

Geo-Mechanical Performance Of Controlled Low Strength Materials With GGBS, Fly Ash, And Bagasse Ash As Cement Replacements

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Abstract

The construction sector generates substantial quantities of industrial by-products such as quarry dust and hollow block powder, which present significant environmental and logistical challenges due to their fine particle nature and limited storage options. While previous research has explored the reuse of such materials in concrete, bricks, tiles, road base layers, and soil stabilization, their application in the development of Controlled Low Strength Materials (CLSM) also referred to as flowable fills remains underutilized.

CLSM is a highly flowable, self-compacting, non-structural backfill material composed primarily of fine aggregates, cementitious binders, water, and industrial wastes. Conventionally, river sand is employed as the fine aggregate due to its favourable geotechnical characteristics. However, the escalating scarcity and environmental cost of river sand necessitate the adoption of sustainable alternatives such as quarry dust. In parallel, the high carbon footprint of Portland cement has encouraged interest in supplementary cementitious materials (SCMs) like Ground Granulated Blast Furnace Slag (GGBS), Fly Ash (FA), and Bagasse Ash (BA), which offer promising potential for partial cement replacement in CLSM.

This study experimentally evaluates the flowability and compressive strength of CLSM mixes incorporating varying proportions of GGBS, FA, and BA as cement substitutes, with quarry dust as a full replacement for natural sand. The objective is to determine the optimal combinations of waste-derived materials that can maximize cement replacement while maintaining or enhancing performance characteristics, thereby supporting environmentally responsible and cost-effective backfill solutions. The research contributes to the advancement of sustainable construction materials in line with Indian practices and standards, with potential applicability in infrastructure, trench reinstatement, and geotechnical rehabilitation projects.

Keywords: Hollow block powder, quarry dust, Controlled low strength material

INTRODUCTION

Controlled Low Strength Material (CLSM) is a highly flowable, self-consolidating, cementitious material specifically engineered as a non-structural backfill alternative to conventional compacted soil [16][23]. Its ability to self-level and flow into confined spaces without the need for mechanical compaction makes it ideal for diverse civil engineering applications such as trench reinstatement, utility pipe bedding, void filling in sewers, tunnel shafts, basements, and abandoned underground structures [27][18]. The use of CLSM significantly reduces construction time, improves workplace safety, and eliminates the need for vibration equipment, thereby minimizing construction noise and labor intensity [20][15][29].

Although the concept of CLSM has its origins in North America where a material referred to as plastic soil-cement was first utilized as pipe bedding during the 1964 Canadian River Aqueduct Project, similar low-strength, self-compacting fills are now being recognized and adapted globally, including in India [25][14]. The early development of CLSM incorporating fly ash and minimal cement content provided significant cost benefits and environmental advantages [19][22][28]. Today, CLSM is interchangeably referred to as flowable fill, controlled density fill, or soil-cement slurry [30][17][26].

In the Indian context, the design and testing of CLSM mixtures can be guided using provisions from established IS codes, including:

- IS 10262:2019 – for concrete mix proportioning.
- IS 1199:1959 – for determining flowability using flow table and slump cone methods.
- IS 456:2000 – for general concrete practices.

- IS 516 (Part 5/Sec 1):2018 – for evaluating compressive strength of low-strength cementitious composites.
- IS 3812 (Parts 1 and 2):2013 – for the use of fly ash.
- IS 383:2016 – for specification of fine aggregates.

The typical CLSM mixture consists of Portland cement, supplementary cementitious materials (SCMs), fine aggregates (or fillers), and water [19][29]. Chemical admixtures such as air-entraining agents or water-reducing admixtures may be incorporated to tailor flow, setting time, and durability [21]. The mix generally includes 80–85% fine aggregate (with particle sizes typically between 4.75 mm and 75 microns), 5–10% cement, and 10–15% SCMs by mass, with a water content in the range of 250–400 L/m³ [30][14]. While natural river sand is traditionally used, increasing attention is being given to alternative materials like quarry fines, reclaimed fines from construction and demolition waste, and recycled aggregates, owing to environmental and resource constraints [15][27].

Despite its relatively low compressive strength (commonly limited to 1.4 MPa or lower to ensure future excavability), CLSM must meet performance criteria related to workability, segregation resistance, and strength development [22][17]. Although several studies have investigated the use of individual pozzolanic materials in CLSM production, there is limited comparative research involving the concurrent use of Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), and Bagasse Ash (BA) sourced from various waste streams [20][26]. These materials, if effectively utilized, offer immense potential in enhancing the sustainability quotient of CLSM [23][16].

This research systematically investigates the influence of three key parameters—type of pozzolanic material (FA, GGBS, BA), water content, and curing duration—on the flowability and compressive strength of CLSM mixtures [28][18]. Quarry dust (QD) is employed throughout the study as a sustainable fine aggregate replacement [31]. The experimental results are expected to provide valuable insights for civil engineers, contractors, and decision-makers seeking to implement eco-efficient and cost-effective CLSM formulations in modern construction and infrastructure projects across India [24][13].

MATERIALS AND METHODS

To develop sustainable and high-performance Controlled Low Strength Material (CLSM) mixtures, this study utilizes industrial and agro-industrial waste materials as partial replacements for cement and natural sand [15][24]. The primary aim is to evaluate the influence of Ground Granulated Blast Furnace Slag (GGBS), Fly Ash (FA), and Bagasse Ash (BA) as supplementary cementitious materials (SCMs), and Quarry Dust (QD) as an alternative fine aggregate, on the flowability and compressive strength of CLSM [18][26][30].

2.1 Materials

2.1.1 Binders

The binder system in the CLSM mixtures consists of:

- Ordinary Portland Cement (OPC), Grade 43, conforming to IS 8112:2013
- GGBS, complying with the specifications of IS 12089:1987
- Fly Ash (Class F), conforming to IS 3812 (Part 1):2013
- Bagasse Ash (BA), collected from sugar industry waste, sieved through a 90-micron sieve to maintain uniformity

2.1.2 Fine Aggregate

- Quarry Dust (QD), sourced from a local crushing plant, was used as the fine aggregate in all mix designs. The material meets the grading requirements of Zone II as per IS 383:2016 and was used as a 100% replacement for natural sand.

2.1.3 Water

- Potable tap water, free from organic impurities and conforming to IS 456:2000, was used for all mixing and curing purposes.

2.1.4 Curing

- All specimens were air-cured under ambient laboratory conditions ($\approx 24 \pm 2$ °C) to simulate field curing scenarios where CLSM is not typically water cured.

2.2 CLSM Mix Proportions

CLSM mortar mixes were prepared in a 1:1 ratio (binder: fine aggregate) by mass. The following three experimental series were developed:

- FA Series: Fly Ash used as a partial replacement for cement
- GGBS Series: GGBS used as a partial replacement for cement
- BA Series: Bagasse Ash used as a partial replacement for cement

In each case, quarry dust (QD) was used as the sole fine aggregate [17][25]. Multiple trial mixes were conducted by varying the water content (w/c ratio) and binder combinations to evaluate flowability and compressive strength [21][28]. The objective was to determine the optimal blend for maximum flow with adequate strength and excitability [31][19].

2.3 Testing Programme

The evaluation of the CLSM mixtures was conducted through a combination of fresh-state and hardened-state tests:

2.3.1 Fresh-State Tests

- Spread Flow Test: Conducted in accordance with IS 1199:1959, using an open-ended cylinder to measure the average spread diameter (D). The Relative Flow Area (RFA) was computed using the formula:

$$RFA = \left(\frac{D}{75}\right)^2 - 1$$

Where:

DDD = Average diameter of spread flow in mm

- Marsh Cone Test: Performed to evaluate the flow time of cementitious slurries to assess workability and fluidity.

2.3.2 Hardened-State Test

- Unconfined Compressive Strength (UCS): Cylindrical specimens of 100 mm diameter × 200 mm height were cast and tested at specified curing ages (3, 7, 28, and 56 days), in accordance with IS 516 (Part 5/Sec 1):2018.

2.4 Experimental Approach

Initial trial batches were produced to determine the optimal water content by measuring spread diameters and calculating the corresponding RFA values. CLSM mixes were evaluated based on:

- Flowability
- Density
- Settlement behavior
- Unconfined compressive strength

The test results facilitated the selection of optimal binder combinations and water contents for eco-efficient, self-compacting CLSM suitable for backfilling and geotechnical applications.

RESULTS AND DISCUSSION

3.1 Flowability Analysis Using Spread Flow Test

The flowability of CLSM mixtures was evaluated using the flow table method in accordance with IS 1199:1959, utilizing an open-ended cylindrical mold of 75 mm diameter and 150 mm height. The spread diameter was measured along six radial directions to account for uniformity, and the average value was used to calculate the Relative Flow Area (RFA) using the following expression:

$$RFA = \left(\frac{D}{75}\right)^2 - 1$$

where DDD is the average spread diameter in millimetres.

Figures 1 to 3 illustrate the variation in RFA for CLSM mixtures incorporating Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), and Bagasse Ash (BA) as total replacements for cement, with different water contents.

The experimental results indicate a progressive increase in flowability with increasing water content for all three pozzolanic materials. This trend is consistent with the reduction in internal friction and viscosity, as the higher water content reduces cohesion and enhances particle mobility. Additionally, mixes with

higher proportions of pozzolanic materials typically form fewer early-stage hydration products, which delays stiffening and increases flow spread. Among all mixes, GGBS-based CLSM exhibited the highest RFA values, confirming its superior fluidity and workability, especially at higher water dosages.

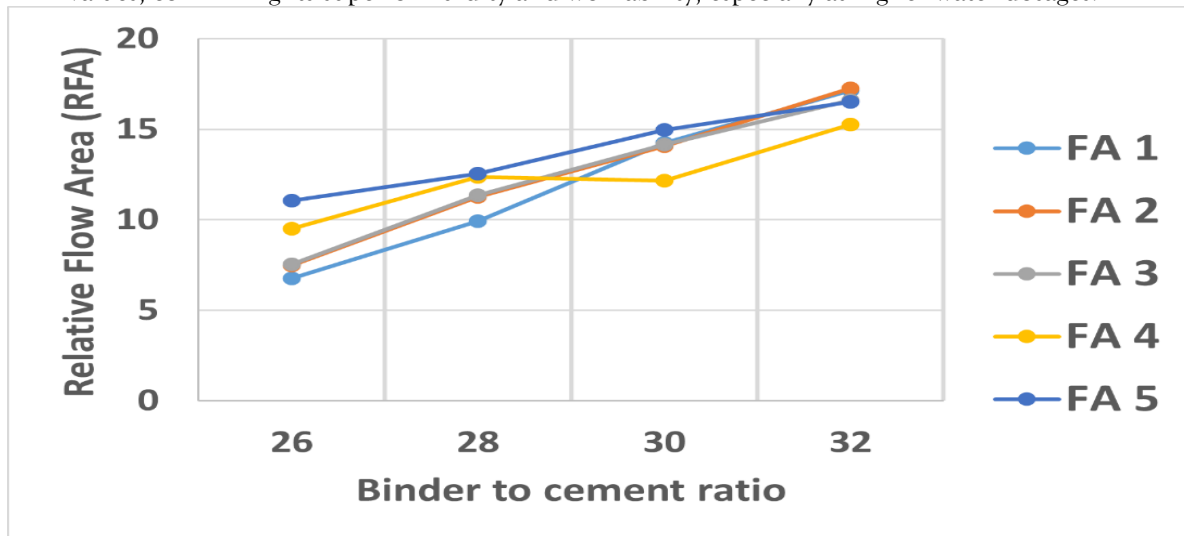


Fig 1: Relative Flow Area values for FA replacement with cement at various water contents

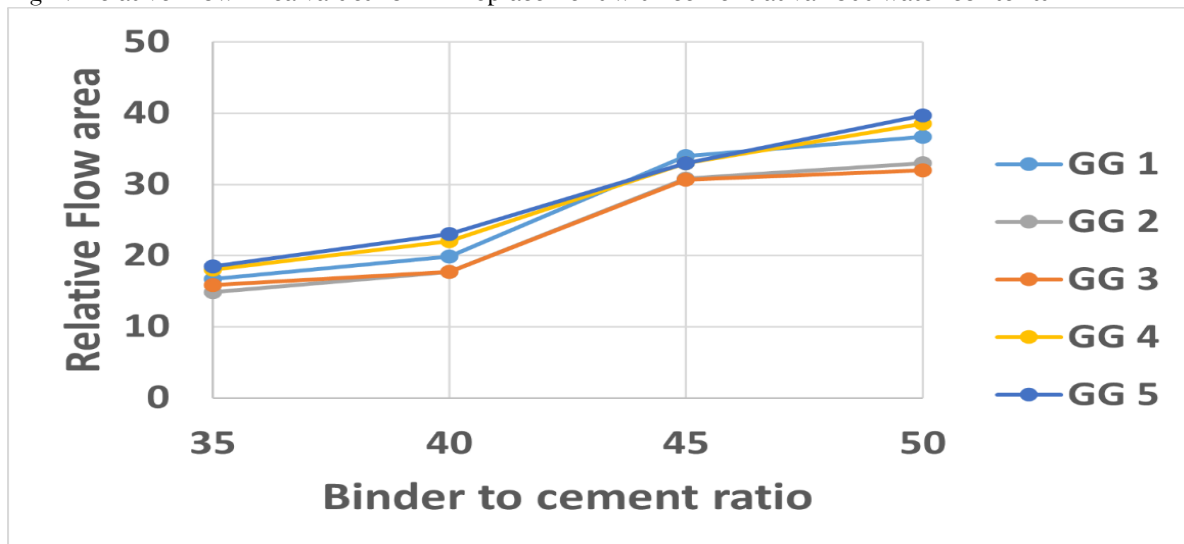
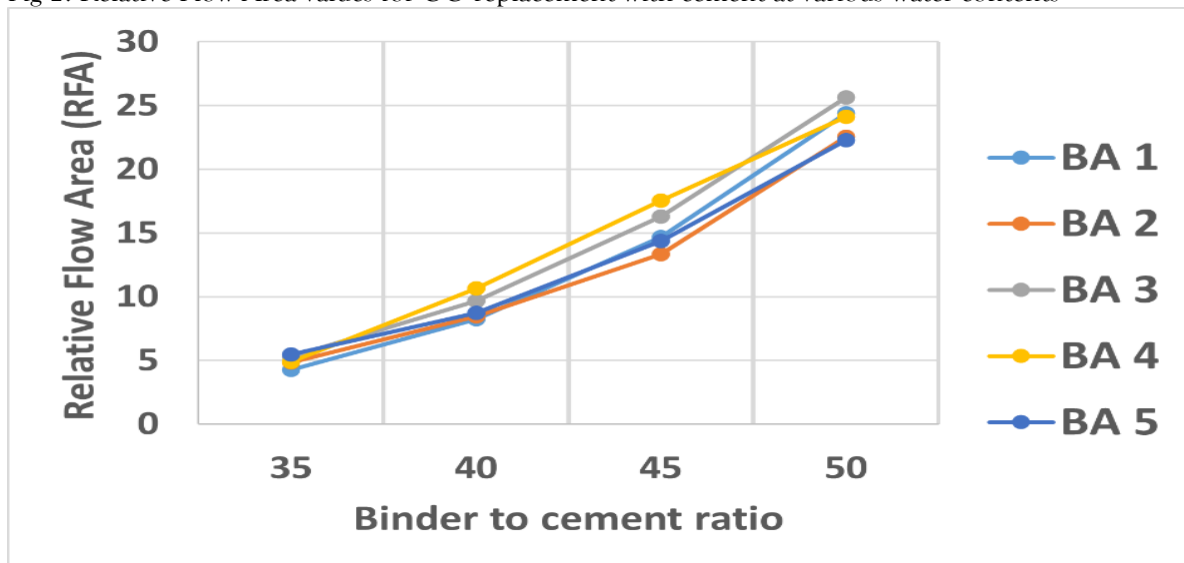


Fig 2: Relative Flow Area values for GG replacement with cement at various water contents



3.2 Unconfined Compressive Strength (UCS)

The mechanical performance of the CLSM mixes was assessed by conducting Unconfined Compressive Strength (UCS) tests on 100 mm × 200 mm cylindrical specimens, as per IS 516 (Part 5/Sec 1):2018. The specimens were tested at curing ages of 3, 7, and 28 days to study early and moderate strength development.

Figures 4 to 6 show the compressive strength results of the three CLSM series FA, GGBS, and BA each prepared with a 1:1 binder-to-quarry dust (QD) ratio and tested across four water content levels.

Observations:

- The compressive strength increased with curing age, confirming the ongoing hydration and pozzolanic activity of the mixes.
- GGBS-based CLSM achieved the highest UCS, reaching up to 6.0 MPa at 28 days, followed by FA (3.1 MPa) and BA (2.7 MPa) at their respective optimum water content levels.
- The UCS of CLSM increased with higher binder content, as the generation of hydration products improved particle interlocking and void filling, resulting in denser microstructures.
- At excessively high water contents, a slight reduction in strength was observed, likely due to dilution effects and increased porosity, even though flowability improved. This highlights the need for an optimized water-to-binder ratio to strike a balance between fluidity and strength.

3.3 Comparative Evaluation of Pozzolanic Materials

Figure summaries reveal that:

- GGBS outperformed both FA and BA in terms of both flowability (RFA ≈ 50) and compressive strength (UCS ≈ 6 MPa).
- The superior performance of GGBS can be attributed to its latent hydraulic reactivity, where its high calcium and alumino-silicate content promotes calcium silicate hydrate (C-S-H) gel formation, contributing to strength gain, particularly at later stages.
- Fly Ash, while moderately reactive, contributed to improved workability due to its spherical particle shape but showed limited strength gain within the 28-day curing window.
- Bagasse Ash, although sustainable and low-cost, exhibited the lowest UCS, likely due to its porous and irregular morphology, high carbon content, and delayed pozzolanic activity.

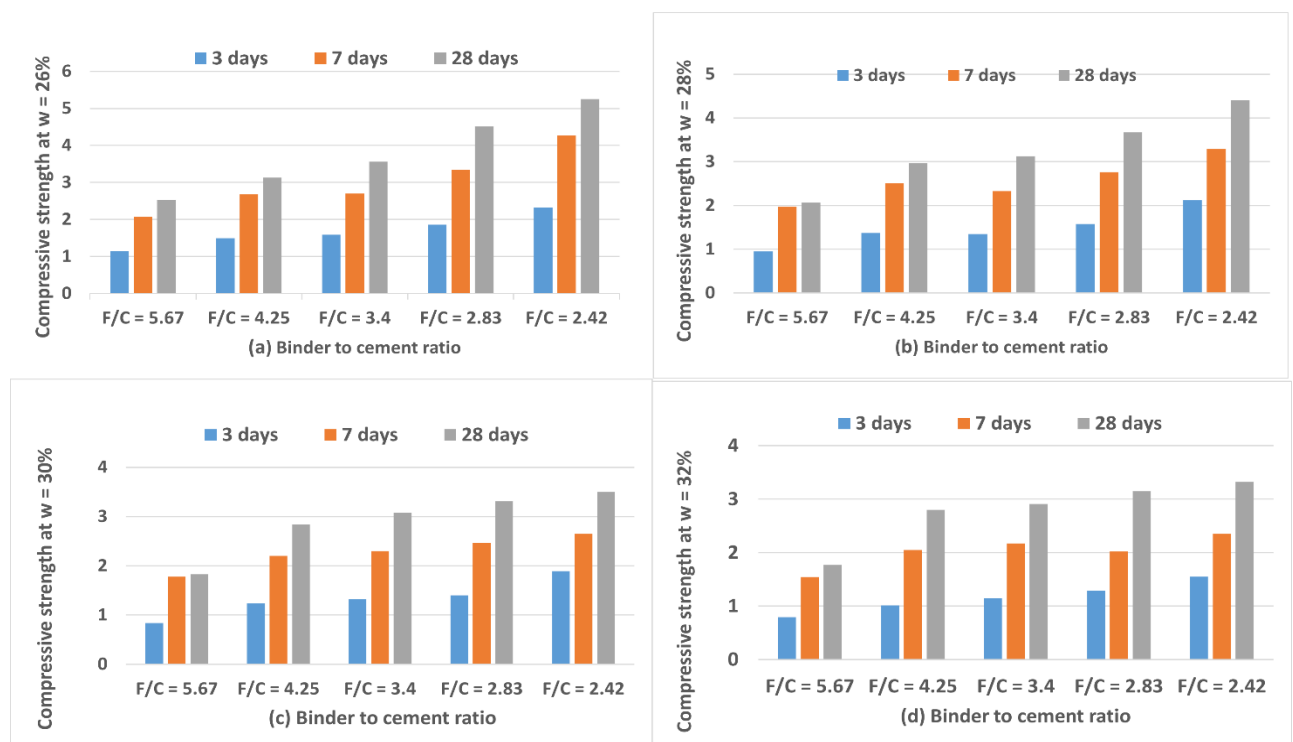


Fig 4: Compressive Strength of CLSM at 3,7 and 28 days for CM 1:1 with FA as secondary cementitious material and QD as replacement to natural sand at (a) water content 26%; (b) water content 28%; (c) water content 30%; (d) water content 32%.

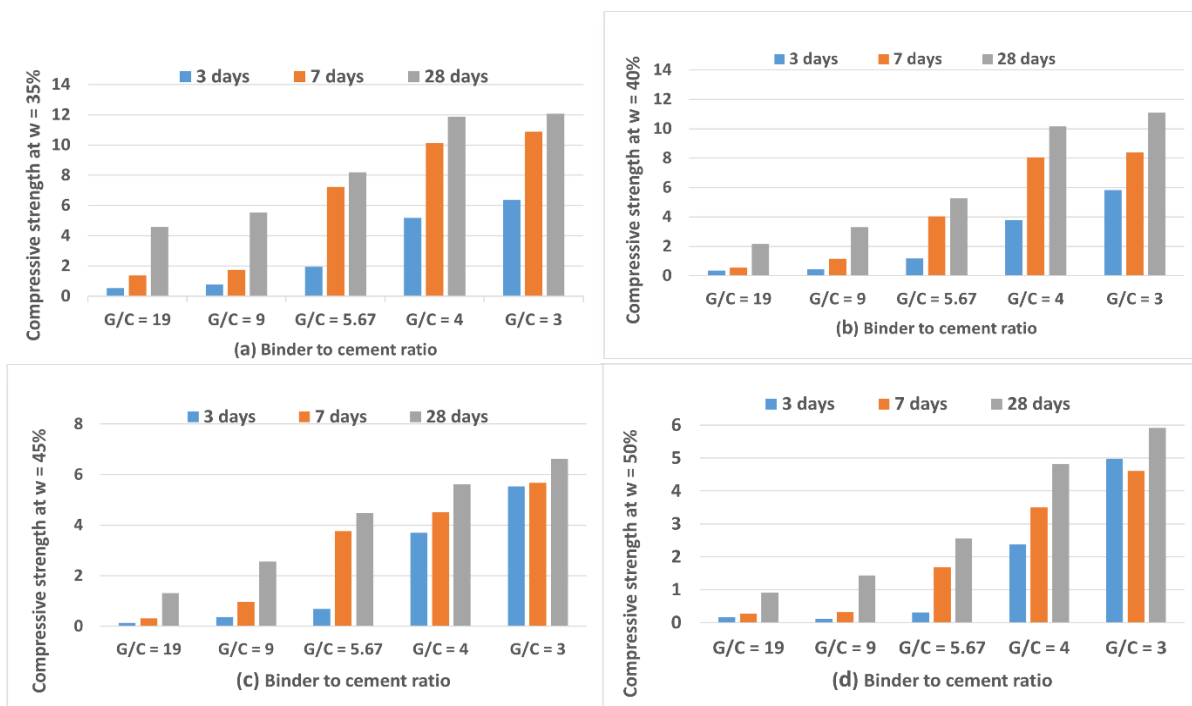


Fig 5: Compressive Strength of CLSM at 3,7 and 28 days for CM 1:1 with G/C as secondary cementitious material and QD as replacement to natural sand at (a) water content 35%; (b) water content 40%; (c) water content 45%; (d) water content 50%.

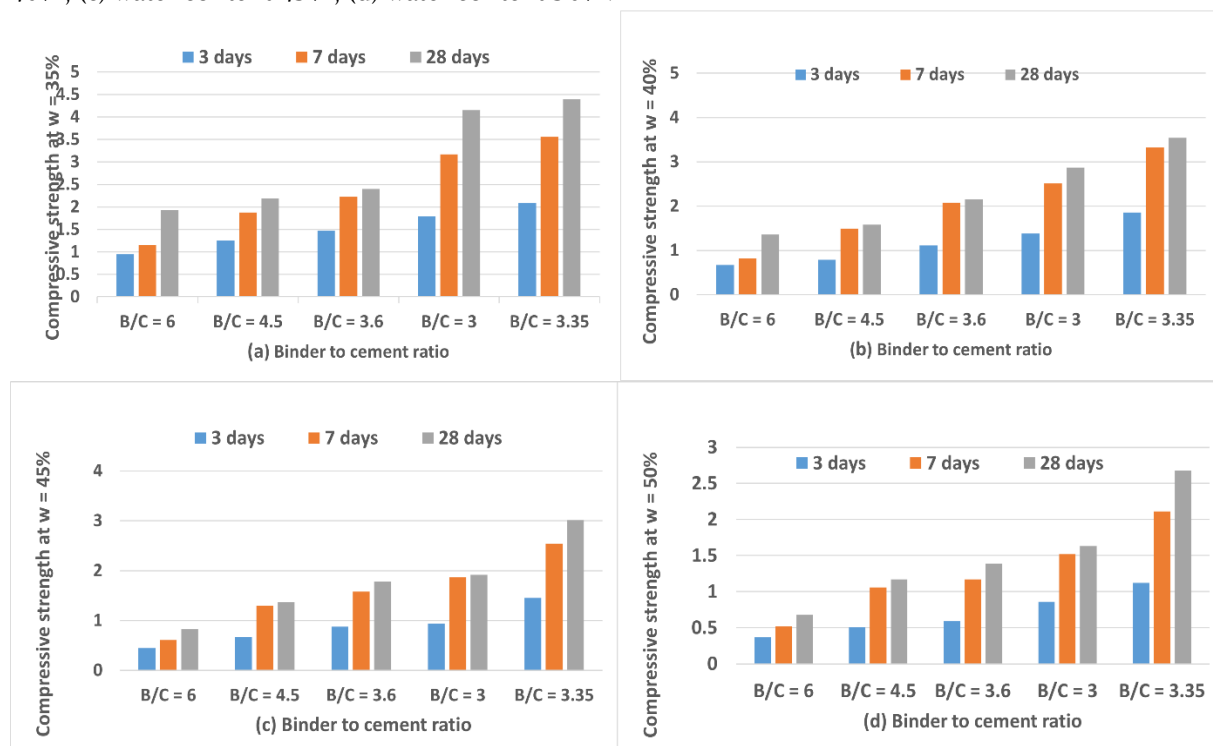


Fig 6: Compressive Strength of CLSM at 3,7 and 28 days for CM 1:1 with B/C as secondary cementitious material and QD as replacement to natural sand at (a) water content 35%; (b) water content 40%; (c) water content 45%; (d) water content 50%.

Strength analysis and effect of pozzolanic material:

Figs 4, 5 and 6, shows the variation of unconfined compressive strength (UCS) with variation in binder content and cement content. As cement content increases, more hydration products continue to generate at microscopic level. The bonding between QD and pozzolanic material increase and the filling the voids in the mixture tends to increase the UCS. Even though the higher water content ensures the better

flowability, the chemical cementitious process between the particles weaken with higher water content, the UCS decreases significantly. On the other hand, with increase in water content and cement content, the UCS tend to increase with more hydration products. Based on the flowability results, increase in water content and binder content together ensures the high flowability and UCS is the only method [7,8]. The UCS increases with increase in curing period and also with binder content. The UCS achieved with three different pozzolanic material FA, GG and BA with their highest water contents are 3.1, 6 and 2.7 MPa respectively. The highest UCS was achieved with GGBS as replacement with cement demonstrating as excellent replacement in CLSM mixes. Also, the highest RFA values were also observed with GGBS was around 50 RFA.

Three different pozzolanic materials were used to study the CLSM UCS properties. Out of which GGBS enhanced UCS significantly. The pre hydration process of GGBS might increase the active silica and aluminium content promoting the CSH gel formation. The GGBS participation will be much higher in the later stages of chemical reaction when compared to other pozzolanic materials [9]. Hence the GGBS the most suitable material to replace cement in CLSM mixes. It also reduces the energy consumption and environmental pollution leading to a most sustainable CLSM mix.

CONCLUSIONS

This study presents a systematic experimental investigation on the utilization of industrial and agro-waste materials—Ground Granulated Blast Furnace Slag (GGBS), Fly Ash (FA), and Bagasse Ash (BA)—as supplementary cementitious materials (SCMs) in the development of Controlled Low Strength Material (CLSM), with Quarry Dust (QD) as the sole fine aggregate.

The following key conclusions can be drawn from the results:

- Water content and pozzolanic material type were identified as the most significant parameters influencing both flowability and unconfined compressive strength (UCS) of CLSM.
- An increase in water content consistently led to an increase in spread flow diameter and Relative Flow Area (RFA), thus enhancing the material's flowability. This is attributed to the reduction in viscosity and internal friction within the mix.
- At higher water contents, a reduction in UCS was observed due to increased porosity and reduced binder efficiency. Hence, optimization of water-to-binder ratio is critical to achieving a balance between workability and strength.
- Among all SCMs tested, GGBS-based CLSM mixes exhibited the best overall performance, achieving both the highest RFA (~50) and maximum UCS (~6 MPa). This superior behavior is linked to GGBS's latent hydraulic reactivity and its role in generating dense calcium silicate hydrate (C-S-H) gel structures.
- FA and BA also showed potential for use in CLSM, with FA offering better workability and BA demonstrating moderate strength development; however, both were outperformed by GGBS.
- The study reaffirms that GGBS is a highly suitable and sustainable alternative to cement in CLSM production, enabling significant environmental benefits by reducing cement consumption and utilizing industrial waste efficiently.

In conclusion, the integration of GGBS and QD in CLSM mix designs offers a viable, eco-friendly solution for backfilling and trench reinstatement applications in Indian infrastructure projects. The outcomes support broader adoption of IS code-based, waste-derived CLSM formulations for achieving cost-effective and sustainable geotechnical engineering practices.

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