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TESTING PROCEDURES ON MATERIALS TO FORMULATE THE INK FOR 3-D PRINTING

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Abstract:

3-D printing has been used in various fields to tackle applications difficult for conventional manufacturing. To realize the full potential of this technology in the transportation sector, it is imperative to identify suitable tests and mixtures for printing inks made of mortar. In this study, several conventional and non-conventional tests on mortars and cement pastes are conducted. This work highlights the correlation between the slump and the deformation test, which indicates to the comportment of the mixture under a stack of printed layers. Moreover, a strong connection between yield stress and mini-slump is observed demonstrating a simplification of the testing procedure and a link between the mortar and the cement paste is developed. In the printing ink design phase, this association enables the prediction of the flowability. The yield stress and the final radius of the mini-slump tests were very well correlated for the admixture tested. The use of the mini-slump test simplifies the testing procedure and allows for quicker formulations of admixtures in the printing ink.

1. INTRODUCTION

Additive manufacturing has gained the interest of a number of industries in the past few years. It has been proposed that the transportation field take advantage of this new technology to build infrastructure. A preliminary project at BAM Infra, in collaboration with the Technical University of Eindhoven, printed a bridge in the Netherlands which was built in pieces and assembled on-site. This mode of production has many benefits including improved energy efficiency, project and resource management, and manufacturing safety due to the absence of formwork [1, 2]. Furthermore without formwork there are fewer wastes. In fact 35% to 60% of a concrete structure price is due to the required formwork [3]. Additionally, without the constraints of conventional formwork, alternative architectural and structural geometries can be considered. The 3D printing technology is not without its drawbacks, which come primarily in the ink material requirements. While classic manufacturing of concrete structure often uses flowable concrete like Self Compacting Concrete (SCC) in order to fill formwork [4], the field of additive construction requires more shape stable materials [5, 6]. The printable mortar, also called ink, has to be able to maintain shape under both its own weight and that of sequentially deposited layers. To further complicate the field, the terms "flowability" and "stability" are rarely rigorously defined. Further advancement of this application requires a precise and measurable characterization procedure.

Studies in digital manufacturing have used the flowability to describe a material's capacity to enter a fluid state and the stiffness to explain its resistance to flow. Standardized tests have been designed to quantify this information about mixtures. The slump test conducted with the Abrams cone [7, 8], the flow test described in the standard ASTM C1437 [9] and the mini-slump test operated with a mold of various shapes

[10-13] are easy to implement and can be conducted respectively on the concrete, the mortar or the cement paste. For the mini-slump a smaller version of the Abrams, which respects the same proportion cone is used [10, 14, 15]. Advanced technological devices, such as rheometers, have been used to measure intrinsic values of these materials, such as viscosity or yield stress [16, 17]. Academic studies often focus on the link between concrete behavior and the rheological properties of cement paste. However, rheometers are limited in industrial practice due to their cost and difficulty to use compared to conventional tests.

In this study, three tests are conducted on mortars (as a printing ink) and two tests on cement paste. For the mortars, the slump, the flow and the deformation under an applied force designed to simulate a 3D printing situation are performed. For the cement pastes the mini-slump and rheological characteristics are measured. Regressions are calculated between mortar, cement and both, in order to link the different results to be able to predict the comportment of mortar with the easiest information we can get. Moreover the presence of different admixtures is analyzed in view of the results on cement.

2. MATERIALS

2.1 Materials properties

A binary cement with silica fumes (GUb-8SF) of specific gravity is 2.8 is used in this study. The sand is a local sand with a specific gravity of 1.65. The water used is tap water.

2.2 Admixtures

Several admixtures are tested. The solid content of the admixtures is determined according to ASTM C494 [18]. Results are presented in Table 1. A superplasticizer (SP) is added to increase the workability of each mixture. The accelerator (A) also increases the workability. The strength-enhancing admixture (X) is a CSH-seed admixture which is known to improve cement hydration and enhances workability. Nanoclays (C) is used to increase the stability of the mix. A viscosity modifying agent (VMA) was also tested to observe its impact mixture. For each mix the procedure of the addition of the admixtures is always the same: they are added to the water in the mixer, as in the ASTM mixing procedure.

2.3 Methodology

2.3.1 Experiments on mortars

2.3.1.1 Small Abrams cone

A cone shaped proportional to the standard Abrams cone for concrete slump test is used. It is 150 mm high, the diameter of the bottom and the top opening are respectively 100 mm and 50 mm. The cone is filled with three layers of mortar 2 minutes after the end of the mixing procedure. Each layer is approximately one third of the volume of the mold and is tamped 25 times with a rod as recommended in the ASTM C143 for Slump of hydraulic-Cement Concrete [8]. The mortar is leveled with the top of the mold. The cone is removed slowly enough to avoid inertia issues (< 0.005 $m.s^{-1}$) [11, 12]. The test is conducted on an acrylic glass plate as proposed by [12] marked with a 2 x 2 cm^2 grid. The slump is measured between the maximum height of the mold and five points on the surface of the cone, as illustrated on Figure 1.

2.3.1.2 Flow test ASTM C1437

Another test is described by the ASTM C1437 [9] for information about the consistency of hydraulic cement mortar. The mortar is unmolded on a special table, which is dropped 25 times in 15 s. The flow of each mix is recorded with the caliper specify in the standard along four diameters described on the table. This test was conducted 1’40’’ after the end of the mixing procedure. The flow is expressed as a percentage of the original base diameter. Equation (1) describes the calculation method.

$$Flow = \frac{Average\ of\ four\ base\ diameters - original\ base\ diameter}{original\ base\ diameter} \times 100 \quad (1)$$

2.3.1.3 Stability test

The stability of the fresh mortar is determined using a method inspired by [6] and [19] that proved that this procedure can simulate the stacking of several layers on each other. A 35 mm high and 60 mm diameter cylinder is molded and immediately unmolded. A plastic tape placed on the wall of the mold still maintained the cylinder until the beginning of the test. After removing the tape, a thin galvanized steel plate is gently put on the top of the cylinder in order to allocate the forthcoming load on the surface. Then a photograph of the cylinder is taken and the height is computed with the picture processing software ImageJ, using a ruler placed on the photo to calibrate the scale (Figure 2.a). The test is conducted controlling a hydraulic press squeezing the cylinder at a constant rate of 1 mm/min. The force is recorded with a 0 to 100 N load cell at a sampling rate of 5 Hz. The press is stopped at 95 N and another photograph of the cylinder is taken. Its height is computed following the same procedure as for the first picture (Figure 2.b). This test is conducted 10 min after the end of the mixing procedure.

2.3.1.4 Mix design of mortars

For the comparison of each mix of mortar, the water / cement ratio is kept at 0.345 and superplasticizer (SP) is added at 0.26 % by weight of cement. For each mix, the admixture residue by oven drying is determined and the corresponding amount of water present in it is subtracted to the total water added. Considering the fact that the final goal is to have a printable mortar, the sand / cement ratio is kept at 1.8 to optimize the amount of paste in the mix in order to enhance its pumpability [2, 20-23]. A 2-level full-factorial design is created to allow each of the four admixtures to be tested in all configurations. This results in 2^4 different mixes. All the mixes are reported in Table 2.

2.3.2 Experiment on cement pastes

2.3.2.1 Mixing procedure and mini-slump of the cement paste

Mixing procedure

In order to achieve a good dispersion of the different admixtures in the paste, the mixing procedure was completed following ASTM C1738. The paste obtained with this standard is expected to have rheological properties analogous to a concrete without its aggregates [24, 25]. A high shear mixer with a water-cooling system is selected to fill the specifications needed. At first, the water and the admixtures are added in the mixer and the temperature is controlled at 23 °C ± 2 °C. Then the cement is poured within 60 s. The mixer is turned on for 30 s at a speed of 10 000 rpm. The paste is allowed to rest for 150 s. Finally the paste is mixed at 10 000 rpm for 30 s.

Mini-slump test

The mini-slump test consists of filling a cone with freshly mixed cement paste and lifting it slowly to allow the paste to flow under its own weight. The cone is a smaller version of the Abrams cone used for slump tests. The mold was designed and 3D printed to form cones of the following dimensions: top diameter, 19 mm; bottom diameter, 38 mm; height, 57 mm [12, 14, 15]. It is placed on an acrylic plate marked with squares of 20 x 20 mm² (Figure 3.a).

First, cement is pumped into a syringe from the mixer and poured into the mini cone. At 2 min after the end of the mixing, the cone is removed and 5 s later a photo is taken from the top of the set-up (Figure 3.b). A second photo is taken 5 min later. Four diameters are measured via ImageJ, an open source photo-processing software, using the grid for scale. The mini-slump (MS) is computed using Equation (2).

$$MS = \frac{(mean\ of\ four\ diameters - inside\ base\ diameter)}{inside\ base\ diameter} \times 100 \tag{2}$$

2.3.2.2 Rheological measurements

Calibration

Before measuring the rheological parameters of the paste, a calibration of the rheometer and the measuring tool has to be done to be sure that it is operating properly. For this purpose the National Institute of Standards and Technology (NIST) proposes to test a calibrated paste, the Standard Reference Material (SRM) 2492 [26]. This mixture is composed of corn syrup, distilled water and limestone. Following the NIST recommendations, 200 g of corn syrup is placed into a wide mouth plastic jar, and then 63.16 g of distilled water is added. It is mixed by hand with a spatula for approximately 5 min or until the paste is homogenous. The mixture is poured into a high shear mixer and the same mixing procedure as for the cement paste is followed to introduce 458.1 g of limestone powder and to mix [24].

The measuring tool was designed following the recommendations of the NIST. It is a 3D printed spindle which geometry aims to decrease slippage [27]. The double spiral spindle is connected to the rheometer by a metal shaft (Figure 4). This measuring tool has a diameter of 25 mm and is 55 mm long from the bottom to the top of the spiral.

The SRM 2492 is poured into a cup holder CC27 in stainless steel and placed into the rheometer MCR 302 using a C-PTD 200 to control the temperature at 23 °C ± 2 °C. All equipment is from Anton Paar. Four tests are conducted, the rotational speed is controlled from 0.1 rpm to 100 rpm for 15 points (the up-curve), then it is decreasing from 100 rpm to 0.1 rpm (the down curve). While controlling the rotational speed, the torque is measured. The up-curve has a role to reset the shear history of the paste. The average raw data of the down curves are computed and calibrated to fit the SRM 2492 certified values using the Bingham approach expressed in the following diagram (Figure 5) [28]. Subsequently, the calibration factors K_τ and K_μ are computed with the Data Calibration Tool of the NIST and are used to determine shear rate, shear stress, yield stress and viscosity of the cement pastes.

Procedure for cement pastes

The cement paste is tested 5 min after the mixing procedure. The test consists in an up-curve of 15 measurements from 0.1 rpm to 100 rpm and a down curve of 20 measurements from 100 rpm to 0.1 rpm. Each measurement is a step during 30 s or until the stabilization of the torque. The Figure 6 shows the procedure, from [28]. After the test, the values of rotational speed and torque are computed and converted respectively into shear rate and shear stress. Moreover, the shear stress τ, the shear rate $\dot{\gamma}$ and the apparent viscosity μ are calculated with Equation (3), Equation (4) and Equation (5) where N and Γ are respectively the rotational speed and the torque:

$$\tau = K_\tau \times \Gamma \tag{3}$$

$$\dot{\gamma} = \frac{K_\tau}{K_\mu} \times N \tag{4}$$

$$\mu = K_\mu \times \frac{\Gamma}{N} \tag{5}$$

Thereafter, the yield stress τ_0 is estimated as the intercept of the linear regression of the curve $\tau = f(\dot{\gamma})$ where $\dot{\gamma} > 1\ s^{-1}$ (Figure 7) in agreement with the publication of the NIST [28]. Similarly, the plastic viscosity is defined as the slope of this curve.

2.3.2.3 Mix design of the cement pastes

The mixes are gathered in Table 3. As for the mortar, the water / cement ratio is kept at 0.345. The amount of water added varies in function of the quantity of water present in the admixtures added. Those 16 tests are to be related to the mortar tests.

2.3.3 Analysis of the results

The fact that a full-factorial design is used allows us to observe all possible combinations of our admixtures and therefore a large panel of results. Linear regressions between the different mortar tests and cement paste tests are conducted to identify relationships between the several experiments. The coefficient of determination and the regression equation are determined. Moreover, the impact of each admixture on each test is studied in order to be able to make assessment on the best mix for 3D printing.

3. RESULTS AND DISCUSSION

3.1 Raw results

The results of all tests are presented in Table 4. The first three columns are results about cement paste and the last three columns concern mortar.

3.2 Correlation between tests on mortar

In order to highlight the correlation between the results of the different test on the mortar, linear regressions have been computed between the flow and the slump (Figure 8), the slump and the deformation (Figure 9) and the flow and the deformation (Figure 10). Equation (6), Equation (7) and Equation (8) can be drawn from these regressions. They are respectively of the following form:

$$Flow = 0.0.6581 * Slump + 74.46 \tag{6}$$

$$Slump = 4.7719 * Deformation - 6.63 \tag{7}$$

$$Flow = 3.3724 * Deformation + 68.181 \tag{8}$$

The coefficient of regression is displayed on the corresponding figure.

3.2.1 Abrams cone slump and ASTM C1437 flow

The regression between ASTM flow and slump leads to a coefficient of determination of $R^2 = 0.83$. Figure 8 shows the confidence interval at 95% for the regression line. In general, there is a good correlation but some mixes introduce discrepancies, especially for low slumps. The variability can come from the sand which was not analyzed for each test but instead taken from a common bag. In previous research about viscosity modifying agents (VMA) in concrete, its presence was observed to increase the flow time and decrease the slump [29, 30].

3.2.2 Abrams cone slump and deformation with stability test

To investigate the correlation between slump and deformation, a linear regression was conducted. Figure 9 shows the confidence interval at 95% for the regression line. As with the previous flow test, the stability test induces greater shear stress in the material compared to the slump test. In these measurements, higher slump values correspond to greater deformation. Previous studies have shown that the deformation of a cylinder under a load represents well the comportment of a printed layer under a charge [6, 19]. In this way, measuring the slump can be sufficient to understand the capacity of a printed layer to support the following one.

3.2.3 ASTM flow and deformation with stability test

The linear regression between the ASTM flow and deformation has the lowest correlation. Figure 10 shows the confidence interval at 95% for the regression line. The induced motion during the 25 drops of the flow test agitates to the cement paste in a way that does not correspond to the behavior during printing, as better simulated by the stability test.

3.3 Requirements of mortar mixtures for 3D printing

In practice, the 3D printing process requires the mixture to be balanced between its physical characteristics such as flow or slump, which have been investigated separately in this study. It should be noted that the printability cannot be assured only by meeting the required values offered here. Some values of flow of 119 % or 118 % lead respectively to a collapse of the printed structure or strong deformation, while for a flow of 113 % or 116 % the deformation is considered acceptable [6]. However, a mortar with a very high fluidity can still be printed. For [31] the optimal mix was the one permitting to print approximately 22 layers or 260 mm without collapsing. This leads to a mixture having a flow of 168 % [31]. In this study, equivalent values of deformation (Table 5) yielded information about the critical decrease. Hence, the value of 6.3 mm is a starting point to ensure stability, but it is assumed that a higher deformation is also acceptable because only a deformation of 13.6 is considered critical. Consequently, the value of 7 mm is taken here as a requirement for deformation. Moreover, the equation linking the slump and the deformation (Equation (7)) leads to a second threshold value of 26.8 mm. Mixes are here considered rejected when above the threshold value which allows a mapping of acceptable mixes (Figure 11). The mixes circled in black are those, based on these criteria, which can be kept to further study on their printability. The flow of our mixtures is always lower than the critical flow of 116 %, but a flow too low can lead to an excessively stiff mortar which is undesirable for printing [2, 6]. With this additional criterion, the 16th mix can also be excluded.

3.4 Correlations for cement pastes

The results on cement paste lead to values of viscosity, yield stress and mini-slump for each mixture. As expected, the viscosity does not correlate with any of the other results on cement paste or mortar [32]. Nevertheless, the yield stress and the mini-slump test have a strong correlation with a power law fit. This approach is also used by [33] but it must be noted that the values of yield stress in that work were found to be lower. In fact, the equation from their experimental results does not fit with the results of this study and the values of yield stress are 10^4 times too high for our data. Similarly, the equation used by [34] and the same modified to account for the surface tension effect by [13] still do not fit properly the observations of this investigation. Both models are displayed alongside with the experimental data and its power law fit on the Figure 12. For low yield stress, the experimental data fits the models previously proposed by other authors. However, for final radii under 50 mm the discrepancy is clear. It is observed that the exponent for the fit of the experimental data is lower than that of the two other models. This can be explained by variation in the conventions of measurements used as this study relies on the recommendations of the NIST. Moreover, the model from [13] study is valid when the long-wave approximation is verified, which is true when the height of the sample is at least twice as small as its radius. In this study, every sample meets those criteria. However, some of them appear to be not submitted to a pure shear flow. In fact, a "hat" described by [35] can be seen for mixes with yield stress above 10 Pa. This is the evidence of an intermediate regime of flow. Models relying on the assumption of fully flowing behavior, consequently, cannot predict yield stress properly. The experimental equations proposed by prior authors are only applicable for mixes with a yield stress superior to 10 Pa, but still predict too high yield values. An accurate yield stress prediction must consider the intermediate flow regime.

For each admixture, the correlation between final spread radius and yield stress is presented in Figure 13. All admixtures lead to well-distributed values of yield stress except for those with accelerator (A), which were found only to have low yield stresses. This was expected because of the water-reducing effect of this admixture. For a better understanding on how each admixture impact the spread radius, the results were represented in four histograms (Figure 14). Each histogram shows eight different mixes with and without the admixture considered. The specific actions of viscosity modifying agent (VMA), strength-enhancing additive (X), accelerator (A) and nanoclays (C) are highlighted. First, the effect of the VMA (Figure 14.a) and the X (Figure 14.b) on the spread of the paste is visible for all mixes, causing an increase of 9.9 mm and 15.5 mm on average, respectively. The effect of A is the opposite, it enhances the flowability of the paste because of its water-reducing effect (Figure 14.c). Mixes with A have seen their final radius decrease by 15.1 mm on average. Finally, C appears to boost the spreading of the paste, but for some ink, the difference between mixes with and without the admixture is very low. For example, between the mixes SP X VMA and SP X VMA C, the increase is only of 0.6 mm. Moreover, for the mixes SP A and SP A C, the one with C has a smaller spread (Figure 14.d). However, on average the increase in the final radius of the spread is 5.7 mm for C.

3.5 Relationship between cement paste and mortar tests

The link between the results on the cement and the mortar has been investigated (Figure 15). The best correlation was found with a power law fit connecting slump and yield stress. The coefficient of determination of this regression is $R^2 = 0.86$. The regression is described by Equation (9).

$$Slump = 195.801 \times \tau_0^{-0.71315} \tag{9}$$

In this regression mixes 13 to 16 have not been considered. Those mixes introduced huge discrepancies in the regression. The results for mortar tests were also subject to some variability with those mixes. Notably, they are the only ones to contain both A and X admixtures. It is proposed that the combined action of those two accelerators induces a quick hardening effect to the mortar which cannot be explained by the power law fit of cement paste yield stress.

4. SUMMARY AND CONCLUSIONS

The relations between different workability tests on mortar were investigated. A standardized flow test of the ASTM, a small-scale variant of the well-known Abrams cone test and a specially designed stability test were implemented and compared. The mini-slump test was conducted on the cement paste and the yield stress was measured by a rheometer. Four different admixtures were tested in a two-level full-factorial design. Regressions were computed to observe relationships between the results and draw conclusions.

When all mixes are involved, the slump of Abrams cone is linearly related well to the deformation with the stability test and the ASTM flow. Therefore, conducting the Abrams cone test with mortar can be more informative about the way the mixture behaves under the load of the stability test and the way it flows following the ASTM procedure. Consequently, it contributes to a better understanding of the way the mortar reacts in a 3D printing context supporting the load of several other mortar layers. The ASTM flow test is also difficult to implement on the site, the easiest test to do is the slump test. Hence, being able to describe the flow by the slump is useful.

For the cement paste, the power law fits the experimental data very well, even if models from literature cannot predict them well. The fact that the paste studied here has a behavior between the spread regime and the flow regime can be the explanation of this discrepancy. With the power law fit, the yield stress of several cement paste is predicted using only the mini-slump test.

Associating the results of cement paste and mortar allow us to be able to get information about one of them without having to test it. The correlation between the yield stress and the slump is quite satisfying. This indicates that the sand in the mortar does not have a significant impact on the yield stress of the material. At the ink design phases, formulation experiments on paste alone allow for faster development in the laboratory stage.

This study demonstrates the fact that the flow of the mortar is a difficult to measure in situ because of its need for specific installations (a flow table). Alternatively, the Abrams cone yields sufficient information to quantify the capacity of the mortar to flow. In fact, the real scale Abrams cone is already widely used for testing concrete slump. The utilization of a smaller one for mortar should be acceptable at the ink design phase. Moreover, in this work several values of characteristics of different mixtures were highlighted in order to identify the acceptable criteria for printing. In addition, the cement paste can bring information about the mortar, accelerating laboratory development.

5. ACKNOWLEDGEMENT

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Table 1: Admixtures

Admixture	Residue by oven drying (%w/w)	Density
SP	25.8	1.050
A	47.2	1.350
X	30.1	1.120
VMA	1.04	1.002
C	N/A	1.000

Table 2: Mix design for mortars

Materials (kg/m^3)				Admixture (%w/w)				
Mix #	Gub-8SF	Sand	Water	SP	X	A	C	VMA
M1	753	1355	254	0.26	-	-	-	-
M2	753	1355	251	0.26	-	-	-	0.004
M3	753	1355	254	0.26	-	-	0.5	-
M4	753	1355	251	0.26	-	-	0.5	0.004
M5	753	1355	248	0.26	-	0.7	-	-
M6	753	1355	245	0.26	-	0.7	-	0.004
M7	753	1355	248	0.26	-	0.7	0.5	-
M8	753	1355	245	0.26	-	0.7	0.5	0.004
M9	753	1355	249	0.26	0.3	-	-	-
M10	753	1355	246	0.26	0.3	-	-	0.004
M11	753	1355	249	0.26	0.3	-	0.5	-
M12	753	1355	246	0.26	0.3	-	0.5	0.004
M13	753	1355	243	0.26	0.3	0.7	-	-
M14	753	1355	240	0.26	0.3	0.7	-	0.004
M15	753	1355	243	0.26	0.3	0.7	0.5	-
M16	753	1355	240	0.26	0.3	0.7	0.5	0.004

Table 3: Mix design for cement pastes

Materials (kg/m3)			Admixture (%w/w)				
Mix #	Gub-8SF	Water	SP	X	A	C	VMA
M1	1505	508	0.26	-	-	-	-
M2	1505	502	0.26	-	-	-	0.004
M3	1505	508	0.26	-	-	0.5	-
M4	1505	502	0.26	-	-	0.5	0.004
M5	1505	496	0.26	-	0.7	-	-
M6	1505	490	0.26	-	0.7	-	0.004
M7	1505	496	0.26	-	0.7	0.5	-
M8	1505	490	0.26	-	0.7	0.5	0.004
M9	1505	497	0.26	0.3	-	-	-
M10	1505	492	0.26	0.3	-	-	0.004
M11	1505	497	0.26	0.3	-	0.5	-
M12	1505	492	0.26	0.3	-	0.5	0.004
M13	1505	486	0.26	0.3	0.7	-	-
M14	1505	480	0.26	0.3	0.7	-	0.004
M15	1505	486	0.26	0.3	0.7	0.5	-
M16	1505	480	0.26	0.3	0.7	0.5	0.004

Table 4: Results for mortar and cement pastes

Mix #	Admixtures	Cement paste			Mortar		
		Viscosity (Pa.s)	Yield stress (Pa)	Mini-slump (%)	Slump (mm)	Flow (%)	Deformation (mm)
Mix1	SP	0.246	9.7	171	37.6	106	10.8
Mix2	SP VMA	0.181	14.5	137	36.6	96	8.7
Mix3	SP C	0.268	12.9	123	31.6	97	8.6
Mix4	SP VMA C	0.205	18.2	105	20.2	85	6.7
Mix5	SP A	0.187	5.4	186	70.0	115.5	13.0
Mix6	SP A VMA	0.212	8.4	155	48.0	110	12.5
Mix7	SP A C	0.258	5.8	196	50.0	107	12.0
Mix8	SP A VMA C	0.209	10.5	137	35.8	97	9.2
Mix9	SP X	0.215	17.5	103	24.6	95	7.2
Mix10	SP X VMA	0.228	25.6	80	27.8	92.5	8.0
Mix11	SP X C	0.228	23.2	91	21.6	92	6.7
Mix12	SP X VMA C	0.221	28.6	78	25.0	84.5	6.7
Mix13	SP A X	0.215	9.0	148	30.2	95.5	5.5
Mix14	SP A X VMA	0.198	13.8	127	27.6	92	6.7
Mix15	SP A X C	0.215	11.5	134	23.8	95.3	5.3
Mix16	SP A X VMA C	0.192	14.1	124	13.0	75.5	4.3

1 mm = 0.0393 in, 1 Pa = 0.000145 psi

Table 5: Values of flow and deformation from literature for printed mortars in regard of our results

	Kazemian 2017		This study results		Zhang 2018	Decision
Flow (%)	Diminution of height of a printed layer (%)	Deformation in height of the 80 mm high cylinder (%)	Equivalent for a 35 mm high cylinder (mm)	Slump from regression (mm)	Height of the printed structure (mm)	
113	6.3	16	5.6	20.1	-	Acceptable
116	6.7	18	6.3	23.6	-	Acceptable
118	11.4	39	13.6	59.8	-	Critical
119	collapse	48	16.8	75.7	-	Rejected
168	-	-	-	-	260	Acceptable
172	-	-	-	-	180	Critical
180	-	-	-	-	156	Critical
200	-	-	-	-	72	Critical
200	-	-	-	-	163	Critical

1 mm = 0.0393 in, 1 Pa = 0.000145 psi