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Printability region for 3D concrete printing using slump and slump flow test

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Abstract

Rheological studies are important for successful 3D concrete printing. The main challenge for successful 3D concrete printing is the complex characteristic the materials should possess. It should be flowable enough to be pumped and extruded through the hose, as well as gaining sufficient strength and stiffness for buildability after the layer by layer deposition. Existing literature has various mixtures proposed for successful 3D concrete printing. Most of these studies used rheometers to measure the dynamic yield stress and plastic viscosity. As the measurement with rheometer is sensitive to the protocols and is controlled by the rheologists, as well as data processing if non-standardized measuring geometries are used, results could vary significantly. This study used standardized field-friendly protocols to measure the slump and slump-flow of the mortars. The pumpability and buildability are evaluated in terms of the pumpability index and maximum height printed before collapsing. These result together with the slump and slump-flow values are used to define the printable region.

Keywords: 3D printing; cementitious material; slump; slump flow; pumpability; buildability.

1. Introduction

There is a growing interest in 3D printing technology in recent years, especially in the building and construction industry [1-3]. 3D concrete printing extrudes cementitious materials to create objects in a layer by layer manner. Since this technique poses the potential to eliminate the use of formwork, rheological properties of the material are especially crucial for the material to be pumped and able to hold its shape after extrusion [4, 5].

The flowability of concrete material is commonly characterised by the Bingham model, where dynamic yield stress and plastic viscosity are obtained. It corresponds to the steady state after strong continuous shear. During a continuous shear, the microstructure is broken thus decreasing the shear stress [6-8]. In the case of concrete and mortar, the presence of sand and gravel further break down the microstructure during shearing [9]. Meanwhile, the state when the microstructure is not disturbed corresponds to the static yield stress, which is higher than the dynamic yield stress. The dynamic yield stress is described as the force needed to sustain the flow, while the static yield stress the force needed to initiate the flow [10]. Thixotropy is thought to be the origin of the discrepancy between static and dynamic yield stress [11]. A type of attapulgite nanoclay showing high thixotropy and has been popularly added in 3D printing cementitious materials [12-16].

Pumpability and buildability are the two main crucial material parameters in concrete printing that relates to the plastic viscosity and the yield stress of the material. Pumpability is defined as the ease of transporting the material from the reservoir to the nozzle. Pumping of concrete material is a complex process. Besides its time-dependent material behaviour, changes in the concrete properties due to pumping conditions such as bleeding and segregation can cause the pumpability of the material hard to predict [17]. Separation of the paste from the aggregates can lead to blockage of the hose. This phenomenon is usually caused by deficient particle size distribution or excessive water to binder ratio [18]. In a properly designed mixture, there should be sufficient surplus paste content to fill the voids between the aggregates. This paste content forms a coating wrapping the aggregates which serve as a “lubricant” between the aggregates when shear stress is applied to the mixture [19]. This lubricant layer reduces the friction between the aggregates and enhances the workability of the mixture [20].

Buildability, which has been recently defined and used for 3D concrete printing applications [21, 22], is dependent on the yield stress of the material, structural build-up of the material, and the shape stability of the cross-sectional shape of the layers. The static yield stress of the material gives the material its initial rigidity. This rigidity, which is related to the initial shape retention capability after extrusion from the nozzle, is required before the structural build-up of the mixture comes into effect. The structural build-up of the material depends on the rate of flocculation and hydration of the binders [6]. If the deposition of the subsequent layer is faster than the structural build-up rate of the material, the structure will fail [21]. The balance between the structural build-up of the material and the printing parameter is important to achieve high buildability. Addition of admixtures such as accelerators can improve the material structural build-up rate [23, 24].

High shape retention capability after extrusion is an important aspect in 3D concrete printing. Without the use of formwork, the material depends on its internal cohesion between the paste and the aggregates. In order for the material to retain its shape after extrusion and be able to sustain the load of subsequent layers, the high static yield stress of the material is required.

Currently, there is no standard test method to measure or quantify pumpability and buildability for 3D printing. Existing research has proposed various mixture for 3D concrete printing with characterized rheological properties with rheometers [14]. However, these rheological tests are sensitive to the protocols and operation procedures by researchers [25, 26]. The values obtained vary among the different apparatus [27]. Hence, in this study, a field-friendly test such as the slump and slump flow tests are used. The slump value is the height of slump after the mould is lifted up. After dropping for 25 times, the material spreads out on the plate and the diameter is measured as the slump-flow values. It could be regarded that dropping for 25 times makes the difference in the mixtures corresponding to the microstructural breakdown. Thus, the slump value is more related to the solid-state of the microstructure and static yield stress and buildability. The slump-flow value is related to dynamic yield stress and pumpability. Past research has shown that the slump value is inversely proportional to the dynamic yield stress [28].

In this paper, the investigation of the slump and slump-flow results will be used to evaluate the pumpability and the buildability of the mixtures. Parameters such as water to binder ratio, sand to binder ratio, fly ash to binder ratio and silica fume to binder ratio are used for

analysis. Additionally, pumpability index, which is a new parameter, will be introduced to characterise the material pumpability. Furthermore, this study aims to map out the printable and non-printable regions for mortar in the slump and slump-flow diagram in order to evaluate the material suitability for 3D concrete printing.

2. Methodology

Four parameters such as water to binder ratio (W/B), sand to binder ratio (S/B), fly ash to binder ratio (FA/B) and silica fume to binder ratio (SF/B) were evaluated for their significance to slump and slump-flow value. In order to select the significant parameters, a full factorial design experiment was carried out. After the significance of the effects were determined, effects that have relatively lower significance were fixed with a constant value. A second set of experiments are then established by varying the significant effects to systematically map out the printable region in the slump and slump-flow diagram. Additional 3D printing tests with a gantry printer were carried out to verify the printable region in the slump and slump-flow diagram established with the second set of experiment.

2.1 Material properties and mix design

Ordinary Portland cement (OPC, ASTM Type 1, Grade 42.5), silica fume (Undensified, Elkem), fly ash (Class F) and river sand were used in this study. In order for the material to be delivered by pumping through a hose with a diameter of 25.4mm, the maximum particle size of the sand is 2mm. The fineness modulus (FM) of the sieved river sand is 2.19, where fine aggregates generally have FM ranging from 2 to 4. Figure 1 shows the cumulative percentage passing and the individual percentage retained results of the raw material by the particle size analyser (Malvern Mastersizer).

Figure 1: (a) Cumulative percentage passing of raw material; (b) Individual percentage retained of raw material

A Hobart mixer was used to prepare the material. Dry components were dry-mixed at 59 rpm for 5 minutes. Water is then added to the mixture for mixing at slow-speed (59 rpm) for 1 minute and follow by 7-minutes of high-speed mixing (198 rpm). The factors with the low level (-1) and high level (+1) are shown in

Table 1.

Table 1: Factors and their levels

Effects	Abbreviation	Symbol	Variable levels	
			-1	+1
Water/ binder ratio	W/B	W	0.45	0.55
Sand/ binder ratio	S/B	S	1.20	2.00
Fly ash/ binder ratio	FA/B	FA	0.10	0.30

Silica fume/ binder ratio	SF/B	SF	0.08	0.12
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2.2 Slump and slump-flow test

A conical mould, as shown in Figure 2, is accordance with the ASTM C230 [29] was used for the slump tests. The slump test procedure starts by filling half of the mould with mortar. It was tamped 20 times uniformly distributed over the cross-section of the mortar. More mortar is filled to the brim of the mould and was tamped as specified for the first half. Excess material is removed by drawing the edge of a trowel with a sawing motion. Subsequently, the mould is removed and the difference in the height is recorded as the slump value. Figure 2 shows the setup of the slump-flow test and the specification follows ASTM C1437 [17]. The preparation protocol of the mortar for the slump-flow test, which follows ASTM C230 [29, 30], is similar to the slump test. After the mould is removed, the flow table is dropped 25 times and the diameter of the mortar is recorded.

Both the slump and slump-flow values for the different mixtures will be mapped out to determine the material region for printability.

Figure 2: Slump-flow test experimental setup (a) before the mould is removed (b) the spread of the material after dropping the table for 25 times.

2.3 Pumping and printing test

A progressive cavity pump (Mai Pictor) with a 10L rotor-stator (MAI-Rotor/Stator 10L) is used for the material delivery system, as shown in Figure 3(a). The pumping speed and the dimension of the rotor-stator such as the rotor pitch determine the flow rate of the material. A

pumping flow rate test is used to quantify the pumpability of different mixtures. This test measures the weight of each mixture being delivered through the pump at a constant speed of 2890 rpm for 30 seconds. This weight and density of the mixtures are used to calculate the flow rate in volume per second (ml/s). A pumpability index, which is the ratio of the flow rate of the mixture and that of water, is introduced to characterize the pumpability of the mixture. Material that has high pumpability index could achieve a flow rate at a slower pump speed as compared to material that has a low pumpability index.

Figure 3: (a) Progressive cavity pump; and (b) gantry printer customized for concrete printing

Furthermore, the actual printing tests are carried out using a gantry printer as shown in Figure 3(b). In order to compare the results between various mixtures, the printing parameters such as flow rate, travel speed, layer height and printing path must be consistent. The flow rate of all mixtures was adjusted by controlling the pump speed before printing. A cylinder structure with a 150 mm diameter and a layer height of 15 mm at a travel speed of 60 mm/s with a flow rate of 23 ml/s are the printing parameters preset for this experiment. Existing literature has used the maximum number of layers printed before collapsing as an indicator for buildability [14, 23, 31]. In this study, the cylinders are printed continuously using the gantry printer until they collapse. This relative comparison is a practical method to determine the mixture that has high yield stress for buildability. The surface texture and the maximum number of layers printed were compared between different mixtures.

3. Results

3.1 Full factorial design experiment analysis

A full factorial design for 4 factors with 2 levels is shown in Table 2. There are only 4 factors thus resulting in 16 mix design for this full factorial design. It measures the responses of every possible combination of the factors and levels. These responses are analysed to provide information about the main effect and the interaction effect. The slump and slump-flow average result are also shown in the right column of Table 2.

Table 2: Slump and slump flow result.

Runs	Factors (coded values)				Results	
	W	S	FA	SF	Slump	Slump-flow
1	-1	-1	-1	-1	4.2	158
2	1	-1	-1	-1	10.2	212
3	-1	1	-1	-1	0.5	112
4	1	1	-1	-1	5.3	183
5	-1	-1	1	-1	3.1	167
6	1	-1	1	-1	7.5	209
7	-1	1	1	-1	0.5	111
8	1	1	1	-1	3.8	152
9	-1	-1	-1	1	2.1	147
10	1	-1	-1	1	6.5	186
11	-1	1	-1	1	0.2	113
12	1	1	-1	1	3.1	153
13	-1	-1	1	1	2.3	138
14	1	-1	1	1	6.2	184
15	-1	1	1	1	0.0	108
16	1	1	1	1	2.0	152

The results obtained from the full factorial design were evaluated by ANOVA (analysis of variance) at 5% significance level shown in Table 3 and Table 4. F-value determines if the source of variation is significant. Larger F-values signify larger significance. The F-values of

W and S are 116.84 and 81.89 respectively as shown in Table 3. These values are significantly higher than the other F-values for the slump test. Similarly, the F-values of W and S for the slump-flow test are significantly higher than those of other parameters. Additionally, the P-value is used to weigh the strength of the evidence, which helps to determine the significance of the result. Small P-values indicate that there is strong evidence that a factor is significant. The P-value of W and S in both slump and slump-flow test are less than 0.001. This means that assuming the W and S have no effect, the observed difference will be obtained in less than 0.01% of studies due to random sampling error. This means that compared with other two parameters the W and S, which are water to binder ratio W/B and sand to binder ratio S/B, have a higher effect on the slump and slump-flow test.

Table 3: Analysis of variance (ANOVA) table for slump result

Source of variation	Degree of freedom	Sum of Square	Mean Square	F-Value	P-Value
W	1	125.73	125.73	116.84	<0.001
S	1	88.12	88.12	81.89	<0.001
FA	1	5.58	5.58	5.19	0.037
SF	1	20.21	20.21	18.78	0.001
W*S	1	3.80	3.80	3.53	0.078
W*FA	1	2.41	2.41	2.24	0.154
W*SF	1	3.85	3.85	3.58	0.077
S*FA	1	0.13	0.13	0.12	0.734
S*SF	1	1.16	1.16	1.08	0.314
FA*SF	1	1.92	1.92	1.78	0.200
W*S*FA	1	0.01	0.01	0.01	0.925
W*S*SF	1	0.16	0.16	0.14	0.709
W*FA*SF	1	0.35	0.35	0.33	0.575
S*FA*SF	1	1.43	1.43	1.33	0.266
W*S*FA*SF	1	0.04	0.04	0.03	0.854
Error	16	17.22	1.08		
Total	31	272.11			

Table 4: Analysis of variance (ANOVA) table for slump-flow result

Source of variation	Degree of freedom	Sum of Square	Mean Square	F-Value	P-Value
W	1	17907.80	17907.80	91.85	<0.001
S	1	12521.50	12521.50	64.22	<0.001
FA	1	225.80	225.80	1.16	0.298
SF	1	1906.50	1906.50	9.78	0.007
W*S	1	26.30	26.30	0.13	0.718
W*FA	1	124.00	124.00	0.64	0.437
W*SF	1	185.30	185.30	0.95	0.344
S*FA	1	132.00	132.00	0.68	0.423
S*SF	1	427.80	427.80	2.19	0.158
FA*SF	1	13.80	13.80	0.07	0.794
W*S*FA	1	57.80	57.80	0.30	0.594
W*S*SF	1	34.00	34.00	0.17	0.682
W*FA*SF	1	331.50	331.50	1.70	0.211
S*FA*SF	1	225.80	225.80	1.16	0.298
W*S*FA*SF	1	30.00	30.00	0.15	0.700
Error	16	3119.50	195.00		
Total	31	37269.50			

3.2 Slump and slump-flow

The 16 slump and slump-flow result obtain in Table 2 were plotted on the slump and slump-flow diagram shown in Figure 4. The relationship between slump and slump flow values could be fitted into a trend line. Additionally, 8 mixtures that are labelled in Figure 4 shows the extreme region of the material characteristic on the diagram. Through the experiment observation, the four data points (run3, run 7, run 11 and run15) on the bottom left of Figure 4 are too stiff and are not flowable. These mixtures show low values of slump and slump flow. They have low values of W/B and high values of S/B. It could be reasoned that a high volume fraction of the aggregates could result in high internal friction between the aggregates

thus resisting flow [32]. On the other hand, mixtures that have a high level of W/B and a low level of S/B have a high slump and slump-flow value. Run 2, run 6, run 10 and run 14 slump and slump-flow values were found to be more than 6mm and 180mm, respectively. With a higher volume fraction of water content, the aggregates in the mixture have a lesser tendency to interact. This reduces the internal friction thus resulting in higher flowability [32].

While the full factorial design result obtained is sufficient to prove that W/B and S/B have a more significant effect than FA/B and SF/B, this result is not sufficient to illustrate the printable region of the material. Furthermore, the results obtained from the factorial design does not show a good scatter of the data points as shown in Figure 4. Intermediate level of the significant effects is therefore required to show a good scatter of data points on the slump and slump-flow diagram. In order to systematically map out the printable region in the slump and slump-flow diagram, another series of mix design experiment that encompasses small increment at different interval is carried out.

Figure 4: Slump and slump-flow results obtained from the factorial design experiment

Table 5 shows the additional series of experiment to increase the scatter of data on the slump and slump-flow diagram. Mix 8 to Mix 23 has a fixed FA/B and SF/B content since these two parameters have a lower impact on the slump and slump-flow test. Furthermore, to reduce the possibility of low slump-flow, the S/B were reduced to a range of 0.8 to 1.6. Similarly, to reduce the possibility of high slump, the W/B were reduced to a range of 0.4 to 0.5. These ranges were selected based on the factorial design experiment. Additionally, Mix 1 to Mix 7

1 were selected to increase the scatter of the data points on the slump and slump-flow diagram
 2 that are not achievable when FA/B is 0.3 and SF/B is 0.06.

3
 4 Table 5: Mix design to map out printable material region

	Mixture composition					
	W/B	S/B	FA/B	SF/B	Slump (mm)	Slump- flow (mm)
Mix 1	0.40	0.80	0.00	0.13	4.67	154
Mix 2	0.41		0.39	0.12	4.00	143
Mix 3				0.10	5.70	149
Mix 4	0.42		0.33	0.06	7.38	182
Mix 5			0.37		7.16	175
Mix 6	0.40		0.40		5.11	159
Mix 7	0.46				9.56	193
Mix 8	0.40		0.30		5.94	169
Mix 9	0.43				8.61	189
Mix 10	0.46				10.66	200
Mix 11	0.50				12.78	212
Mix 12	0.40	1.00			4.56	162
Mix 13	0.43				5.89	177
Mix 14	0.46				6.67	191
Mix 15	0.50			9.89	213	
Mix 16	0.40	1.30		2.94	135	
Mix 17	0.43			4.72	160	
Mix 18	0.46			5.61	174	
Mix 19	0.50			8.94	203	
Mix 20	0.40	1.60		0.00	112	
Mix 21	0.43			2.42	136	
Mix 22	0.46			3.28	146	
Mix 23	0.50			6.28	182	

From Figure 5, a trend similar to Figure 4 was observed. However, Figure 5 shows a more scattered data points across the slump and slump-flow diagram as compared to Figure 4. With this good scatter of data points, it allows the classification of the printable region. It is observed in Figure 5 that with the increase in W/B or the reduction in S/B, the slump and slump-flow value increase. Increase in the volume fraction of the water content or the reduction in the aggregates volume fraction can reduce the friction caused by the interaction between the interparticle which would increase the slump or slump-flow value.

Due to the reduction in S/B content for this series of experiment, most of the data points have a slump-flow of more than 130mm. By visual inspection, or according to the authors' experience, the slump-flow value below 130mm was too stiff to be smoothly pumped and a value above 210 mm was too flowable to make a cohesive printed filament. Figure 5 shows the region of the slump and slump-flow diagram which excluded Mix 11, Mix 15 and Mix 20 from further analysis since these mixtures are not suitable for printing. This enables the study to focus on the materials that have a slump value between 2mm and 12mm and slump-flow values between 130 and 210 mm.

Figure 5: Slump and slump-flow: Region of interest.

Six data points were selected from the extreme ends in the region-of-interest for analysis, as shown in Figure 6. These six specimens were denoted by their mixture number and the two different regions L (lower region) and U (upper region) as shown in Figure 6.

Figure 6: Slump and slump-flow separated into two regions with the mix number and region alphabet of selected mixture for further analysis.

3.4 Pumping flow rate

The blank bars in Figure 7 show the flow rate of the 6 selected samples as well as that of water that were tested with the delivery system. Comparing the selected sample with water gives an interesting insight on the difference of the pumpability of the viscous cementitious materials and a Newtonian fluid. The different interaction between the particles in the mixture causes the difference in the flow rate. As seen from Figure 7, with the same pumping speed at 2890 rpm, different mixtures show different volumetric flow rate. In order to obtain a dimensionless parameter to characterise pumpability, a pumpability index is introduced to compare the pumpability of mixtures with the Newtonian fluid, i.e. water. The pumpability index is defined as the ratio of the flow rate of concrete to that of water at the pumping speed of 2890 rpm. It was observed in Figure 8 that the pumpability index is proportional to the slump-flow value of the samples.

In consideration that the flow rate would affect the size of the filaments after extrusion and printing quality [33], it is crucial to keep the flow rate consistent for all mixture during printing for comparison. Therefore, pump speeds are adjusted for all the mixtures to make sure that they have the same flow rate of around 23 ml/s for extrusion and printing, as shown as the dark bars in Figure 7.

Figure 7: Pumping flow rate of different mix design

Figure 8: Pumpability index and slump-flow of the selected mixtures

3.5 Printing investigation

In order to illustrate the 3D printing performance of the mixtures in the lower and upper region, cylinders using these mixtures are printed as shown in Figure 9. All of the selected mixtures are printed until the structures collapse. The photos shown in Figure 9 were the last layer of the cylinder printed before it collapses. The maximum heights of the structures are used to indicate the buildability of the mixtures.

Mixtures with low slump and slump-flow values appear to have a rough texture on the surface of the filaments as shown in Figure 9 (a)-(c). High shape retention, large voids/cracks and low pumpability index are some of the characteristics of such behaviour. Mix 21L and Mix 16L, as shown in Figure 9 (a) and (b) respectively, have a low pumpability index. These voids and cracks cause instability in the structure which eventually result in structural failure. Furthermore, it is notable that high material stiffness may result in lower interlayer bonding strength [34].

On the other hand, mixtures that have a high slump and slump-flow values appear to have a smooth surface and a lower amount of voids and cracks as shown in Figure 9 (d)-(f). Lower shape retention, smooth surface, high pumpability index are some characteristic of such behaviour. As the pumpability index increases, the maximum height that it can print reduces. Mix 19U and Mix 10U slump under its own weight within a few layers of printing. The internal cohesiveness of the material is not able to sustain the weight of the structure thus causing the material at the bottom layer to slump. This slump causes instability and eventually causing the structure to fail, as shown in Figure 9 (f).

Figure 9: Maximum layers printed for different mixture

(a) Mix 21L; (b) Mix 16L; (c) Mix 22L; (d) Mix 9U; (e) Mix 19U; and (f) Mix 10U

From Figure 9, Mix 21L, Mix 16L and Mix 22L have too much breakage and voids. This lower region is deemed as not suitable for printing. On the other hand, if the sample does not have sufficient cohesion, it is not possible for a subsequent layer to be lay upon, therefore Mix 10U is also not suitable for printing.

Mix 9U and Mix 19U shows good surface finish. However, due to the slow structural build-up rate, Mix 9U and Mix 19U has only printed 17 and 14 number of maximum layers respectively. Depending on the requirement time frame of the project, the time-gap of the printing parameter can be increased to match the structural build-up rate of these mixtures. However, it is not the optimal choice. Therefore, these mixtures are neither in the non-printable region nor the acceptable printing region.

Based on the observation above, the acceptable printing region should be within the area as shown in Figure 10; the slump value between 4 and 8 mm and the slump flow value between 150 and 190 mm.

Figure 10: Printable and non-printable region on a slump/slump-flow graph

Figure 11 shows the correlation of the slump value, pumpability index and the maximum number of layers for each mixture. The trend of the pumpability index and the slump value appear to be correlated. For the lower region, the higher the pumpability index and slump-flow value, the higher the maximum number of layers are printed. In contrary, for the upper region, the lower the pumpability index and slump-flow value, the higher the maximum number of layers are printed. It could be reasoned that for lower region, pores and discontinuity is the main reason why the structure lost integrity and collapses. In this case, high pumpability index helps to feed more material and less discontinuity, thus increasing maximum height. In contrary, for upper region, the high slump and low static yield stress make the structure instable. These samples collapse due to the slump of the bottom layers. The material strength gain is insufficient to sustain the stress from the weight of the subsequent layers. Overall, it could be reasoned that an optimal region for high maximum height exists between upper and lower region. It seems to justify the high buildability in the printable region in Figure 10. Further verification is going to be done in the next section.

Figure 11: Slump, pumpability index and maximum printed layer before the collapse of selected mixtures.

Mix 22L and Mix 9U is near to the edge of the acceptable printing region. These two mixtures were used to examine the extreme region of a printable mixture. The slump of the bottom filament was recorded after each layer is deposited to examine the behaviour of the filament during actual printing. The 3rd filament from the bottom was used for analysis. The first two layers were not used for measurement to eliminate the possibility of uneven print-bed. A camera was used to capture the filament after each deposition of a layer. These photos were analysis with an image processing program (ImageJ) and the change in the slump of the filament was presented in Figure 12.

It was observed that in Mix 22L have a step-wise reaction to the vertical stress acting upon when subsequent layers are deposited. The filament is able to hold on to the same slump value for a few layers before slump and subsequently holding on to the new slump value for the next few layers. This slump process increases the filament width, which increases the filament top surface area thus increases the yield point. On the other hand, Mix 9U, a mixture that has a high slump and slump-flow values has a certain slump in the filament when each layer is deposited. The filament is not able to withstand the vertical stress acting on it thus its yields with every layer deposited.

Figure 12: Change in the thickness of filament with every layer deposited

3.6 Validation of printable region

In order to verify the acceptable printing region describe in section 3.5, four mixtures (Mix 3, Mix 8, Mix 12 and Mix 23) were selected as shown in Figure 13. These four mixtures were selected because they are the extreme points within the acceptable printing region. Selecting mixture at the extreme points helps to characterise other mixtures within the region. Table 6 shows the different result obtained in the order of increasing pumpability index. As anticipated, high slump-flow values correlated to high pumpability index.

Figure 13: Four mixture selected for verification

Table 6: Results obtain for the mixtures within acceptable printing region

	W/B	S/B	FA/B	SF/B	Slump (mm)	Slump- flow (mm)	Pumpability index	Max layer printed
Mix 3	0.41	0.80	0.39	0.10	5.7	149	0.52	28
Mix 12	0.4	1.0	0.30	0.06	5.94	165	0.53	26
Mix 8	0.4	0.8	0.30	0.06	4.5	166	0.65	19
Mix 23	0.5	1.6	0.30	0.06	6.3	185	0.67	22

Figure 14 shows the maximum number of layers printed for the different samples. Although the four samples are within the acceptable printing region, the surface finish of the samples varies to some extent. The surface finish improves as the pumpability index increase. Nevertheless, the four mixtures' surface finish are within satisfactory limits.

Figure 14: Maximum layers printed for the different mixture (a) Mix 3; (b) Mix 12; (c) Mix 8; and (d) Mix 23

Buildability and pumpability are two of the key material properties needed for successful printing. While not taking the hydration of the cementitious particles into consideration, buildability and pumpability are closely related to the slump and slump-flow of the material. While the materials may have the same slump, they may behave differently when stress is

1 applied. Material with a low fluidity paste and a low-volume fraction of sand can have the
2 same slump value as a material with high fluidity paste and a high-volume fraction of sand.
3 This is the case for Mix 3 and Mix 23. The low fluidity in the paste of Mix 3 dominates the
4 contribution to the material rigidity and the high-volume fraction of sand in Mix 23
5 dominates this contribution. As shown in Figure 13 and Figure 14, Mix 3 and 23 have the
6 similar slump values but the material characteristic such as buildability, surface finish and
7 pumpability index vary significantly (See Table 6). Therefore, the slump-flow value provides
8 another magnitude to characterise the material behaviour during and after 3D printing.
9 Although slump-flow seems to be proportional to the slump value, slump-flow helps to
10 differentiate different material behaviour when stress is applied.

11
12 Besides the slump and slump-flow values, the pumpability index is also introduced to better
13 characterize the pumping behaviour. The pumpability index is also correlated to the slump
14 and slump-flow value. The high pumpability index is related to a good surface finish as well
15 as low buildability.

16
17 Figure 15 shows the deformation in the slump of the filament when each layer is added. A
18 significant slump on the measured filaments was observed when the first layers were
19 deposited above. This was a common trend for all mixtures. It is noticed that this slump is
20 caused by stress induced during deposition of the direct subsequent layer. Mixtures that have
21 a low slump value is better at withstanding this initial slump. As the deposition of the layer
22 progresses further, this additional stress is gradually reduced.

23
24 A stepwise behaviour is noticed for Mix 3 and Mix 12. These two mixtures exhibit a more
25 solid-like behaviour when compared to Mix 8 and Mix 23. Similar to Mix 22L, this solid-like
26 behaviour allows the mixture to support high vertical stress and can, therefore, be printed
27 with more layer without slumping. On the other hand, Mix 8 and Mix 23 exhibits a more
28 paste-like behaviour similar to Mix 9U.

Figure 15: The slump of filament for the mixtures within acceptable printing region

4. Conclusion

This study used standardized field-friendly protocols to measure the slump and slump-flow values of the mortars. It is found that compared with fly ash and silica fume replacement ratio, water to binder ratio and sand to binder ratio play a much bigger role in the slump and slump flow values. The slump and slump flow results are also correlated for these mixtures.

The pumpability and buildability of 3D printable concrete are evaluated in terms of the pumpability index, surface quality and maximum height printed. The 3D printing tests show that the surface quality increases with slump-flow value and pumpability index. The buildability in terms of maximum height is the optimal in a middle range. Mixtures with a slump between 4 and 8 mm and a slump flow value between 150 and 190 mm give a smooth surface and high buildability. Thus, the material printable region is defined according to the slump and slump-flow values. With this simple and standardized method, printability of the mixtures can be determined before 3D printing.

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