WEP Warwick Evans Publishing

Transactions on Engineering and Technology Research
ISSN: 2960-1797, eISSN: 2960-2246 | Volume 4
ACEGE 2024

Mechanical Properties of 3D Printed Concrete and its Application in Civil Engineering

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Abstract. Rapid urbanization worldwide is placing higher demands on the efficiency and quality of the construction industry. Three-dimensional Printed Concrete (3DPC) technology, with its digital design and additive manufacturing processes, offers a promising avenue for advancement. This paper discusses the potential and challenges of 3DPC in terms of mechanical properties, environmental impact and economic benefits. The technological process of 3DPC, its advantages over traditional concrete, and its optimization in key mechanical properties are studied. The environmental benefits of Three-dimensional (3D) printing technology, including reduced construction waste, material savings and lower energy consumption, are also analysed. In addition, the economic advantages of 3D printing technology are described, including labour costs, material costs and construction efficiency. The conclusion emphasizes that 3DPC technology has substantial advantages in improving construction efficiency and realizing complex design. Case studies such as Qingpu Park in Shanghai and the Museum of the Future in Dubai have further demonstrated the practicality and innovative potential of 3DPC technology. The research of 3DPC technology has important theoretical and practical significance for promoting technological innovation and realizing sustainable development in the construction industry.

Keywords: 3D Printed Concrete; Additive Manufacturing Process; Mechanical Property Optimisation; Environmental Benefit Assessment; Economic Cost Analysis.

1. Introduction

In recent decades, the process of urbanisation has resulted in a notable expansion of infrastructure construction. Concurrently, the repair of existing building structures has become an increasingly challenging and difficult undertaking. Concrete is one of the most widely used materials in the civil engineering industry, and it is required to possess both high strength and superior workability. Three-dimensional printing first emerged in the industry in 1984, at a time when it was perceived as a costly and intricate technology. Nevertheless, with the advent of increased modernisation, three-dimensional (3D) printing technology has been perfected by scientists and is now being utilised in a multitude of industries, including healthcare and manufacturing, amongst others [1]. In the contemporary era, the concept of digital manufacturing is understood to entail the utilisation of digital models for the application and production of materials. It is posited that 3D printing represents a technology that will transform the manufacturing industry and play an indispensable role in the third technological revolution. In particular, in a society where the reduction of energy consumption, the enhancement of industrial efficiency and the minimisation of environmental pollution are of paramount importance, 3D printing technology is emerging as a significant avenue for innovation and sustainable development within the civil engineering industry. Despite the advent of 3D printing technology, the reliability of 3D Printed Concrete (3DPC) for practical applications remains a topic of reasonable assessment. Accordingly, this paper is dedicated to an in-depth examination of 3DPC, with a particular emphasis on the mechanical properties of 3DPC, including compressive properties, tensile properties, toughness, and rheological properties. A further analysis of the 3DPC is conducted by comparing its properties with those of conventional silicate concrete. The safety and reliability of the 3DPC are then assessed in accordance with the relevant technical standards and specifications. Meanwhile, in accordance with the principles of sustainability, the entire preparation and construction process of 3DPC is subjected to scrutiny. The associated carbon emissions and energy consumption are discussed, and the specific efficacy is considered from an economic standpoint. Subsequently, the paper will provide a detailed examination of the outcomes of 3D printing applications, with a particular focus on the case study of Shanghai Qingpu Park. This will facilitate an evaluation of the tangible impacts and potential challenges associated with the technology in question. In conclusion, a comprehensive assessment of 3DPC as a material is presented, along with an analysis of its future prospects.

2. Overview of 3DPC

3DPC represents a novel, contemporary approach to building materials technology. Primarily based on computer modelling and utilising additive construction techniques, it involves the stacking of concrete materials in layers, thereby directly facilitating the construction of modules. Firstly, engineers must utilise mathematical modelling to complete the three-dimensional digital modelling of the product with the assistance of computer software. The model is meticulously detailed to encompass the internal structure of the concrete, its geometry, and to satisfy specific functional requirements. It is then transformed into a print-ready file, which translates the information into layers for printing. Subsequently, the requisite raw materials are loaded into the 3D printer, the constructed model is identified by the printer, and the machine is operated to ensure precise completion of the manufacturing process. Following the printing process, the engineer may be required to undertake preliminary treatment of the material, including surface finishing, inspection, maintenance and preliminary enhancement treatment, in order to achieve a fully completed 3D printing process. The fabrication process of a specific 3DPC product is illustrated in Fig. 1.

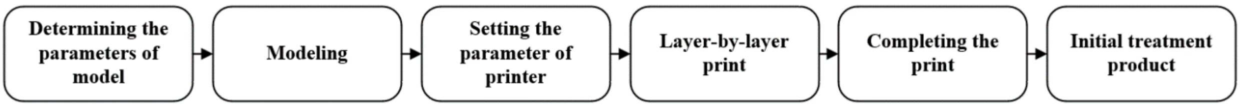

Figure 1. The flowchart of 3DPC production

The most crucial element of the 3DPC production process is the use of additive manufacturing. In contrast to the conventional subtractive manufacturing approach, additive manufacturing involves the deposition of material in layers to create the object. The desired material is incorporated into each layer, and the position and quality of the material are regulated by precise incisions through the 3D printer's nozzle, in addition to stacked deposition. The layer-by-layer construction methodology enables the fabrication process to be conducted without the necessity for external support. The concrete materials employed in 3D printing are distinct from those used in traditional concrete. To facilitate the layer-by-layer stacking inherent to this fabrication process, 3DPC typically exhibits good fluidity, enabling the raw concrete material to flow smoothly and rapidly through the print nozzle without causing clogging. It is essential that the concrete maintains fluidity while also exhibiting satisfactory viscosity, ensuring that the time between deposits is sufficient to generate the requisite mechanical strength for stacking. The realisation of these properties often necessitates the incorporation of specific chemical additives into the 3D printing process, including concrete flow modifiers and coagulation regulators. Additive manufacturing represents a highly efficient and promising construction technology in the civil engineering field, although it remains in its infancy in terms of practical implementation. Nevertheless, scientists have already demonstrated the feasibility of producing wall elements in a laboratory setting [2]. The distinctions between 3DPC and the conventional fabrication methodology are illustrated in Table 1.

Table 1. Differences between traditional methods and 3D printing technology

Differential aspects	Conventional Concrete	3DPC
Construction method	Built with reduced materials Low degree of automation	Built with additive materials; High degree of automation
Materials	Standardised aggregates, cement, asphalt, reinforcing steel, etc.	Wide range of materials; special formulations; precise material usage; high material utilisation
Design variability	Easy to realise more regular geometries, but difficult to realise in complex structures	Realisation of complex geometries and details; increasing the freedom of construction; more creative and innovative
Construction efficiency and costs	Consuming a lot of manpower and material resources; long construction period	Lower construction cycle; larger initial research investment funds; saving the traditional construction process of labour costs and time costs; the total cost of construction is lower.

3. Mechanical Properties of 3DPC

Compressive strength represents a pivotal indicator of the capacity of concrete materials to withstand axial pressure. The compressive strength of traditional concrete is primarily influenced by the water-cement ratio of the raw material, the type of aggregate, and the compactness of the concrete. In contrast, the compressive strength of 3DPC is affected by its distinctive layer-by-layer stacking method. The compressive strength of 3DPC is closely associated with the printing path, printing speed, and interlayer bonding strength during fabrication [3]. A reduction in printing speed during the fabrication process can facilitate increased contact time between the layers, thereby enhancing the degree of bonding between the concrete constituents. This, in turn, increases the bonding force between the layers and the overall compressive performance. In their investigation of the compressive properties of 3DPC, several scholars have conducted experimental studies to ascertain the impact of various factors on compressive strength. For instance, Fan et al. [4] examined the impact of these variables on the compressive performance of 3DPC by modifying the printing path and layer thickness. Their findings indicated that the printing path and the thickness of each concrete layer can markedly enhance the compressive strength at a specific layer degree.

Furthermore, the rheological properties of the material exert a significant influence on its compressive strength, as the rheological properties directly determine the quality of extrusion and deposition of the material during the printing process [5]. The special process of 3DPC requires freshly mixed concrete to have good fluidity and hardening ability, which differs from the traditional concrete. This is the key to achieving successful printing, collectively referred to as the printability. When the rheological properties do not meet the requirements of printability, the printing process is prone to failure. For example, if fibres or clays are not added to the raw materials used, which in some cases can lead to poor rheological properties and failure of the printing process. A substantial body of research has demonstrated that the incorporation of specific additives can markedly enhance the rheological properties of the material. For instance, Zhao et al. [6] investigated the impact of carbon nanotubes on the rheological characteristics of concrete. Their findings indicated that the yield stress of 3DPC exhibited a positive correlation with the concentration of carbon nanotubes, suggesting that this additive can effectively improve the material's rheological properties.

The adhesive strength, also termed interlayer bonding strength, represents a pivotal performance indicator in the investigation of the mechanical properties of 3DPC, which is constructed through a process of layer-by-layer stacking. The adhesive strength between each layer exerts a decisive influence on the mechanical properties of the overall structure and is directly correlated with the safety of the concrete structure. The adhesion strength is a determining factor in whether peeling or crack formation occurs between the different printed layers when subjected to external forces. High viscous strengths help to ensure structural integrity and increase durability, whereas low viscous strengths may result in the detachment of layers, which in turn reduces the safety and service life of the structure. The base strength of 3DPC is influenced by its basic structure, while the strength of each concrete layer is influenced by a number of factors, including the print path, the speed of the print, and the interval between prints of each layer. Wolfs et al. [7] indicated that the specific three process parameters had a significant effect on the mechanical properties of the product concrete. Furthermore, the interval time between layers was identified as having a significant impact on the curing process of the concrete. As the interval time increases, the fluidity of the concrete surface of the previous layer gradually decreases, leading to significant changes in the concrete surface. These changes have a significant impact on the adhesive properties of the layers. Furthermore, Silverbrand et al. [8] identified at least thirteen factors affecting the tensile and shear bond strengths of concrete with respect to the basic properties of the concrete, the quality of the surface, layer arrangement, and curing process, as well as a number of other human factors. Furthermore, the impact of concrete surface texture on internal shear is equally noteworthy. In 2017, Kazemian et al. [9] conducted a comprehensive investigation into the interlayer surfaces of 3DPC, wherein they discovered that an enhancement in micro-surface roughness markedly enhances the interlayer adhesive properties. The interlayer can be treated during the printing process in ways that enhance its adhesive properties. For instance, bonding agents can be sprayed on the interlayer, or the interlayer can be polished mechanically. These treatments increase the contact area and friction between the layers, which improves the interlayer's adhesive strength.

It is of paramount importance to conduct comprehensive safety and reliability assessments prior to the implementation of 3DPC in actual building projects. Such assessments have a significant impact on the design and construction of the building structure, as well as on the safety and longevity of the building during its intended use. The primary consideration in ensuring the safety of concrete buildings is their structural integrity. Given that 3DPC is assembled in layers, the strength of the bond between layers has a direct impact on the overall structural integrity. Insufficient bond strength between a layer and the previous or next layer may result in interlayer slippage, cracking, or even the collapse of the building under the influence of external forces. Furthermore, in the context of large-scale construction, it is of paramount importance to exercise strict control over the materials employed in order to guarantee their consistent quality. In addition, appropriate measures must be implemented to prevent the occurrence of defects such as voids and cracks. Concurrently, factors such as the shrinkage and deformation characteristics of the material must be considered at the design stage, and the negative effects of these factors must be minimised by optimising the design. Furthermore, consideration must be given to the durability of the material when it is in use over an extended period of time. For instance, freeze-thaw resistance can be enhanced through the incorporation of specific additives, while chemical erosion resistance necessitates the utilisation of raw materials exhibiting superior corrosion resistance and the application of protective coatings. Pacheco-Torgal et al. [10] have conducted extensive research into the corrosion resistance of 3DPC in a variety of chemical environments, including acid, alkali and salt.

4. Environmental Impact and Economic Performance Analyses

The advent of 3DPC has transformed the construction industry. Its performance in a number of aspects, including energy consumption, carbon emissions, cost and efficiency, offers significant research value and potential for application. From an energy consumption perspective, 3DPC technology draws upon a multitude of energy sources. The equipment must operate continuously for an extended period during the printing process, resulting in a considerable consumption of electricity, which represents a significant source of energy expenditure. Furthermore, the process of preparing the concrete material, which encompasses mixing, conveying and handling, also results in energy consumption. In the case of projects that necessitate supplementary surface treatment or structural reinforcement, the post-processing phase also gives rise to further energy consumption. Although 3DPC technology is highly effective in reducing construction waste and conserving materials, and is capable of reducing some of the energy consumption inherent to traditional construction methods, the considerable demand for electrical energy to power the continuous operation of the equipment necessitates further evaluation and optimisation of the technology's overall energy efficiency [11].

The issue of carbon emissions represents a significant challenge that must be addressed in the context of 3DPC technology. Cement, the primary constituent of concrete, is a significant source of elevated carbon emissions. The production of cement is a significant source of carbon dioxide emissions, with an estimated 0.7 to 1 tonne of this gas released for each tonne of cement produced. Therefore, although 3DPC technology has the potential to reduce carbon emissions on construction sites by using precise materials, the overall carbon footprint is still affected by the cement production process. Consequently, the reduction of carbon emissions through the selection of appropriate materials and the implementation of enhanced processes represents a pivotal challenge in the advancement and implementation of this technology [12].

In terms of cost-benefit analyses, 3DPC technology demonstrates its distinctive economic potential. Although the initial investment in 3D printing equipment is considerable, particularly in terms of the necessity for a significant capital outlay on the purchase and maintenance of high-performance printing equipment, the potential for long-term cost savings is a significant advantage. In comparison to conventional construction techniques, 3DPC has the potential to markedly diminish labour costs, given the high degree of automation inherent to the printing process and the consequent reduction in the necessity for human input. Furthermore, the design of 3DPC for precise material usage results in a reduction of material waste and, consequently, material costs. In construction projects with intricate structural designs, 3DPC can circumvent the additional expenses associated with the extensive utilisation of fixed structures in conventional methodologies, thereby further reducing the overall construction cost. Therefore, despite the higher initial investment, 3DPC technology is demonstrated to outperform traditional building techniques in terms of overall economics in specific application scenarios, especially in mass production and complex structural design [13].

The advantages of 3DPC technology are particularly significant in terms of construction efficiency. The most significant benefit of this technology is its capacity for rapid prototyping, whereby the actual building structure is generated directly from the digital model, obviating the necessity for the intermediary steps typically required in construction, such as mould making and repeated adjustments. This approach not only accelerates the rate of construction progress but also reduces the incidence of errors and the costs associated with rework during the construction phase. Furthermore, the layer-by-layer approach employed by 3DPC greatly reduces material waste and results in a more environmentally friendly construction process. Furthermore, 3DPC facilitates the straightforward realisation of intricate geometrical designs, which may necessitate a considerable investment of time and resources in conventional construction techniques. Consequently, 3DPC technology has exhibited unparalleled efficiency and flexibility in construction projects that necessitate the fabrication of intricate shapes or the fulfilment of bespoke specifications. Nevertheless, despite the evident advantages of 3DPC technology in terms of efficiency, its broader implementation continues to be constrained by the need to reconcile the competing demands of material strength and printing speed. The challenge of ensuring the quality and safety of building structures while maintaining high efficiency represents a pivotal avenue for future research.

5. Case Studies

The application of 3DPC technology in the construction sector has witnessed considerable advancement in recent years, with the Shanghai Qingpu Park and Dubai Museum of the Future representing two prominent instances of its successful implementation. The 3DPC technology was first applied on a large scale in China in the context of the Shanghai Qingpu Park's 3D-PC landscape project. The project team employed the use of 3D printing technology to construct a diverse range of architectural elements, including benches, corridors, and landscape walls within the park. These structures illustrate the potential of 3DPC technology in the creation of complex curved surface designs, while also demonstrating the advantages of this technology in the context of public facilities and landscape design. These advantages include the reduction of construction cycles and the minimisation of material waste, as evidenced in reference [14]. The application of 3DPC technology in the Qingpu Park project has the dual benefit of enhancing construction efficiency and providing greater flexibility and creative space for personalised design. This makes it an important example of the promotion of 3D printing construction technology in China.

Conversely, the Dubai Future Museum exemplifies the cutting edge of 3D-printed architectural technology on a global scale. As the inaugural major public building project in the Middle East to employ 3DPC technology, the Dubai Museum of the Future represents a radical departure from conventional architectural norms. The project features a highly complex and artistically curved structure, a design that would have posed a significant challenge to traditional construction methods. However, this was successfully accomplished with the help of 3D printing technology [15]. The utilisation of 3D printing has enabled the museum to meet the rigorous standards of structural integrity and durability, while also exhibiting resilience in extreme climatic conditions. The construction of the Dubai Museum of the Future not only improves construction efficiency and reduces construction waste, but also provides valuable empirical evidence in support of the application of 3D printing technology in the construction of complex buildings. The successful completion of this project demonstrates the significant potential of 3DPC technology in addressing future building needs and paves the way for technological innovation in the global construction market [16].

The cases of Dubai Museum of the Future and Shanghai Qingpu Park show that the application of 3DPC technology in the construction sector has significant potential for practicality and innovation. Overall, in order to fully utilise the advantages of 3DPC technology, further research and better development in terms of material properties, printing accuracy, cost-effectiveness and environmental impact are needed. Future research should focus on the optimisation and standardisation of 3DPC technology, as well as its integration with traditional construction processes, in order to promote the application of the technology in a wider range of fields.

6. Conclusion

This paper makes a comprehensive study of 3d printing technology. The process, mechanical properties, environmental impact and economic benefits are analysed in detail. It assesses the effectiveness of practical applications of 3DPC technology and identifies potential challenges through case studies.

(1) 3DPC technology adopts computer-aided design and additive manufacturing process to facilitate efficient construction of building components. The compressive strength and interlayer bonding strength of 3DPC are essential to ensure the safety and durability of the structure. However, the current research on its rheological properties and additives is systematic, which restricts its reliability in practical applications.

(2) The application of 3DPC technology has been shown to have significant environmental benefits, including reducing construction waste and saving materials. However, the issue of increased carbon emissions during cement production shows that additional measures are needed in terms of material selection and process improvement to minimize the overall environmental impact of 3DPC

technology. Although 3DPC technology requires a large initial investment, its advantages in labour costs, material costs, and construction efficiency make it economically viable in mass production and complex structural design.

(3) The case studies of Shanghai Qingpu Park and Dubai Museum of the Future illustrate the potential of 3DPC technology in realizing complex design and improving construction efficiency, which provides an empirical basis for the further development and application of 3DPC technology.

(4) 3DPC technology has great application potential in the field of architecture. However, it also faces some challenges, including technological maturity, environmental impact and economic assessment. In particular, there is a lack of research on the long-term performance and durability of 3d printing technology under different environmental conditions. In addition, specific specifications and standards for practical engineering applications have not yet been established. Finally, the economic analysis applied in projects of different sizes requires further research. It is suggested that future research should focus on addressing the shortcomings of existing research and promoting the development of 3DPC technology towards standardization, scale and environmental compatibility.

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