Determination of the limit conditions as function of the thickness and inclination of the wall for 3D printed extrudable ceramic bodies

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Abstract

As for plastic materials printed by fused deposition model (FDM), the 3D printed ceramics obtained by extrusion process have their limitations in terms of geometry. As an example, the inclination of the walls that can be obtained without the use of support varies according to the thickness and number of layers, among other parameters. Using a delta 3D Printer for extrudable ceramic bodies, a series of terracotta conical pieces were printed varying the inclination and thickness of the workpiece and the consistence of the ceramic bodies (moisture content). This work constitutes a first step for the creation of algorithms for 3D printing by extrusion for different ceramic bodies, in a way analogous that it is find for in FDM printer for different plastic materials.

Key words: Additive Manufacturing; 3D Printing, Extrudable Ceramic bodies;

Introduction

Extrusion 3D printing, one of the additive manufacturing technologies for ceramic materials, also known as Robocasting, presents as a route of great potential for the dissemination and popularization of the production of ceramics of complex geometry. This is due to its low cost when compared to routes such as binder jetting onto successive layers of powders, photopolymerization of resins with high powder content (stereolithography), laser sintering and direct printing of suspensions trough print heads [1-4]. These additive manufacturing technologies besides extrusion, are mainly used to obtain technical ceramics with high performances in terms of mechanical and functional properties.

We begin to see this popularization with the development of extrusion systems with relatively simple software where artisans and ceramic artists can obtain pieces with geometries impossible to be obtained by traditional methods such as turning, slip casting and manual modeling. It is also pointed out that the ceramist can also intervene in the shaped piece, either by means of mechanical actions, or using englobes and glazes. One is also to consider obtaining pieces for decoration of interior walls of high relief with unique design, there already could be considered a production in small scale.

We would like to remind that the extrusion 3D printing process can also be used for the development of special high density ceramic products, requiring the use of more complex systems. As an example, the use of two extrusion nozzles, one for the base material (i.e.: Alumina or zirconia) and a second one for support material eliminated during sintering and subsequent dissolution in water or acid (i.e.: $CaCO_3$) [5]. It is also mentioned the obtaining of materials for application in odontology and medicine through the extrusion of alternating layers of different materials by means of bio plotters where piston extrusion is used.

The objective of the present work was to determine the maximum height of the workpieces that can be obtained without the use of support material in additive manufacturing by screw extrusion, as a function of the slope and thickness of the wall and the consistency of the ceramic bodies. The following parameters were set: extruder nozzle diameter, print speed and height of deposited layer for terracotta bodies. This is a first step in the creation of algorithms for extrusion 3D printing for different ceramic bodies, analogous to existing algorithms for the 3D printing of plastic materials used in fused deposition modeling (FDM) printers.

Preparation of the ceramic bodies

Terracotta bodies supplied by Paschoal Giardullo Massas® was used, with 7.8wt.% of residue retained in sieve of 100 mesh. The clay, packed in plastic bags, presented moisture contents varying between 23 and 26 %wt. After determination of the moisture content of the clay as received, batches of 2 kg of were prepared, adding the calculated amount of water gradually to obtain the desired consistency, concomitantly with kneading. After addition and mixing, the moisture content was determined again and, when were necessary, corrections were made by the addition of 10ml of water. The determination of the moisture content was done using infrared light drying device, and the samples were cooled in a desiccator before final weighing. Upon reaching the desired moisture the ceramic bodies were then placed in the printer reservoir, which is connected to the mini extruder by means of a flexible tube.

Printing of test pieces

The conical test pieces, starting with a base of 25mm, were printed using a screw extrusion 3D printer with a printable volume of 15cm diameter and 18cm height, model DuraPrinter E01, manufactured by WD Equipment Ltd. The pressure of 5 to 6 bar applied in the reservoir takes the clay to the mini extruder, whose variable speed motor ensures a constant feed of the ceramic bodies. Figures 1 show the screw extrusion 3D printer and fired terracotta ceramics obtained in the DuraPrinter "E" series.

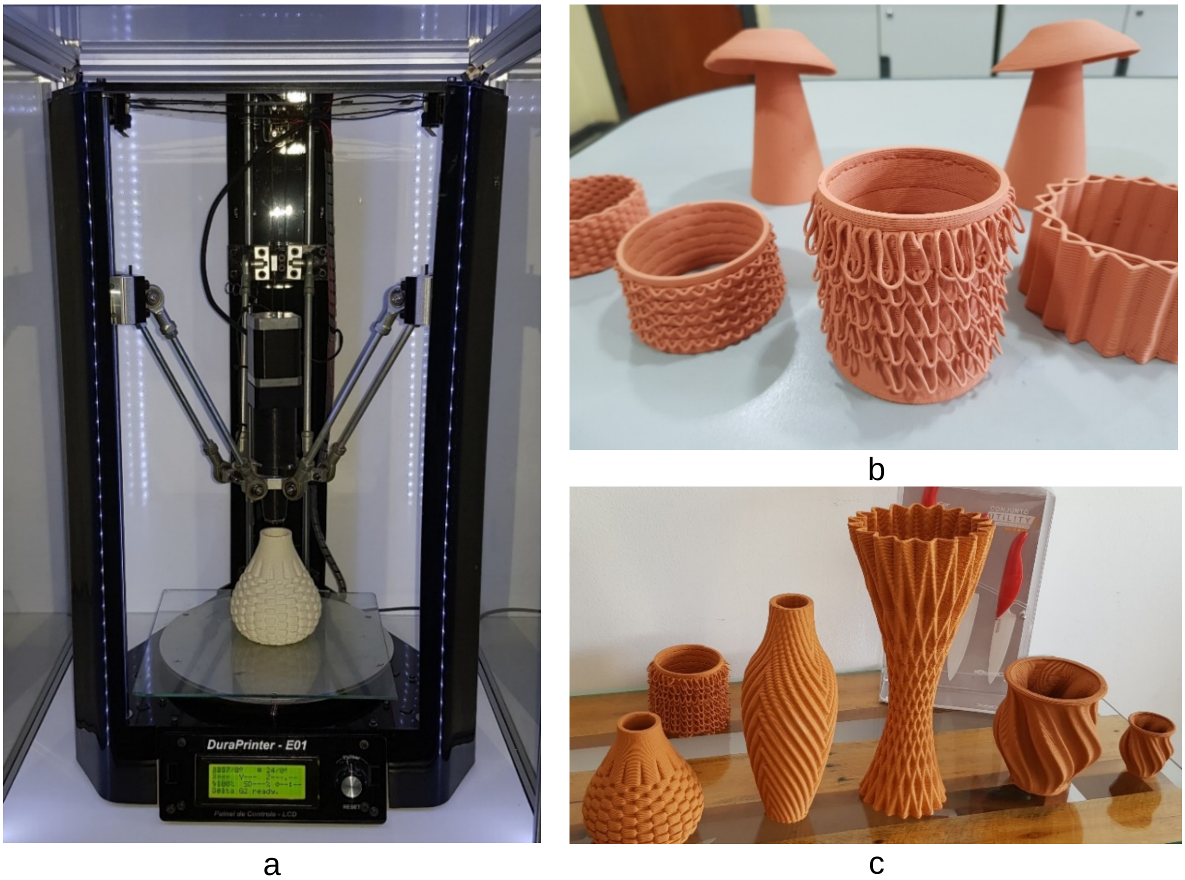


Figure 1 - (a) Screw extrusion 3D printer; (b) and (c) 3DP fired terracotta

In the first part of the work, the following parameter were fixed:

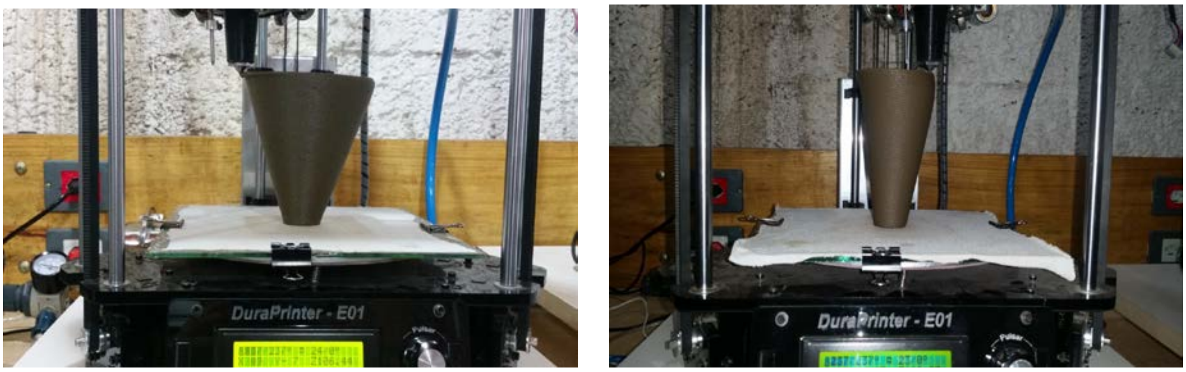
- Extruder nozzle diameter: 2mm;
- Height of the layer deposited: 1mm;
- Average printing speed: 20mm/s; and
- Moisture content: 29 wt.%.

The wall thickness was varied from 2 to 6mm by contiguous deposition of successive layers of 2mm, and the wall angle being varied from 0° to 60°. For each condition considered, three tests were performed, taking the average of the heights reached, except in cases where the difference of heights from the first to the second test was less than 5%. In previous work [5], it was observed that conical shaped test pieces without support structure collapse between 50 and 60 degrees in relation to normal. Thus, up to 50º the variation interval adopted was 10 by 10 degrees, becoming 1 degree from 50º until the collapse of the structure.

In a second phase, the ceramic bodies with different consistencies - 27wt%, 31wt% and 33wt% moisture content -, were tested at the maximum angle of inclination for each of the three wall thicknesses tested in the first part of the work, keeping constant all other printing parameters.

Results and discussion

Figures 2 and 3 show limiting situations for extrusion 3D printing without support, easily observable when working with cylindrical and conical structures. In Figure 2-a, for the impression of 2mm wall thickness, the maximum height reached for a conicity of 20º was 105mm, when it is no longer possible the deposit extrusion filament onto the previous layer. In Figure 2-b, for a conicity of 10°, deformation occurs due to the weight of the last layers from the height of 120mm, just before the structure collapses at a height of 128mm.



a b

Figure 2 - 2mm wall thickness (a) Conicity of 20º; (b) Conicity of 10º.

As it can be observed in Figure 3-a for a wall thickness of 6mm and 0° of conicity, the collapse of the structure occurs when it reaches 100mm in height, due to the low angle and the low value of the internal diameter/wall thickness ratio, when the test body follows the movement of the print nozzle. This is due to the fact that the shear stress of the material became higher than the limit value of the elastic zone, when permanent plastic deformation occurs. Similar effect, however to a lesser extent, can be seen in Figure 3-b, for a conicity of 10º, when deformation occurs from 100mm until collapses at a height of 117mm.

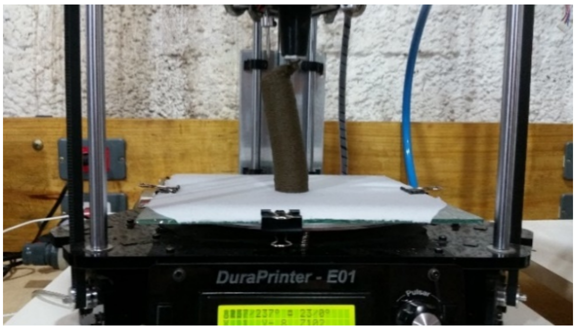


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Figure 3 - 6mm wall thickness: (a) Conicity of 0º; (b) conicity of 10°.

Figure 4 shows the data of test pieces with wall thickness of 2mm (1 layer), when it is observed the above 50º sharp change in the tangent of the “average maximum height Vs. angle of inclination of the wall in relation to the normal (conicity)” curve, where the superposition of the filament leaving the extruder nozzle becomes less and less effective.

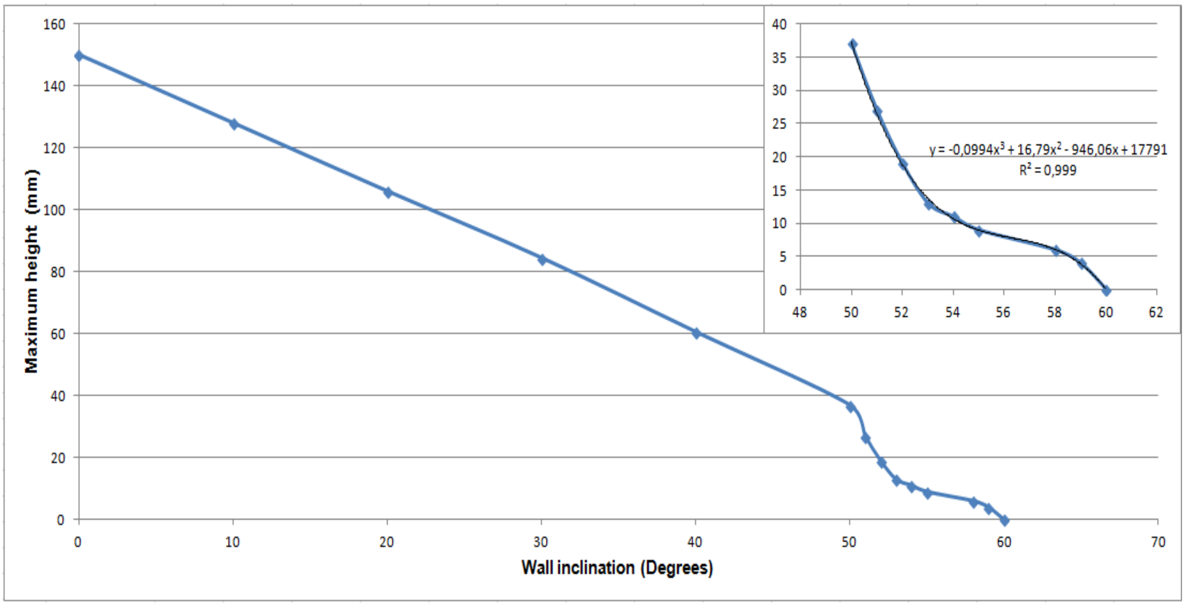

Figure 4 - Wall inclination Vs Test specimen height for 2mm wall (1 layer)

Figure 5-a shows quite clearly this sharp drop in the maximum height reached for at 51 degrees, when the overlapping of filaments layers become less and less efficient, which assume forms closer to the cylindrical, as can be seen most clearly in Figure 5-b.

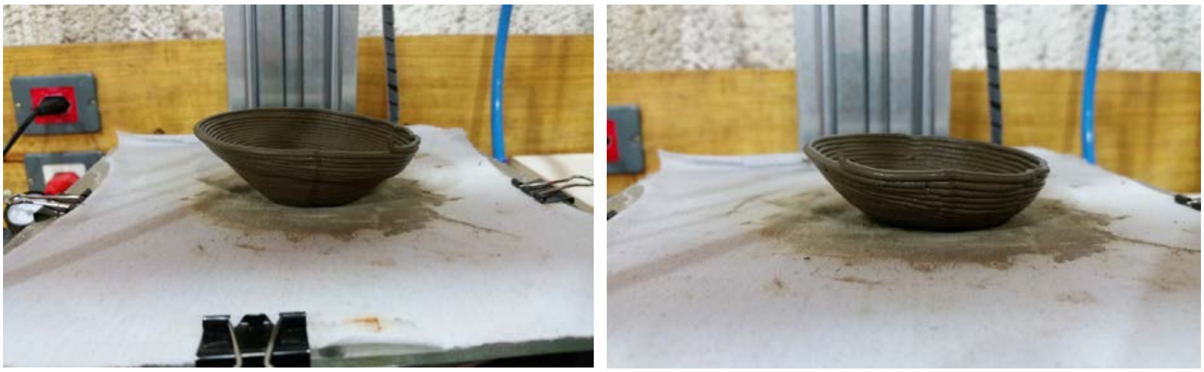

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Figure 5 - Collapsed specimens. (a) slope of 51º; (b) slope of 52°

Figures 6 and 7 show the results obtained for wall thickness of 4mm and 6mm, respectively with 2 and 3 layers of 2mm, with a marked increase in the maximum height of the specimen when compared to those obtained with a thickness of 2mm (1 layer). For wall thicknesses of 4mm and 6mm, it was only possible to print parts with a maximum inclination of 30 ° and 20 ° due to the limitation of the printing height of the 3D printer used.

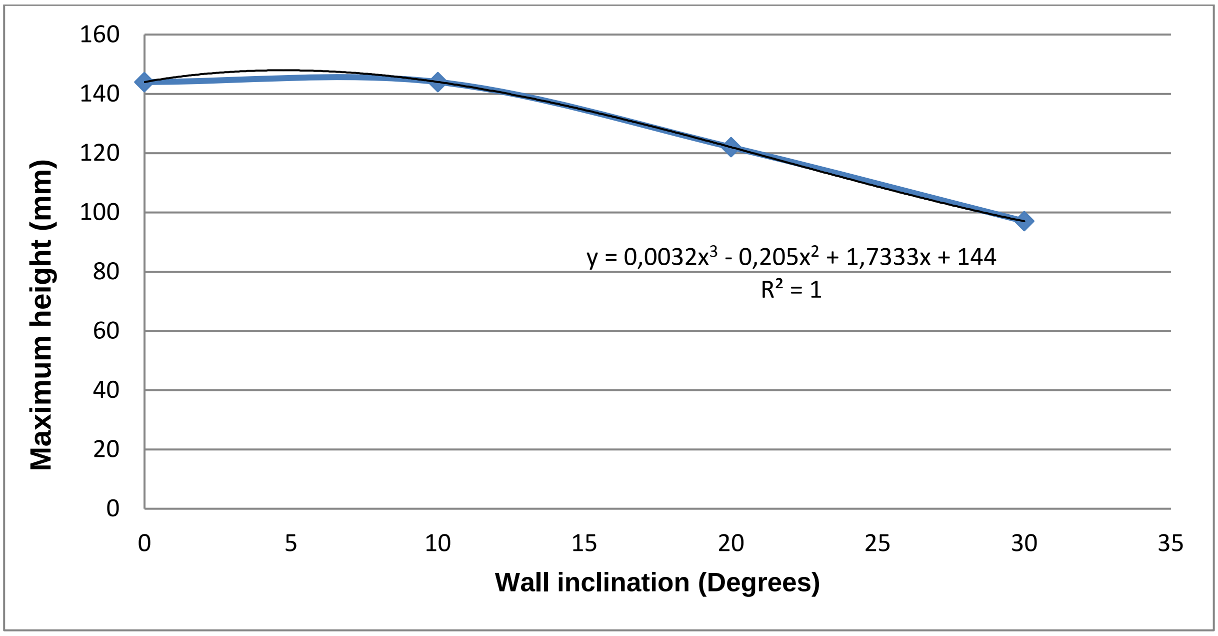

Figure 6 - Wall slope Vs Test specimen height for 4mm wall (2 layer)

There is a change of inclination of the curve "Maximum Height Vs. Conicity" for the 6mm print layer when compared to the 2mm and 4mm thickness curves due to the low angle and the low value of the internal diameter/wall thickness ratio when the test body follows the movement of the nozzle as shown in Figure 3.

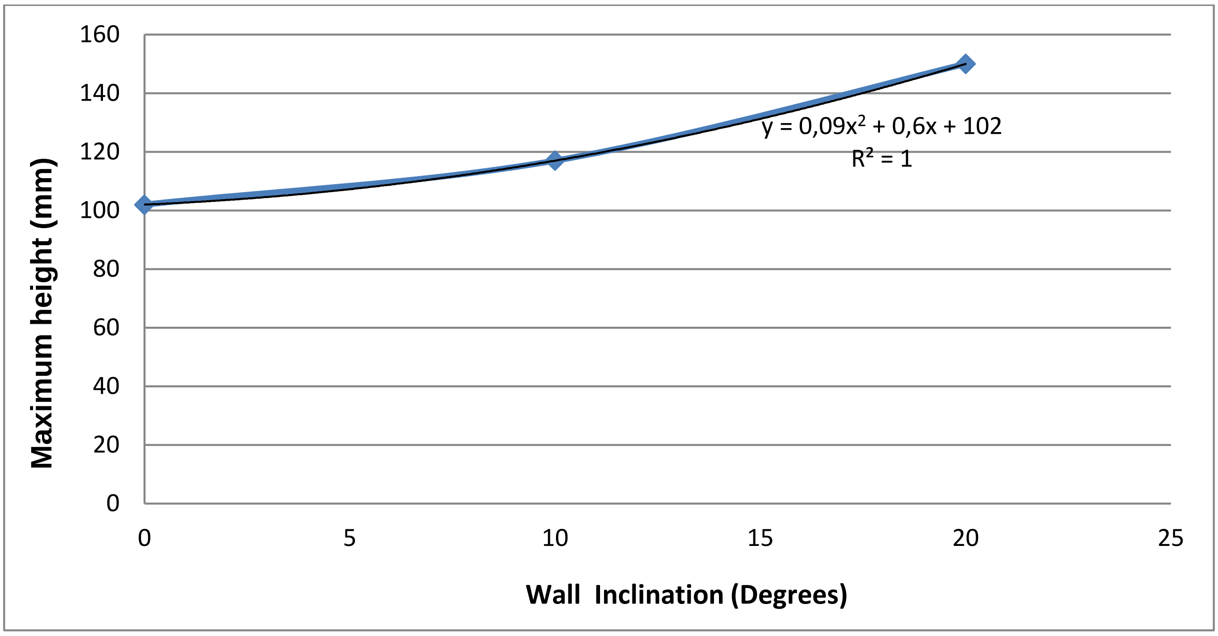

Figure 7 - Wall Inclination Vs Test specimen height for 6mm wall (3 layer)

To verify the influence of the consistency of the ceramic body on the behavior of the curve "Maximum Height Vs. Conicity", tests with a thickness of 2mm were carried out in bodies prepared with moisture content of 27, 31 and 33 weight percent. By observing the curves shown in Figure 8 (29wt%), tests were performed with slope of 10, 30 and 50 degrees, the latter being the limit before the collapse of the structure.

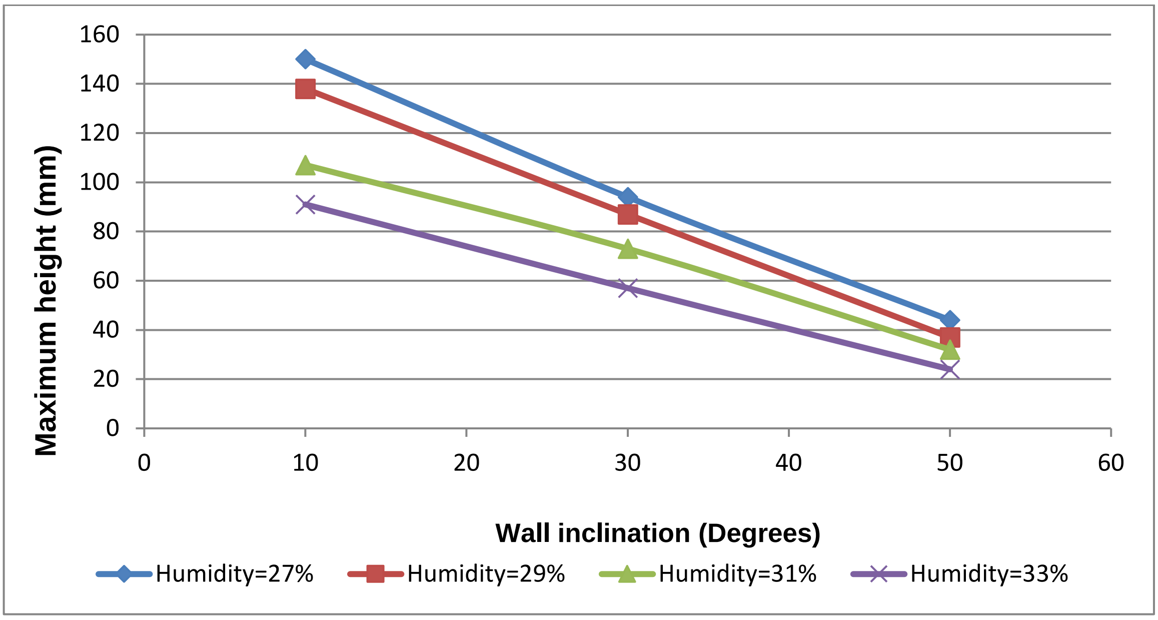

Figure 8 - Wall inclination Vs. Test specimen height - 2mm wall - different humidity.

As expected, the increasing percentage of water in the ceramic bodies causes a decrease of the of the printed structure, as can be observed in Figure 8. Although the specimens with water content of 27% presented better results in relation to the others, a significant increase in extrusion pressure was observed.

Conclusions and proposed futures works

The results obtained constitute an important tool for the design of terracotta ceramic pieces to be obtained via 3D printing by extrusion process, also known as Robocasting. For ceramic terracotta bodies with 29% humidity, a wall angulation of more than 50° generates difficulties in reproducing the design geometry in 3D to be printed, as well as a decrease in the height of the pieces to be printed without support material. Above 29% humidity the limits of height and inclination of the walls become smaller and smaller.

From the systematic survey of the behavior of other tri-axial ceramic such as porcelains and stoneware, correlated with a measurement of a parameter of the ceramic bodies that represents their intrinsic rheological behavior, we consider that it will be possible to construct algorithms to be taken as the basis for the determination of the parameters recommended for a given ceramic body to be printed.

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