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A Systematic Literature Review: 3D Printing Concrete with Industrial Waste as Cement Replacement Materials

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ABSTRACT

The emerging area of 3D printing concrete (3DPC), which uses industrial waste product to substitute cement, is examined in this comprehensive overview of the research literature. The article summarizes recent studies on the use of several industrial by-products as partial or complete substitutes for Ordinary Portland Cement (OPC) in 3DPC compositions, including fly ash, slag, silica fume, and building and deconstruction debris. It looks at how these substitutions affect 3DPC's endurance, mechanical performance, rheological characteristics, and sustainable development. In order to give academics and practitioners in the fields of construction, materials science, and environmental sustainability a thorough understanding, the study also highlights important issues and potential avenues for further investigation in this multidisciplinary field.

KEYWORD: 3D Printing Concrete, Industrial Waste, Cement Replacement Materials, Properties of 3D Printing concrete.

INTRODUCTION

Extensive investigation and development aimed at creating sustainable building products and building techniques has been sparked by the growing environmental issues related to the construction sector [1-3]. The manufacturing of ordinary Portland cement (OPC), the main binder in standard concrete, contributes significantly to the industry's environmental impact [4-6]. Carbon dioxide (CO_2), a significant greenhouse

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gas, is released into the environment during the energy-intensive cement manufacture procedure [7-9]. Cement manufacture is thought to be responsible for around 8% of the world's anthropogenic CO_2 emissions [10-12]. This concerning figure highlights the pressing need for novel building techniques and substitutes cementitious compounds that might lessen the built environment's negative environmental effects [13-16].

With the introduction of 3D printing, commonly referred to as additive production, the construction sector is going through a technical revolution concurrent with the push for environmentally friendly materials. With the ability to create intricate shapes, personalize building elements, minimize waste products via accurate deposition, and facilitate on-site construction, 3DPC offers an important change in the field of construction [17]. This method creates three-dimensional structures using software models by depositing a particularly developed concrete combination layer by layer. Beyond only automation, 3DPC proposes to open up novel design options, improve the productivity of construction, and encourage resource optimization.

Industrial waste products are being investigated as cement substitutes [18-21] in 3DPC due to the confluence of modern production technology and environmentally friendly components. Construction and demolition waste (CDW), fly ash [22, 23], silica fume [24, 25], ground granulated blast furnace slag (GGBS) [26, 27], sugarcane bagasse ash [28-31], wheat straw ash [32-35] and other industrial by-products are produced in enormous amounts worldwide and can present difficult disposal issues. Nonetheless, a large number of these waste materials have pozzolanic or cementitious qualities that make them appropriate for use as supplemental cementitious materials (SCMs) in the construction industry. These SCMs can either completely or partially substitute OPC in 3DPC formulations, lowering the concrete's greenhouse gas emissions, keeping waste out of landfills, and perhaps improving the digitally created structures' effectiveness [36].

The present level of research on the use of waste from industry as cement substitutes in 3DPC is explored in this comprehensive research review. It seeks to give a thorough summary of the different kinds of waste from industry that have been studied, their effects on the rheological characteristics of 3DPC combinations, their effect on the durability and mechanical behaviour of digitally printed concrete components, and their role in contributing to the construction technique's overall ecological responsibility. This overview seeks to educate scientists, engineers, and policymakers regarding the opportunity of 3DPC with industrial byproducts to shift the building construction sector to achieve a more environmentally friendly and energy-efficient future by assembling the body of existing knowledge, highlighting emerging study directions, and identifying key challenges.

METHODOLOGY

The defined parameters were followed in conducting this comprehensive review of literature. Significant academic research databases, such as Scopus, Web of Science, and Google Scholar, were thoroughly searched using terms like "3D printing concrete," "additive manufacturing concrete," "industrial waste," "cement replacement," "supplementary cementitious materials," "fly ash," "slag," "silica fume," and

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"construction and demolition waste." In order to capture the latest developments in this quickly developing topic, the search was focused on peer-reviewed publications produced between 2015 and 2023. A comprehensive synthesis of the results was carried out after publications were filtered according to their pertinence to the subject.

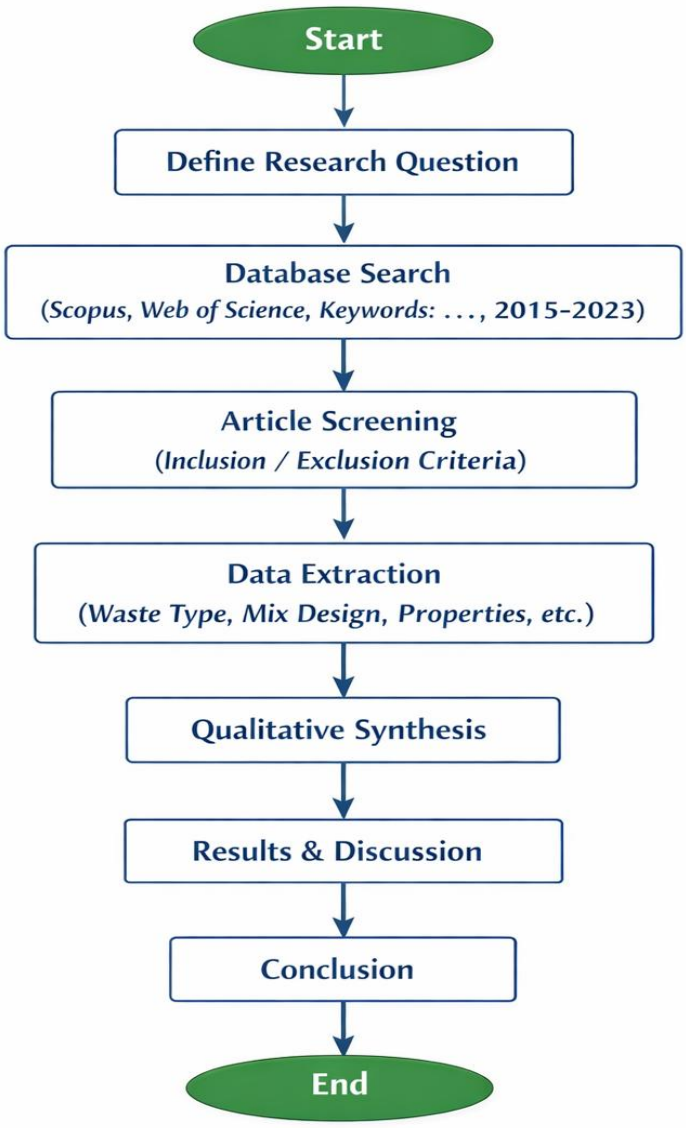

Figure 1: Flow Diagram for this Study

RESULTS AND DISCUSSION

Types of Industrial Waste Utilized

The best-known waste products that have been studied as SCMs in 3DPC are as follows:

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- **Fly Ash:** A common byproduct of burning coal, fly ash has pozzolanic qualities. Workability and long-term strength can be enhanced by including it into 3DPC [37].
- **Ground Granulated Blast Furnace Slag (GGBS):** This iron-producing byproduct has latent hydraulic qualities. It can improve 3DPC's durability and lower the heat of hydration [38].
- **Silica Fume:** A byproduct of the manufacturing of silicon metal and ferrosilicon alloys, silica fume greatly increases the structural integrity and decreases the permeability of concrete. Nevertheless, the rheology of 3DPC mixes may be impacted by its large surface area [39].
- **Construction and Demolition Waste (CDW):** Cementitious ingredients or virgin aggregates could be partially substituted with recycled concrete aggregate made from CDW. This tackles depletion of resources as well as waste management [40].

Impact on Rheological Properties

For layer-by-layer deposition to be effective, 3DPC's rheological characteristics such as workability, buildability, and extrudability are essential. These characteristics can be greatly impacted by the addition of industrial wastes:

- **Workability:** Water consumption can be raised by fine SCMs such fly ash and silica fume, which may make workability worse. Nevertheless, a thixotropic characteristic that is advantageous for buildability can also result from their pozzolanic processes [37].
- **Buildability:** Printable components must be able to support one another without deforming too much. SCMs can affect buildability by influencing yield stress and setting time. It is frequently required to optimize the mix design using suitable admixtures [36].
- **Extrudability:** The distribution of particle sizes and viscosity have an impact on how easily the combination of concrete particles is capable of being injected and ejected via the nozzle. Rheology-modifying chemicals or mix percentage modifications may be necessary for certain industrial wastes [39].

Mechanical Performance

For applications in construction, 3DPC's mechanical qualities such as its tensile, flexural, and compressive strengths are crucial.

- **Compressive Strength:** Owing to the pozzolanic and latent hydraulic processes, numerous investigations show that substituting fly ash or GGBS for some OPC can result in equivalent or even better compressive strength, especially at a later stage [38]. On the other hand, early-age strength may be reduced by excessive levels of substitution or inappropriate particle packing.
- **Interlayer Adhesion:** The produced component's structural integrity depends on the stability of the link between produced layers. To achieve good interlayer adhesion, SCM-influenced hydration kinetics and rheological characteristics are crucial [17].

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Durability and Environmental Sustainability

The use of industrial wastes in 3DPC offers significant environmental benefits by reducing CO_2 emissions and diverting waste from landfills.

By lowering carbon dioxide released and keeping trash out of landfills, the incorporation of waste from industries in 3DPC has a major positive impact on the planet.

- **Decreased Carbon Footprint:** Concrete's embodied carbon may be significantly reduced by substituting SCMs for OPC [41].
- **Increased Durability:** Certain SCMs, including silica fume and GGBS, can increase concrete's lifespan by strengthening its resistance to harsh conditions such sulfate assault and chloride penetration [38].
- **Resource Conservation:** Using recycled resources, such as CDW, lessens the environmental effect of excavation and collecting raw materials while also conserving natural resources [40].

Challenges and Future Directions

Despite the encouraging developments, a number of obstacles still exist:

- **Variability of Waste Materials:** Obtaining predictable outcomes in 3DPC may be difficult because to the variable quality and characteristics of industrial garbage materials. Pre-treatment techniques and standardization are required.
- **Optimization of Mix Designs:** It takes a lot of study and frequently the integration of complex admixtures to create reliable mix designs that combine mechanical performance, rheological needs, and sustainability objectives.
- **Long-Term Performance:** To completely comprehend the long-term performance and durability of 3DPC containing industrial garbage under varied environmental circumstances, more study is required.
- **Scalability and Standardization:** For 3DPC with SCMs to be widely used, industry standards and efficient manufacturing procedures must be developed.
- **The incorporation of Recycled Aggregates:** Investigation is still being done on how to successfully integrate recycled aggregates from CDW into 3DPC while preserving printability and mechanical qualities [40].

CONCLUSION

Sustainable building methods might be further advanced by including industrial waste products as cement substitutes in 3D printed concrete. According to study, elements including fly ash, GGBS, silica fume, and recycled CDW may be efficiently used to create 3DPC with desired mechanical, durability, and rheological qualities while also lessening its effect on the surrounding environment. To enable the general application of this cutting-edge technology, additional investigation is necessary to solve issues with material deviation, mix design optimization, long-term performance, and standardization.

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