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 treatment, particularly for Cu^{2+}, Pb^{2+}, and Cd^{2+}. The authors demonstrate that additive manufacturing enables the fabrication of porous and geometrically optimized structures, which exhibit high surface area and enhanced mass transfer properties. The amorphous aluminosilicate matrix developed during geopolymerization provides a high density of reactive sites, significantly improving the adsorption capacity for metal ions.

Han et al. [20] have proven that it is technically feasible to produce a geopolymer using bauxite residue combined with PVA (polyvinyl alcohol) fibres, for the production of sustainable, structurally robust components suitable for additive manufacturing in civil construction.

Sun et al. [21] investigated the use of bauxite residue as a supplementary cementitious material in fiber-reinforced 3D-printed concrete, highlighting improvements in both mechanical and rheological properties. However, even with high consumption of bauxite residue (close to 90 kg/m³) the authors presented compositions with almost 1000 kg of binders per m³ of concrete produced, showing that the dosing strategy was not sustainable.

Zhou et al. [22] focused on evaluating the pozzolanic reactivity of activated bauxite tailings and their influence on the mechanical properties and rheological performance of 3D-printed concrete mixtures. The authors demonstrated that, once activated, bauxite tailings exhibit substantial reactivity with hydroxides and calcium aluminates which contributes to strength development and enhances interlayer bonding, a critical factor for the structural integrity of 3D-printed elements. In the present paper, we show that it is possible to produce cementitious components formulated with bauxite residue, environmentally safe, with a complex design, without the need for moulds, no generation of production waste, and with low binder consumption (cement + silica fume less than 350 kg/m³). This approach indicates the architectural potential of bauxite residue compositions for the construction of large-scale buildings in a simple and fast way.

2. Methodology

The strategy adopted in this project involved the development of a cementitious formulation incorporating untreated bauxite residue and a low binder content, designed to be printed using the 1k concept, that is, as a single-component system in which all the necessary constituents (binder, aggregates, finer materials, water, and admixtures) are mixed together prior to printing. This approach eliminates the need to add other materials during the 3D printing process, simplifying the operational workflow compared to multi-component (2k) systems.

In this approach, all the constituents are pre-homogenized and mixed in a single batch. After adjusting the consistency by water addition to meet the required rheological conditions, the product is stored and transported to the printer, where it is deposited layer by layer. The printed elements are then cured with 98 % relative humidity at room temperature.

The formulation of the binder was based on the following proportions per cubic meter: 310 kg of Portland cement, 30 kg of silica fume, 10 kg of hydrated lime, and 35 kg of untreated bauxite residue. To optimize particle packing, a blend of sands with a maximum grain size of 1.6 mm was used, along with specific admixtures for rheological tuning.

As mentioned, the use of UBR in the composition increases complexity, since the raw materials must guarantee the environmental safety of the components produced, avoiding the leaching of potentially harmful ions.

Silica fume and hydrated lime were primarily added to promote the chemical immobilization of hexavalent chromium Cr(VI) ions present in the UBR, which predominantly exist as chromate anions CrO_4^{2-} in alkaline media. Silica fume, mainly composed of amorphous silicon dioxide

SiO_2, plays a key role in reducing Cr(VI) to Cr(III), a less toxic and more stable species. This reduction occurs through interactions between surface silanol groups (Si–OH) and Cr(VI) anions, enabling redox reactions and/or surface complexation mechanisms [23–27]. Studies have shown that the efficiency of Cr(VI) removal can be enhanced by combining silica fume with other materials, such as metal oxides, which increase both adsorption capacity and redox potential.

Hydrated lime $Ca(OH)_2$, in turn, contributes to the system's alkalinity by releasing OH^- and Ca^{2+} ions. Although it does not directly promote the reduction of Cr(VI), it may facilitate limited adsorption or co-precipitation processes, leading to the formation of low-solubility compounds such as calcium chromate $CaCrO_4$), particularly at lower temperatures.

Another relevant component in bauxite residue is sodium, mainly present as soluble Na^+ ions. To improve the retention of these ions and enhance the overall fixation of metallic species, bentonite clay was incorporated into the formulation (15 kg/m^3). Rich in montmorillonite, bentonite exhibits high cation exchange capacity, thus contributing to ion exchange-based sorption mechanisms [26, 28–30].

Prior to the printing tests, laboratory-scale rheological evaluations were conducted to assess the formulation's *printability*. The mixing stage was analysed through *rotational rheometry*, which indicated low energy demand for processing, allowing preparation without the need for complex industrial equipment. The material displayed a pseudoplastic rheological profile, which is essential for continuous pumping.

Extrudability was assessed using the *Benbow and Bridgwater* method by monitoring extrusion pressure. Shape retention and buildability were evaluated via the *squeeze flow* test. Detailed descriptions of the extended rheological assessment methods can be found in [31]. Based on these results, the pump control parameters and printer software were adjusted to ensure the feasibility of the additive manufacturing process.

The primary objective of this study was to demonstrate the feasibility of producing components with complex geometries through 3D printing using cementitious formulations incorporating UBR. The components presented were designed by architects and designers, serving not only as functional prototypes but also as aesthetic and structural explorations of the material's potential. Some of these pieces were showcased at industry fairs or submitted to design competitions, highlighting both the technical viability and the creative possibilities enabled by this sustainable material.

Beyond the scope of object-scale production, the knowledge generated through the development, testing, and printing of these components forms the foundation for scaling up the technology. The goal is to apply the same formulations for the additive manufacturing of structural elements such as walls and columns, contributing to sustainable construction practices and enabling the use of industrial waste in the fabrication of full-scale buildings.

2.1 Mixing and Printing Process

The mortar mixing process was conducted using an Anvi-120 mixer, with batch sizes of 90 kg of dry materials. All constituents were pre-homogenized in their dry state prior to mixing. The bauxite residue, utilized without any prior chemical or physical treatment, was first dispersed in the mixing water to form a homogeneous suspension. This suspension was then incorporated into the dry blend inside the mixer.

To ensure consistency in the fresh properties and printability across all batches, the mixing procedure was standardized with a total duration of five minutes. Upon completion, the fresh mixture was transferred to the pump vessel (Anvijet-120), which fed the extrusion system. The material was subsequently conveyed to a Scara-type 3D Potter printer, initiating the additive manufacturing process to produce the components.

Figure 1 schematically presents the processing workflow, including the preparation steps for the UBR suspension, its incorporation into the mixer, and the equipment used for both mixing and pumping (top section of the figure). The bottom section displays the 3D printer setup alongside an example of a component produced with the UBR-based mixture. Notably, in the background of this image, an L-shaped wall measuring 1.50 meters in height is shown, which was fabricated using the reference mixture (i.e. without UBR). This wall represents the intended scale and typology of structural elements targeted for future applications with the UBR-based formulation.

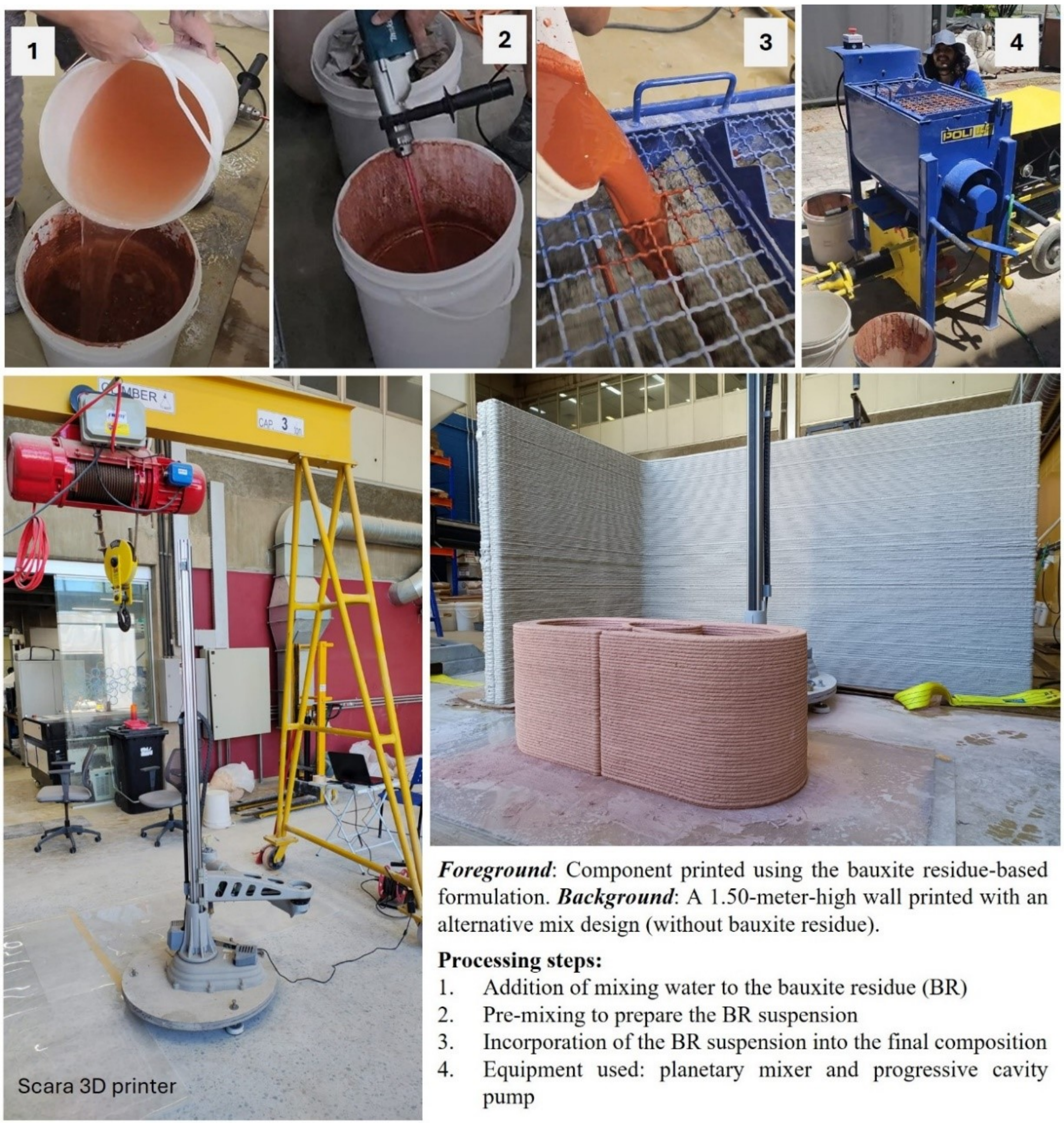

Figure 1. Below, the 3D printer and an example of a component printed with the bauxite residue-based composition are shown. Above, the processing steps for preparing and incorporating the bauxite residue (UBR) into the mixer are illustrated, along with the equipment used for mixing and pumping.

3. Components Developed and History Behind the Projects

The bench shown in Figure 2 was designed by Brazilian designer Ronaldo Mangabeira, from Studio Manga_be (@ronaldomangabeira), and draws inspiration from the asymmetric arches that characterize the façade of the historic *Palacete-Cor-de-Rosa* of Marchioness of Itamaraty, located in Rio de Janeiro, Brazil. The top image shows the bench during the 3D printing process. On the bottom left, the final piece is displayed in an outdoor setting, highlighting its distinctive asymmetric arches. On the bottom right, the façade of the historic *Palacete*.

Figure 2. "Itamaraty Bench", developed by Studio Manga_be Architecture and Design. The top image shows the bench during the 3D printing process using a bauxite residue-based cementitious formulation. On the bottom left, the final piece is displayed in an outdoor setting, highlighting its distinctive asymmetric arches. On the bottom right, the façade of the historic *Palacete-Cor-de-Rosa* of Marchioness of Itamaraty, located in Rio de Janeiro, is presented (the architectural reference that inspired the designer).

This building holds significant historical and architectural value for the country and is officially protected as a national heritage site by IPHAN (National Institute of Historical and Artistic Heritage). Originally built in 1851 to serve as the residence of the Baron of Itamaraty, the palace, also known as the Palace of Arches, later became the headquarters of the Ministry of Foreign Affairs of Brazil from 1899 until 1970, when the capital was transferred to Brasília. Today, it houses the Itamaraty Representation Office in Rio de Janeiro.

The architectural language of the palace merges influences from Baroque, Neoclassical, and early Modernist styles, common in imperial Brazil. Its iconic asymmetric arches convey a sense of nobility, solemnity, and grandeur, qualities intrinsically tied to the palace's diplomatic function. Symbolically, arches are often interpreted as representations of openness, dialogue, and connection among nations, perfectly aligned with the mission and spirit of Brazilian diplomacy. The 'arch' becomes not only an aesthetic feature but also a visual metaphor for bridging cultures and fostering communication.

In addition to enhancing the rheological properties and printability of the mixture for 3D printing, bauxite residue was deliberately selected for its natural reddish hue, which echoes the characteristic colour of the palace façade, creating a direct material and visual dialogue between the product and its architectural reference.

The bench was showcased at the 14th Brazilian Design Award (2024), where it received the Bronze Medal in the Product Design category, recognizing both its aesthetic value and innovative use of sustainable materials. The piece is currently on display at *HubIC*, the Construction Innovation Hub at the University of São Paulo (USP), where it continues to serve as an example of how design, technology, and sustainability can converge to shape the future of construction.

Figure 3 presents the *Chaise Longue*, an exclusive piece designed by Portal 3D (@_portal3d) for submission to the 14th Brazilian Design Award (2024). Image 1 captures the additive manufacturing process using a sustainable cementitious formulation reinforced with bauxite residue. Images 2 and 3 showcase the finished lounge from top and side views, highlighting the meticulous layering precision, the fluidity of the geometry, and the distinctive textural expression inherent to the extrusion-based 3D printing process. Image 4 displays the final piece in an exhibition environment, exemplifying how advanced manufacturing, sustainable materials, and design-driven innovation converge to redefine the boundaries of contemporary furniture.

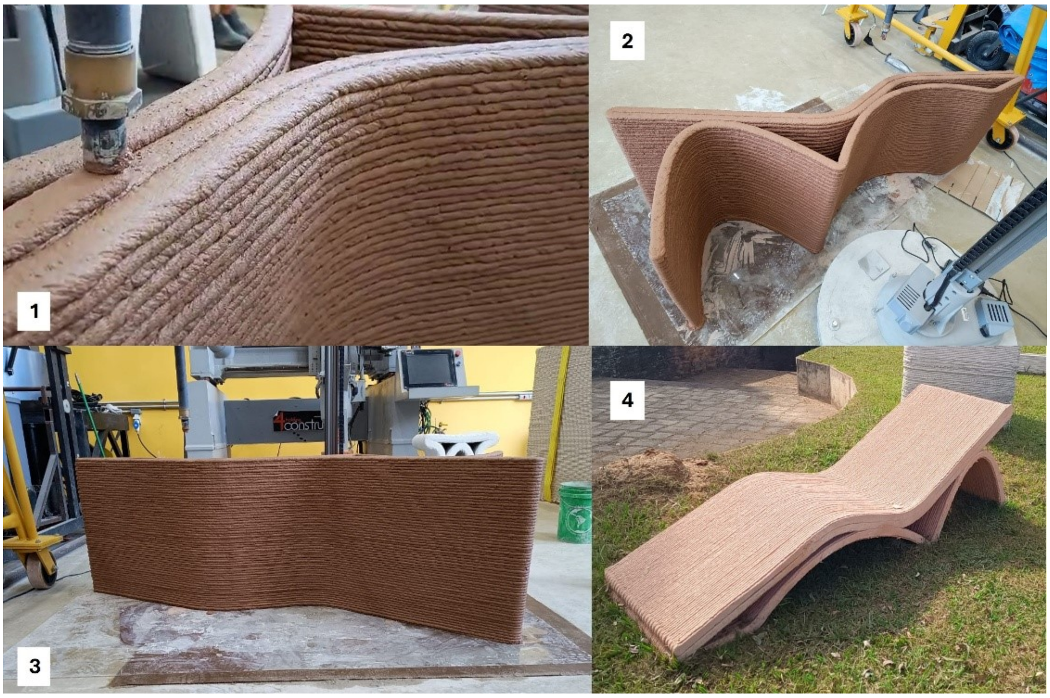

Figure 3. *Chaise Longue* printed with formulation with UBR. On the left top (1) is presented the additive manufacturing process during the 3D printing. Images 2 and 3 show the completed chaise from top and side perspectives, and image 4 presents the final product displayed in an exhibition setting.

The design draws conceptual inspiration from the *Pão de Açúcar*, one of the most iconic natural landmarks of Rio de Janeiro and a global symbol of Brazilian cultural identity. More than a geological formation, the *Pão de Açúcar* embodies the very essence of Rio de Janeiro: a synthesis of beauty, resilience, diversity, openness, and the celebration of life in harmony with nature.

The chaise can be understood as a topological abstraction of Rio's landscape, where the prominent peak symbolizes the *Pão de Açúcar*, the undulating curves evoke the surrounding rock formations, and the voids represent the interplay of sea, sky, and horizon. The rhythmic balance between solids and voids, elevations and depressions, convexities and concavities, mirrors the dynamic contour of the city's most celebrated coastal skyline.

The *client's vision* was clear: *to develop a furniture piece that seamlessly integrates functionality, contemporary aesthetics, cultural identity, and environmental responsibility*. The goal was to materialize a design that not only delivers ergonomic comfort but also narrates a story of how digital fabrication and circular economy principles can coexist with artistic expression and local heritage.

Among the key challenges were translating the complex topography of the *Pão de Açúcar* into a structurally sound and ergonomically viable product, while maintaining the sculptural purity of the form. Additionally, it was essential to ensure the material performance and long-term durability of a piece manufactured using a sustainable cementitious composite incorporating UBR without compromising on aesthetics or functionality.
The eco-efficient formulation incorporating UBR was also employed in the production of benches showcased at Casacor 2024 (https://casacor.abril.com.br/pt-BR/mostras/sao-paulo-2024), Latin America's largest exhibition of architecture, landscaping, and interior design.

Designed by renowned businesswoman Fábia Toqueti (@fabia_toqueti), the benches were fully customized for the 'Terreiro' space, created by Alexandre Salles of Estudio Tarimba (@ale_salles). They collectively spell out the word AYE (meaning "earth" in Yoruba), honouring one of the largest ethnic groups in West Africa, predominantly found in present-day Nigeria, as well as parts of Benin and Togo.

This exhibition paid tribute to Afro-Brazilian ancestry, highlighting its profound historical, cultural, and religious significance. The installation's terracotta colour palette evokes the traditional beaten-earth courtyards, fostering an immersive atmosphere that connects visitors to ancestral roots and the land.

The process and its outcomes are illustrated in Figure 4, which shows different stages of the project. The top left image highlights the recognition of the installation featured on the cover of a major design magazine, underscoring its relevance and impact. The top right image depicts the 3D printing process of the AYE benches, illustrating the layered manufacturing technique enabled by the extrusion-based printing system. The bottom left image shows the benches during the post-production stage, developed by the Portal 3D team at DCLab (https://sites.usp.br/dclab), prior to installation. Finally, the bottom right image displays the benches in their final setup at Casacor 2024.

Originally, the project intended to feature *taipa* (rammed earth) as the central element. However, the designer embraced cutting-edge 3D printing technology, enabling the creation of organic, fluid forms that perfectly harmonize with the exhibition's conceptual narrative.

The bench installation was critically acclaimed, earning the prestigious *Best Art Installation Award* (https://vejasp.abril.com.br/cultura-lazer/casacor-2024-premio-melhor-ambiente-vencedores/). Furthermore, it attracted extensive media coverage across leading news outlets, underscoring the innovative fusion of sustainable materials, cultural heritage, and advanced fabrication techniques.

In addition to the high-profile pieces developed for exhibitions and collaborations with renowned designers, a wide variety of other components were designed and printed using the UBR-based formulations throughout the development process. These components, although not showcased in cultural events or design fairs, demonstrate the remarkable versatility and adaptability of the material. Some examples are illustrated in Figure 5.

Figure 4. AYE benches exhibited at Casacor 2024, Latin America's largest architecture, landscaping, and interior design exhibition (bottom right). The top right image shows the 3D printing process of one of the benches, highlighting the layered manufacturing technique. The top left features the exhibition's recognition on the cover of a prominent Brazilian magazine. The bottom left image captures the benches after the production phase at hubic, developed by the Portal 3D team, prior to installation at the exhibition.

As shown, the components exhibit a range of colours and textures, resulting from variations in the composition, specifically the content and source of the bauxite residue. Additionally, certain pieces were produced using only the fine fraction of the material (excluding sand), enabling even smoother finishes and refined geometries.

These results clearly demonstrate that technology is not limited to a single type of product or application. A broad spectrum of customized components can be manufactured on demand, including furniture, architectural elements, artistic installations, urban furniture, structural components, and prototypes for industrial design. Regardless of the adjustments in formulation, all the printed components fully met the technical and functional requirements defined for the project.

This versatility reinforces the potential of 3D printing with bauxite residue as a sustainable and highly flexible manufacturing solution, capable of delivering eco-friendly, aesthetically appealing, and structurally reliable products for diverse sectors, from construction and architecture to design and urban development.

4. Conclusions

This study demonstrates the technical feasibility of producing eco-efficient cementitious components incorporating UBR through extrusion-based 3D printing. The developed formulations enabled the fabrication of components with complex geometries, free from traditional formworks, with zero production waste and with significantly reduced binder consumption (around 350 kg/m³ of product).

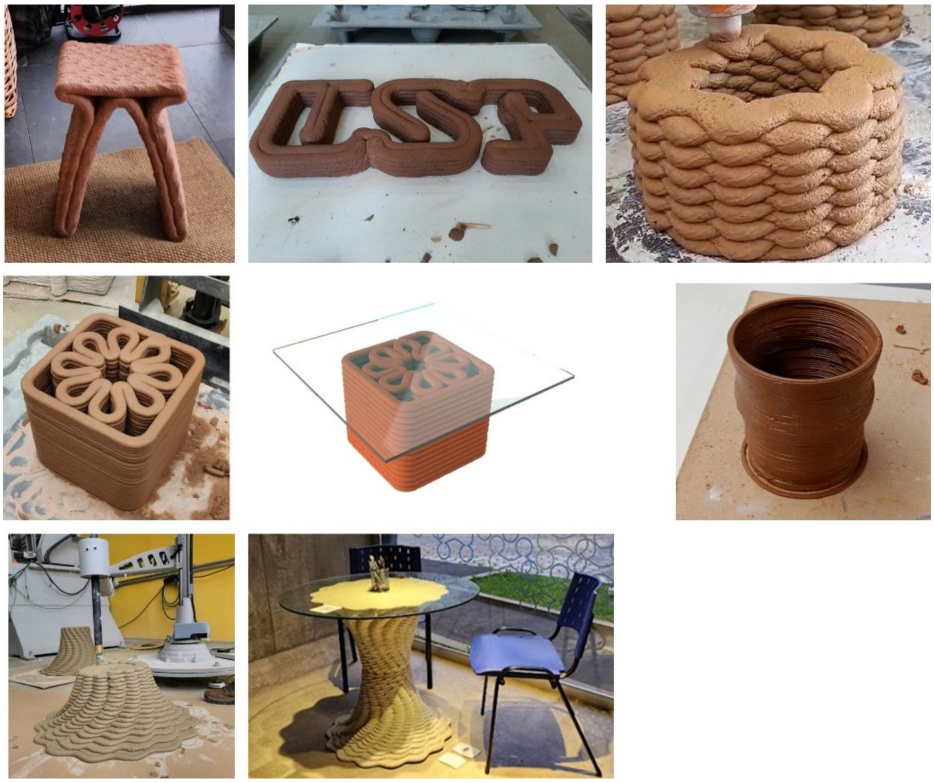

Figure 5. Examples of pieces printed with the bauxite residue formulation.

The research also provided practical evidence of the versatility and aesthetic potential of UBR-based compositions, particularly due to their natural terracotta colour, which adds architectural value without the need for additional surface treatments. Several high-value-added components were developed in collaboration with renowned designers and exhibited in prominent design events, receiving widespread recognition for their innovative use of sustainable materials.

From an environmental standpoint, the formulation strategy focused not only on reducing binder content but also on ensuring chemical stability. The synergistic use of hydrated lime, silica fume, and bentonite proved effective in mitigating the leaching of soluble ions such as sodium and hexavalent chromium, thereby ensuring the environmental safety of the components. However, the detailed scientific discussion of the immobilization mechanisms is addressed in a separate publication.

Despite the promising results at the object and prototype scale, further research is required to validate the performance of these materials in structural applications. This includes scaling up the technology for the production of full-size elements, such as walls, columns, and slabs, followed by comprehensive mechanical testing and long-term durability evaluations under varying environmental conditions.

In addition, the development of standardization protocols for UBR-based 3D printed materials is essential to ensure regulatory compliance and facilitate market adoption. A detailed life cycle assessment should be conducted to accurately quantify the environmental benefits compared to conventional construction methods.

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.

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