3D-Printing Concrete with Bauxite Residue

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Abstract

The combined use of bauxite residue and Portland cement presents a promising option for its large-scale utilization. Extensive research has been conducted on this topic, primarily focusing on the performance and durability of concrete. Moreover, over the past decade, the rapid advancement of large-scale engineering structures has significantly increased the demand for innovative materials and construction techniques. In this context, the development of 3D-printing technology, as an additive manufacturing method, that is, a process which builds components layer by layer directly from digital models, has introduced transformative potential to modern construction practices. However, 3D-printing in construction faces several challenges: the materials must be extrudable while maintaining their shape during curing to ensure structural integrity and long-term durability and additionally, binder consumption in these mixtures is often higher than in conventional concrete compositions. Consequently, there has been a growing demand for supplementary cementitious materials such as silica fume, metakaolin, limestone, etc. to reduce the environmental footprint of construction. Within this scenario, the large-scale application of untreated bauxite residue (UBR) in these compositions presents a unique opportunity to develop high-value components with geometric freedom, eliminating the need for traditional formwork and reducing construction waste. In addition, it is an alternative to produce components with lower binder consumption (below 350 kg/m³ of binder), associated with the potential for dematerialization of the construction, that is, the reduction of material usage through optimized designs enabled by 3D-printing, since the UBR has characteristics that favour the printability of the compositions. Another advantage is their natural terracotta colouring, which offers architectural appeal without the challenges commonly associated with conventional concrete. Therefore, this initial study focuses on the development of UBR-based compositions for 3D-printing of some architecturally designed components as proof of concept of the potential for use on a larger scale. Some components were shown in thematic exhibitions or exposed to natural degradation conditions to assess their long-term durability and overall quality. Following the promising results at the object and prototype scale, further research is required to validate the performance of these materials in structural applications.

Keywords: Bauxite residue, Cement compositions, 3D-printing, Low cement, UBR valorisation.

1. Introduction

The construction sector plays a crucial role in the global economy due to its impact on infrastructure development, urbanization, and job creation. According to a report published by the McKinsey Global Institute in 2017 [1], the construction industry, including related sectors such as real estate development and engineering services, accounted for approximately 13 % of the global Gross Domestic Product (GDP) at that time. However, more recent estimates suggest that the direct contribution of the construction industry alone represents around 6 % of global

GDP [2]. This difference reflects the methodological approach used, where broader analyses incorporate the entire construction value chain and associated industries, while narrower evaluations focus exclusively on the execution of construction activities. Regardless of the approach, the construction sector remains one of the largest and most significant contributors to the global economy.

Despite its economic relevance, it remains one of the least productive industries. Over the past two decades, productivity in the sector grew at an average rate of only 1 % per year – significantly lower than that observed in manufacturing industries such as automotive and consumer goods, which averaged around 3.6 % annually. According to the study, if labour productivity in the construction industry were to reach the levels achieved by manufacturing, this could potentially represent a global profitability increase of up to 1600 billion USD. This gain is associated with a range of structural measures, including regulatory reform and the advancement of automation in construction processes – an increasingly critical factor in a global context marked by infrastructure and housing deficits, a shortage of skilled labour, and a decline of economically active population [3,4].

Another critical aspect to consider in this analysis is the significant environmental impact associated with the construction industry. Beyond its well-documented productivity inefficiencies, the sector is also highly unsustainable, representing the largest global consumer of natural resources and raw materials. This demand exacerbates environmental impacts, including resource depletion and high CO_2 emissions, underscoring the need for sustainable alternatives [5]. Within this context, there is a demand for new technologies and processes, which not only increase productivity and reduce costs, but also contribute to the mitigation of environmental impacts thus making the sector more sustainable and aligned with current demands for decarbonization and efficiency.

The integration of 3D-printing technology into cement-based construction has opened new pathways for the fabrication of complex components, eliminating the need for formwork, reducing labour intensity, and improving overall efficiency [6]. Despite its potential, one of the main limitations of extrusion-based 3D printing lies in the high binder demand, which considerably raises the environmental impact because of the high carbon emissions linked to Portland cement production [4,5]. To address this issue, some supplementary materials have emerged as sustainable alternatives, offering a lower carbon footprint and economic advantages, since they do not require calcination or energy-intensive processing [9], as it is for untreated bauxite residue (UBR) [10–15].

However, incorporating high volumes of these materials modifies the particle packing density and surface area of the mix, which directly influences its rheological behaviour – particularly yield stress and plastic viscosity [4]: while moderate content can enhance flowability, excessive substitution may lead to undesirable increases in viscosity, compromising pumpability and interlayer adhesion during printing [16]. Thus, regarding the use of bauxite residue in the composition, the complexity increases, because in addition to rheological adequacy, raw materials must be chosen to ensure the environmental safety of the components produced, avoiding the leaching of potentially harmful ions. Therefore, optimizing the rheological performance of compositions with low-cement content and using bauxite residue as supplementary material remains a key challenge for advancing eco-efficient 3D printing in construction [17].

The effect of bauxite residue was already studied by some authors in 3D-printing compositions. *Sonebi et al.* [18] evaluated the combined effects of bauxite residue, nano-clay, and natural fibers on the fresh-state and rheological properties of concrete designed for 3D printing. *Almeida et al.* [19] investigated the potential of geopolymers formulated with bauxite residue and fly ash, processed through 3D printing, as efficient adsorbent materials for heavy metal removal in water

Finally, techno-economic analyses are crucial to evaluate the commercial viability of this solution, considering raw material logistics, production scalability, and potential incentives associated with waste valorisation and carbon footprint reduction.

Overall, this research not only advances the development of sustainable cementitious materials but also reinforces the role of digital construction technologies in promoting circular economy practices. It contributes to addressing the pressing challenges of the construction sector, particularly in terms of sustainability, productivity, and material efficiency.

5. References

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