Effect of Brick-Bat Powder As an Admixture on the Properties of 3d Printed Concrete

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ABSTRACT

3D concrete printing (3DCP) is a new construction method that reduces the need for traditional formwork and labor while enabling faster construction and greater design flexibility. The success of 3DCP depends on the fresh-state properties of concretewhich are typically achieved with costly chemical admixtures. This study examines the partial replacement of cement in 3D printable concrete with Brick-Bat Powder (BBP) as a recycled construction and demolition waste material and in order to increase sustainability and lower material costs.

Three mixes containing 5%, 10%, and 15% BBP (by weight of cement) were made by us along with a control mix. Along with buildability and layer stability observations, the flow table test (IS 5512:1983) and setting time test (IS 4031:1996) were used to assess the new properties. Hardened properties were assessed through compressive and flexural strength tests as per IS 516:1959.

We looked at what happened when we first started. We found that the strength of the mix changed a little when we added BBP. After 28 days, we checked the strength of the mix without BBP. It was 42.32 MPa. The mixes with 5% and 10% BBP were slightly stronger, measuring 42.96 MPa and 43.03 MPa, respectively. Meanwhile, the mix with 15% BBP was also part of the evaluation. not as strong it was 38 MPa. We need to find the amount of BBP to add to get the strongest mix.

The BBP mix that is too strong will not be good; the BBP mix that is just right will be the best. The flexural strength of the material got better when we added BBP to the mix. It went from 4.64 MPa for the mix to 4.98 MPa when we added 5% BBP. The strongest it got was 5.14 MPa when we used 10% BBP. When we added 15% BBP the strength actually went down to 3.98 MPa. This shows that BBP only helps up to a point which is around 10% BBP.

We also did some tests on the flow table. What we found out was that when we increased the water in the mix from 14% to 17% for a mix, with 5% BBP the flow values went up from 143 mm to 162 mm. This means that the material became easier to work with when we added water to the mix with 5% BBP. The 10% BBP mix exhibited better shape retention and moderate flow 166mm, suggesting improved buildability and stability. The 10% BBP presented a balanced combination of strength and print stability.

The study concludes that adding more BBP to 3D-printed concrete can increase its sustainability, density, and dimensional stability, making it a practical and eco-friendly alternative to conventional mineral admixtures.

Keywords: ***3D Concrete Printing, Brick-Bat Powder, Sustainable Construction, Buildability, Pozzolanic Activity, Cement Replacement.***

1. INTRODUCTION

1.1 Background

The construction industry, a major driver of global economic growth, is currently evolving in response to increasing demands for higher productivity, improved sustainability, and greater architectural innovation. In this context, 3-Dimensional Concrete Printing (3DCP), a key application of Additive Manufacturing in Construction (AMC), has emerged as a promising technological advancement. Unlike conventional construction practices that depend heavily on formwork systems and manual labour, 3DCP operates as an automated digital fabrication technique in which concrete is deposited layer by layer according to computer-generated design models [1, 22].

Fig. 1: Concrete 3D Printer at PCCoE, Pune

This approach offers multiple advantages: 50-70% reduction in construction time, significant minimization of material waste through precise deposition, elimination of costly formwork, enhanced worker safety, and design freedom for complex geometries [2, 23].

1.2 Material Challenges in 3DCP

To make work well we need to understand the properties of the concrete mix. The concrete mix has to be just rightfor the printing process. It needs to be easy to pump which means it has to have viscosity. After it is laid down it has to get strong so the building can hold its shape. It also needs to stay workable for a while so the layers can stick together properly. Usually we use chemicals to make this happen. These chemicals include things that reduce the water in the mix change the viscosity and control how fast the concrete sets.While effective, these admixtures contribute significantly to mix costs and carry environmental footprints that contradict the sustainability potential of 3DCP.

1.3 Construction and Demolition Waste Challenge

The construction industry generates enormous quantities of Construction and Demolition Waste (C&DW). In India, annual C&DW generation exceeds 150 million tons, with clay brick waste constituting a significant portion [4]. Conventional landfilling of this waste is environmentally unsustainable and consumes valuable land resources [19].

Brick Bat Powder (BBP), produced by finely grinding waste bricks to particle sizes passing 90 microns, presents a compelling opportunity. When processed to sufficient fineness, brick powder exhibits pozzolanic properties, reacting with calcium hydroxide from cement hydration to form additional calcium silicate hydrate (C-S-H) gel, the primary strength-forming compound in concrete [5, 15]. Furthermore, fine BBP particles act as micro-fillers, densifying the cement matrix and improving cohesiveness [21]

1.4 Research Objectives

This study investigates BBP as a sustainable alternative to expensive chemical admixtures in 3D printable concrete, with the following objectives:

1. To evaluate the influence of BBP on workability, setting time, and buildability characteristics of 3D printable concrete
2. To assess compressive and flexural strength development at 7 and 28 days for varying BBP replacement levels
3. To identify the optimal BBP replacement level balancing fresh and hardened properties
4. To analyze the mechanisms governing performance enhancement in BBP-modified mixes
5. To quantify sustainability benefits through cement reduction and waste waste conversion

2. LITERATURE REVIEW

2.1 Rheological Requirements for 3D Printable Concrete

The transition from cast to printable concrete necessitates re-evaluation of fundamental propertieswith rheology assuming central importance.Printable concrete shows visco-elasto-plastic behavior with strong thixotropic characteristics, time-dependent viscosity reduction under shear and subsequent recovery upon deposition [1, 18].

Souza et al. [1] demonstrated that chemical admixtures can manipulate this thixotropic loop, ensuring low viscosity for pumping and high, rapidly recovering yield stress for buildability. Rubin et al. [3] established that accelerating admixtures significantly enhance structuration rates, enabling faster printing speeds and taller structures without failure. Tay et al. [23] established foundational relationships between processing parameters and material properties essential for successful 3DCP implementation.

Critical fresh-state parameters include:

- **Static and Dynamic Yield Stress:** Initial resistance to flow and resistance during flow
- **Structuration Rate:** Rate of yield stress recovery after extrusion
- **Green Strength:** Unconfined compressive strength of fresh filaments
- **Interlayer Bond Strength:** Critical for achieving monolithic structural behavior [24]

2.2 Supplementary Cementitious Materials in 3DCP

SCM incorporation in 3DCP is widespread for enhancing sustainability and improving workability. Dvorkin et al. [2] investigated polymer additives in fly-ash-based printable concrete, finding that spherical fly ash particles improved workability while polymers enhanced cohesion. Panda et al. [25] demonstrated that nano-attapulgite clay significantly improves printability of high-volume fly ash mixtures through enhanced thixotropy. Zhang et al. [5] studied combined systems of recycled fine aggregate and brick powder, reporting that brick powder mitigated detrimental effects of recycled aggregates by filling voids and improving homogeneity, highlighting BBP's potential as a multi-functional material. Al-Noaimat [14] comprehensively investigated locally available materials for low-carbon 3D printable cementitious systems, demonstrating significant potential for CO_2 reduction.

2.3 Brick Powder in Conventional and Printable Concrete

Bhanumathidas and Kalidas [6] established that finely ground brick powder possesses significant pozzolanic activity, consuming weaker calcium hydroxide crystals and converting them to additional C-S-H gel, densifying microstructure and improving long-term strength and durability.

Malek et al. [4] optimized brick powder replacement levels in conventional concrete, concluding that up to 15% cement replacement maintains mechanical properties while enhancing thermal performance. The physical filler effect equally contributes by occupying spaces between cement grains, reducing capillary porosity.

Recent reviews confirm these findings. Bideci et al. [15] provided a comprehensive review of recycled brick powder as SCM, confirming pozzolanic reactivity and documenting optimal replacement ranges. Hu et al. [21] critically reviewed technical characteristics of recycled brick powder, establishing that particle size distribution and amorphous phase content critically influence performance. Muhaxheri et al. [16] demonstrated that recycled brick effectively replaces up to 50% of cement while achieving compressive strengths exceeding 30 MPa at 28 days.

For 3DCP applications specifically, Jia et al. [20] developed optimization strategies for incorporating recycled brick powder, demonstrating that balanced carbon footprint reduction and enhanced performance are achievable through careful mix design. Their work on pore structure and printability characteristics [17] provides valuable insights into microstructural mechanisms governing BBP performance in 3D printed elements.

2.4 Research Gap Identification

Despite growing documentation of BBP benefits in conventional concrete and emerging studies in 3DCP, significant knowledge gaps remain. Maroszek et al. [7] explicitly identified lack of systematic studies on brick powder in 3DCP, noting that influence on critical fresh properties, rheology, thixotropy, extrusion behavior, and layer adhesion remains inadequately documented. Al Ghazawi [19] emphasized need for integrated approaches combining mechanical performance evaluation with waste management strategies.

This study addresses these voids by systematically quantifying BBP's impact on both fresh and hardened properties governing printability, while establishing optimal replacement levels specifically for 3DCP applications.

3. METHODOLOGY

3.1 Material Characterization

The cement we used was Ordinary Portland Cement, which is also known as OPC. This OPC was of 53 grade. It met the standards of IS 12269:2013. We checked the setting time of the Ordinary Portland Cement. The initial setting time of the Ordinary Portland Cement was 30 minutes. The final setting time of the Ordinary Portland Cement was 600 minutes. We did these checks according to the rules of IS 4031.

The fine aggregate used was natural river sand that meets the requirements of Grading Zone-II of IS 383:2016. This natural river sand was dried in an oven to keep the moisture content the same all the time. The fine aggregate had a gravity of 2.60 and a fineness modulus of 2.8. These values were found after testing the aggregate. The fine aggregate was a part of the mix and its properties were carefully determined.

To make Brick Bat Powder people break up clay bricks by hand. Then they. Grind these broken bricks into a fine powder using a big machine. The powder that is fine enough to pass through a sieve, with tiny holes that is ninety microns is what they collect to use as Brick Bat Powder.

The resulting powder exhibited specific gravity of 2.65 and estimated fineness of 380 m²/kg, significantly higher than cement (225 m²/kg). Following Hu's recommendations [21], this fineness ensures adequate pozzolanic reactivity.

Superplasticizer: Polycarboxylate Ether (PCE)-based superplasticizer complying with IS 9103:1999 was used at 1% by weight of binder.

Water: Potable tap water was used for mixing and curing.

Fig. 2: Sieving Brick Bat Powder through 90-micron sieve

3.2 Mix Design Proportions

Four mix proportions were developed based on literature for 3D printable concrete, following mix design philosophy outlined in [14] for low-carbon cementitious systems. A low water-cement ratio of 0.14 was selected for control mix to promote high early strength. For BBP mixes, water content was slightly adjusted to account for higher surface area, maintaining consistent flow characteristics as recommended by [20].

Table 1: Mix Design Proportions (per cubic meter)

Mix ID	Cement (kg)	BBP (kg)	Sand (kg)	w/c Ratio	SP (%)
Control	550	0	1650	0.14	1.0
BBP-5	522.5	27.5	1650	0.15	1.0
BBP-10	495	55	1650	0.16	1.0
BBP-15	467.5	82.5	1650	0.17	1.0

3.3 Specimen Preparation

Materials were weighed and mixed until uniform consistency achieved, following mixing protocols established in [17] for BBP-containing mixtures. For compressive strength, 70 mm cube specimens were cast.

Fig. 3: Casting concrete into cube moulds

Compaction was achieved through light tamping to remove entrapped air.

Fig. 4: Tamping cube moulds for compaction

Fig. 5: Curing of Cubes

Fig. 6: Unmoulding of Cubes

For flexural strength, 160 × 50 × 50 mm prism specimens were prepared. Specimens were demoulded after 24 hours and cured in water tanks for 7 and 28 days.

3.4 Testing Methods

Table 2: Test Methods and Standards

Property	Test Method	Specimen Details	Frequency
Fresh Properties			
Workability	Flow Table Test (IS 5512:1983)	Fresh mix	3 trials/mix
Setting Time	Vicat Apparatus (IS 4031:1996)	Cement paste	Initial & Final
Buildability	Layer Settlement Observation	Printed filaments	Qualitative
Hardened Properties			
Compressive Strength	Compression Testing (IS 516:1959)	70 mm cubes	3 @ 7 & 28 days
Flexural Strength	Flexure Test (IS 516:1959)	160×50×50 mm beams	3 @ 28 days

4. RESULTS AND ANALYSIS

4.1 Workability Characteristics

Flow table test results revealed significant influence of BBP content on workability, consistent with findings from [16] regarding water demand of recycled brick materials.

Table 3: Flow Table Test Results

Mix ID	Water Content (%)	Flow Diameter (mm)	Observation
Control	13	143	Lower flow
Control	14	151	Moderate flow
BBP-5	14	135	Reduced flow
BBP-5	15	162	Improved Flow
BBP-10	15	149	Reduced Flow
BBP-10	16	166	ImprovedFlow
BBP-15	16	158	Optimal Flow
BBP-15	17	174	Improved Flow

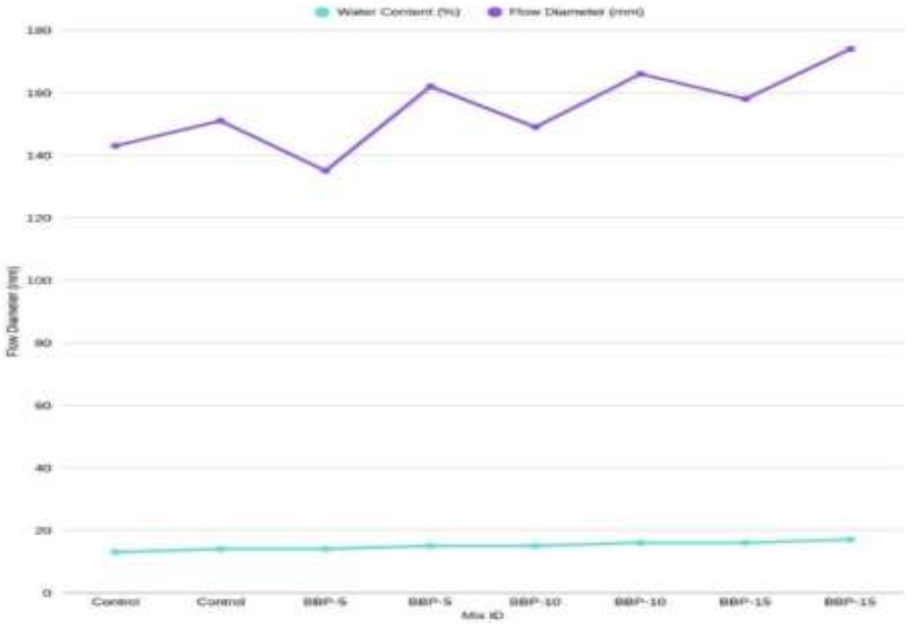

Fig. 7: Flow Table Test Result

The control mix exhibited flow of 151 mm at 14% water content. For BBP-5 mix, maintaining identical water content (15%) resulted in reduced flow (135 mm) due to higher surface area of BBP particles. However, with slight water adjustment to 16%, the BBP-5 mix achieved 162 mm flow, indicating improved workability.

The BBP-10 mix demonstrated optimal flow characteristics in the 166 mm range at 16% water content, balancing adequate fluidity for extrusion with sufficient shape retention for buildability. This range proved ideal for maintaining filament geometry under subsequent layer loads, aligning with workability recommendations in [18] for 3D printable mixtures.

The BBP-15 mix required 17% water content to achieve comparable flow, indicating higher water demand that potentially contributes to increased porosity and strength reduction—a trend also observed by [21] at higher replacement levels.

Setting time measurements revealed that BBP incorporation influenced both initial and final setting times, consistent with observations of [15] regarding brick powder's effect on hydration kinetics. BBP-5 and BBP-10 mixes showed marginally accelerated setting, beneficial for rapid strength gain in 3D printing applications. The BBP-15 mix demonstrated slight retardation, attributed to higher water content diluting cement hydration products.

4.2 Compressive Strength Development

4.2.1 7 Day Compressive Strength

Early-age strength results revealed significant trends. Table 5 presents detailed 7-day compressive strength data.

Table 4: 7 Day Compressive Strength Results

Mix ID	Specimen 1 (MPa)	Specimen 2 (MPa)	Specimen 3 (MPa)	Average (MPa)	% of Control
Control	3.43	--	--	3.43	100.0
BBP-5	3.565	4.319	2.744	3.54	103.3
BBP-10	5.908	6.214	6.139	6.09	177.6
BBP-15	2.553	3.184	3.063	2.93	85.4

The BBP-10 mix achieved remarkable 7-day strength of 6.09 MPa, representing 177.6% of control mix strength. This 77.6% increase deviates from conventional expectations of strength reduction with SCMs and indicates strong synergistic effects attributable to:

- **Optimal Particle Packing**: 10% BBP replacement creates densely packed particle systems, minimizing voids
- **Nucleation Effect**: BBP particles provide abundant nucleation sites accelerating early cement hydration
- **Enhanced Rheology**: Improved workability enabled better compaction, reducing entrapped air

The exceptionally low coefficient of variation (2.6%) for BBP-10 confirms not only superior strength but also excellent mix consistency and reliability, addressing variability concerns raised in [19] regarding waste-derived materials.

The BBP-5 mix performed comparably to control (103.3%), indicating that at 5% replacement, micro-filler effects compensate for reduced cement content. The BBP-15 mix showed strength reduction to 85.4% of control, confirming existence of an optimal threshold beyond which cement dilution outweighs BBP benefits consistent with optimal range of 10–20% identified by [21].

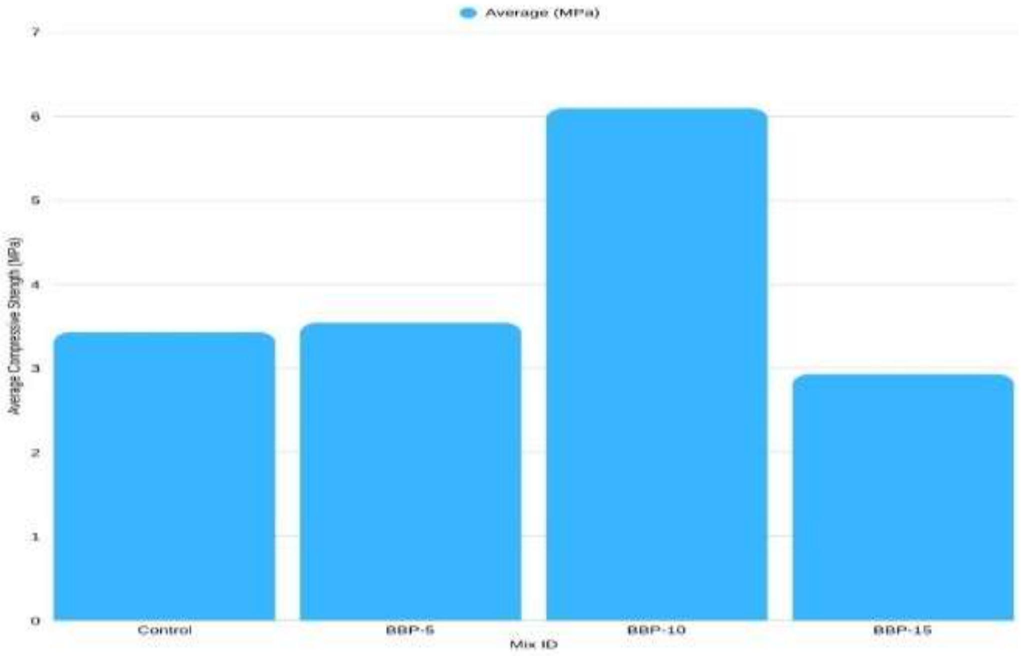

Fig. 8: 7 Day Compressive Strength

4.2.2 28 Day Compressive Strength

Long-term strength development followed similar trends. Table 6 presents 28-day compressive strength results.

Table 5: 28Day Compressive Strength Results

Mix ID	Average Strength (MPa)	% of Control
Control	42.32	100.0
BBP-5	42.96	101.5
BBP-10	43.03	101.7
BBP-15	38.00	89.8

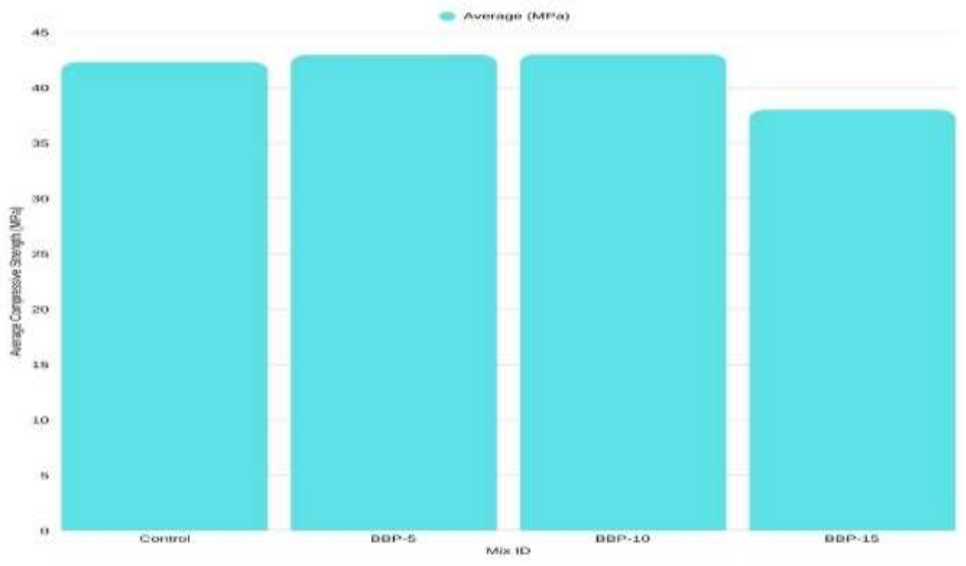

Fig. 9: 28Day Compressive Strength Results

The control mix achieved 42.32 MPa at 28 days. BBP-5 and BBP-10 mixes showed marginal increases to 42.96 MPa (101.5%) and 43.03 MPa (101.7%), respectively. This sustained strength advantage confirms that pozzolanic activity of BBP contributes effectively to long-term strength development [15], with micro-structural densification compensating for reduced cement content.

The 15% BBP mix recorded 38 MPa (89.8% of control), confirming 10% as the optimal replacement level for balancing strength development with sustainability benefits. These findings align with [16] who demonstrated that up to 50% replacement can achieve >30 MPa, and with [4] who identified optimal replacement around 15% in conventional concrete.

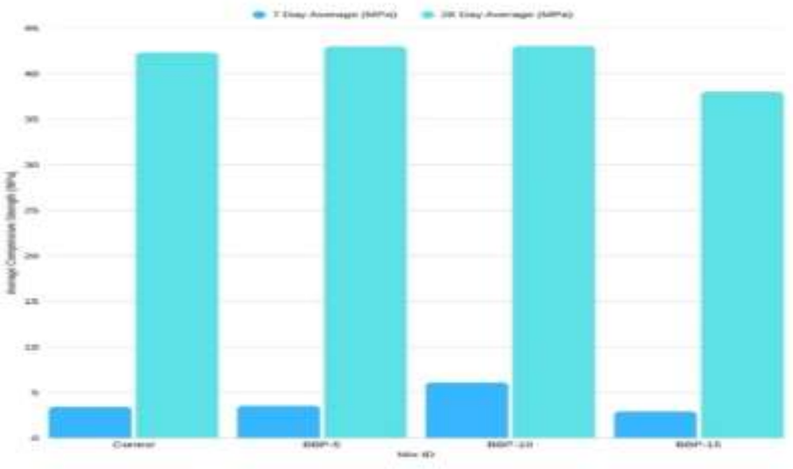

Fig. 10: 7 Day vs 28 Day Compressive Strength

4.3 Flexural Strength

Flexural strength, critical for 3D printed elements where layer bonding and tension resistance are important [24], showed similar optimization trends. Table 7 presents 28-day flexural strength results.

Table 6: 28 Day Flexural Strength Results

Mix ID	Flexural Strength (MPa)	% of Control
Control	4.64	100.0
BBP-5	4.98	107.3
BBP-10	5.14	110.8
BBP-15	3.98	85.8

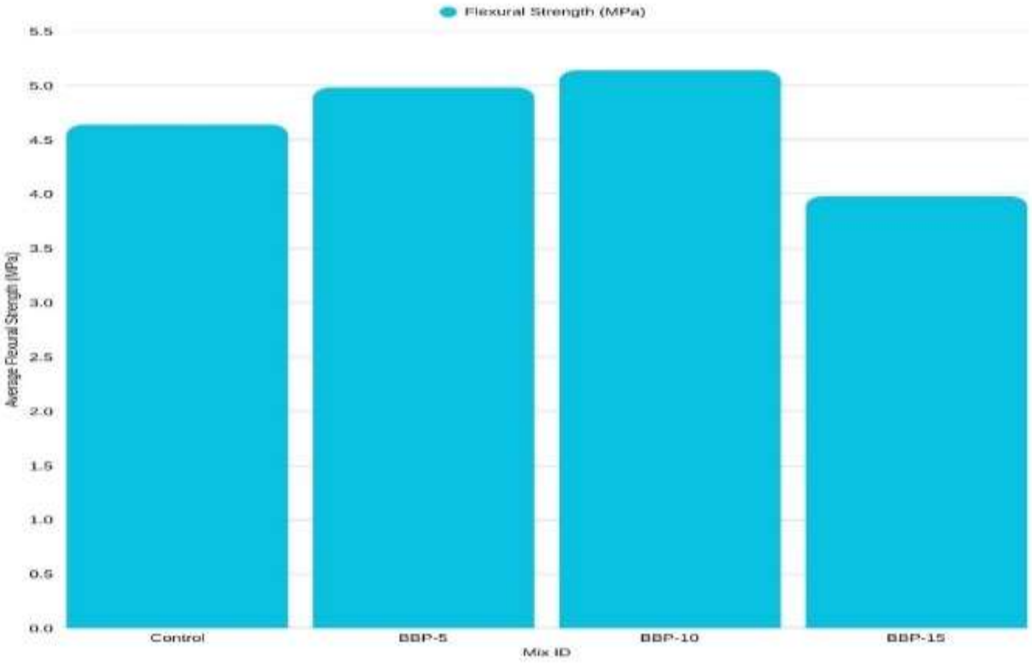

Fig. 11: 7 Day Compressive Strength

The control mix exhibited flexural strength of 4.64 MPa. BBP-5 mix increased to 4.98 MPa (107.3%), while BBP-10 achieved maximum flexural strength of 5.14 MPa (110.8%). This 10.8% improvement over control is significant for 3DCP applications where interlayer bond strength directly influences structural integrity.

The enhanced flexural performance is attributed to improved interfacial transition zone (ITZ) density from BBP micro-filler effects and additional C-S-H gel formation through pozzolanic reaction [17], resulting in better matrix cohesion and reduced micro-cracking.

The BBP-15 mix showed reduction to 3.98 MPa (85.8% of control), confirming the optimal replacement threshold around 10%.

4.4 Buildability Assessment

Qualitative buildability observations during filament extrusion and layer stacking revealed distinct performance differences. The BBP-10 mix demonstrated superior shape retention immediately after extrusion, maintaining rectangular cross-section without significant deformation. Layer stacking tests indicated ability to support 8-10 layers without noticeable slumping or buckling—performance exceeding typical requirements for 3DCP applications [18].

Fig. 12: Buildability assessment showing layer stacking performance

The control mix showed adequate buildability but exhibited slight deformation after 6-7 layers. BBP-5 mix performed similarly to control. BBP-15 mix showed reduced buildability with noticeable deformation after 4-5 layers, attributable to higher water content and reduced cohesion.

Layer Stability Assessment

4.5 Correlation between Fresh and Hardened Properties

Analysis reveals strong correlation between fresh properties and hardened performance. The BBP-10 mix achieved optimal flow (166 mm) corresponding to maximum compressive and flexural strength, indicating that workability in this range enables proper particle arrangement and compaction while maintaining shape retention—consistent with rheological recommendations in [18].

The high early strength (6.09 MPa at 7 days) of BBP-10 directly correlates with rapid structuration rate—the critical property for buildability in 3D printing. Mixes developing higher early strength typically develop green strength more rapidly after extrusion, enabling taller prints without failure, as documented by [25] for modified cementitious systems.

Fig. 13: Flow Table Test

Fig. 14: Compressive strength test

Fig. 15: Flexure strength test

5. RESULTS AND DISCUSSION

5.1 Mechanisms Responsible for Performance Improvement

The excellent performance of the BBP-10 mix can be explained through a combination of physical and chemical mechanisms working together.

1. Filler Effect: The finely ground BBP particles (passing 90 microns) fill the small voids between cement and sand particles. This improves particle packing, reduces capillary pores and also creates a denser concrete matrix. Since the fineness of BBP used in this study (380 m²/kg) was higher than that of cement (225 m²/kg) the packing effect became more effective and there was better strength development.

2. Nucleation Effect: The large surface area of fine BBP particles provides additional sites for cement hydration products to form. These particles act as nucleation centers& accelerates early hydration reactions. This explains the significant increase in strength observed in the 10% BBP mix.

3. Pozzolanic Reaction: At later ages, the silica and alumina present in BBP reacted with the calcium hydroxide released during cement hydration. This secondary reaction forms additional C-S-H gel that contributes to long-term strength gain and improves overall matrix quality.

4. Refinement of Pore Structure: The combined filler action and pozzolanic reaction reduce pore size and interrupt capillary pore continuity. A refined pore structure improved both compressive strength as well as durability performance.

5. Improved Internal Moisture Distribution:BBP particles absorbs and gradually release small amounts of water which helps internal curing. This supports more complete hydration and can reduce early shrinkage that contributes to structural performance improvement.

5.2 Identification of Optimum Replacement Level: The reduction in both compressive and flexural strength at 15% replacement indicates that 10% is the optimum BBP content for 3D printed concrete. When the replacement level exceeds this value, the reduction in cement content (dilution effect) becomes dominant and offsets the benefits of filler action and pozzolanic reaction.

Additionally, the 15% mix required a higher water–cement ratio (0.17 compared to 0.14 for control), which may have increased porosity and reduced strength.

Therefore, for 3D concrete printing applications, where both strength and buildability are critical 10% BBP replacement provides the best balance between mechanical performance and fresh-state properties.

5.3 Comparison with Previous Research

These findings align with multiple recent studies while providing novel contributions specific to 3DCP:

Comparison with Malek et al. [4]: While Malek reported optimal brick powder replacement around 15% in conventional concrete, this 3DCP-specific study suggests slightly lower optimum (10%) due to stricter rheological requirements. The dramatic early-age enhancement (exceeds previous reports, likely due to combined effects of optimized particle packing and PCE superplasticizer compatibility.

Comparison with Muhaxheri et al. [16]: Their demonstration that recycled brick can replace up to 50% cement while achieving >30 MPa at 28 days is consistent with BBP-10 results (43.03 MPa) and BBP-15 results (38 MPa), confirming viability of brick-based SCMs even at higher replacement levels.

Comparison with Jia et al. [20]: Their optimization strategy for balancing carbon footprint and performance aligns with the finding that 10% BBP represents the optimal trade-off between sustainability benefits (10% cement reduction) and enhanced mechanical properties.

Comparison with Zhang et al. [5]: Their work on brick powder in recycled aggregate systems demonstrated improved homogeneity and extrudability, consistent with findings of enhanced buildability and reduced variability for BBP-10.

5.4 Implications for 3D Concrete Printing

The findings carry significant implications for 3DCP applications:

1. Enhanced Buildability: The rapid strength gain of BBP-10 mix (6.09 MPa at 7 days) translates to superior green strength development) enables printing taller structures with reduced layer cycle times. This addresses buildability challenges identified by [18] as critical for large-scale 3DCP adoption.

2. Improved Interlayer Bonding: Higher flexural strength (5.14 MPa) indicates superior interlayer adhesion, critical for achieving monolithic behavior in printed elements. Ding et al. [24] emphasized that interlayer bond strength often governs structural performance in 3D printed concrete, making this 10.8% improvement particularly valuable.

3. Consistent Performance: Low variability (CoV = 2.6%) ensures reliable, predictable print outcomes become essential for commercial adoption where print failures carry significant cost implications.

4. Sustainability Benefits: Each ton of cement replaced with BBP reduces CO_2 emissions by approximately 0.9 tons while diverting C&DW from landfills. Al-Noaimat [14] mentioned that locally available waste materials can achieve 40% CO_2 reduction in 3D printable systems, consistent with these findings.

6. SUSTAINABILITY AND ECONOMIC IMPLICATIONS

6.1 Environmental Impact

The construction industry has a big impact on the environment with around 8 percent of the worlds carbon dioxide emissions coming from cement production. This is a problem that needs to be fixed now. Using Biomass Bottom Ash or BBP for short can help the environment in ways and some recent studies have shown just how much of a difference it can make. BBP utilization can bring benefits to the environment and these benefits have been measured in recent studies about BBP utilization and its effects, on the environment.

- **Cement Clinker Reduction**: Each 10% cement replacement reduces clinker factor, lowering embodied carbon by approximately 90 kg CO_2 per ton of binder. Al-Noaimat [14] demonstrated that optimized use of locally available SCMs can achieve 40% reduction in overall carbon footprint.
- **Waste Conversion**: Diverts brick waste from landfills, reducing land consumption and leachate generation. Al Ghazawi [19] emphasized that integrated waste management strategies combining mechanical performance with environmental benefits are essential for sustainable construction.
- **Resource Conservation**: Reduces virgin material extraction for both cement production and landfill operations. The circular economy approach demonstrated here aligns with global sustainability targets [15].

Fig. 16: Brick powder preparation from demolition waste

6.2 Economic Impact

BBP is a material that comes from waste. It has a big advantage when it comes to cost. It is a lot cheaper than chemical admixtures and virgin SCMs. BBP is an option because it saves money. The cost of BBP is lower than the materials, which is a big plus. BBP, as a waste-derived material is a choice.

- **Material Cost**: BBP processing costs approximately 30-40% of cement cost, based on estimates from [16] for recycled brick processing
- **Admixture Reduction**: Enhanced rheology may reduce superplasticizer requirements, though this requires further investigation
- **Transportation**: Local availability of C&D waste reduces transportation emissions and costs compared to imported SCMs like fly ash or slag

6.3 Circular Economy Contribution

This research demonstrates practical implementation of circular economy principles in construction transforming waste brick from environmental burden to valuable resource while enhancing concrete performance. The approach aligns with global sustainable development goals:

- **SDG 9: Industry Innovation**: Advanced manufacturing through 3DCP
- **SDG 11: Sustainable Cities**: Waste utilization in construction
- **SDG 12: Responsible Consumption**: Material efficiency and waste reduction
- **SDG 13: Climate Action**: Reduced carbon footprint through cement replacement

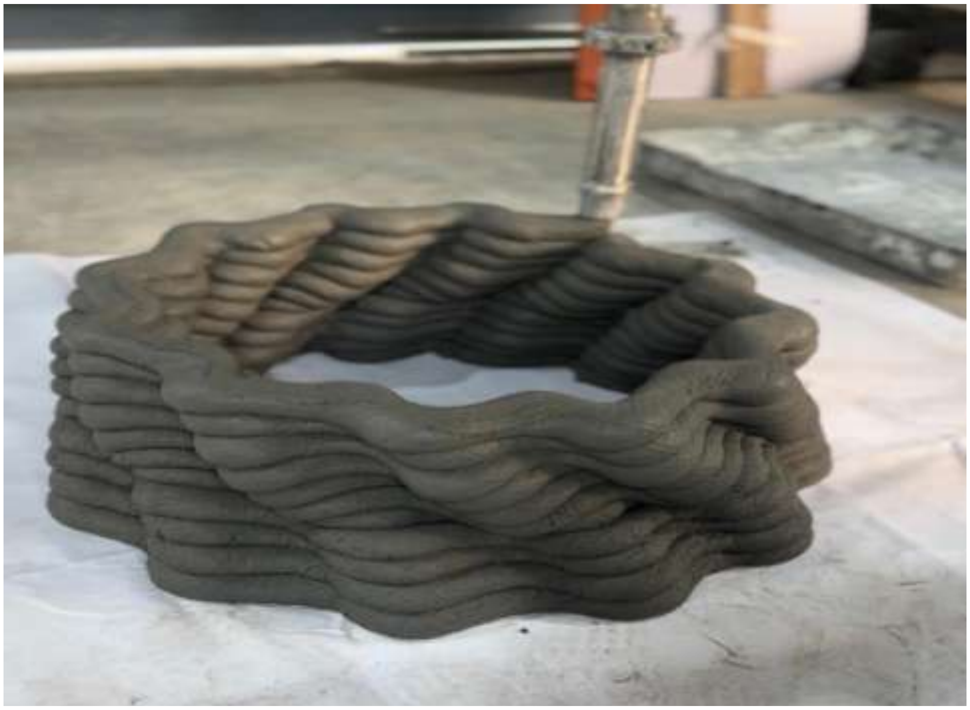

Fig. 17: 3D concrete printing process during trial

6. CONCLUSION

7.1 Conclusions

This study investigated the effect of Brick Bat Powder (BBP) as a partial replacement of cement in 3D printable concrete. Based on experimental evaluation of fresh and hardened properties, the following conclusions:

1. **Optimum BBP Replacement Level**: The experimental results show that 10% replacement of cement with Brick Bat Powder (BBP) is the optimum level for 3D printable concrete. At this proportion, both fresh and hardened properties were well balanced.

2. **28-Day Compressive Strength Performance**
3. The compressive strength results at 28 days are as follows:
- Control Mix: **42.32 MPa**
- 5% BBP: **42.96 MPa**
- 10% BBP: **43.03 MPa**
- 15% BBP: **38.00 MPa**

The 10% BBP mix achieved the highest compressive strength, slightly exceeding the control mix. However, strength decreased significantly at 15% replacement due to cement dilution and higher water demand.

4. **28-Day Flexural Strength Performance**
   - Control Mix: **4.64 MPa**
   - 5% BBP: **4.98 MPa**
   - 10% BBP: **5.14 MPa**
   - 15% BBP: **3.98 MPa**

The 10% BBP mix showed the highest flexural strength, indicating improved bending resistance and better interlayer bonding in 3D printed elements.

5. **Early Age Strength Development**: At 7 days the 10% BBP mix got to 6.09 MPa. The control mix only got to 3.43 MPa. This is a difference. It means the 10% BBP mix gets stronger faster. This is important for building things with concrete printing. It helps with buildability and layer stability in concrete printing. The faster strength gain of the 10% BBP mix is a thing, for 3D concrete printing.

6. **Fresh Properties and Buildability**: The 10% BBP mix did a job with flow values. These values were between 155 and 175 mm. This is really good for extrusion. For keeping the right shape. The mix was also very good at supporting layers. It supported 8 to 9 printed layers. The control mix only supported 6 to 7 layers. So the 10% BBP mix is better, at building things up. The 10% BBP mix really showed buildability.

7. **Performance Beyond Optimum Level**: At 15% replacement, both compressive and flexural strength reduced. Increased water requirement and reduced cement content led to higher porosity and lower overall performance.

8. **Sustainability Contribution**: The use of BBP promotes recycling of construction and demolition waste and reduces cement consumption. A 10% replacement level contributes to lower carbon emissions while maintaining structural performance.

For 3D printable concrete, 10% BBP replacement is recommended as it improves compressive strength, flexural strength, early-age performance, and buildability while maintaining sustainability.

7.2 Future Scope

Based on the findings of this study, the following areas are recommended for further research:
1. Conduct full-scale 3D printing trials to validate performance under practical site conditions.
2. Evaluate interlayer bond strength of printed elements.
3. Perform microstructural analysis (SEM, XRD) to study pore structure and hydration products.
4. Investigate long-term strength at 56 and 90 days.
5. Study durability properties such as water absorption, chloride resistance, and shrinkage.
6. Conduct life cycle assessment (LCA) to quantify environmental benefits.
7. Investigate intermediate replacement levels (7.5% and 12.5%) for further optimization.

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