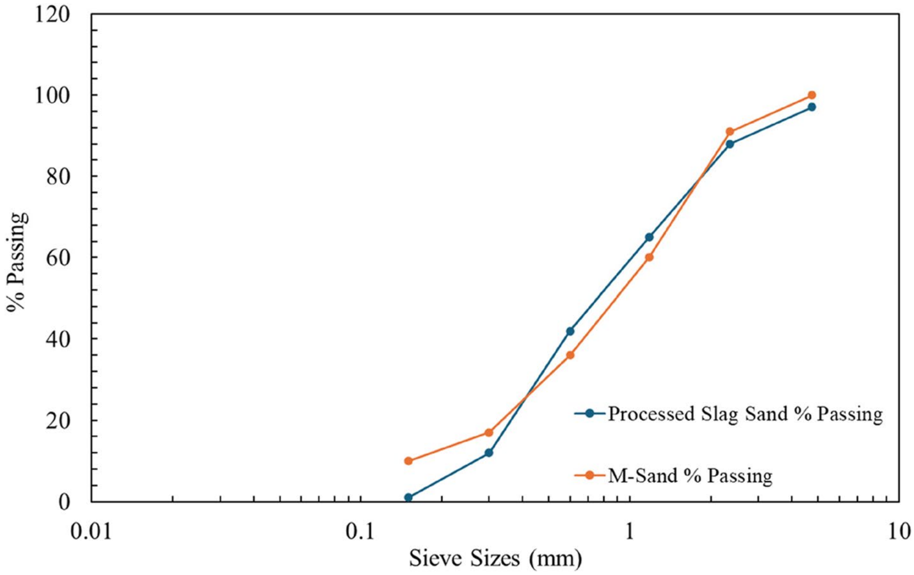


Fig. 4 Particle-size distribution chart – PSS & M-sand

were selected based on their chemical composition and physical properties. A total of 45 specimens were prepared having 3 trials for each type, and they were cured for 7 and 28 days under controlled conditions to achieve the desired properties (Table 3). The methodology of the study focused on evaluating the properties of CLSM, including flowability (conducted on a flow table shown in Fig. 5) and compressive strength. Various tests such as SEM, XRD, and UCS were conducted following standard protocols. All the mixture proportions were prepared according to American Concrete Institute (ACI)229 R guidelines [1]. Due to the absence of standardized procedure for the mixture, a trial-and-error method was carried out in Horbart Manufacturing's mechanical mixer.

4.2 Preparation for UCS tests

UCS is a highly significant property to decide the application of CLSM. The sample preparation for CLSM mixes was conducted as per ASTM specifications (ASTM

Table 3 Specimen mix ratio details

Series	Mix ID	Fly ash (g)	CETP Sludge (g)	Processed slag sand (g)	Water (mL)	W/B ratio
A	A1	500	600	1100	1200	1.09
	A2	500	600	1100	1250	1.13
	A3	500	600	1100	1300	1.18
B	B1	500	650	1150	1400	1.21
	B2	500	650	1150	1450	1.26
	B3	500	650	1150	1500	1.30
C	C1	500	700	1200	1600	1.33
	C2	500	700	1200	1650	1.37
	C3	500	700	1200	1700	1.41
D	D1	500	750	1250	1800	1.44
	D2	500	750	1250	1850	1.48
	D3	500	750	1250	1900	1.52
E	E1	500	800	1300	2000	1.53
	E2	500	800	1300	2050	1.57
	E3	500	800	1300	2100	1.61

W/B ratio Water/Binder Ratio

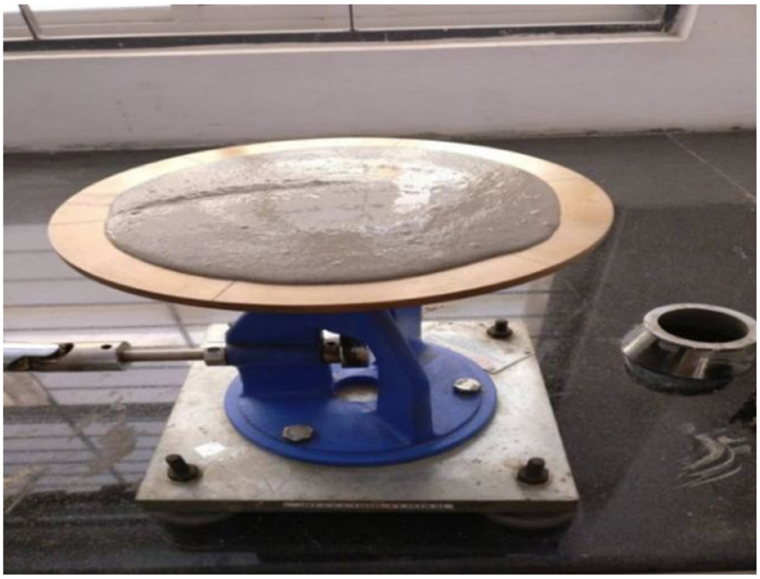


Fig. 5 Flow table test

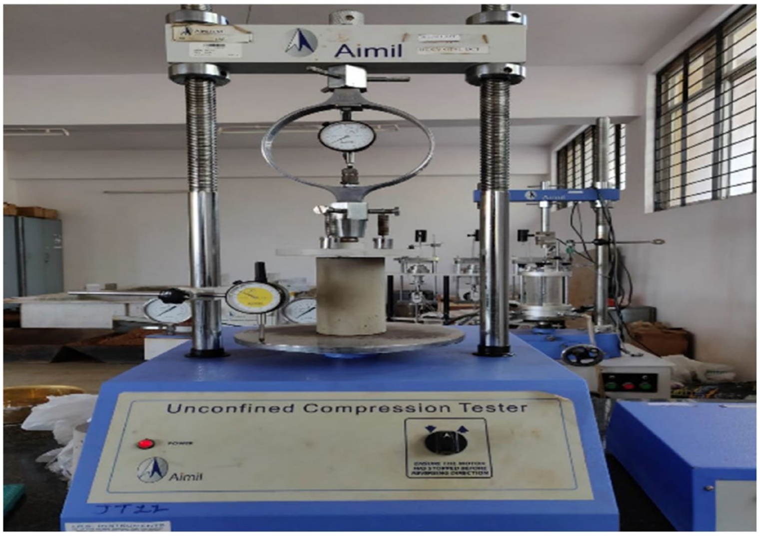


Fig. 6 UCS test setup

D4832-10). UCS samples of 75 mm diameter and 150 mm height were prepared. The UCS test (Fig. 6) was performed at a strain rate of 1.25 mm min^{-1}. The inner surface of the mould is made smooth by specially polishing so that the samples can be extruded easily. Also, the sides are smeared with oil to further decrease the side friction. While preparing the samples, it is ensured that no air entrainment occurred in the samples. This is achieved by slowly pouring the sample with continuous tapping. The samples along with mould are enveloped in a cling film to prevent evaporation. After 24 h of curing in desiccators, the samples are extruded out from the mould.

4.3 Preparation for flowability tests

It is the main plastic property of CLSM, which determines its flowable characteristics. The requirement of a superior CLSM mix is to flow readily when pumped at the site without segregation, and the proportion of water in the mix is extremely critical to determine the flowability [15, 16]. CLSM mix prepared was checked for flowable property as per ASTM specifications [11]. Flowability can be found by measuring the spread diameter of a CLSM mix in a steel or plastic flow cylinder of diameter 75 mm diameter and 150 mm height. The flow values should be between the ranges of 19 cm to 28 cm. The flow diameter should be more than 200 mm if the mix must be a flowable mix. An upper limit of 300 mm flowability was fixed to obtain a mix of required consistency and to reduce the segregation in the mix during pumping.

5 Study of microstructure

5.1 Scanning *electron* microscope (SEM) analysis

SEM analysis was performed on Mix E-3 sample (highest UCS value). The influence of curing on the microstructure of CLSM is examined through SEM. It can be seen in Fig. 7a that, after the first 7 days of curing, a well-defined structure of CLSM matrix has been developed. The reason for this could be the binder materials; particularly, CETP sludge with fly ash must have reacted to form a variety of products. The observed structure

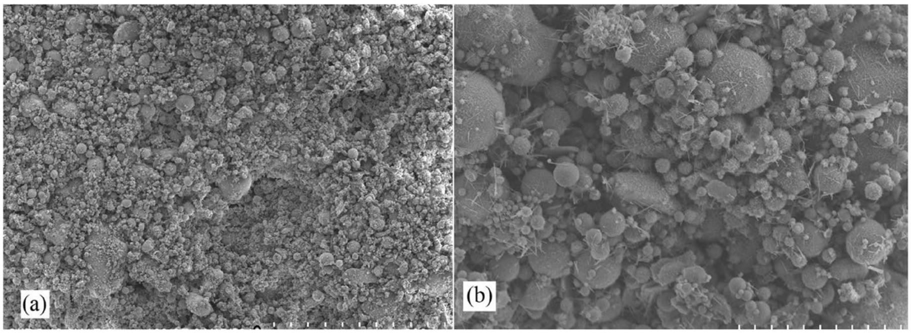


Fig. 7 SEM images at (**a**) 7 days and (**b**) 28 days

was the amorphous filamentous structure encompassing the complete matrix. The pointed crystallites, as seen in Fig. 7b, are the likelihood of formation of calcium-silicate hydrate(C-S–H) and ettringite on the fly ash spheres. The relatively unaltered particle structure of the CETP sludge spheres indicates that it did not experience complete hydration at 28 days. Further, the hydration products appear more mature displaying a denser C-S–H structure encompassing the entire CLSM matrix.

5.2 X-ray diffraction (XRD) analysis

XRD spectra of the CLSM at 7 and 28 days are illustrated in Fig. 8 for Mix E-3. The concentration of mullite peaks, specifically, reduced at 28 days signaling the involvement of fly ash in hydration reactions. The chief pointed crystallites hydration recognized after 28-day sample was of calcium hydroxide. The "smaller peaks" refer to less prominent features in the graph, indicating the presence of calcium carbonate and ettringite in smaller quantities within the sample being analyzed. Essentially, it's pointing out that these two compounds are present, but not in large amounts.

6 Results and discussion

In this section, a thorough dissection of experimental outcomes is presented. The CETP sludge's chemical makeup was scrutinized, highlighting its potential as a filler in CLSM production. The performance of the CLSM samples, particularly their flowability and UCS, is evaluated, suggesting their structural robustness and diverse applicability [17]. The section also includes a comparative study with other CLSM research, providing a wider perspective. The optimal mix ratio is identified, with a discussion on the selection criteria. The novelty of this research lies in the innovative utilization of CETP sludge, a hazardous waste, contributing to sustainable waste management and industrial growth.

6.1 Flowability and UCS

From Fig. 9, it can be inferred that most of the CLSM mixes considered were in the range of 20–30 cm, and the minimum flowability value was found to be 19 cm for Mix E; whereas the maximum flowability value of 24 cm was found for Mix A. For higher solid contents, the flowability values got reduced as more water was required to bind the materials and maintain the consistency & fluidity of the mixes.

All samples hardened within 24 h of sample preparation making it evident that there was a rapid increase in compressive strength as the CETP content increased, till 28 days for the samples. Figure 10 illustrates the development of compressive strength at 7 and 28 days, respectively. CETP sludge and Fly ash together may have a pozzolanic effect, improving the compressive strength. The maximum strength achieved was mix-E series with UCS value 5.5 MPa at 28 days curing and the minimum strength achieved was mix-A series with UCS value of 1.8 MPa.

The flowability and UCS of the developed CLSM were evaluated to assess their performance. Flowability, a critical property of CLSM, was measured using a flow test as per ASTM D-6103–04 specifications. The results showed that the flowability values varied across the different mix series, with the minimum and maximum flowability values observed for Mix E and Mix A,

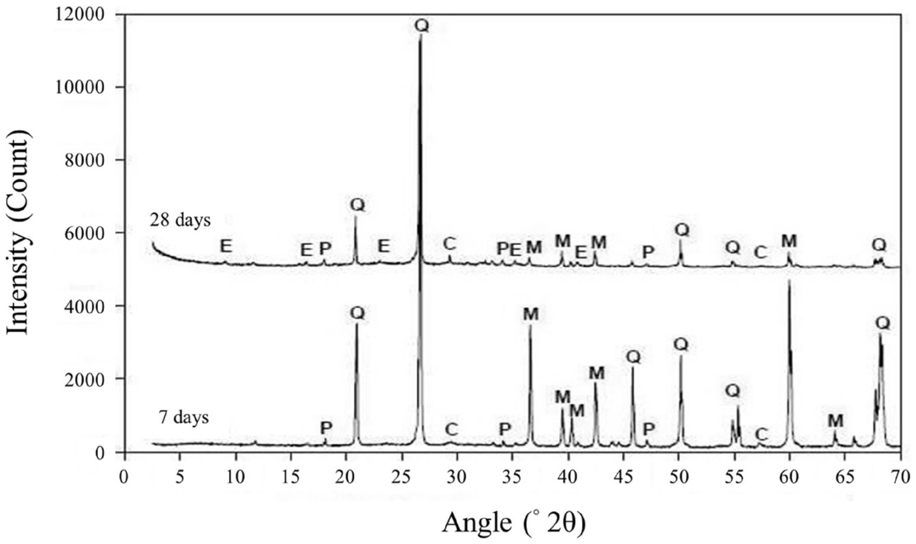


Fig. 8 XRD spectra of Mix E-3 at 7 and 28 days

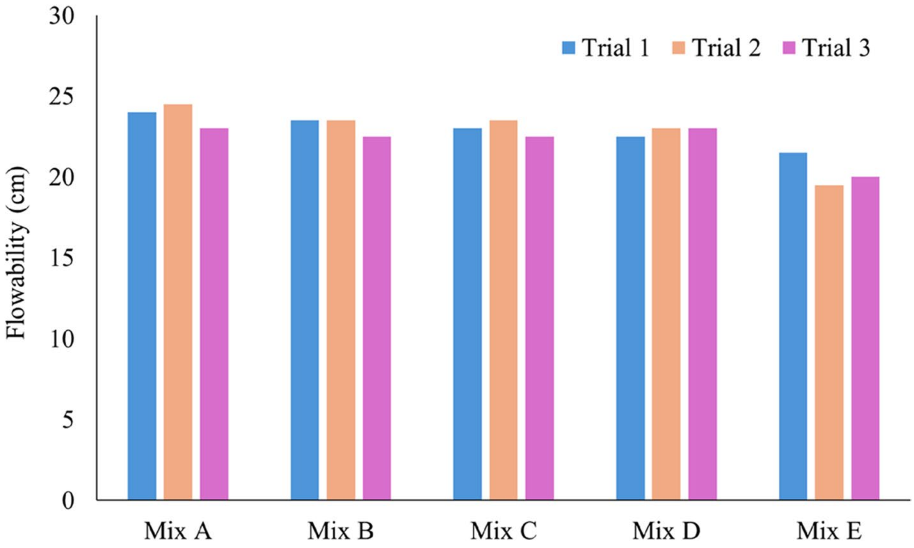
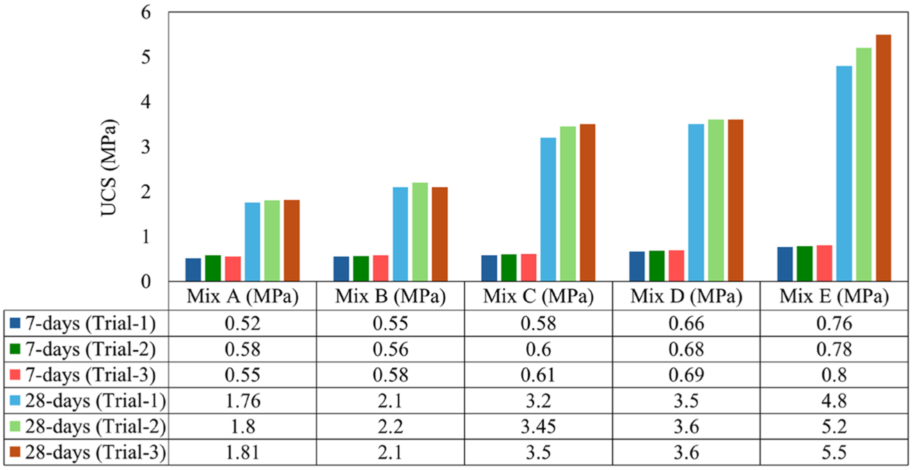


Fig. 9 Results of flowability test



	Mix A (MPa)	Mix B (MPa)	Mix C (MPa)	Mix D (MPa)	Mix E (MPa)
■ 7-days (Trial-1)	0.52	0.55	0.58	0.66	0.76
■ 7-days (Trial-2)	0.58	0.56	0.6	0.68	0.78
■ 7-days (Trial-3)	0.55	0.58	0.61	0.69	0.8
■ 28-days (Trial-1)	1.76	2.1	3.2	3.5	4.8
■ 28-days (Trial-2)	1.8	2.2	3.45	3.6	5.2
■ 28-days (Trial-3)	1.81	2.1	3.5	3.6	5.5

Fig. 10 Comparison of UCS of mixes after 7 and 28 days of curing

respectively. The UCS, a significant property to determine the application of CLSM, was evaluated as per ASTM D-4832–23 [10]. The results revealed that the minimum compressive strength was attained by mix A-1, while the maximum compressive strength was achieved by Mix E-3 at 28 days of curing. These results provide valuable insights into the performance of the developed CLSM and its potential applications.

6.2 Chemical properties of CETP sludge

XRF analysis of the CETP sludge is done to recognize the mineral composition of the sludge. Table 4 illustrates the XRF analysis for the CETP sludge. The physical appearance of the CETP sludge is pale grey in color. The specific gravity is found to be 2.19, and dry density of 571 kg m^{-3} (after ramming by a metal rod). The chemical composition of the CETP sludge provides valuable insights into the suitability of this industrial waste material for current research which are summarized as follows:

Table 4 Chemical composition of CETP sludge (as obtained by XRF analysis)

Element	Percentage
SiO_2	21.6
Al_2O_3	2.0
CaO	21. 2
Fe_2O_3	4.3
MgO	0.9
pH (10% suspension)	9.6

- The presence of SiO_2 (21.6%) and Al_2O_3 (2.0%) indicates the potential for these constituents to contribute to the binding and strength development of CLSM. Both SiO_2 and Al_2O_3 are known to participate in pozzolanic reactions when combined with appropriate activators such as calcium hydroxide during hydration. These reactions result in the formation of additional cementitious compounds, contributing to the overall strength and durability of the CLSM matrix.
- The CaO content of 21.2% suggests the presence of calcium-based compounds in the CETP sludge. Calcium compounds, such as calcium hydroxide, are known to play a crucial role in the development of strength in cementitious materials. The presence of CaO in the sludge indicates the potential for the formation of additional calcium-rich compounds during the hydration process, further enhancing the strength characteristics of the CLSM.
- The Fe_2O_3 content of 4.3%suggests the presence of iron oxide in the CETP sludge. Iron oxide can act as a coloring agent in cementitious materials but does not significantly contribute to the strength development. However, it is important to consider the overall iron content in the sludge, as high levels of iron oxide may have adverse effects on the color and appearance of the final CLSM product.
- MgO (0.9%) can potentially interfere with the hydration reactions and adversely affect the strength development of the CLSM. It is important to carefully manage the magnesium content in the sludge to ensure optimal performance of the final CLSM product.
- The pH value of 9.6 for the 10% suspension of CETP sludge indicates an alkaline nature. Higher pH can be attributed to the presence of CaO and other alkaline compounds in the sludge. The alkaline nature of the sludge is favorable for cementitious reactions and can contribute to the overall performance and durability of the CLSM.

Upon examination of the CETP sludge's chemical composition through XRF, it becomes apparent that it encompasses a variety of crucial elements and compounds. These constituents have the potential to significantly bolster the mechanical attributes and overall performance of CLSM. It is noteworthy that the proportions SiO_2 (21.6%), Al_2O_3 (2.0%), and CaO (21.2%) might not be substantial when juxtaposed with conventional mineral materials. However, within the context of waste materials such as CETP sludge, these percentages are indeed consequential. These constituents allude to the existence of cementitious compounds within the sludge. Moreover, the alkaline pH value (9.6 in a 10% suspension) signifies conducive conditions for hydration reactions, a critical aspect of cementitious materials. Nonetheless, it is imperative to exercise careful consideration and optimization of the Fe_2O_3 (4.3%) and MgO (0.9%) contents to ensure the CLSM's desired performance is not compromised.

The chemical analysis of CETP sludge also reveals significant concentrations of SiO_2, Al_2O_3, CaO, and Fe_2O_3, with a pH of 9.6. Though this sludge does not contain heavy metals, its environmental impact is considerable. The high pH and specific compound concentrations can lead to ecological imbalances if not properly managed. Recent advances in sludge reclamation and reuse technologies, such as high-solids centrifuges, egg-shaped digesters, and temperature-phased anaerobic digestion, are transforming sludge into cleaner, less voluminous, and more safely reusable class A bio-solids. These developments, along with decreasing trends in sludge landfilling and incineration, reflect the increasing emphasis on sustainable sludge management practices [18].

6.3 CETP sludge as a filler material

The chemical structure of the fly ash reveals the presence of various constituents, including CaO (1.2%), Al_2O_3 (26.7%), SiO_2 (63.8%), SO_3 (0.5%), K_2O (1.2%), TiO_2 (2.2%), MnO_2 (0.04%), Fe_2O_3 (4.3%), Cr_2O_3 (0.04%), and MgO (0%) as shown in Table 1. These constituents play a significant role in the reactivity and cementitious properties of fly ash. The low CaO content of 1.2% suggests that the fly ash belongs to Class F, which is characterized by low lime content. Class F fly ash is known for its pozzolanic properties and can contribute to the strength development and durability of cementitious materials. The physical parameters of the fly ash were found to be specific gravity of 2.23, indicating the density of the fly ash and its relative weight compared to water. A higher specific gravity suggests a denser material, which can contribute to the overall density and strength of the CLSM. The fineness value of 524 $m^2\ kg^{-1}$ indicates the surface area of the fly ash particles. A higher fineness value suggests finer particles, which can enhance the reactivity and pozzolanic activity of the fly ash. The percentage of particles retained on a 45 μm sieve (12.2%) provides information about the particle size distribution of the fly ash. This parameter is important in determining the workability/flow parameters of the CLSM mixtures. The pH value of 8.6 indicates the alkaline nature of the fly ash. The alkaline nature is beneficial for promoting cementitious reactions and can contribute to the overall performance and durability of the CLSM.

6.4 Comparative analysis with other CLSM studies

This section presents a comparative analysis of the current study with other relevant studies in the field of CLSM. The comparison is based on several key parameters, including the materials used, mix ratio, flowability, UCS, and the novelty of the research. In the current study, CETP sludge was used as the primary material, with a specific mix ratio that yielded specific flowability and UCS results. The novelty of this study lies in the use of CETP Sludge in the production of CLSM. In a study by Amin and Abdelsalam [5], rice husk ash (RHA) and fly ash were used in the production of sustainable concrete. The novelty of their study was the efficiency of RHA and fly ash as reactivity materials in sustainable concrete. Study was conducted on CLSM using bottom ash and solid waste sediment [7]. It was found that more water was required to maintain the same flowability for CLSMs made with sediment. The mixture ratio was not provided in their study. However, they observed that the flowability decreased with the increase of bottom ash content. In earlier study, red mud and fly ash were used as replacement materials for cement in CLSM [19]. They used 20 different mix ratios and found that the flowability improved with the addition of fly ash and red mud. This comparative analysis provides a broader perspective on the various materials and methods used in the production of CLSM. It also highlights the unique contributions of each study to the field of CLSM research.

6.5 Optimal mix ratio and selection criteria

Considering the above factors and the results obtained, the best mix ratio appears to be the one used in Mix E-3, which consists of 500 g of fly ash, 800 g of CETP sludge, 1300 g of PSS, and 2100 mL of water. This mix ratio resulted in the highest UCS of 5.5 MPa at 28 days of curing. The determination of the best mix ratio is based on the desired properties of the CLSM, such as flowability and compressive strength. In this case, Mix E-3 provided the highest compressive strength, which is a crucial factor for the performance of CLSM. Additionally, the flowability of the mix is also an important factor, and it was found that as the content of sludge increased, the flowability decreased. However, Mix E-3 still maintained a satisfactory level of flowability, making it the best mix ratio based on the results of this study. It is important to note that the "best" mix ratio might vary depending on the specific requirements of a project or application. Factors such as cost, availability of materials, environmental impact, and specific performance requirements (e.g., strength, durability, permeability) can all influence the selection of the mix ratio. Therefore, while Mix E-3 showed the best performance in this study, other mix ratios might be more suitable for different applications or under different conditions.

The novelty of this research lies in its innovative use of CETP sludge, a waste product, as a constituent material in CLSM. This approach not only provides a sustainable method for the disposal of CETP sludge but also enhances the properties of CLSM, making it a viable construction material. The study further contributes to the field by providing a comprehensive analysis of the effects of different mix ratios on the properties of CLSM, thereby offering valuable insights for future research and practical applications. This research, therefore, presents a significant step towards sustainable construction practices and waste management.

7 Conclusion and scope for further studies

7.1 Conclusions

The present work deals with the utilization industrial byproducts CETP sludge, class-F fly ash, PSS in development of CLSM. The properties of fresh and hardened samples have been evaluated. The published literature related to the use of different industrial byproducts in CLSM production and the variation in properties of CLSM based on the materials used for production has been studied to establish a clear methodology for the current research. Following conclusions were drawn based on the studies & analyses conducted above:

- The properties of CLSM depend largely on the fines content of the materials and water- binder ratio adopted in the mix.
- From the flowability, it was found that Mix E series had a minimum flow value of 18 cm, and mix A series had a maximum flow value of 24 cm.
- The sludge content had a significant effect on the flowability of the mixes. As the content of sludge increased, the flowability was found to decrease.
- From UCS tests, it can be noticed that the minimum compressive strength attained was mix A-1 with 1.8 MPa and maximum compressive strength attained was Mix E-3 was 5.5 MPa at 28 days.
- A well-defined structure of CLSM matrix was developed after 7 days of curing.
- The relatively unaltered particle structure of the CETP sludge spheres indicates that it did not experience complete hydration at 28 days. Further, the hydration products appear more mature displaying a denser C-S–H structure encompassing the entire CLSM matrix.
- The concentration of mullite peaks, specifically, reduced at 28 days signaling the involvement of fly ash in hydration reactions.

7.2 Scope for further research

The following points collectively outline a comprehensive roadmap for future research, addressing technical, environmental, economic, and societal aspects:

- ✓ ***Exploration of Alternative Materials:***Investigating the use of other industrial waste materials in conjunction with CETP sludge to enhance the properties of CLSM, focusing on sustainability and performance.
- ✓ ***Optimization of Mix Ratios:*** Conducting a detailed study to determine the optimal mix ratios of CETP sludge, slag sand, and other components to achieve desired mechanical properties.
- ✓ ***Long-term Performance Analysis:*** Evaluating the long-term performance of CLSM containing CETP sludge under various environmental conditions, including exposure to moisture, temperature fluctuations, and chemical agents.
- ✓ ***Environmental Impact Assessment:*** Study of the environmental impact of utilizing CETP sludge in construction materials, including a lifecycle analysis and the potential effects on soil and groundwater.
- ✓ ***Economic Feasibility Study:*** Analyzing the economic feasibility of using CETP sludge in CLSM, considering factors such as material costs, availability, and potential savings from waste reduction.
- ✓ ***Scale-up to Industrial Applications:*** Exploring the scalability of the developed CLSM for industrial applications, including field trials and collaboration with industry partners.
- ✓ ***Integration with Existing Standards:*** Working towards integrating the findings into existing construction standards and guidelines, ensuring compliance with regulatory requirements.
- ✓ ***Development of New Testing Methods:*** Creating and validating new testing methods specific to CLSM containing CETP sludge, to accurately assess its properties and performance.
- ✓ ***Public Awareness and Education:*** Develop strategies to increase public awareness and education regarding the sustainable use of industrial waste materials in construction, promoting broader acceptance and implementation.
- ✓ ***Interdisciplinary Collaboration:*** Fostering collaboration with experts in related fields such as environmental science, civil engineering, and economics to create a holistic approach to the development and application of sustainable construction materials.

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Authors' contributions

Skanda Kumar B N: Conceptualization, Methodology, Chandrashekhar R, Chandregowda C: Data curation, Writing- Original draft preparation, Suhas R, Sreenatha M: Writing—Reviewing and Editing, Validation, Shashishankar A: Supervision.

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Declarations

Competing interests

⇒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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