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Development Of An Optimized 3d Printable Concrete Mix Incorporating Construction And Demolition Waste For Sustainable Construction

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Abstract: The growing demand for sustainable construction practices, increasing environmental pollution and the rising impact of construction activities has led to the exploration of new technologies and sustainable materials. 3D printing in construction is rapidly emerging as an innovative alternative to conventional building practices, enabling faster, more precise, and cost-effective fabrication of complex structures. However, the high cement content traditionally used in printable concrete raises sustainability concerns due to its significant carbon footprint. To address this challenge, this project explores the development and application of sustainable concrete mixes for 3D printing by partially replacing cement and natural aggregates with supplementary cementitious materials such as fly ash, silica fume along with recycled aggregates and fibers like basalt, polypropylene fiber. The waste materials offer environmental benefits by reducing landfill waste and material demand, their successful integration requires optimizing concrete mix proportions and printing parameters to balance properties like early strength, flow, and overall structural integrity. By integrating green materials into 3D-printed concrete, the project aims to significantly reduce environmental impact, enhance resource efficiency, and promote the large-scale adoption of sustainable construction practices.

***Index Terms* -** 3D concrete printing, Sustainable construction, Printable concrete, Supplementary cementitious materials, Recycled aggregates, Fibre-reinforced concrete, Compressive Strength, Durability.

1. INTRODUCTION

The construction industry continues to expand rapidly, but this growth has been accompanied by increasing environmental concerns. The production of Ordinary Portland Cement (OPC) is energy intensive and contributes significantly to global carbon dioxide emissions. At the same time, large quantities of construction and demolition waste (CDW) are generated from infrastructure development, renovation, and urban expansion. The disposal of such waste and the continuous extraction of natural aggregates pose serious sustainability challenges. These concerns have encouraged researchers to explore alternative and resource-efficient approaches in concrete mix design.

Concrete performance is largely dependent on its mix proportions. The selection and proportioning of binders, aggregates, mineral admixtures, chemical admixtures, and fibres determine the fresh properties, strength development, durability, and overall structural behaviour of the material. Therefore, a carefully designed and experimentally validated mix is essential to ensure consistent performance. Rather than focusing only on compressive strength, modern mix design also considers sustainability, material efficiency, and microstructural optimization.

Supplementary cementitious materials such as fly ash and silica fume have been widely used to partially replace cement and enhance concrete performance [3]. Class F fly ash improves workability due to its spherical particle shape and contributes to long-term strength through pozzolanic reactions. Silica fume, with its extremely fine particle size, improves particle packing and reduces pore connectivity, resulting in a denser and stronger matrix [1]. The combined use of these materials not only enhances mechanical performance but also reduces cement consumption, thereby lowering environmental impact.

In addition to binder modification, the incorporation of recycled materials such as construction and demolition waste has gained significant research attention. When properly processed and graded, CDW can serve as a partial replacement for natural fine aggregates. Previous studies have shown that controlled incorporation of recycled aggregates can produce structurally acceptable concrete while promoting sustainable material utilization [2]. However, variations in particle size distribution, fines content, and density require detailed material characterization before use in mix design.

Fibre reinforcement is another strategy employed to enhance the performance of cementitious composites. Polypropylene fibres are commonly used to control plastic shrinkage cracking and improve tensile resistance without substantially affecting density [4]. Their effectiveness depends on uniform dispersion and compatibility with the cement matrix, both of which must be considered during proportioning.

Although considerable research has been conducted on sustainable concrete materials, inconsistencies in raw material properties often lead to variations in performance. This highlights the importance of systematic material characterization and rational mix proportioning.

The present study focuses exclusively on the development of a sustainable concrete mix through detailed evaluation of constituent materials and optimized mix design considerations. Ordinary Portland Cement, fly ash, silica fume, manufactured sand, construction and demolition waste, chemical admixtures, and polypropylene fibres were characterized based on relevant physical properties prior to incorporation. The scope of this work is limited to mix design development and material characterization, without structural application or fabrication processes. The objective is to establish a balanced and sustainable cementitious composite capable of achieving adequate mechanical performance while promoting responsible material utilization.

2. METHODOLOGY

2.1. MIX DESIGN CONSIDERATIONS

The mix was designed without the inclusion of coarse aggregates in order to achieve improved homogeneity and enhanced particle packing density. The absence of coarse aggregates allows better control over matrix uniformity and reduces internal heterogeneity, which is essential in fine-grained cementitious systems.

A reduced water content was adopted to promote the formation of a dense microstructure with lower capillary porosity. Lower water content is known to enhance compressive strength and durability characteristics; however, it significantly reduces workability. To compensate for this reduction and ensure proper dispersion of binder particles, chemical admixtures were incorporated. The selected approach therefore represents a balance between mechanical performance and workable consistency.

The binder system consisted of Ordinary Portland Cement (OPC), Fly ash, and silica fume. Partial replacement of cement with supplementary cementitious materials was adopted to improve sustainability and microstructural refinement. Fly ash contributes to improved workability and long-term strength development through pozzolanic reactions, while silica fume enhances packing density due to its ultra-fine particle size and improves the overall compactness of the hardened matrix. The combined binder system was proportioned to reduce cement consumption while maintaining adequate mechanical performance.

Fine aggregates were selected based on grading characteristics and packing efficiency. Manufactured sand served as the primary fine aggregate, while processed construction and demolition waste (CDW) was incorporated as a partial replacement to promote sustainable resource utilization. The grading of both materials was evaluated to ensure compatibility within the composite matrix and to maintain structural stability.

Polypropylene fibers were included in the mix to improve tensile resistance and control plastic shrinkage cracking. Fibre incorporation enhances crack-bridging capacity and contributes to improved post-cracking behaviour of the hardened composite. Overall, the mix design strategy emphasized sustainable material utilization, optimized particle packing, controlled water content, and enhanced mechanical performance

2.2. MATERIALS AND THEIR CHARACTERIZATION

The properties of individual materials significantly influence the overall behavior of the developed composite. Therefore, detailed experimental characterization of each constituent material was carried out prior to mix proportioning.

2.2.1. Ordinary Portland Cement

Ordinary Portland Cement was used as the primary binding material. The specific gravity of the cement was determined as 3.15, which lies within the standard range for OPC. Cement hydration leads to the formation of calcium silicate hydrate the primary compound responsible for strength development in hardened concrete. The presence of cement ensures structural integrity and adequate early-age strength of the composite matrix.

2.2.2. Fly Ash

Class F fly ash was incorporated as a supplementary cementitious material to partially replace cement. The specific gravity of fly ash was determined using the pycnometer method and was found to be 2.39. The test was conducted by filling a calibrated flask with fly ash and water, removing entrapped air, and calculating the relative density based on mass–volume relationships. The obtained value confirms the lower density of fly ash compared to cement.

The spherical morphology of fly ash particles improves packing characteristics and reduces inter-particle friction within the mix. Furthermore, the pozzolanic reaction between fly ash and calcium hydroxide results in the formation of additional C–S–H gel, thereby enhancing long-term strength and durability.

2.2.3. Silica Fume

Silica fume was incorporated as a micro-filler to improve matrix densification. The specific gravity determined using the pycnometer method was 2.23. Due to its extremely fine particle size, silica fume fills micro-voids between cement grains, leading to improved packing density and reduced permeability. Its inclusion refines the pore structure and contributes to enhanced compressive strength of the hardened composite.

2.2.4. Manufactured Sand

Manufactured sand conforming to Zone III grading was used as the primary fine aggregate. The specific gravity of M-sand was determined as 2.42. Bulk density was measured using the standard container method and was found to be 1700 kg/m³. Based on the measured bulk density and specific gravity, the porosity of the material was calculated as 29.8%.

The measured values indicate satisfactory packing characteristics and reduced void ratio. Proper grading of manufactured sand plays a significant role in maintaining strength, dimensional stability, and overall uniformity of the composite.

2.2.5. Construction and Demolition Waste (CDW)

Processed construction and demolition waste was incorporated as a partial replacement for natural fine aggregate to enhance sustainability. Sieve analysis was conducted in accordance with IS 383:2016 to determine particle size distribution. The oven-dried CDW sample was passed through standard sieves ranging from 4.75 mm to 75 µm, and cumulative percentage retained values were used to calculate the fineness modulus.

The fineness modulus was determined as 3.00, indicating relatively coarse grading. Based on IS 383:2016 classification, the material falls under Zone III. The percentage of fines passing the 75 µm sieve was found to be 2.5%, which is well within permissible limits. The relatively coarse grading and low fines content contribute to controlled water demand and improved dimensional stability within the cementitious composite.

2.2.6. Chemical Admixtures

Chemical admixtures were incorporated to improve the workability and stability of the cementitious composite without increasing water content. A superplasticizer was used to enhance flow characteristics and ensure uniform consistency. The dosage was adjusted based on the binder composition. The addition of superplasticizer improved particle dispersion within the mix, reduced internal friction, and enhanced overall fluidity. Proper dosage ensured better mixing, uniform distribution of fine materials, and improved consistency of the composite. However, excessive use may lead to instability or segregation; therefore, careful dosage optimization was necessary.

A viscosity modifying admixture (VMA) was also incorporated to enhance cohesiveness and internal stability. VMA increases the viscosity of the paste, thereby reducing segregation and bleeding. Its inclusion improved paste stability and ensured uniform distribution of solid particles throughout the composite, contributing to consistent fresh properties

2.2.7. Polypropylene Fibers

Polypropylene fibers were incorporated to enhance tensile resistance and control plastic shrinkage cracking. Fiber reinforcement improves crack-bridging capacity and reduces the propagation of microcracks in the hardened matrix. The inclusion of fibers contributes to improved ductility and post-cracking behavior without significantly affecting the density of the composite.

2.3. MIX PROPORTION

A fine-aggregate-based cementitious composite was developed through systematic laboratory proportioning and controlled mixing procedures. The objective of the mix development was to obtain a homogeneous, dense, and mechanically stable cementitious matrix using selected sustainable and performance-enhancing materials.

Manufactured sand was used as the sole fine aggregate in the composite, with a total fine aggregate content of 1241 kg/m³. The binder system consisted of Ordinary Portland Cement, fly ash, and silica fume, which were collectively treated as a composite binder to enhance particle packing, microstructural refinement, and long-term strength development. The total binder content adopted in the developed mix was 827 kg/m³, ensuring sufficient paste volume for effective coating of fine aggregates and fiber reinforcement. The detailed control mix proportions are presented in Table 1.

A water–binder ratio of 0.32 was selected to achieve a balance between workability and matrix densification. This ratio was chosen to allow adequate hydration of binder materials while minimizing capillary porosity, thereby contributing to improved strength and durability characteristics. To maintain workability at the selected water–binder ratio, a superplasticizer was incorporated. The superplasticizer improved dispersion of binder particles, reduced internal friction within the mix, and enhanced overall flow characteristics without increasing water demand. This ensured uniform mixing and consistent fresh-state behavior of the composite.

Polypropylene fibers were included as discrete reinforcement within the matrix to improve tensile resistance and control plastic shrinkage cracking. The fibers enhance crack-bridging capacity and contribute to improved post-cracking performance in the hardened composite without significantly affecting density.

Table 1: Control mix proportion

MATERIAL	**WEIGHT** (Kg/m3)
Binder	827
Sand	1241
Water	232
Fiber	0.15% of Binder
Super Plasticizers	1% of Binder

The mix was prepared under controlled laboratory conditions to ensure uniformity and repeatability. Initially, the dry materials, including sand and the composite binder, were thoroughly blended to achieve homogeneous distribution. Water premixed with the superplasticizer was then gradually introduced while mixing continuously to ensure proper dispersion of particles. Finally, fibres were added carefully to prevent agglomeration and to achieve uniform distribution throughout the matrix. The developed composite exhibited adequate cohesiveness and uniform consistency during mixing. The systematic proportioning approach ensured compatibility among binder materials, fine aggregate, chemical admixture, and fibre reinforcement. The adopted mix formulation reflects a balanced integration of conventional and supplementary cementitious materials aimed at enhancing sustainability while maintaining satisfactory mechanical performance.

2.3.1. Construction Demolition Waste replacement in fine aggregate

To investigate the potential utilization of recycled materials in the developed composite, manufactured sand was partially replaced with processed construction and demolition waste (CDW) at incremental levels of 5%, 10%, 15%, 20%, 25%, 30%, 35%, and 40% by weight of fine aggregate. The detailed mix identification and corresponding replacement percentages are presented in Table 2.

The replacement was carried out systematically while maintaining all other mix parameters constant, including total binder content, water–binder ratio, superplasticizer dosage, and fibre content. This approach ensured that the influence of CDW incorporation could be evaluated independently without interference from other variables.

Table 2: CDW replacement in control mix proportion

Mix No.	MIX 1	MIX 2	MIX 3	MIX 4	MIX 5	MIX 6	MIX 7	MIX 8
Percentage Replacement	5%	10%	15%	20%	25%	30%	35%	40%

3. COMPRESSIVE STRENGTH TEST

For conducting the compression test, concrete cubes of each mix proportion were cast, cured under standard conditions (as shown in Fig.1 and Fig.2), and tested using a compression testing machine. The maximum load at failure was recorded (as illustrated in Fig.3), and the compressive strength was calculated. The results obtained were used to evaluate the strength performance of each mix.

Fig 1: Mix prepared and casted

Fig 2: Water curing

Fig 3: Compressive strength test

4. RESULTS AND DISCUSSION

The developed composite was evaluated through 28-day compressive strength testing to assess its mechanical performance. The control mix was first examined to establish a reference for comparison. The optimized composite, prepared with manufactured sand as the sole fine aggregate and a composite binder system at a water–binder ratio of 0.32, achieved a 28-day compressive strength of 44.34 N/mm². This strength reflects effective particle packing and adequate matrix densification achieved through systematic mix proportioning. The combined use of cement, fly ash, and silica fume contributed to microstructural refinement through filler effects and pozzolanic reactions, leading to improved bonding within the matrix.

The superplasticizer ensured proper dispersion of binder particles without increasing water demand, while polypropylene fibres enhanced crack resistance and internal stability. The overall performance of the control mix demonstrated balanced workability and mechanical strength, establishing it as the optimum reference composition.

To examine the effect of recycled fine aggregate on strength performance, manufactured sand was partially replaced with construction and demolition waste (CDW) at incremental levels ranging from 5% to 40%. The 28-day compressive strength results indicated that partial replacement up to 10% resulted in a slight improvement in strength, with values of 43.44 N/mm² at 5% and 44.66 N/mm² at 10% replacement. This marginal increase may be attributed to improved particle packing and internal friction characteristics contributed by the processed CDW particles. The comparative variation in compressive strength for all mixes is presented in Fig. 4.

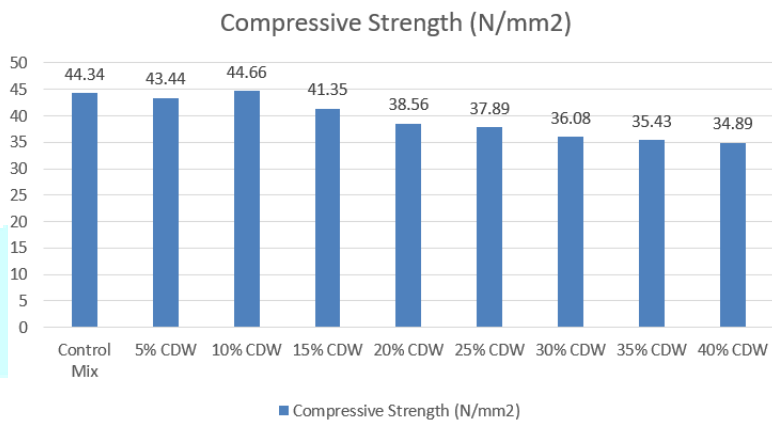

Fig 4: compressive strength

Beyond 10% replacement, a gradual reduction in compressive strength was observed. The strength decreased to 41.35 N/mm² at 15% replacement and further declined progressively to 38.56 N/mm², 37.89 N/mm², and 36.08 N/mm² at 20%, 25%, and 30% replacement levels, respectively. At higher replacement percentages of 35% and 40%, the compressive strength reduced to 35.43 N/mm² and 34.89 N/mm². The decreasing trend at higher CDW contents may be associated with increased porosity, weaker interfacial transition zones, and the comparatively lower strength characteristics of recycled aggregate particles.

Overall, the results indicate a clear relationship between CDW replacement level and compressive strength, highlighting the sensitivity of mechanical performance to fine aggregate substitution.

5. CONCLUSION

The study successfully developed a sustainable fine-aggregate-based cementitious composite through systematic mix proportioning and material characterization. The optimized control mix, prepared with a composite binder system and a water–binder ratio of 0.32, exhibited satisfactory cohesiveness and mechanical performance. The incorporation of superplasticizer improved workability, while polypropylene fibres enhanced crack resistance and matrix stability.

Partial replacement of manufactured sand with construction and demolition waste (CDW) demonstrated that replacement levels up to 10% maintained or slightly improved 28-day compressive strength. Beyond this level, a gradual reduction in strength was observed with increasing CDW content, primarily due to the inherent characteristics of recycled aggregate particles.

Overall, the results confirm that controlled incorporation of CDW as a partial fine aggregate replacement is technically feasible and supports sustainable construction practices without significantly compromising structural performance.

6. REFERENCE

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