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Preliminary study on multi-functional building components utilizing variable density foamed concrete via 3D printing

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Abstract. Over the last decades, lightweight foamed concrete has gained recognition and widespread adoption in the construction industry, owing to its intrinsic multifunctionality and versatility. Notably, the ability to achieve a broad range of densities through mix design adjustments makes this material appealing for fulfilling different essential functions, including mechanical strength and thermal insulation. Moreover, recent studies exploring the application of foamed concrete in Additive Manufacturing processes underline the considerable advantage of combining the peculiar properties of foamed concrete with the benefits associated with automated procedures.

In the present study the application of multi-density foamed concretes in the fabrication of multifunctional engineered building components through 3D Concrete Printing (3DCP) processes is investigated. The possibility of employing medium-density foamed concrete for 3D printing topologically optimized structural sections and ultra-lightweight foamed concrete for filling these sections with thermal insulation purpose is proposed. This innovative solution allows for the fulfillment of multiple performance requirements - high mechanical performance and excellent thermal insulation - within a single cohesive cementitious element, thus eliminating the need to assemble numerous monofunctional layers of different materials.

The primary properties of the two proposed foamed concrete mixes were investigated. Compressive strengths of 7.04 MPa and 5.40 MPa were achieved for cast and 3D-printed medium-density foamed concrete, respectively. Thermal conductivities of 0.205 W/mK and 0.072 W/mK were obtained for medium-density and ultralight-density foamed concrete, respectively. A successful 3D printing application with medium-density foamed concrete was executed using a collaborative robotic arm, and the possible pouring of ultralight-density foamed concrete to produce multi-density building components was assessed.

Keywords: Additive Manufacturing; 3D Concrete Printing; Multifunctional building components; Ultra-lightweight foamed concrete; Variable density.

1 Introduction

The utilization of foamed concrete (FC) offers the opportunity to combine the benefits provided by lightweight concrete compared to conventional concrete, such as weight reduction, multifunctionality, versatility in application, economic and environmental advantages, with those offered by this specific type of lightweight concrete. Among the latter, it is particularly noteworthy that FC can be easily produced using common materials available universally, and it can be manufactured across a wide range of densities. This versatility is particularly intriguing: by simply adjusting the mix design, FC can be produced within a density range from 90 kg/m³ [1] to 1800 kg/m³, enabling a broad spectrum of applications ranging from structural (at higher densities) to non-structural applications with thermal and acoustic insulation functions (at lower densities) [2], [3], [4]. In this regard, an appealing application opportunity arises from the combined use of FCs at different densities to manufacture building components characterized by the coexistence of properties typically achieved by coupling different single-functional materials, such as mechanical performance and thermal insulation. This results in a multifunctional product with properties tailored to specific requirements based on the particular application case, while also simplifying recycling operations and offering improved end-of-life building recycling rates [5], [6].

Furthermore, in this context, the combined use of FC and 3DCP is particularly well-suited for such applications. Indeed, among the benefits associated with 3DCP compared to traditional construction practices [7], the formal freedom, and the ability to place the material only where structurally and/or functionally necessary enable the definition of sections characterized by alternations of solid and void spaces in a completely unrestricted and customizable manner. This, in turn, facilitates the potential integration of materials with different functions and properties [5].

The present study investigates the potential use of FC at varying densities and the utilization of 3DCP to fabricate multi-density, multifunctional building components characterized by both high mechanical performance and excellent thermal properties. Specifically, the utilization of a medium-density 3D-printable FC (3D-800) is proposed for the structural portions of the building component, while an ultra-lightweight FC (UL-300) is intended to be poured into the cavities outlined by the printing path of the former, primarily serving as thermal insulation. Mechanical strength of 3D-800 and thermal conductivity of both 3D-800 and UL-300 were assessed using standard tests. Subsequently, 3D-800 was employed in a 3DCP application utilizing a universal collaborative robotic arm to fabricate the structural portions of a component, specifically designed as a case study within this investigation. Following 3D-printing, one of the two identical elements produced during the robotic application was utilized to investigate the potential incorporation of ultra-lightweight poured material (UL-300) into the cavities outlined by the printing path. From the qualitative evaluation of the results obtained from the practical application, the potential use of FCs at different densities for the proposed application has been confirmed, and some considerations for further investigations aimed at enhancing the final product have been drawn.

2 Materials and Methods

In the current study, two mixes were employed: a 3D-printable foamed concrete, referred to as 3D-800, with a target dry density of 800±50 kg/m³; and an ultra-lightweight foamed concrete, referred to as UL-300, with a target dry density of 300±50 kg/m³. The selection of densities serves as an illustrative case-study aimed at achieving targeted mechanical performance tailored to the intended application, also emphasizing potential structural uses, while highlighting its contribution to the thermal performance that characterizes the entire building component, including the portion primarily dedicated to the structural function.

Both formulations were prepared using Portland cement CEM I 52.5 R (*c*), conforming to the EN 197-1 standard, a Viscosity Enhancing Agent (*VEA*) previously utilized in other studies by the authors [8], a superplasticizer manufactured by Master Builders Solutions Italia Spa (*sp*), a protein-based foaming agent (*fa*), and tap water (*w*). The mixing-foaming method and the pre-formed foaming method were employed to produce 3D-800 and UL-300, respectively. In the case of the pre-formed foaming method, the foam (*f*) was generated with a foaming agent concentration of 5% by volume and was characterized by a density of 80±5 g/l [9]. The weight-based mix proportions of the two distinct formulations employed in this study are detailed in **Table 1**.

Table 1. Weight-based mix proportions of the two mixes employed in the present study.

Mix	*w/c*	*VEA/c*	*sp/c*	*fa/c*	*f/c*
3D-800	0.45	10%	0.25%	3.1%	-
UL-300	0.33	7%	0.5%	-	0.56

The mixing procedure was conducted using a vertical mixer operating at high intensity (3000 rpm). This choice was informed by previous research findings [8], which highlighted its efficacy in fostering a superior microstructure in the hardened material. This is attributed to the creation of smaller and more uniformly distributed pores, thereby enhancing mechanical performance. Varying mixing techniques were employed depending on the production method for either 3D-800 or UL-300. For 3D-800 (mixing-foaming method), the process involved initially dry mixing cement and VEA for at least 1 minute to ensure even distribution. Subsequently, all liquids (water, superplasticizer, and foaming agent) were added, and the mixture was stirred until achieving the desired fresh density of the cement paste. In the case of UL-300 (pre-formed foaming method), the procedure began with dry mixing cement and VEA for a minimum of 1 minute to achieve uniformity. Water and superplasticizer were then added and mixed until a cement paste was formed. Finally, a precise quantity of pre-formed foam was incorporated, and mixing continued until complete integration allowing to reach the target fresh density.

Key hardened-state properties of the two formulations were evaluated as follows. For 3D-800, three cubic cast specimens measuring 4 cm on each side were prepared to determine the 28-day compressive strength. Following a 24-hour setting period, the specimens were demolded and subjected to air curing at a controlled temperature of

20±3 °C and relative humidity of 60±5% until the testing date. Additionally, 3D-printed specimens were produced to gain a deeper understanding of the effective mechanical properties of the 3D-printed elements. After a 24-hour period covered with plastic sheets, the 3D-printed specimens were subjected to air curing under the same controlled conditions as the cast specimens. Compressive strength tests were carried out in accordance with the UNI EN 196-1 standard, employing a Zwick-Line Z050 testing machine (load capacity of 50 kN) in force control mode, with load rate of 1000 N/s. 3D-printed specimens were printed with vertical orientation of the nozzle (vertical down flow), and the load rate was applied in the same direction during testing. For thermal conductivity assessment, three slabs of dimensions 50x50x3 cm^3 were cast for both 3D-800 and UL-300. After 24 hours, the slabs were demolded and subjected to the same aforementioned air curing conditions. Before testing, the slabs were oven-dried to constant weight at 110±5°C. The heat flow meter method, utilizing cold and hot plates set at 15°C and 40°C respectively, was employed [10].

In conclusion, 3D-800 was utilized to 3D-print two identical case-study printing path specifically designed to evaluate the 3D-printability of the material. 3D-Printing was performed with the support of IndexLab using a Universal collaborative robotic arm equipped with a circular-section nozzle of 1.2 cm diameter, at a printing speed of 30 mm/s. Subsequently, the cavities defined by the printed path of one of the components were filled with poured UL-300 to qualitatively assess the feasibility of producing multi-density components using a combination of 3D-printed structure and poured ultra-lightweight infill, and to explore any potential influence between the two materials.

3 Results and Discussion

3.1 Compressive strength

28-day compressive strength was only evaluated for 3D-800, as this material was specifically engineered to fully meet the mechanical strength requirements of the proposed multi-density building components. In addition to cast specimens, 3D-printed specimens were prepared and tested in order to evaluate the effective compressive strength of the 3D-printed material employed to produce the proposed building components.

After testing, the dry density of the specimens was determined by oven-drying the specimens at 110±5°C. The specimens were weighed at 24-hour intervals until they reached a state of approximately constant weight (with a weight loss ≤ 1% in a 24-hour period). Actual mean dry density and test results, accompanied by the standard deviation and coefficient of variation, are outlined in **Table 2**. The designations (C) and (P) refer to the cast and 3D-printed specimens, respectively.

The average 28-day compressive strength of 3D-800 resulted equal to 7.04 MPa and to 5.40 MPa for cast and 3D-printed specimens, respectively. Despite the distinct - and not commonly employed - production method utilized in this study, namely the mixing-foaming method, these values demonstrate alignment with values obtained in prior works referenced by the authors regarding 3D-printable foamed concretes of

similar density produced using the pre-formed foaming method [8], [10]. Furthermore, the results are in line with those of 3D-printed foamed concrete with similar density reported in the literature [11].

Table 2. Test results related to compressive strength of 3D-800.

Mix	target dry density [kg/m^3]	actual mean dry density [kg/m^3]	28-day compr. strength [MPa]	standard deviation [MPa]	coefficient of variation [-]
3D-800 (C)	800±50	820	7.04	0.11	0.02
3D-800 (P)	800±50	820	5.40	0.13	0.02

Given that the compressive strength of both cast and 3D-printed specimens exceeds 5 MPa, 3D-800 is deemed suitable for its intended function within the multi-density building components proposed in the present study. Furthermore, the achieved compressive strength not only qualifies the material for non-structural applications, as proposed in this study, but also opens possibilities for structural use in load-bearing constructions. Further studies should focus on assessing the same property on real-scale prototypes in order to further confirm the use in the foreseen application field.

3.2 Thermal conductivity

Thermal conductivity was assessed for both 3D-800 and UL-300. While the fulfillment of thermal insulation performance is primarily addressed by the specifically designed ultra-lightweight filling material, namely UL-300, 3D-800, being a low-density foamed concrete, also presents a certain porosity so it significantly contributes to the overall thermal performance, as well. For this reason, thermal conductivity was evaluated for both materials.

Before testing, the specimens were oven-dried at 110±5°C and were weighed at 24-hour intervals until they reached a state of approximately constant weight (with a weight loss ≤ 1% in a 24-hour period). At the end of the drying process, the dry density was recorded. Actual mean dry density and test results, accompanied by the standard deviation and coefficient of variation, are outlined in **Table 3**.

Table 3. Test results related to thermal conductivity of the two mixes employed in the study.

Mix	target dry density [kg/m^3]	actual mean dry density [kg/m^3]	thermal conductivity [W/mK]	standard deviation [W/mK]	coefficient of variation [-]
3D-800	800±50	793	0.205	0.00075	0.0036
UL-300	300±50	315	0.072	0.00081	0.0112

The average thermal conductivity of 3D-800 and UL-300 resulted equal to 0.205 and 0.072 W/mK, respectively. Upon comparing the values associated with both materials, it becomes evident that the reduction in density from 800 kg/m³ to 300 kg/m³ leads to a notable decrease in thermal conductivity, estimated at around 65%. This

reduction can be attributed to a significant rise in porosity, resulting in improved thermal insulation properties [10]. Despite employing a different production methodology for 3D-800 in this study, namely the mixing-foaming method, the obtained values align closely with those of extrudable foamed concretes with similar density presented previously by some authors of this paper, which were prepared using the pre-formed foaming method [10]. Furthermore, the results are in line with those of foamed concrete with similar density reported in the literature [12].

3.3 Multi-density multi-functional components

The proposed application for the two materials analyzed thus far, in terms of their mechanical and/or thermal properties, entails the fabrication of multi-functional building components using a single material, namely foamed concrete, at different defined densities. During the design phase, these densities, along with the formal characteristics of the component, are chosen based on the specific function and consequent performance requirements of the intended application.

The designed component produced in this study was chosen as a case-study to showcase the capacity to fully leverage the design flexibility and complex geometric control offered by 3D Concrete Printing (3DCP) while ensuring the coexistence of sections with different densities of the same material provided by foamed concrete. The 3D-printed curvilinear trajectory of the building component not only provides formal complexity for expressive purposes of the exposed faces but also ensures functional complexity through the internal cross-section, which comprises a combination of solid and void areas, enabling the incorporation of sections with varying densities and consequent varying properties, such as compressive strength and thermal conductivity.

Application: 3D-printing and ultra-lightweight filling. 3D-800, specifically designed for robotic applications, was utilized for a 3DCP application employing a Universal collaborative robotic arm. The designed 3D-printed path was replicated to produce two identical 3D-printed objects. Immediately following extrusion, the voids delineated by the printing path of one of the two printed objects were manually filled with UL-300 poured material. The outcome achieved at the end of the printing and filling process as well as the hardened-state result regarding the multi-density component are depicted in Fig. 1.

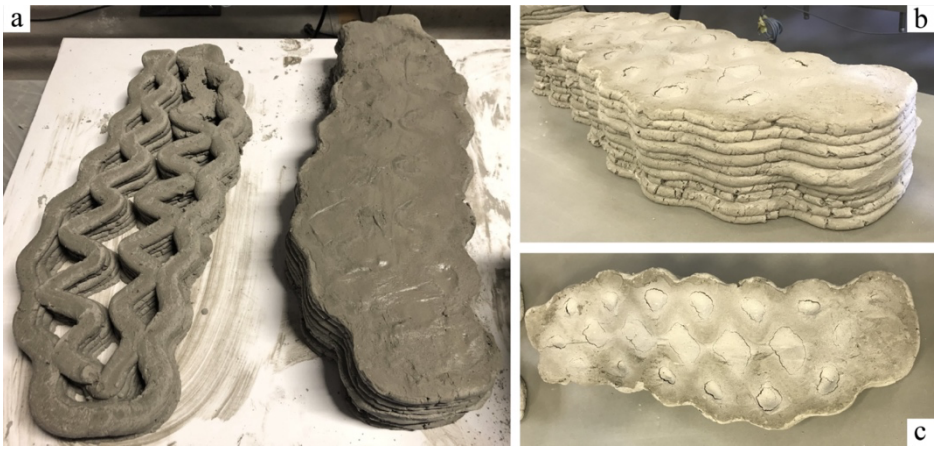

Fig. 1. Fresh-state components (a): 3D printed path and multi-density component; hardened-state multi-density component (b, c).

The 3D printing experiments validated the effective use of 3D-800 in 3DCP processes, providing experimental confirmation of its favorable properties for efficient pumping, extrusion, and layer-by-layer 3D printing in absence of formworks. A qualitative assessment, both in the fresh and hardened states, of the two produced objects allowed for the evaluation of several final characteristics, such as geometric conformity, print quality, and potential reciprocal influence of the two materials in scenarios involving different density. Undoubtedly, the 3DCP process results to have a decisive effect on the properties of the final product and its aesthetic quality, making the production phase pivotal in terms of potential improvements. A comparison between the two produced objects reveals that the ultra-lightweight filling cast within the 3D-printed cavities did not cause any deformation due to the hydrostatic pressure exerted by the filling on the printed sections, thus confirming the feasibility of producing multi-density, multi-performance building components as proposed in the present study. However, from the qualitative analysis in the hardened state, some drying shrinkage phenomena, particularly affecting the ultra-lightweight filling, have been highlighted. Nevertheless, these phenomena could potentially be reduced or eliminated through possible variations in the mix design of the infill material, such as introducing microfibers into the mixture or specific additives tailored to such functions.

4 Conclusions and outlook

The present study investigates the potential of leveraging the wide density range offered by FC and the benefits provided by the use of 3DCP to produce customizable multi-density and multi-functional building components tailored to specific performance requirements. Particularly, the use of printable FC with higher density (3D-800) for the structural portions of the component and ultra-lightweight FC (UL-300) to be poured inside the cavities defined by the printing path, primarily serving as thermal insulation, is proposed. This density combination may enable the production of multi-functional building components using a single material, namely FC, thus simplifying the production process and the recycling operations while increasing the building's end-of-life recyclability rate.

After assessing some of the main properties of the two proposed materials, namely compressive strength for 3D-800 and thermal conductivity for 3D-800 and UL-300, an experimental application is proposed involving the use of a universal collaborative robotic arm for the production, replicated twice, of the medium-density (3D-800) structural portions of a case-study building component, and, for only one of them, the subsequent pouring of ultra-lightweight (UL-300) filling inside the cavities defined by the printing path.

The results obtained from the experimentation confirm the potential combined use of 3DCP and FC at different densities to produce innovative multi-density and multi-functional building components. Further studies should focus on optimizing the final product, in terms of quality of both the printed portions and the cast filling, as well as on evaluating the properties of the final components. These studies should consider both the printing process and the properties of the mixes used. Through the selection of mixes within a wide density range offered by the use of FC, the proposed compo-

nent type could be customized according to the performance needs - mechanical, thermal, acoustic - of the specific case.

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