– Technical Paper –

DEVELOPMENT OF ECO-FRIENDLY CONTROLLED LOW-STRENGTH MATERIAL UTILIZING FRESH CONCRETE WASTE AND BY-PRODUCTS

Ebsa B. HATEU*1 Akira HOSODA*2 Ngoc T. PHAN*3 and Mitsuya MIYAMOTO*4

ABSTRACT

This study investigates the utilization of concrete sludge powder (CSP), reused waste from the sludge cake generated by returned concrete and concrete truck cleaning, as a partial replacement for Improved Water Absorption (IWA) fine aggregate in Controlled Low-Strength Material (CLSM). The processed CSP was incorporated into CLSM mixes at replacement levels of 0%, 10%, 15%, 20%, and 25% by weight of the IWA fine aggregate. Experimental results indicate that up to 20% replacement with CSP produces an eco-friendly CLSM suitable for backfilling buried pipes.

Key words: controlled low-strength material, eco-friendly material, by-products, fresh concrete waste, improved water absorption fine aggregate, excavatability, backfilling buried pipes

1. INTRODUCTION

The vast global concrete production, estimated at 25 billion tons annually, generates a significant amount of construction and demolition waste, including returned concrete. Returned concrete denotes unused, unset material that is returned to the plant in concrete trucks as excess. Typically, returned concrete generated by ready-mixed deliveries accounts for 0.4-0.5% of total production, although this proportion can increase to 5-9% during peak periods. Globally, it is estimated that over 125 million tons of returned concrete are generated annually [1].

The escalating global emphasis on sustainable construction practices has spurred extensive research into the utilization of industrial byproducts and concrete waste [2]. This pursuit of resource efficiency and waste reduction aligns with the circular economy principles, aiming to minimize environmental impact while optimizing material usage [3].

The Improved Water Absorption (IWA) system revolutionizes the recovery of returned concrete at ready-mixed concrete plants, offering a sustainable and efficient solution for concrete production. This innovative process involves adding a special admixture directly into concrete trucks and utilizing high-speed stirring to adhere cement paste or mortar to aggregates, transforming them into new aggregates. Unlike conventional washing methods, the IWA system drastically reduces waste generation by significantly lowering waste output. The IWA aggregate production process involves collecting returned fresh concrete in a dedicated pit. A special admixture for granulation, incorporating water-absorbing polymers and inorganic composites, offers zero environmental impact and eliminates the need for treatment plant investment [1].

Concrete sludge, a waste generated from washing concrete truck chutes, can also be reused by transforming the dried sludge cake into fine particles using specialized equipment. Furthermore, the supernatant water, a byproduct remaining after sludge solids separation, can be utilized as mixing water, reducing the dependency on potable water [4].

The American Concrete Institute (ACI) 229 committee defined Controlled Low-Strength Material (CLSM) as self-compacting cementitious backfill materials [5]. A distinctive feature of CLSM technology is its capacity to safely and efficiently incorporate diverse by-products and waste materials. The development of eco-friendly CLSM mixes aligns with the growing demand for sustainable construction materials and contributes to the advancement of circular economic principles in the construction industry [3, 6].

The ACI Committee 229 document serves as the primary guideline for CLSM in the United States and has been extensively referenced globally [2, 5]. In Japan, liquefied soil stabilization methods have been widely adopted in various construction projects, enabling the effective geotechnical reuse of construction-generated soil. The technical manual for fluidized soils, a key Japanese technical manual, incorporates advancements in fluidized soil technology, and its principles can be applied to CLSM due to the similarities between the two materials [7].

Previous studies on concrete waste have focused on incorporating recycled concrete aggregates into CLSM [3, 8, 9]. However the effective utilization of waste generated from returned concrete in eco-friendly CLSM has been relatively less explored [10].

*1 Graduate Student, Graduate School of Urban Innovation, Yokohama National University, JCI Student Member

*2 Professor, Institute of Urban Innovation, Yokohama National University, JCI Member

*3 Lecturer, Department of Civil Engineering, University of Technology and Education, The University of Danang

*4 President, Nagaoka Ready-Mixed Concrete Company

Table 1 General criteria and requirements for CLSM application and target performance in this study

Reference	CLSM Application	Criteria and Requirements to Be Fulfilled
This study adheres to the Technical Manual for Fluidized Soils of Japan (Targeting performance)	Eco-Friendly Excavatable CLSM (Backfilling buried pipes)	○ Flowability (spread of 140 mm or more) ○ Minimal subsidence (bleeding less than 3%) ○ Fresh mix wet density of 1.40 g/cm³ or more ○ Easy to re-excavate (manually or mechanically) ○ 28-day unconfined compressive strength of 200-600 kN/m² ○ Backhoe excavatability 28-day strength of 500-1000 kN/m² ○ Quick setting time (at least 130 kN/m² under roads and 50 kN/m² under sidewalks when open to traffic)

The target performance criteria for the proposed eco-friendly CLSM in this research are summarized in Table 1, in accordance with the Technical Manual for Fluidized Soils in Japan, with the aim of meeting the requirements for backfilling buried pipe.

This study optimizes an eco-friendly CLSM mixture proportion utilizing IWA fine aggregate with concrete sludge powder (CSP), thus improving the use of industrial byproducts and fresh concrete waste for backfilling buried pipes. A thorough experimental investigation was conducted to evaluate both the fresh and hardened properties of the CLSM mixtures.

2. MATERIALS AND TEST METHODS

2.1 Materials

In this study, an industrial by-product, ground granulated blast furnace slag (GGBFS) 4000 specified in Japanese Industrial Standard (JIS A 6206), was utilized as the binder, possessing a density of 2.89 g/cm^3 and a specific surface area of 4370 cm²/g.

Fresh returned concrete waste deposited at the storage pit is transformed into a granular material by adding a special admixture for granulation and mixing for 2-3 minutes [1]. The resulting granular material is then transferred to a drying-out bay. The granular material is sieved to obtain the desired fine or coarse IWA aggregate, which can then be stockpiled or stored in airtight plastic containers. The IWA fine aggregate used in this study was obtained from the ready-mixed concrete plant in Shizuoka Prefecture. It has a surface dry density of 2.03 g/cm^3, and a water absorption of 14.2%. As depicted in Fig. 1, the particle-size distribution of this IWA fine aggregate, with all particles passing through a 10 mm nominal sieve size, aligns with JIS A 5308.

Concrete sludge waste generated at concrete plants is collected in sedimentation pits and dewatered to reduce moisture content. The dried sludge cake is then crushed mechanically into a fine powder. The dust collection system is employed to separate the fine CSP particles from the coarser sludge sand. The collected CSP is then packed and stored in unopened bags under cool and dry conditions. In the present study, CSP sourced from the ready-mixed concrete plant in Okayama Prefecture was utilized as a filler. It has a density of 1.89 g/cm^3. As shown in Fig. 1, the particle-size distribution of the sludge powder indicates that all particles pass through a 0.60 mm nominal sieve size.

Supernatant water, recycled from concrete washing wastewater at the ready-mixed concrete plant in Shizuoka Prefecture, was employed as the mixing water for CLSM mix. This supernatant water has a density of 1.0 g/cm^3 and a pH of 11. As a byproduct of washing leftover concrete, the supernatant water contains a significant amount of calcium hydroxide.

The chemical composition of the materials used is presented in Table 2. The high calcium oxide content suggests the presence of calcium-based compounds, such as calcium hydroxide formed during hydration, which are crucial for strength development in the CLSM. The alkaline nature of reused concrete waste promotes cementitious reactions, improving the performance and durability of CLSM. The alkalis in the returned concrete enhance the hydraulic activity of the GGBFS, thereby improving the strength and hardening of the CLSM [3].

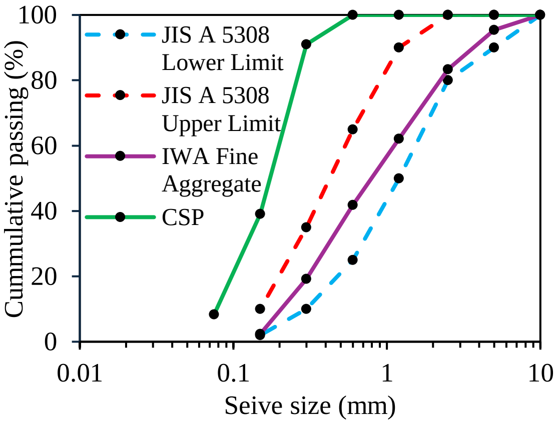


Fig. 1 Particle size distribution of materials

Table 2 Chemical composition of material used in this study

Materials	Chemical Composition (%)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	TiO_2	MnO	ZnO	K_2O	LOI
GGBFS 4000	33.02	14.44	0.79	42.03	5.80	2.00	0.41	-	-	0.65	0.90
CSP	16.61	2.89	8.73	67.99	-	1.47	0.74	0.18	0.12	0.88	-
IWA Fine Aggregate	18.47	3.58	9.81	64.52	-	2.13	0.84	0.22	0.14	-	-

2.2 Test Methods

2.2.1 Mixing Procedure for Freshly Mixed CLSM

The mixing procedure begins by blending the solid ingredients in the mixer for 30 seconds to ensure a homogenous blend. Then, half of the mixing water is added and mixed for 1 minute. Next, the remaining half of the mixing water is added and mixed for another minute [2]. This procedure was adopted from Folliard et al. [6] as a recommended practice for use in CLSM to control consistency and ensure sufficient workability. The freshly mixed CLSM mix is depicted in Fig. 2a and Fig. 3a.

2.2.2 Fresh CLSM Test Methods

a) Flowability test

The flowability of the CLSM was evaluated by conducting flow tests according to the Japan Highway Public Corporation standard (JHS A 313–1992), "Test Methods for Air Mortar and Air Milk". An 80 mm x 80 mm open-ended cylinder was used, and the flow values were measured at two locations, in the vertical and horizontal directions. The average value was obtained, as shown in Fig. 2b and Fig. 3b.

b) Wet density test

The constant volume method was used in this research to determine the wet density of the CLSM. A constant volume container with a capacity of 531 cm^3 was filled with a freshly prepared CLSM sample, and the total mass of the sample was measured as shown in Fig. 2c and Fig. 3c. The wet density was then calculated by dividing the mass of the CLSM sample by the fixed volume of the container.

c) Bleeding test

To examine the segregation properties of CLSM, bleeding tests were conducted according to the Japan Society of Civil Engineers standard (JSCE F 522), titled "Test Method for Bleeding Rate and Expansion Rate of Injection Mortar for Prepacked Concrete (Polyethylene Bag Method)." After mixing, each CLSM sample was placed in a polyethylene bag with a diameter of 50 mm and filled to a height of 200 mm. The amount of bleeding water that accumulated on the surface was measured after 3 hours and again after 24 hours, as shown in Fig. 2d and Fig. 3d.

The bleeding rate was then calculated using Equation Eq. 1.

$$B_r = \frac{B}{V} \times 100 \tag{1}$$

where,

B_r : bleeding rate (%)
B : volume of bleeding water (mL)
V : volume of the specimen (mL)

d) Air content Test

The air content of freshly mixed CLSM was measured using the pressure method outlined in JIS A 1128, with a slight modification. The fluid fresh CLSM was placed in a single layer without rodding, instead of in the three equal layers specified for conventional concrete [6]. The air content was then determined by the reading shown on a calibrated pressure gauge, as illustrated in Fig. 2e and Fig. 3e.

e) Hardening time test

This study evaluated the hardening time, which represents the estimated transition from a plastic to a hardened state for the CLSM, by following the procedures outlined in JIS A 1147, with a minor modification. Unlike conventional concrete mixes, CLSM mix was not subjected to sieving, as it is not a requirement for this material [6]. A needle penetration test, as described in Fig. 3f, was conducted on the eco-friendly CLSM containing 20% CSP, ensuring it meets the minimum strength requirement before being opened to traffic. Hardening time can be as short as 1 hour, but generally takes 3 to 5 hours under normal conditions [5].

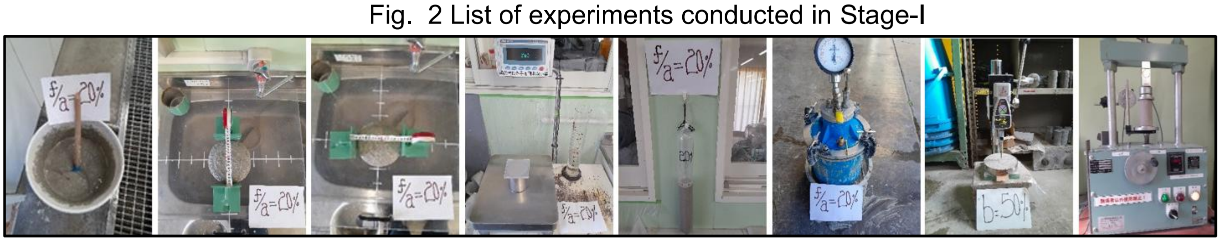
2.2.3 Hardened CLSM Test Methods

a) Unconfined Compressive Strength test

Unconfined compression tests were conducted, as depicted in Fig. 3g, in accordance with the JIS A 1216, "Unconfined Compression Test Method for Soil". The CLSM mixture was poured into 50 mm diameter,

a) Fresh CLSM b) Flowability c) Wet density d) Bleeding e) Air content

Fig. 2 List of experiments conducted in Stage-I



a) Fresh CLSM b) Flowability c) Wet density d) Bleeding e) Air content f) Penetration g) Strength

Fig. 3 List of experiments conducted in Stage-II

100 mm high cylindrical molds. Specimens were cured at a constant room temperature of 20°C for 7 and 28 days [11].

b) Excavatablity

Maximum unconfined compressive strength criteria are provided to ensure excavatability for applications where future removal of the CLSM is desirable. In this study a 28-day strength limit of 1000 kN/m² targeted for re-excavatability in backfilling buried pipes. According to the Technical Manual for Fluidized Soils in Japan, an unconfined compressive strength of 200-600 kN/m² is suitable for backfilling, while backhoe excavatability requires a 28-day strength range of 500-1000 kN/m². The eco-friendly CLSM developed is deemed excavatable either by manual or mechanical methods, with a target strength range of 200 to 1000 kN/m² to optimize excavatability and overall performance [7].

3. EXPERIMENTAL PROGRAM

The proposed methodology, outlined in the flow diagram presented in Fig. 4, aims to achieve the desired workability and compressive strength for CLSM used as backfill for buried pipes. The main properties required, workability in the fresh state and compressive strength in the hardened state, are critical for the intended application.

The methodology is divided into two stages: Optimizing aggregate content based on fresh properties and incorporating CSP as a filler by partially replacing IWA fine aggregate.

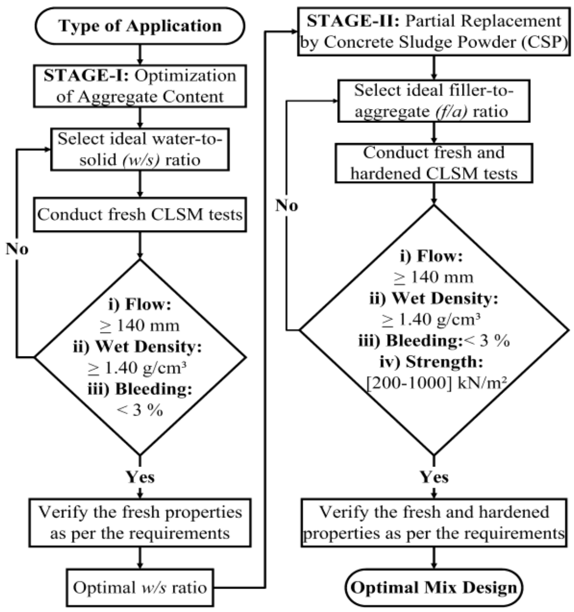


Fig. 4 General methodology for the mix design

The utilization of GGBFS as a binder in CLSM, recognized for its long-term strength development properties, minimizes the likelihood of re-excavation [8]. The binder content is consistently maintained at 50 kg/m³ across both stages to manage this effectively, ensuring controlled and predictable strength.

3.1 Stage-I: Optimization of Aggregate Content

In this initial stage, the focus is on achieving the targeted workability. The primary objective is to determine the optimal IWA fine aggregate content at maximum flowability, guided by the water-to-solid (*w/s*) ratio, where "solid" refers to the total mass of IWA fine aggregate and binder.

3.1.1 Mixture proportions

The *w/s* ratios used in this study, optimized after conducting experimental trials, are 18%, 21%, 22%, and 24%, assuming a situation of saturated surface-dry conditions for the IWA fine aggregate [12]. These ratios were carefully selected to ensure the desired workability and performance of the eco-friendly CLSM mix design. The details of the Stage-I mix proportions are included in Table 3.

Table 3 Mix proportions in Stage-I

w/s (%)	1m³ of Eco-Friendly CLSM Mixtures			
	GGBFS	IWA Fine Aggregate	Supernatant Water	Air (%)
	(kg/m³)			
18	50	1378	264	3.9
21	50	1345	286	3.4
22	50	1315	307	2.8
24	50	1282	326	2.5

3.2 Stage-II: Partial Replacement by Concrete Sludge Powder

The second stage involves the partial replacement of the optimized IWA fine aggregate content (determined in Stage-I) with CSP. The replacement follows the filler-to-aggregate (*f/a*) ratio, where "aggregate" represents the combined mass of IWA fine aggregate and CSP.

3.2.1 Mixture Proportions

At this stage, CSP was incorporated into CLSM mixes, by replacing IWA fine aggregate at levels of 0%, 10%, 15%, 20%, and 25% by weight at each *f/a* ratios. The initial mix from Stage-I (0% replacement) serves as the baseline. The details of the Stage-II mix proportions are included in Table 4.

Table 4 Mix proportions in Stage-II

f/a (%)	1m³ of Eco-Friendly CLSM Mixtures				
	GGBFS	CSP	IWA Fine Aggregate	Super-natant Water	Air (%)
	(kg/m³)				
0	50	-	1315	307	2.8
10	50	131	1175	307	2.6
15	50	195	1105	307	2.5
20	50	259	1036	307	2.4
25	50	323	968	307	1.9

4. RESULTS AND DISCUSSION

4.1 Stage-I: Optimization of Aggregate Content

The tests conducted in the first stage focused solely on the fresh properties of CLSM as outlined in the methodology by considering different *w/s* ratios.

The flow test results illustrated in Fig. 5a, reveal that higher *w/s* ratios increase the average flowability, ranging from 192.5 mm to 232.5 mm. At all *w/s* ratios, flowability exceeded the minimum flowability requirement of 140 mm.

The wet density test results indicated that as the *w/s* ratio increased, the fresh density of the CLSM mix decreased, reflecting higher water content and lower packing density (Fig. 5b). This indicates that the solid concentration of the CLSM mix decreases as the *w/s* ratio increases resulting in a decrease in the packing density of the mix. The findings illustrated in Fig. 5b reveal that wet density values ranged from 1.81 to 1.87 g/cm³, all exceeding the required target of 1.40 g/cm³.

Bleeding tests conducted according to JSCE F 522 showed that higher *w/s* ratios resulted in an increased bleeding rate (Fig. 5c). For a *w/s* ratio of 24 %, the bleeding percentage was 3.83% after 3 hours and 3.35% after 24 hours, surpassing the target of 3%.

In Stage-I of the methodology, maximized flow was a primary focus to ensure adequate water content while incorporating the filler material and assessing its properties in subsequent Stage-II. A *w/s* ratio of 22% was determined to be the optimal mix for proceeding to the next stage of the experimental procedure. In Stage-II, the water content remains constant as established in Stage-I.

4.2 Stage-II: Partial Replacement by Concrete Sludge Powder

This stage investigates the effects of partially replacing IWA fine aggregate with CSP.

The second stage focused on both plastic and hardened properties of CLSM to assess its suitability for backfilling buried pipes. The optimal *w/s* ratio of 22% from Stage-I was used as a control mix, replacing IWA fine aggregate with CSP.

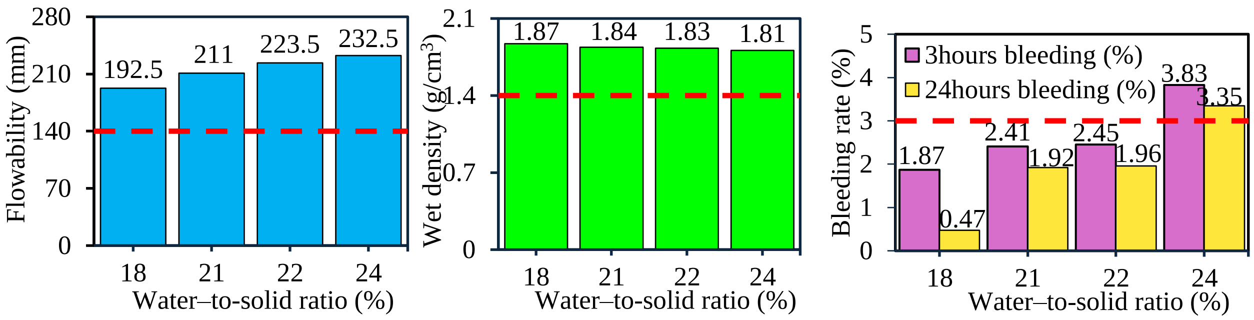
Flow tests as shown, in Fig. 6a revealed that increased *f/a* ratios led to decreased flowability, dropping from 223.5 mm to 109 mm. At a *f/a* ratio of 25%, the flow value fell below the target of 140 mm. The higher *f/a* ratio required additional water for sufficient workability, affecting the control mix.

Wet density tests, as shown in Fig. 6b, indicated that as the *f/a* ratio increased, fresh density decreased, ranging from 1.83 to 1.73 g/cm³, while still meeting the requirement of 1.40 g/cm³.

Bleeding test results, as described in Fig. 6c, which indicate stability and cohesion, decreased with higher *f/a* ratios, remaining below the target of 3% after both 3 and 24 hours. The utilization of CSP effectively reduces bleeding, enhancing the eco-friendliness of CLSM.

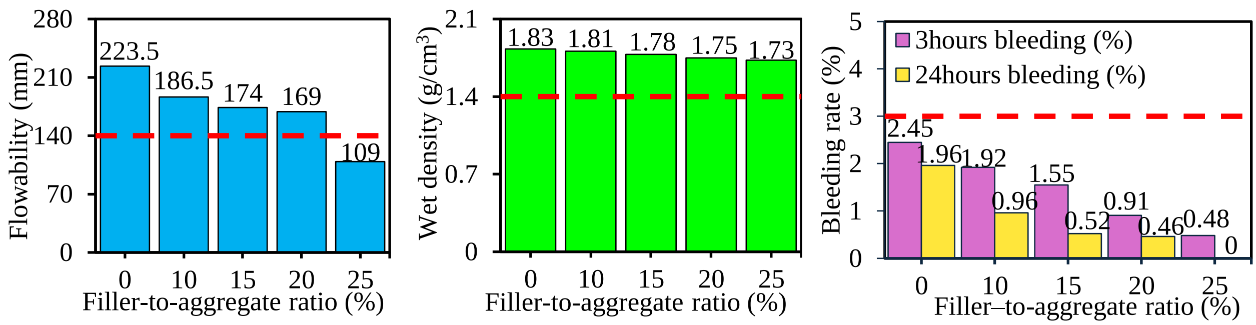
The estimated CLSM hardening time was measured using the JIS A 1147 penetration resistance method. The CLSM with *f/a* ratio of 20% had a hardening time of 2 hours, attributed to better packing density and the hydraulic activity of GGBFS enhanced by alkaline calcium hydroxide in the supernatant water. The high pH environment in the supernatant water, enriched with hydroxyl ions due to the presence of calcium hydroxide and alkalis from the residual paste materials in the returned concrete, promotes the dissolution of the glassy structure and accelerates the hydration of GGBFS, thereby enhancing the hardening and strength development of the CLSM mix [3, 13].

Unconfined compressive strength test results, as described in Fig. 7, conducted on the specimens at 7 and 28 days demonstrate an increase as the *f/a* ratio exceeded 10%. Interestingly, the strength slightly



a) Effects of *w/s* on flowability b) Effects of *w/s* on wet density c) Effects of *w/s* on bleeding

Fig. 5 Water-to-solid ratio effects on the plastic properties of eco-friendly CLSM mixtures



a) Effects of *f/a* on flowability b) Effects of *f/a* on wet density c) Effects of *f/a* on bleeding

Fig. 6 Filler-to-aggregate ratio effects on the plastic properties of eco-friendly CLSM mixtures decreased at the 10% ratio compared to the control mix without CSP, suggesting that a higher proportion of the filler above 10% contributes to improved compressive strength by effectively utilizing its filler effect to reducing voids in CLSM matrix [2].

The Technical Manual for Fluidized Soils in Japan sets a compressive strength limit of 1000 kN/m² to allow future excavation by mechanical equipment such as backhoes. Furthermore, the strength results indicate that the strength values across all *f/a* ratios remain within the excavatability limits, implying that excavatability can be achieved by adjusting the strength of the CLSM.

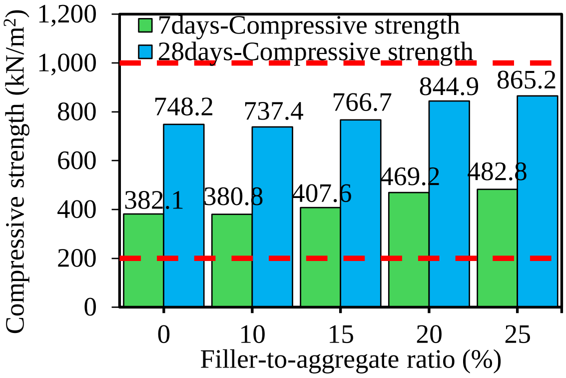


Fig. 7 Unconfined compressive strength

This study primarily aimed to maximize the utilization of CSP as a filler to enhance the stability of the mixture by reducing bleeding water and increasing the strength properties, while promoting eco-friendliness as a sustainable material. The findings from Stage-II demonstrated that utilizing 20% CSP as a filler was an effective approach for developing a novel, eco-friendly CLSM.

5. CONCLUSIONS

The following conclusions are drawn from the experimental results:

(1) The results showed that eco-friendly, cementless CLSMs can be made using industrial by-products and concrete waste, supporting sustainable construction and a circular economy.
(2) CLSM flowability decreased as CSP substitution increased, with replacements exceeding 20% resulting in flow rates beyond the acceptable range.
(3) The study found that incorporating up to 20% CSP significantly enhanced CLSM mix stability by reducing bleeding, ensuring consistent application.
(4) The incorporation of CSP increased unconfined compressive strength while keeping it within the desired excavatability strength range of 200 to 1000 kN/m², confirming its suitability for buried pipe backfilling applications.

The limitation of this study is the use of fixed GGBFS content to meet the strength criterion for re-excavation. Future research could explore varying GGBFS content, long-term strength development trend, and re-excavation feasibility using the Removability Modulus (RE) based on ACI guidelines.

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