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Improving the energy performance of a 3D-printed wall using recycled material

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Abstract. In this paper, we present the results of a preliminary experimental campaign conducted on a 3D-printed wall 40 cm thick made of three concrete walls, connected by metal pins and concrete curbs to form three types of cavity - one rectangular and two triangular. The tests were performed in a climatic chamber at the *Pietro Pisa Laboratory* of the University of Brescia. The wall thermal performance has been evaluated by examining four scenarios in which the cavities have been filled with insulating material made of cellulose-based recycled flakes characterized by a declared thermal conductivity of 0.038 W/mK. The wall thermal transmittance U is measured based on the temperatures and heat fluxes measured through the structure. Based on the degree of filling, the wall thermal transmittance ranges between 1.58 W/m^{2}K for the wall without insulation, and 0.28 W/m^{2}K for the configuration with all cavities completely filled.

1. Introduction

The 3D-Printing Concrete (3DPC) technology allows the conversion of digital models into real ones through, as the name suggests, a 3D printer that deposits a concrete mixture layer-by-layer. This technology has gained the interest of the scientific community since it can reduce construction waste by 60%, production time by 70%, and labor costs by 80% [1]. However, the lack of regulation prevents the widespread of this technology with few exceptions. The geometrical printability and standardization of 3D printing concrete components are high-priority concerns that need to be addressed by codes and regulations [2,3].

3D manufacturing allows flexibility in the geometry design, and it can be either implemented to realize prefabricated elements, or in situ. As a result of the movement of a mechanical arm, 3D walls are not typically chunk elements but rather have cavities. Thus, only the indispensable elements are created, namely the frames that must guarantee the structure's stability and strength.

Several studies have analyzed the properties of 3D-printed walls from different points of view: fire resistance [4], mechanical resistance [5,6], and thermal performance [7-9]. For example, the numerical analysis in [7,8] analyzed how 3D-printed wall configuration affects the thermal transmittance U, and it was stated that thermal performance improvement can be achieved by filling the cavities of the walls. In [9], the mechanical and thermal performance of seven 30 cm-wide walls was investigated as a function of the concrete design. Other investigations compared the effect of introducing parallel cavities and of increasing cavities size: it was shown that the first option is more effective. Based on the climate zone and the compactness ratio of the building, the Italian regulations [10,11] define for buildings a maximum allowable value of the mean overall heat transfer coefficient (by thermal transmission). Typical values are reported in Table 1. Due to their superior thermal performance, vertical opaque walls should have a thermal transmittance U lower than those in Table 1, where the maximum heat transfer coefficient is expressed as a function of $X=A_{env}/V_g$ where A_{env} is the building surface envelope and V_q is the building volume.

In this paper, thermal aspects are the focus of the research. This preliminary study evaluates the thermal performance of the 3D-printed wall shown in Figure 1 and identifies ways to reduce its thermal transmittance. As 3D printing allows for a wide range of wall profiles, it is possible to incorporate cavities to be filled with insulating material, thereby enhancing the thermal resistance of the wall. The aim of this study, outlined in this paper, is to quantify the increase in thermal resistance based on the level of wall insulation. The results obtained can assist designers in predicting varying insulation levels.

Table 1. Maximum overall heat transfer coefficient in W/m^{2}K by the thermal transmission for new buildings realized in the Italian area [10,11].

	ZONES A and B	**ZONE C**	**ZONE D**	**ZONE E**	**ZONE F**
$X < 0.4$ m^{-1}	0.80	0.80	0.80	0.75	0.70
0.4 m$^{-1} \le X \le 0.7$ m^{-1}	0.63	0.60	0.58	0.55	0.53
$X > 0.7$ m^{-1}	0.58	0.55	0.53	0.50	0.48

Figure 1. The 3D-printed wall analyzed at the *Pietro Pisa Laboratory* of the University of Brescia (Italy). The left picture shows the wall realized for structural analysis, and the right picture shows the details of the wall interior.

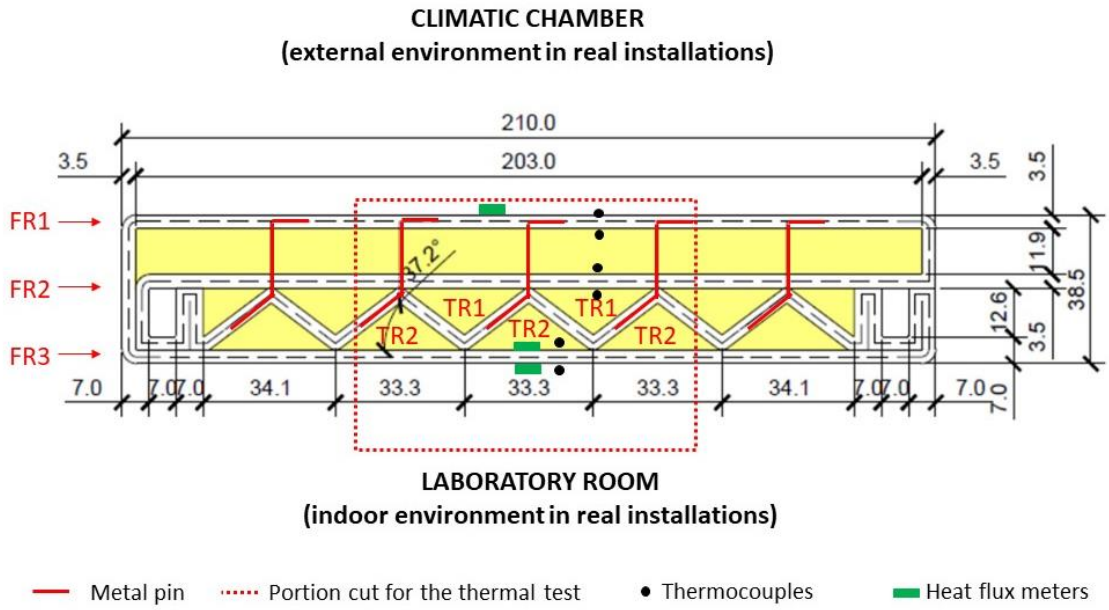

Figure 2. Wall cross section and dimensions (in centimetres). A portion of the wall (framed in the red dotted line) 1 m x 1m x 0.39 m has been cut and installed in the climatic chamber.

2. Methods and results

The aim of the experiments described in this paper is the preliminary evaluation of the thermal transmittance *U* of the 3D-printed wall shown in Figures 1-3. The experimental tests have been performed at the *Pisa Laboratory* at the University of Brescia. A real-size wall has been realized for structural analysis, and a square portion with a side length of 1 m has been cut to be tested in a climatic chamber. According to Figures 1 and 2, the analyzed structure consists of three walls connected through curbs and metal pins, forming cavities of different shapes - one rectangular and two triangular. The wall cavities have been filled with recycled material made of cellulose flakes obtained from newspapers, with a declared thermal conductivity of 0.038 W/mK [12]. Several degrees of filling have been analyzed, and results have been compared to the reference case represented by the empty wall. In this way, it has been assessed how different cavities filling degrees affect the wall thermal performance. The wall is made of a pre-mixed concrete product designed for 3D extrusion technologies: it consists of polymer fibers[a], and sand with a maximum diameter of 2 mm. The mortar ensures self-support during the printing phase, maintaining the shape envisaged by the starting 3D model, while at the same time ensuring excellent workability and progressive development of mechanical strength.

The structure analyzed is a portion of a larger wall realized for structural analysis. The wall has been installed in a climatic chamber, and thermocouples and heat flux meters have been installed in the wall as schematized in Figure 2. The wall is made of three parallel frames connected through curbs and metal pins to form three main types of cavity: in relation to the climatic chamber position, the two external cavities have a triangular shape, while the internal one is rectangular.

[a] Diameter of aggregates 0-2 mm. Bulk density of premixed powder 1.15 ± 0.15 kg/dm^3 [12].

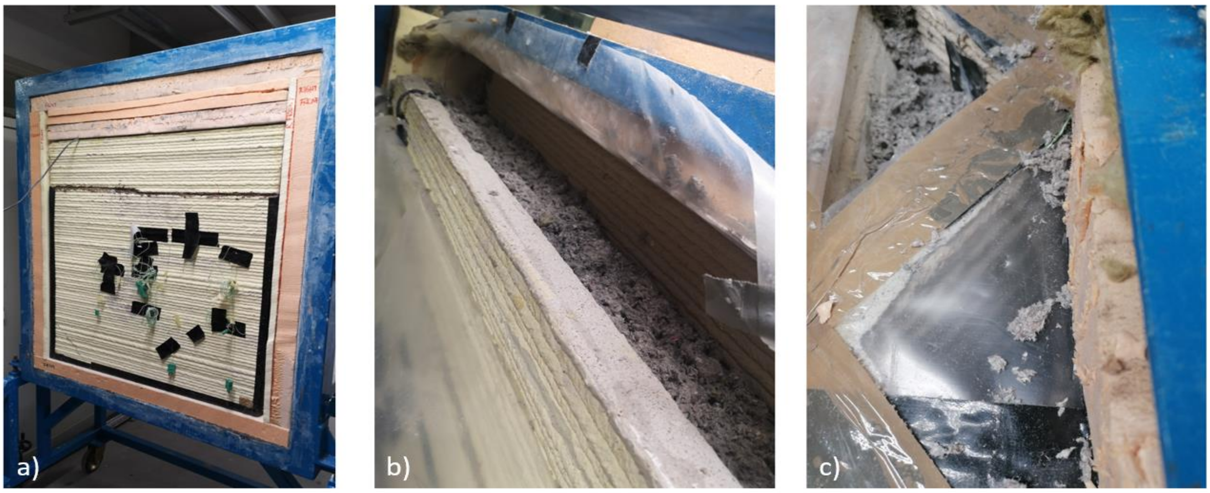

Figure 3. **a**) The wall has been mounted in a metal frame (in blue colour), and XPS panels (in pink colour) have been installed to limit lateral heat losses, **b**) the rectangular cavity filled with recycled cellulose flakes, **c**) each cavity has been sealed with impermeable plastic sheets to limit air circulation between adjacent cavities.

Table 2. Description of the tests performed in the climatic chamber.

Test name	Test description	Weight of insulation	Climatic chamber temperature	Laboratory ambient temperature
EMPTY	No insulating material in the cavities	0 kg	60.3±0.1°C	27.9±1.2°C
BIG	Insulating material in the rectangular cavity	4.2 kg in the rectangular cavity	60.5±0.2°C	24.6±0.8°C
TR_1	Insulating material also in the triangular cavities *TR1*	+ 2.9 kg in the *TR1* cavities	60.5±0.1°C	24.7±0.3°C
FULL	Insulating material in all the cavities.	+ 3.5 kg in the *TR2* cavities	60.5±0.1°C	25.5±1.0°C

As can be seen in Figure 2, the structure is 1 m x 1 m x 0.38 m in dimensions and consists of three parallel continuous walls – denoted as *FR1*, *FR2* and *FR3*. In real constructions, wall *FR3* faces the indoor environment. Walls *FR1* and *FR2* are connected using small metal pivots to form a rectangular cavity. Walls *FR2* and *FR3* are connected by inclined curbs which form two series of triangles denoted as *TR1* and *TR2*: the base of triangles *TR1* is located on wall *FR2*, whereas the base of triangles *TR2* is located on wall *FR3*. The metal pivots are B450C construction bars 6 mm in diameter. To limit lateral heat flux, XPS panels have been installed along the wall perimeter (Figures 3 a-b) and, to reduce air circulation between adjacent cavities, each of them has been sealed employing impermeable plastic sheets (Figure 3 c). The temperature measured along the wall is reported in Figure 4. During the tests, the temperature in the climatic chamber has been set at 60°C, while the external temperature (laboratory temperature) was maintained at about 25°C, with limited fluctuations that could not be prevented.

According to Table 2, four tests have been performed in which the cavities have been filled with insulating material made of flakes obtained from pure newsprint cellulose with a declared thermal conductivity λ of 0.038 W/mK [12]. In the test denoted as EMPTY, no filling was used so air could flow freely; however, the plastic sheets positioned at the top and the bottom of the structure reduced the air exchange among the cavities, even if it cannot be prevented completely. In test BIG, the rectangular cavity bounded by *FR3* and *FR2* was filled with 4.2 kg of insulating material (Figure 3 b). In test TR_1, the triangular cavities *TR1* were filled with 2.9 kg of insulating material, while cavities *TR2* were left empty (Figure 3 c). Finally, in test FULL, 3.5 kg of insulating material was added to *TR2* cavities. The different insulation weights have ensured the same material density in all the cavities. The structure was equipped with three thermal flow meters and K-type thermocouples, and two thermocouples have been used to measure the temperature in the climatic chamber and in the laboratory room respectively, as schematized in Figure 2. At each considered point, two thermocouples have been installed to determine the temperature.

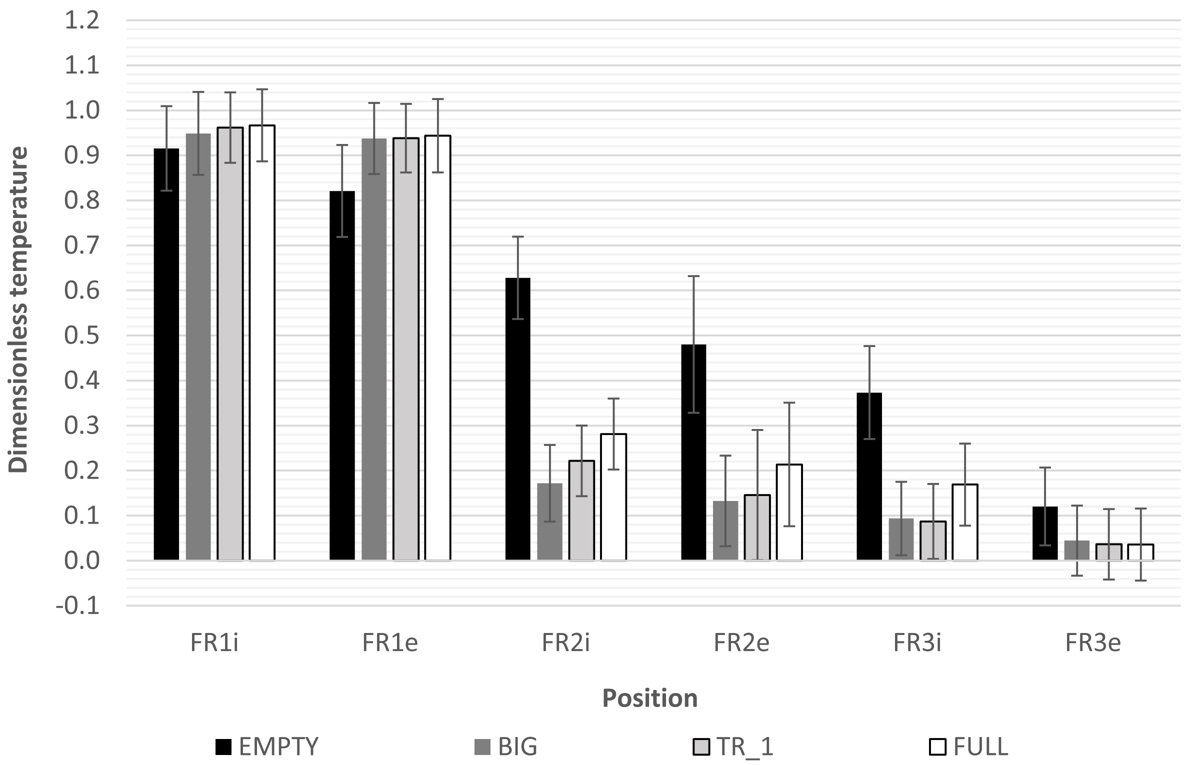

Figure 4. Temperature measured on the surfaces of the wall. The subscript '*i*' refers to the side oriented towards the climatic chamber, while the subscript '*e*' refers to the side oriented toward the laboratory. $FR1_i$ and $FR1_e$ have been measured on wall *FR1*, $FR2_i$ and $FR2_e$ on wall *FR2*, $FR3_i$ and $FR3_e$ on wall *FR3*.

The thermal transmittance *U* has been obtained as $U=q''/\Delta T$ where q'' is the specific heat flux measured by the heat flow meters, and ΔT is the difference between the temperature measured in the climatic chamber and the laboratory respectively. The specific heat flux q'' and the wall thermal transmittance *U* are reported in Table 3.

Table 3. Specific heat flux *q″* and thermal transmittance *U* measured for the different wall configurations.

CONFIGURATION	*q''* [W/m^2]	U [W/m^{2}K]
EMPTY	54.04 ± 1.42%	1.58 ± 0.03
BIG	12.16 ± 6.31%	0.34 ± 0.02
TR1	11.35 ± 6.76 %	0.32 ± 0.02
FULL	10.01 ± 7.67%	0.28 ± 0.02

The worst situation is the one with all cavities empty, as it entails the greatest thermal transmittance *U*. On the other hand, filling the largest cavity, reduces the thermal transmittance significantly, from 1.58 W/m^{2}K to values lower than 0.34 W/m^{2}K. This shows that preventing convective motion inside the rectangular cavity, that is, the largest one, is critical. By comparing the thermal transmittance *U* measured for configurations BIG, TR_1 and FULL, increasing the filling degree does not change the thermal performance significantly, since triangular cavities do not guarantee continuous and thick insulation. Moreover, as concrete is more conductive than insulating material, the heat flux through the curbs accounts for most of the heat transfer between *FR2* and *FR3*. By comparing the heat flux measured for case EMPTY with the others, the percentage reduction in the specific heat flux is 77.5% for case BIG, 79.0% for case TR1, and 81.5% for case FULL.

By comparing the measured thermal transmittance *U* with those imposed by the Italian regulation [10] and reported in Table 1, it emerges that filling the rectangular cavity with insulating material makes the wall suitable to be used in the Italian area, but other considerations need to be done to assess whether the overall heat transfer coefficient accomplishes the regulations. However, leaving the wall empty does not satisfy any of the climatic zones' requirements.

To better understand the influence of the filling on the wall's thermal performance, temperatures measured along the wall and shown in Figure 4 are analyzed. It is important to note that, as specified in Table 2, the laboratory temperature was not the same for all the tests, and this could have slightly affected the detected values. By analysing the temperature diagram, the greatest temperature variations through the wall occurred within the larger cavity ($FR1_e$ and $FR2_i$), and the greatest variation is detected for configuration BIG, as expected. Indeed, the rectangular cavity is the thicker one, and it is crossed by the metal pins only. For the configuration EMPTY, the temperature decreases along the thickness almost homogeneously. The temperature in the laboratory was comparable for the configurations BIG, TR1 and FULL, and the temperature measured on $FR3_e$ is almost the same. By analyzing the temperature detected at the position denoted as $FR2_i$, higher values are measured for a higher degree of filling. By comparing the temperatures detected for cases BIG and TR_1, emerges that filling the triangular cavity *TR1* does not affect the temperatures on the more external walls; however, given the lower thermal transmittance *U* detected, the filling is beneficial.

Heat transfer takes place by conduction, convection, and radiation. Convective motions may occur in empty cavities with a consequent increase of the heat transfer depending on cavity size and shape. Therefore, from a thermal point of view, a correct design must consider this aspect and ensure that convective motions are limited if not negligible, for example, by working on the cavities' shape and dimensions.

Therefore, 3D-printed walls need to be adequately insulated to meet the thermal insulation requirements that, however, depend on the considered location. The curb design should be done both from the standpoint of structural resistance and energy saving. For example, shapes that lengthen the path would reduce the thermal bridge effect. The thermal transmittance *U* can be reduced by substituting the metal pivots with plastic ones, to limit their thermal bridge effect. To improve the thermal performance also in the summer period characterized by important temperature fluctuations along the day, it would be advisable to consider heavy insulating materials to increase the temperature wave phase shift. As the cavities are closed, it is possible to use end-of-life materials as filling materials [14,15] that do not provide adequate fire protection if used individually, but which do not pose a problem if confined within the cavities.

3. Conclusions and future works

The paper presents the results of an experimental campaign performed on a 3D-printed wall that presents cavities that have been filled with recycled insulating material. In line with what is expected, the greatest degree of filling determines the lowest thermal transmittance value; however, the filling of more external cavities does not affect the thermal performance strongly. Results have shown that to meet the values of thermal transmittance U prescribed on the Italian territory, the cavities of the structure cannot be left empty, but a certain degree of filling is required. Since 3D-printed walls are light structures, to improve their thermal performance also in the summer period, when external ambient conditions are not stationary, it would be advisable to consider insulating material with high thermal capacity to reduce the periodic thermal transmittance. In this case, it will also be necessary to make assessments from a structural point of view. In the next phase of the project, experimental data will be compared with numerical results to validate numerical models capable of simulating the wall thermal behaviour.

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