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# Mortar for 3D printers using river sand, Portland cement and hydraulic lime

**Key words:** 3D printing, mortars, hydraulic lime, resistance, compression

## Introduction

The 3D printing in concrete is a new, economically sustainable system that provides multiple advantages such as speed, automation and therefore the optimization of the process. Also, the independence of human labor during execution would reduce labor costs and risks (Hager, Golonka & Putanowicz, 2016).

Currently there are several companies that have bet big capital in the world of printing according to Campillo Mejía (2017). The printable materials for construction can be concrete (mixture of cement, gravel, sand and water) or mortars (mixture of cement, fine aggregate and water). The mortars for these printers are made according to the characteristics that the developer requires without reaching a standardization nor to define the minimum desirable properties of the materials for this new technology, which prevents its application in a massive way (Wu, Wang & Wang, 2016). Consequently, many researchers begun to make several mortars with different types of raw material taking into account that the main basis of all of them are Portland cement mixed with other materials such as aggregate, natural fibers or synthetic fibers, many combinations have been tested (Altamirano, Cuevas & Sanchez, 2015).

The properties of the material to be printed became a main element in the 3D printing process in construction (Malaeb et al., 2015) and many studies have been developed on this issue. The properties of a concrete made with fly ash, silica fume and fibers, developing a printable mortar, with constant flow and other mechanical properties such as the compressive strength of the material were studied by Le et al. (2012). The variation of the physical and mechanical properties of the mortar depending on the type of cement used were analyzed by Khalil, Aouad, El Cheikh and Rémond (2017), and Salguero (2018). They produced mortars with ordinary Portland cement (OPC) and calcium sulfo aluminate cement (CSA), however, the printed samples exhibited a variable compression resistance at different points, due to the additional porosity related with the workability of the mixture. From the cited studies it is clear that mortars for use in 3D printing must comply with some properties before their settlement such as workability, adherence and speed of setting; and other properties after their settlement such as compressive strength, being the latter the main characteristic considering the structural behavior of the printed elements.

The technology and the methods of construction by means of 3D printing have had a remarkable advance in the last decade, from the first elements printed in a workshop and that later had to be assembled in site, until the appearance of the portable printers that allow the total elaboration of the constructions on site (Torres Remón, 2016). Nevertheless, it is important to have local materials that allow the execution of buildings at low cost and efficiently, these materials must have good properties of workability, setting and resistance (Sakin & Kiroglu, 2017). This construction technology that uses cement mortars, among other materials, is spreading worldwide and will soon arrive in Ecuador. Little has been researched about the capacity of local materials to satisfy the need for 3D printing, although the systematic application of mixing designs, with appropriate adjustments for local materials is an imperative for the development of this technology (Van Zijl & Tan, 2017).

To fill this gap, the objective of the present research was to investigate the conditions of workability, setting and strength of four mortars made with Portland cement types I and HE with the addition of hydraulic lime. In this way, it seeks to reduce the limitations faced by construction based on 3D printing, while developing new materials that may possibly offer different properties for the construction industry.

## Material and methods

First, the research team explored suitable dosages that according to the literature allows to design a printable mortar. Considering the results obtained by the dosage used by Salazar (2016), it was taken as a reference to prepare 50 kg of cement mortar: 62.25 kg of sand, 50 kg of Portland cement, 17.3 kg of water and 0.13 kg of plasticizer. Mentioned dosages were elaborated with types I and HE cement, fine aggregate, plasticizer additive and water with the addition of different percentages of hydraulic lime. In addition, based on this information, seven pilot dosages were elaborated and tested for compression strength, based on the ASTM C39-05 standard (American Society for Testing and Materials, 2005).

### Analysis of physical properties

**Moisture content.** The ANSI/ /ASTM D2216-71 test procedure (American National Standard Institute/American Society for Testing and Materials, 1979) suggests to obtain the moisture content of a soil. A representative portion of fine aggregate is placed in a previously weighed container, then it is introduced to the drying oven, maintaining a temperature of 110°C for 24 h. Then, the dry weight is obtained and the moisture content is calculated.

**Granulometry.** The ASTM D422 test procedure indicates drying a sample of river sand to obtain a constant mass at a temperature of 110°C, take 1,000 g of the sample and place it in a series of sieves located downwards: Nos 4, 8, 16, 30, 50, 100, 200 (American Society for Testing and Materials, 2014).

### Analysis of mechanical properties

**Short-term compression resistance test.** Sixteen test tubes were manufactured for each proposed dosage. These specimens have a cubic form of 50 × 50 mm, the same ones that were tested under compression at early ages, such as 6, 9, 12 and 24 h, following the procedures of the ASTM C109/C109M-07 standard (ASTM, 2007).

**Long-term compression resistance test.** As experimental knowledge, 64 specimens were prepared, 16 for each type of mixture in the form of standardized cylinders of 10 cm in diameter by 20 cm in height, to be tested in compression. The samples were subjected to a water cure and were tested by compression at ages 7, 14, 21 and 28 days.

**Workability.** To measure the workability of the mixtures, ASTM C187-04 standard (ASTM, 2004) was used, the test determines the consistency of the mortar in its fresh state. It is important to define the exact time in which the conical mold rises to produce the runoff, this is a variable defined by the decrease or increase in the diameter of the stabilized mixture as time increases.

### Statistical analysis

Finally, after carrying out the described tests, statistical analyzes were performed using the software Minitab 16 (MiniTab Inc. PA, USA), in order to obtain descriptive information on the mixtures developed.

## Results and discussion

The results obtained based on the dosage of Khalil et al. (2017) by variating amounts of lime and plasticizer, and cement type are detailed in Table 1.

### Moisture content

Results of moisture content measured in nine river sand samples are shown in Figure 1. The average water absorption of 1.86% was taken as representative value for mortar design, considering the low variability. It is considered appropriate that the percentage of absorption is less than 5% in fine aggregates for mortar uses.

### Granulometry

Table 2 indicates a value of fineness modulus of 2.66 and the results that are within the limits established by the ASTM C33-03 standard (ASTM, 2003), not inferior to 2.3 nor superior to 3.1. Therefore, it can be expected that the material presents good workability and texture.

### Organic content in fine aggregate

This test was performed under the ASTM C33-03 standard (ASTM, 2003), which showed a similarity with color 1, a sample is presented in Figure 2.

TABLE 1. Pilot dosages for 50 kg of cement

| Specification | Sand | Cement | Lime | Water | Additive |
|---|---|---|---|---|---|
| | kg | | | | |
| Dosing for cement I with water percentage correction | 62.25 | 50.00 | 0.00 | 25.44 | 0.14 |
| Dosage 1 plus 10% lime in relation to the percentage of cement | 69.72 | 50.00 | 5.00 | 28.27 | 0.15 |
| Dosage 1 plus 7% lime in relation to the percentage of cement | 67.19 | 50.00 | 3.50 | 27.36 | 0.15 |
| Dosage 1 plus 12% lime in relation to the percentage of cement | 71.55 | 50.00 | 6.00 | 28.91 | 0.16 |
| Dosing for cement I with correction of the percentage of plasticizer and water | 62.25 | 50.00 | 0.00 | 21.00 | 1.00 |
| Dosage for HE cement with correction of the percentage of plasticizer and water | 62.25 | 50.00 | 0.00 | 20.75 | 1.00 |
| Dosage for cement I with correction of the percentage of plasticizer and water | 62.25 | 50.00 | 0.00 | 24.05 | 0.50 |

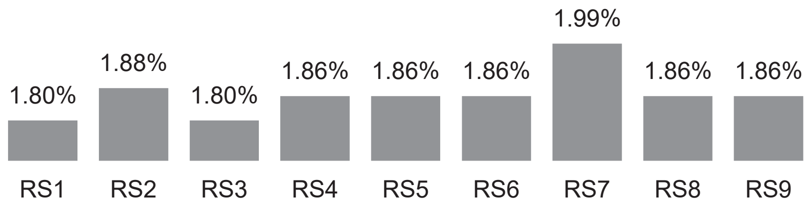

FIGURE 1. Moisture content in river sand samples

TABLE 2. Summary of the granulometric test of fine aggregate

| Specification | Partial retention | Accumulated retention | Crosses |
|---|---|---|---|
| | % | | |
| Sieve 4 | 0.00 | 0.00 | 100.00 |
| Sieve 8 | 0.10 | 0.10 | 99.90 |
| Sieve 16 | 14.20 | 14.30 | 85.70 |
| Sieve 30 | 22.80 | 37.10 | 62.90 |
| Sieve 50 | 28.30 | 65.40 | 34.60 |
| Sieve 100 | 20.50 | 85.9 | 14.10 |
| Sieve 200 | 9.80 | 95.7 | 4.30 |
| Tray | 4.30 | 100.00 | 0.00 |
| Fineness module | | 2.66 | |


FIGURE 2. Collation through a color plate for the analysis of organic matter content in the fine aggregate

## Mechanical properties

The results of compressive strength for each of the dosages are shown in Figure 3. As can be seen in Figure 3, the higher strength was obtained with the D6 for cement type HE, it has a compressive strength remarkable superior to the other dosages for 7, 14, 21 and 28 days age. Following, the best dosage with cement type I is the D5. The inclusion of lime to 10% does not significantly affect the compressive strength of the mortar made with cement type I (D3, D4 and D5). However, it produces lower resistances than without the use of lime. Table 3 lists the final dosages selected for this research work.

## Workability

The results of the ASTM C187-04 test are summarized in Table 4. The diameters of workability have a tendency of decreasing in time, which means that there is no runoff and mixtures are stabilized immediately. Mortar M-0-HE starts with a diameter of 22 cm and reaches a 16 cm one, complying with the norm that is 15 cm, which is considered as a minimum diameter for good workability (Table 4).

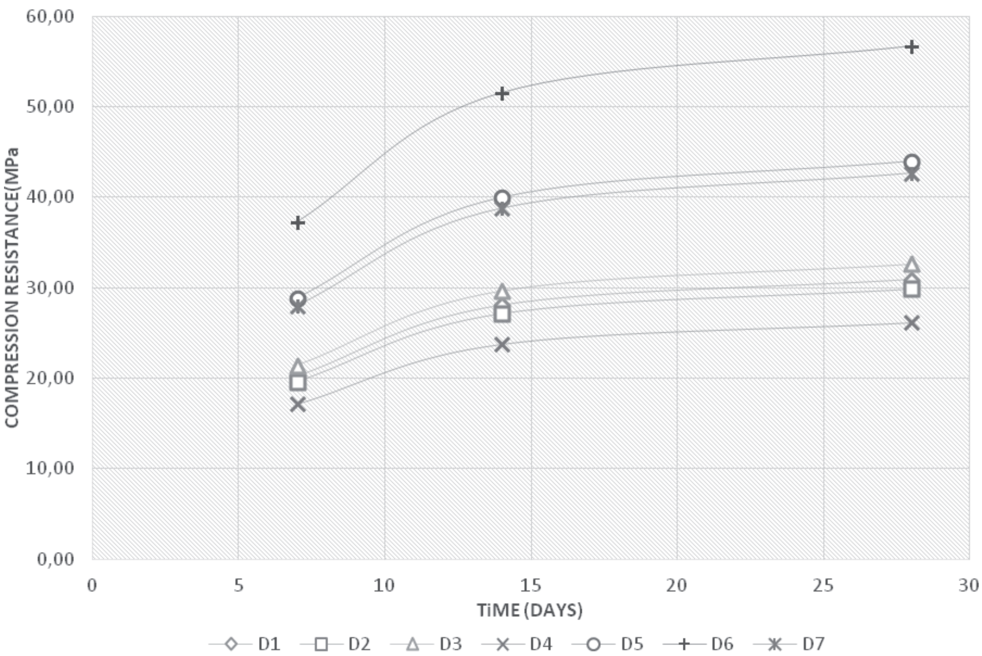


FIGURE 3. Evolution of the long-term compressive strength

TABLE 3. Summary of dosages

| Mortar | Cement type | Sand | Cement | Lime | Water | Plasticizer |
|---|---|---|---|---|---|---|
| | | kg | | | | |
| M-0-I | Portland cement type I | 62.25 | 50.00 | 0.00 | 21.00 | 1.00 |
| M-7-I | Portland cement type I | 67.2 | 50.00 | 3.50 | 25.45 | 1.00 |
| M-0-HE | Portland cement type HE | 62.25 | 50.00 | 0.00 | 20.75 | 1.00 |
| M-7-HE | Portland cement type HE | 67.2 | 50.00 | 3.50 | 22.45 | 1.00 |

TABLE 4. Established diameters to evaluate workability

| Time [min] | Diameter [cm] | | | |
|---|---|---|---|---|
| | M-0-I | M-7-I | M-0-HE | M-7-HE |
| 1 | 21 | 18 | 22 | 19 |
| 2 | 19.5 | 16 | 19.5 | 16.5 |
| 3 | 19 | 15 | 18 | 15.5 |
| 5 | 16.5 | 14.8 | 16 | 14.3 |

**Resistance to short-term compression**

A statistical analysis of significance for the results of the test was carried out on 64 cube samples, values that are shown and analyzed from Figure 4 and Table 5.

In Table 5, it is observed that the mortar M-0-HE presented the best compression result at 24 h of setting and is also superior to the others, while the mortars M-0-I and M-7-I they are partially the same; as well as the significant difference of each one of the obtained values is identified.

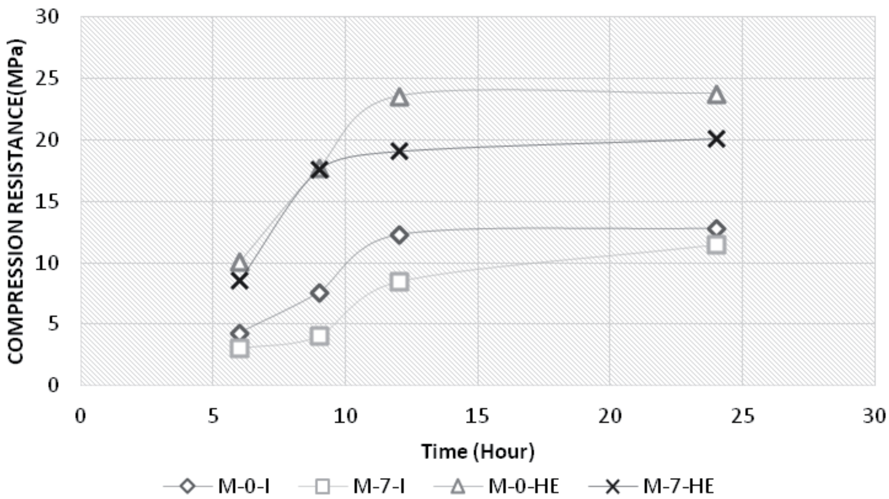


FIGURE 4. Evolution of short-term compressive strength

TABLE 5. Statistical analysis of specimens tested in the short term

| Hour | Specification | M-0-I | M-7-I | M-0-HE | M-7-HE |
|---|---|---|---|---|---|
| 6 | average compression resistance [MPa] | 4.08 | 3.04 | 10.11 | 8.59 |
| | deviation E | 0.23 | 0.33 | 0.22 | 0.39 |
| | letter | C | D | A | B |
| 9 | average compression resistance [MPa] | 7.60 | 4.05 | 17.73 | 17.58 |
| | deviation E | 0.30 | 0.27 | 0.84 | 0.39 |
| | letter | B | C | A | A |
| 12 | average compression resistance [MPa] | 12.29 | 8.45 | 23.56 | 19.01 |
| | deviation E | 1.34 | 0.75 | 0.25 | 0.87 |
| | letter | C | D | A | B |
| 24 | average compression resistance [MPa] | 12.81 | 12.30 | 23.80 | 20.16 |
| | deviation E | 0.39 | 0.58 | 0.80 | 1.06 |
| | letter | C | C | A | B |

A, B, C and D indicate significant differences through the Tukey test ($p < 0.05$).

## Resistance to long-term compression

The results of ASTM C39-05 test carried out on 64 specimens are shown in Figure 5 and its summary of data in Table 6.

It can be seen in Figure 5, that the four types of mixtures show different results during the analyzed period, with the mortar M-0-HE having the highest resistance to compression at 28 days with a remarkable difference. The results of Tables 5 and 6 after analyzed, it can be said that the mortar with the higher resistance to compression in the short and long term is the mortar M-0-HE, due to the type of cement used (type HE). This cement has less quantity of bicalcium

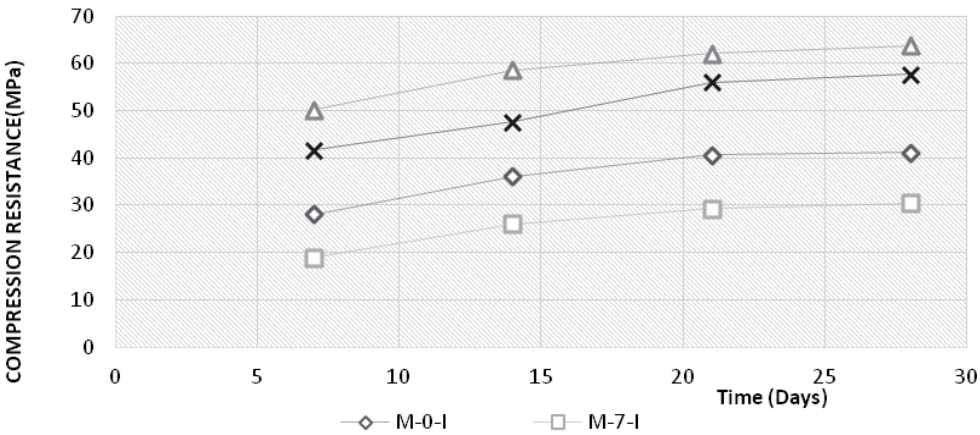


FIGURE 5. Evolution of long-term compressive strength

TABLE 6. Statistical analysis of long-term tested specimens

| Day | Specification | M-0-I | M-7-I | M-0-HE | M-7-HE |
|---|---|---|---|---|---|
| 7 | average compression resistance [MPa] | 21.46 | 19.09 | 37.97 | 42.39 |
| | deviation E | 1.63 | 1.25 | 0.82 | 2.30 |
| | letter | C | D | A | B |
| 14 | average compression resistance [MPa] | 31.10 | 25.50 | 52.92 | 46.96 |
| | deviation E | 1.64 | 0.89 | 0.43 | 1.04 |
| | letter | C | D | A | B |
| 21 | average compression resistance [MPa] | 37.63 | 26.56 | 58.54 | 55.40 |
| | deviation E | 1.22 | 1.94 | 0.92 | 2.36 |
| | letter | C | D | A | B |
| 28 | average compression resistance [MPa] | 40.80 | 29.80 | 61.67 | 55.73 |
| | deviation E | 1.17 | 1.05 | 0.98 | 2.40 |
| | letter | C | D | A | B |

A, B, C and D indicate significant differences through the Tukey test ($p < 0.05$).

silicate (C2S) which causes high early resistance and increase at advanced ages, thus confirming what is stated in the literature. It is noticeable that all the results achieved exceed the specified value of a structural concrete that is 21 MPa, which is an advantage that must be exploited for the use of these mortars in other applications. Moreover, the mortar M-0-HE has the best results due to its better workability and optimal long and short term resistance, aiming to printability. Nonetheless, mortars including lime (M-7-I and M-7-HE) has in average a 10% less compression strength resistance at similar ages than non-lime mixtures.

FIGURE 6. Mortar test in 3D printing

Figure 6 presents an image of the results of the various preliminary tests of the mortars designed in this investigation.

## Conclusions

With the local materials used in this research it was possible to obtain a mortar suitable to be used in 3D printers, since it meets the required parameters of workability and compression resistance. The mortar that presents better mechanical characteristics to be used in 3D printers is the sample M-0-HE composed of Portland cement type HE of high resistance and river sand. However, the remaining mortars can also be tested for printing process since their characteristics are in accordance with the stipulations for such purpose.

The inclusion of hydraulic lime to the mortar mix reduces the compressive strength of the studied specimens.

The dosages developed in this research were composed of a high content of cement, resulting in high cost, however, more components could be added to the mixture that can partially supply the cement and that can preserve or improve the properties of the mortars.

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## Summary

**Mortar for 3D printers using river sand, Portland cement and hydraulic lime.** The 3D printing is a construction technology that uses mortar to make elements and structures. In this research, four types of mortar were elaborated using Portland cement types I and HE, adding hydraulic lime. Mortars with cement types I and HE without hydraulic lime presented higher resistance to compression than mortars made with lime. The four mortars had an adequate resistance to compression and features that are suitable for use in 3D printers.

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