3D-Printable Concrete for Energy-Efficient Buildings

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Contributor: Manideep Samudrala, Syed Mujeeb, Bhagyashri A. Lanjewar, Ravijanya Chippagiri, Muralidhar Kamath, Rahul V. Ralegaonkar

Rapid construction with an energy-efficient approach is a major challenge in the present construction industry. Cement, a carbon-intensive material, is mainly used in the construction industry and hence increases the sector's carbon footprint on the environment. Raw material characteristics play an important role in defining the physical, chemical, and mechanical properties of 3D concrete. Raw material characterization includes finding particle size distribution, specific gravity, density, and morphology.

Keywords: 3DCP ; 3D-Printable Concrete ; Energy-Efficient Buildings

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1. Introduction

In this era of rapid urbanization, faster construction has become a major issue. Three-dimensional concrete printing (3DCP) utilizes a 3D printer that allows concrete to print in layers and in the required geometry. Three-dimensional concrete has greater potential value in the present construction industry [1]. It helps in building structures without the use of formwork and thereby reduces the construction cost. Three-dimensional concrete printing helps to complete construction with high accuracy and low-cost building components, and it facilitates easy remote-area construction [2]. In recent years, 3DCP has gained attention in the global construction sector due to its ability to facilitate faster construction. This technology helps in the reduction of the labor force and of wastage during the construction phase. It directly reduces the total cost of construction by making the construction sustainable [3][4].

An important aspect of 3D concrete printing is the machine that prints the structure. A 3D printer uses a Cartesian coordinate system for printing the structures. A printer has been designed with a mini bed size of 1 m × 1 m × 1 m [5]. The entire motion of the printer is controlled using software that includes a G-code as input, which controls the nozzle motion.

The 3D printer has a gantry crane to which the nozzle is attached. Concrete is allowed to fall through this nozzle [6]. An Italian civil engineer built a D-shaped 3D printer that prints layers of a thickness of 5–10 mm [7]. The extrusion nozzle plays an important role in determining the shape stability of the printed concrete. Nozzles have different shapes such as circles, rectangles, U-shapes, and inverted U-shapes [8]. These move with different speeds ranging from 10 mm/s to 100 mm/s and it has been demonstrated that the nozzle with a 15 mm diameter releases concrete smoothly [9]. A screw-type nozzle is preferred to control the extrusion speed [10]. For better consistency, the nozzle lift should be the same as the thickness of the printed layers [11]. The layer width is increased linearly with increased extrusion velocity, and printability is increased at lower printing speed.

Larger quantities of cement are used in 3D concrete to accommodate the strength lost due to the elimination of coarse aggregate and to maintain rheology. This has led to an increase in energy content and the carbon footprint on the built structure. Energy efficiency and thermal performance also play a major role in the design of concrete. Wall structures play a key role in the energy efficiency of a building or structure. Three-dimensional concrete printing is mainly used as a walling material, owing to which thermal performance is a major issue in the design of 3D concrete. Consequently, there is a need to incorporate supplements for cement in the concrete that reduce the quantity of cement while maintaining the necessary thermal comfort [12][13]. Ground granulated blast furnace slag (GGBS), fly ash, and silica fume are some known industrial byproducts that are used as a partial replacement for cement [14][15]. Different tests regarding the physical and chemical properties of the materials that are used have been performed [16][17]. Based on the results obtained, the usage of these materials in the mix is controlled [18]. The addition of cementitious supplements is performed stage-wise and their effect on the physical properties of the concrete is noted down. A mega-scale 3D printing system is required to print the concrete and to check its different properties.

The present literature focuses on the study of the partial substitution of cement with cementitious supplements such as GGBS, fly ash, and silica fume along with the 3D printing system and its nozzle requirements. The impact of rheological, physico-mechanical, and thermal properties, along with the technical challenges faced, is studied to check the suitability of 3D-printable concrete in energy-efficient buildings.

2. Rheological Properties of Fresh Concrete

Another key aspect in the success of the 3D-printable concrete lies in its fresh concrete properties. The fresh concrete that is taken for printing should possess rheological properties such as pumpability, extrudability, printability, thixotropy open time, buildability, and setting time [4]. Different tests are performed to find the rheological properties of fresh concrete. As there is no standard procedure for testing these rheological properties, results are obtained by using any appropriate method.

Flowability is the property of fresh concrete that allows the material to move smoothly from the extrusion nozzle. A flowability test is performed by using flow table apparatus, and the flow value is noted. Segregation or bleeding creates difficulty in printing the concrete. Stiff concrete creates an extra demand on the pump, which causes failure in the machine. From the obtained results, it is known that the material with a higher yield stress has less flowability [19]. Flowability also depends on the presence of the optimum aggregate content in the concrete [20].

Extrudability is the ability of the fresh concrete to pump out from the nozzle smoothly without clogging the nozzle. It is also defined as the ability of the concrete to print continuously without any breakage [21][22]. Printing becomes easier only if the concrete is sufficiently extrudable.

Buildability is defined as the ability of fresh printable concrete to exist in the form of bonded layers that bear the load of the newly printed concrete without collapsing [22][23]. It can be related to the green strength of the concrete. The higher the green strength, the higher the ability of the fresh concrete to bear the load, which directly increases its buildability. The test establishes the number of layers that can be printed without collapse. The buildability of 3DCP is improved by using different kinds of admixtures and by active rheological control [24].

Printability is defined as the ability to design the end product or the structure to its desired shape and architecture [25]. It is the difference in the original design and the end geometry that is obtained from printing. Three-dimensional concrete printing is highly prized for its flexibility in creating complex geometries that are difficult to obtain using conventional methods [26][27].

Thixotropy open time (TOT) is defined as the time taken to clog the nozzle from extruding the concrete [28]. It is the time taken by the concrete to lose its extrudability property. It indirectly depends on the setting time of the concrete: the higher the setting time, the higher the thixotropy open time.

Studies show that there is no relationship between yield stress and thixotropy. A minimum of 10,000 N mm rpm of thixotropic value is necessary for 3DCP [29]. All the above rheological properties that are studied are interlinked with the mix design of the concrete.

3. Energy Efficiency of 3DCP

Energy efficiency has become an important factor in the construction industry. It is necessary to make construction sustainable and maintain a thermally comfortable environment. Achieving this with the help of thermal performance is discussed further.

Thermal Performance

Thermal performance is a key factor in energy-efficient buildings, where maintaining thermal comfort is essential. It plays a vital role in 3DCP, as walling material constitutes a majority of the structure. A small commercial building model was demonstrated for 3DCP to show its energy-saving potential [30].

Thermal comfort can be improved by reducing the thermal conductivity of the material, which depends on various factors such as aggregate type, porosity of concrete, water-to-cement ratio, and density. Heat transfer can be reduced by using lightweight concrete [31]. The thermal conductivities of concrete in a saturated state have higher values than those of concrete in dry state due to the high heat diffusivity of water [32].

The thermal conductivity of concrete is measured using the steady-state box method, the steady-state hot plate method, and the transient hot wire method. In the steady-state box method, the device contains a hot box and a cold box with concrete inserted between them. The thermal conductivity measurement is achieved by calculating the difference in the air temperature between the boxes. A guarded red-hot plate is used in the steady-state hot plate method, with a concrete sample between two red-hot plates. The rate of heat flow and the temperature difference between them provide a measurement of the thermal conductivity. In the hot wire technique, the thermal conductivity is found by noting down the temperature at a distance from the hot wire.

The usage of GGBS in concrete resulted in a slight increase in the thermal conductivity of the concrete [33]. Fly ash usage in concrete helps in its reduction [34]. The thermal conductivity is reduced when cement is replaced with silica fume [35]. The usage of polyurethane in 3DCP walls reduced energy by 9500 kW per year more than the one without any insulation for a built-up area of 1200 m^2 and a wall thickness of 100 mm [36]. To improve the thermal performance of conventional concrete, insulation materials such as expanded polystyrene (EPS), polyurethane, and extruded polystyrene (XPS) with thermal conductivities ranging from 0.02 to 0.04 W/mK are added to the mix [37]. The application of these materials in 3DCP helps in enhancing the thermal performance of the concrete by reducing its thermal conductivity. The usage of phase change materials also helps in reducing the thermal conductivity of the wall [27].

Reducing thermal conductivity helps to attain thermal comfort in the structure. This results in a reduction in the cooling load on air conditioners, thereby reducing the electricity consumption and, in turn, lowering the burning of fossil fuels.

4. Life Cycle Assessment (LCA) of 3DCP

Life cycle assessment (LCA) is a tool used to discover the environmental impact of product manufacturing from cradle to grave. It helps to identify the sustainability aspect of products [38]. Defining the goal and scope sets out the intended purpose of study. The life cycle inventory analysis deals with the input of materials used in different stages of construction. The life cycle impact assessment recognizes the potential environmental impacts, and the final stage evaluates the results. Global warming potential is the most assessed indicator, measured in kg CO_2 eq., which indicates the carbon footprint of the end product [39]. Three-dimensional concrete printing helps to make sustainable construction [40]. It is an automated construction with less wastage of material, a shorter construction time, and reduced greenhouse gas (GHG) emissions [30]. The additive manufacturing technique, also referred to as 3DCP, constructs the building in layers with high precision and accuracy. It helps in reducing the environmental impact [41]. Cement plays a significant role in the environmental impact of the concrete, which can be reduced by using cement supplements such as GGBS, silica fume, and fly ash [42]. As 3DCP minimizes waste generation to a greater extent, waste treatment of 3DCP is lower than in conventional concrete [43]. Optimizing the distribution of materials reduces the environmental impact by 15% [44].

5. Costing of 3DCPs

Cost is a significant factor to consider in any construction project, and this also applies to 3DCP. The feasibility of 3DCP products is determined by comparing their cost to commercially available products. The cost calculation of 3DCP structures is complex and involves considering various costs in all stages of construction [45]. This includes considering the cost of printing and assembly, which can be higher for 3DCP than for traditional construction methods. The initial cost of 3DCP is generally higher, and the demand for 3DCP products in the market is low. The cost of 3DCP is also affected by social changes, making cost calculation more complicated.

Studies have shown that the cost of prefabricated houses constructed using 3DCP in Japan is 8% higher than that of their available counterparts [46]. However, in Shanghai, a building constructed using 3DCP was more economical than a conventionally constructed building [47]. This inconsistency in cost makes it difficult to determine whether 3DCP is economical or not.

In India, an 1100 sq. ft. building is constructed using 3DCP for a cost of INR 23 lakhs, and various internet sources suggest that 3DCP costs approximately INR 5000–7000 per m^3 of concrete. The cost of wall components can be higher due to the cost of printing materials [48], but overall costs can be reduced by minimizing the cost of manpower, as the entire 3DCP process is automated. However, the use of software components can also increase the cost of 3DCP [49].

In conclusion, a clear empirical formula is needed for the accurate cost calculation of 3DCP to determine its economic feasibility compared to traditional construction methods.

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