



HAL
open science

Underwater 3D printing of cement-based mortar

B. Mazhoud, A. Perrot, V. Picandet, Damien Rangeard, E. Courteille

► **To cite this version:**

B. Mazhoud, A. Perrot, V. Picandet, Damien Rangeard, E. Courteille. Underwater 3D printing of cement-based mortar. *Construction and Building Materials*, Elsevier, 2019, 214, pp.458-467. 10.1016/j.conbuildmat.2019.04.134 . hal-02122198

HAL Id: hal-02122198

<https://hal-univ-rennes1.archives-ouvertes.fr/hal-02122198>

Submitted on 22 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial | 4.0 International License

UNDERWATER 3D PRINTING OF CEMENT-BASED MORTAR

Brahim MAZHOUD^{a*}, Arnaud PERROT^a, Vincent PICANDET^a, Damien Rangeard^b, Eric Courteille^b

^a Univ. Bretagne Sud, UMR CNRS 6027, IRDL, F-56100 Lorient, France

^b INSA Rennes - EA 3913, LGCGM, F-35000 Rennes, France

Postal address: UBS – IRDL, Centre de Recherche C. Huyghens – BP 92116 – 56321 LORIENT– France

brahim.mazhoud@univ-ubs.fr

arnaud.perrot@univ-ubs.fr

vincent.picandet@univ-ubs.fr

damien.rangeard@insa-rennes.fr

eric. Courteille @ insa-rennes.fr

* Corresponding author: Tel: +33.2.97.87.45.77, Fax: +33.2.97.87.45.72

Abstract

Nowadays, the development of renewable marine energies and needs for coastal protection to face global warming issues goes simultaneously with the fast development of digitally based construction methods such as concrete 3D printing. This creates the conditions to change the coastal and off-shore construction methods. Therefore in this study, we assess the possibility to design an underwater 3D printing materials. This possibility needs to develop cement-based materials that are simultaneously printable (pumpability, fast structuring) and also resistant to water washing out. After a mix design protocol that complies with the rheological requirements of the concrete and its water anti-washout properties (through permeability measurements), 3D printed samples has been fabricated in air and underwater. Then, the compressive strength of hardened printed mortar has been measured in order to validate the concept of the process.

Keywords: Cement-based material; Rheology; Anti-washout admixture; 3D printing.

24 **1. Introduction**

25 Concrete 3D printing technologies have received significant attention in the construction industry.
26 Especially, extrusion-based methods seems to be the most advanced technology [1–5]. The potential
27 benefits of this technique are various [6,7]: time and cost reduction, quality and safety improvement,
28 reduction of environmental impact by using topology optimization and fabrication of multi-functionalities
29 elements by taking advantage of complex geometries [8].

30 In the extrusion 3D printing methods, layers of cement-based are successively deposited by a robotic arm
31 to fabricate construction elements or a whole structure. Many researchers have reported that the stability of
32 the structure under printing can be described as a competition between the structural build-up rate of the
33 cement-based material and the rate of increase of the load acting on the structure due to its increasing height
34 [5,9]: This means that the mortar must have gained sufficient strength to withstand the vertical load
35 generated by the subsequently printed materials [10]. It is important to note that structural build-up of
36 cement-based materials is also involved in other building process such as self-compacting concrete
37 formwork pressure, multilayer casting,... [11–16].

38 The ability of the deposited layers to sustain its own weight is linked to its rheology (and its evolution in
39 time) and more particularly to both yield stress and elastic modulus [3,17]. During the layer by layer
40 building of a wall, the first deposited layer undergoes the heaviest load. In order to ensure the wall stability
41 during the process, the yield stress of the cement-based material must be high enough to sustain this load.
42 Here, a paradox appears: the mortar must be sufficiently fluid for pumping and extrusion flow but at the
43 same time strong enough to ensure the stability of the structure. The structural build-up of the deposited
44 concrete can here beneficially use to allow for the mix-design of a material that is fluid during extrusion
45 and sufficiently rigid after being left at rest after deposit. Structural build-up of the cement-based materials
46 leads to an increase of the macroscopic yield stress over resting time [18–22]; this mechanical strengthening
47 is mainly due to CSH bridges created at the contact points between cement particles (nucleation) and
48 appears before cement setting time (so-called “dormant period”) [23]. For ordinary Portland cement, the
49 yield stress of cementitious materials linearly increases during the first hour of rest [19]. After this first

50 linear evolution, Perrot et al. have developed a model that describes an exponential increase of the yield
51 stress. Another reason of concrete 3D printing failure can be due to self-buckling especially when the printed
52 shape has high slenderness. In this case, the elastic properties of the sample are crucial [20,24].

53 Nowadays, the development of marine energies and new means of production based on the technique of
54 3D printing can influence off-shore construction methods. The idea of using, in place, underwater additive
55 manufacturing, where the effect of gravity is decreased and the greater freedom of form, seems attractive.
56 This technique could be used not only for the implementation of anchors and foundation systems, for the
57 maintenance of submerged structures but also for the building of artificial reefs, a mandatory compensatory
58 measure for setting up marine energy plants. This last problem really seems to be able to find an answer in
59 the development of underwater 3D printing. Indeed, the preservation of marine biodiversity is both an
60 environmental emergency (maintaining sufficient fish stocks for fishing) and an economic one.

61 According to a survey on literature dealing with concrete 3D printing, no study has been reported on the
62 possibility to print concrete elements directly underwater. Therefore, the main objective of this study is to
63 show that it is possible to print concrete underwater. To achieve this objective, anti-washout admixture
64 (AWA) has been added to cement mortar in order to decrease the permeability of the cement mortar in the
65 fresh state. Hence, special care has to be given to the mix-design of a formulation having high washout
66 resistance [25,26]. In fact, the permeability of the fresh-state cement mortar must be adjusted to prevent
67 surrounding water to intermix with the fresh mortar in the case of printing in submerged conditions. Indeed
68 Assaad and Issa [27] have shown that the reduction of the permeability of the underwater concrete in the
69 fresh state reduce the washout loss.

70 Firstly, the influence of water to cement mass ratio (W/C) and AWA content on yield stress (and its
71 evolution with time) and elastic modulus of the studied mortars will be assessed in order to evaluate and
72 predict the so-called buildability of the tested materials. High yield stress will prevent the structure to
73 collapse due to the weight of the printed structures and is also representative of the interparticle forces at
74 microscale [28–30]. This means that high yield stress provides stronger bond between cement particles and
75 thus prevent washout. High elastic modulus will prevent the buckling of the structure during printing.

76 In addition, permeability measurements were used to quantify the effect of W/C and AWA content on the
77 cementitious material permeability (in the sense of hydraulic conductivity). For that purpose, a constant
78 water head device for permeability measurement dedicated to cement-based materials and developed by
79 Picandet et al. [31] and validated in other studies [32–34] has been successfully used. Low permeability
80 will be representative of a dense microstructure that will be more accessible to the water outside the
81 material.

82 Finally, 3D printing of mortar carried out underwater or not and at different printing head speeds, are
83 presented and the subsequent mechanical properties (compressive strength) of the printed elements are
84 measured.

85 **2. Materials and methods**

86 **2.1. Binder**

87 An ordinary Portland Cement (CEM 1 52.5N) with particle size distribution ranging between 0.1 and 100
88 μm with a mean grain diameter of approximately 15 μm and specific density of 3.15 is used. Its specific
89 surface estimated with Blaine device is 3390 cm^2/g . According to Vicat needle test, The initial setting time
90 of the cement is 90 minutes and the final one is 245 minutes. River sand 0/2, with a density of 2600 kg/m^3
91 and coming from Brittany is added to the tested mortar. In order to prevent the presence of large sand
92 particles with diameter greater that can lead to pumping and extrusion blockage, the sand was sieved by
93 means of a sieve of mesh 1 mm before use. The limestone filler used in this work has grain size ranging
94 from 0.1 to 100 μm ($d_{50} = 15 \mu\text{m}$).

95 In order to mix-design printable mortar, the superplasticizer was added to the formulation. It is a
96 commercial polycarboxylate superplasticizer containing 20% of dry polymer. In this study, a single dosage
97 of 3 % in mass of cement was chosen (maximum recommended dosage with a polymer dry extract over
98 cement equal to 0.6%). The superplasticizer was added to the mixing water. Such dosage provides the best

99 dispersion of the cement particles. Consequently, pore size are smaller and then the permeability of the
 100 mortar is reduced as shown by Perrot et al. [33].

101 The anti-washout admixture used in this study is a commercial white powdered admixture for concretes
 102 dedicated to deep structures. The main active molecules of this product is cellulose ether. It makes it
 103 possible, in particular, to ensure the cohesion and homogeneity of the concrete during casting and to
 104 counteract the phenomena of segregation and / or phase separation. It also promotes the stability of concrete
 105 during pumping. The AWA powder is first mixed with dry elements. The dosage of AWA is given as the
 106 AWA to cement mass ratio.

107 The different ratios and mix compositions are summarized in Table 1. For all the formulations the ratio
 108 SP/C was kept fixed to 0.03.

109 **Table 1: Mass ratios of the components of different studied cement mortar**

Formulations	Ratio			Percentage (%)		
	AWA/C	W/C	SP/C	Cement	Sand	limestone filler
M1_0.38_3%SP_0.5%AWA	0.005	0.38	0.03	32.5	50.0	17.5
M1_0.39_3%SP_0.5%AWA		0.39		32.5	50.0	17.5
M1_0.40_3%SP_0.5%AWA		0.40		32.5	50.0	17.5
M1_0.42_3%SP_0.5%AWA		0.42		32.5	50.0	17.5
M1_0.437_3%SP_0.5%AWA		0.437		32.5	50.0	17.5
M1_0.46_3%SP_0.5%AWA		0.46		32.5	50.0	17.5
M1_0.39_3%SP_1%AWA	0.01	0.39	0.03	32.5	50.0	17.5
M1_0.40_3%SP_1%AWA		0.40		32.5	50.0	17.5
M1_0.41_3%SP_1%AWA		0.41		32.5	50.0	17.5
M1_0.42_3%SP_1%AWA		0.42		32.5	50.0	17.5
M1_0.437_3%SP_1%AWA		0.437		32.5	50.0	17.5
M1_0.46_3%SP_1%AWA		0.46		32.5	50.0	17.5
M1_0.39_3%SP_1.5%AWA	0.015	0.39	0.03	32.5	50.0	17.5
M1_0.40_3%SP_1.5%AWA		0.40		32.5	50.0	17.5
M1_0.41_3%SP_1.5%AWA		0.41		32.5	50.0	17.5
M1_0.42_3%SP_1.5%AWA		0.42		32.5	50.0	17.5
M1_0.437_3%SP_1.5%AWA		0.437		32.5	50.0	17.5
M1_0.46_3%SP_1.5%AWA		0.46		32.5	50.0	17.5

110 Dry powder constituents were first mixed together for 2 min at slow speed in a planetary mixer. After this
 111 step, water was added to dry mix. Then, the mixing phase consisted of four steps: 1 minute at slow speed,

112 followed by 3 minutes of mixing at high speed. After stopping the mixing, the bowl is scraped in order to
113 homogenize the mortar. Lastly, the mixing was continued for 2 minutes at fast speed.

114 **2.2. Yield stress measurement**

115 Usually, the measurement of yield stress was carried out by rotational rheometry, especially using vane
116 geometry [5,33,35–37]. In this study, the cone penetrometer was used. This type of measurement is easy to
117 carry out and has been shown to be accurate for printable firm materials [38]. Also non-destructive static
118 plate tests could have been used to monitor structural build-up but this technique requires larger quantities
119 of material in order to obtain sufficient settlement to induce shear at the plate surface [39,40].

120 The standard BS ISO 13765-1:2004 characterises the use of the cone penetrometer [41]. Indeed, this test
121 aims to determine the workability and the consistency of the mortar under a certain stress caused by the
122 dropping cone (under gravity).

123 Firstly, the cement mortar is introduced in conical molds in two compacted layers (25 strokes per layer) in
124 order to have a homogeneous material with limited entrapped void. The excess mortar is removed using a
125 trowel or a spatula and the mold is placed under the dropping cone. Then, the testing machine is adjusted
126 so that the tip of the cone is in contact with the surface sample. Finally, the cone is dropped during 5
127 seconds: it penetrates into the mortar sample under its own weight. The penetration depth is measured with
128 accuracy of 0.01 mm. Measurements are replicated 5 times and the average value is taken into account. The
129 dispersion of the measurements is also computed.

130 The yield stress of the materials is computed from the depth of penetration h of the standardized cone used
131 in this study (tip angle of 30° , mass of 80 g). The yield stress computation comes from the force balance
132 between gravity and friction on the cone surface:

$$\tau_0 = \frac{m \times g \times \cos^2 \theta}{\pi h^2 \times \tan \theta} \quad (1)$$

133 Where h is the penetration depth (m), m the cone mass (kg) and g the gravity acceleration.

134 Roussel [18,19] has defined a structural build-up coefficient A_{thix} which models the constant rate of
135 increase of the yield stress over resting time [18,42]:

$$\tau_0(t_{rest}) = \tau_{0,0} + A_{thix}t_{rest} \quad (2)$$

136 Where $\tau_{0,0}$ is the initial yield stress of the material and t_{rest} is the resting time.

137 Recently, Perrot and co-authors have shown that the Roussel model deviates from the yield stress evolution
138 after one hour of rest [35,37]. They have developed a non-linear law that describes the yield stress
139 exponential increase for longer resting time. In this model, the authors used a time parameter (t_c) that
140 corresponds to the time when the yield stress increase becomes non-linear [35,37].

$$\tau_0(t_{rest}) = \tau_{0,0} + A_{thix}t_c(e^{t_{rest}/t_c} - 1) \quad (3)$$

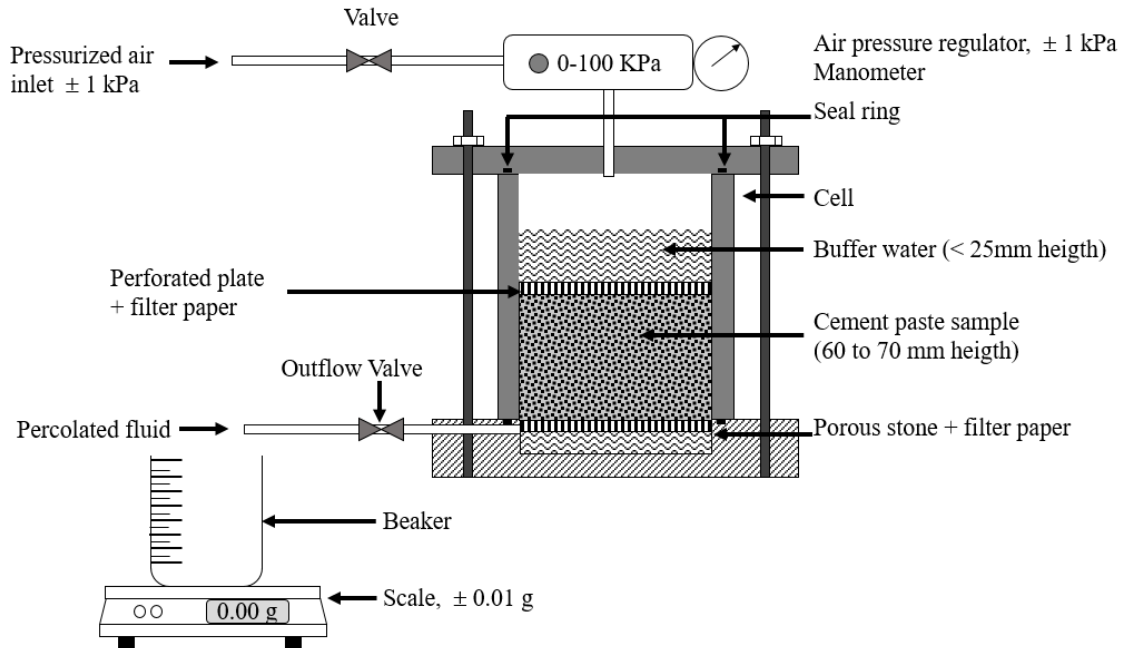
141 In order to describe the yield stress evolution over resting time, cone penetration tests were carried out at
142 regular intervals of 10 min on the same sample. The yield stress was measured at different resting times
143 after the end of mixing (5, 15, 25, 35, 45, 55 and 65 minutes).

144 **2.3. Measurement of material permeability at the fresh state**

145 A mortar-dedicated device (Figure 1) developed by Picandet et al. [31] is used for the measurement of the
146 permeability of the tested materials. This device allows to measure the volume of fluid flowing through the
147 mortar submitted to pressure gradient. The steel cell containing the tested mortar is connected to air pressure
148 inducing water head with a 1 kPa accuracy.

149 The mortar is placed on a filtration system which consists in 2 thin Fisherbrand® filter papers (thickness of
150 160 μm and mesh size of 8 μm) placed over a porous stone. This filtration system is saturated with water
151 before testing. A perforated plate with filter paper covers the top of the sample for a homogeneous pressure
152 repartition. About 250 ml of water is added over the sample to guaranty the water-saturation of the mortar
153 during the whole test.

154 For the measurement of the mortar volume, the sample is weighted before the beginning of the test. Just
 155 after pouring the mortar, vibration is applied to minimize entrapped air. The sample height is measured,
 156 before the beginning and after the end of the test. This allows the computation of the mortar density and of
 157 the test-induced settlement due to pressure gradient application. Tests started 15 minutes after the contact
 158 between water and cement.



159

160 **Fig. 1 : Permeability measurement device [31]**

161 The permeability coefficient, k , is computed using Darcy's law (Eq. (1)):

$$k = Q \times \frac{h_i}{S \times \Delta H} \quad (4)$$

162 Where Q is the measure water flow rate measured with the scale (as shown in Figure 1), h_i the sample
 163 height and ΔH is the water head.

164 At the beginning of the test, the water flow rate Q is maximal due to the consolidation of the tested material.
 165 Then, Q decreases to reach a plateau whose value is used in order to compute the permeability coefficient.

166 The consolidation also decreases the amount of water initially present in the mortar. This decrease in the
167 water content is evaluated by measuring the material settlement.

168 **2.4. Elastic modulus of fresh mortar**

169 In order to measure the elastic modulus of fresh mortar, arheometer equipped with a plate geometry was
170 used. The test consists in an unconfined one-dimensional compression of a mortar cylinder 38 mm high
171 and 50 mm diameter. The sample was placed between two parallel plates. Constant rate of displacement
172 protocol was performed at 1 mm/min. For each mortar three samples were tested. The test protocol consists
173 of two cycles of loading and unloading. The first cycle is of the order of one-tenth of a millimeter in order
174 to obtain a plane surface. The second cycle was performed to calculate the elastic modulus.

175 **2.5. 3D concrete printer and printing parameters**

176 The home-made 3D printer used in this study is a combination of a 6-axis robot (with a payload of 195 kg)
177 with a Giema TP5 electric pump initially dedicated to rendering operations (pressure capacity: 20 bar –
178 max flow rate: 40 l/min).

179 Tested mortar is prepared separately using a 100 litres concrete mixer and is then poured into the pump
180 reservoir. A 6 m long, and 35 mm in diameter hose pipe is used to connect the pump reservoir to the nozzle
181 mounted on the robot arm. Rectangular nozzle with the cross section of $21 \times 40 \text{ mm}^2$ was used to extrude
182 and deposit the mortar.

183 Different printing speeds (16, 18, 20 and 25 mm/s) were used to print the mortar in the water and only one
184 speed (25 mm/s) was used to print it in the air, with a deposit height of 20 mm and a mortar flow rate of
185 about 3 l/min (Figure 2). After 24 hours, the different specimens were kept in the containers with water at
186 controlled environment (20 °C and 50% relative humidity) until testing.

187 In order to avoid material blockage in the hose pipes at startup and to facilitate pumping, a lubricant called
188 slip (synthetic product or cement slurry W/C ratio between 0.5 and 0.8) was pumped before the mortar.



189

190 **Fig. 2: Ongoing 3D printing of mortar –left: sample printed in air, right: sample printed in water.**

191 **2.6. Compressive strength of printed samples**

192 In order to verify if the printed samples had compressive strength in accordance with expectations,
193 compressive strength measurements were carried out; 76 mm high with a rectangular cross-section of 45x45
194 mm² were tested in compression using a 50 kN loading frame (constant rate of displacement of 1 mm/min).

195 For each printing speed, four specimens were tested and the averaged compressive strengths were then
196 computed and compared.

197 The elastic modulus, E in GPa, was calculated using Eq. (2) in the linear part of the stress-strain curve:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (4)$$

198 Where σ and ε are respectively the axial stress and axial strain. The axial strain is computed by dividing
199 the displacement by the initial height of the sample.

200 Before each compressive strength, samples are weighted and measured in order to compute their apparent
 201 densities.

202 3. Mix-design and fresh-state properties

203 3.1. Initial yield stress and Structural build-up rate

204 Figures 3 to 5 show the evolution of the yield stress in function of the resting time for the mortars for
 205 different W/C. Fitting of Roussel linear model [18,19] and Perrot et al. non-linear model [35] are also drawn
 206 in these figures.

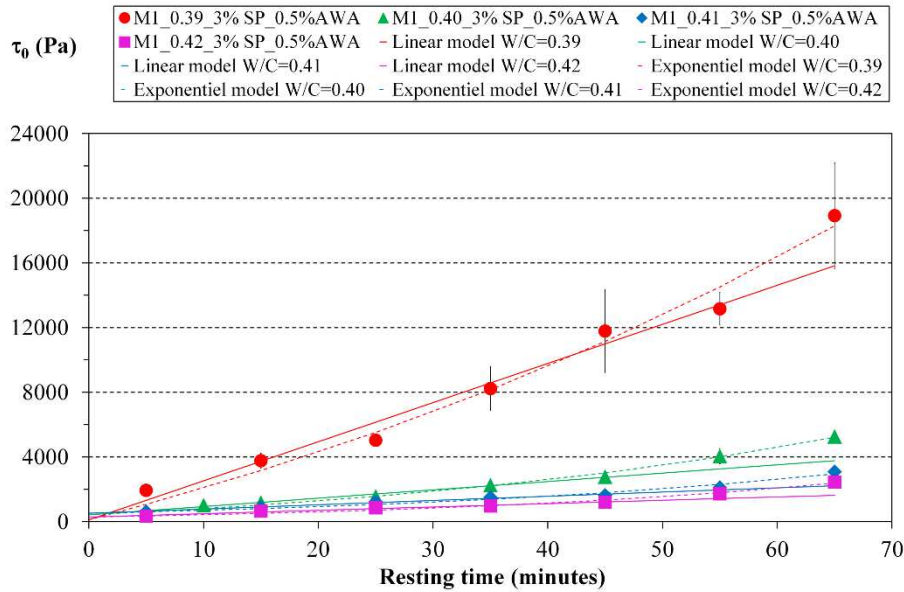
207 It highlights that the increase of the yield stress of the tested cement mortar is almost linear during the first
 208 45 min. In this period, the Roussel model accurately predict the structural build-up at rest. For longer resting
 209 period, the model developed by Perrot et better predicts the increase in yield stress [35]. It means that the
 210 A_{thix} coefficient, determined by Roussel model during the first 45 min can be efficiently used to model the
 211 yield stress increase. All measured values of A_{thix} are plotted in Fig. 8 and Fig. 9.

212 Fitting parameters of both models are summarized in Table 2.

213 **Table 2: Model parameters**

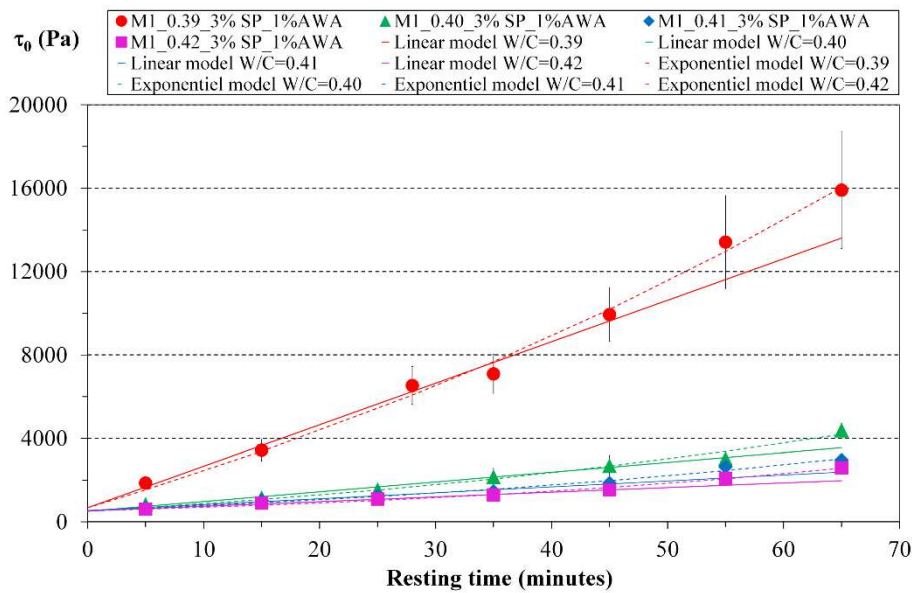
Formulations	E/C	Roussel linear model (Roussel.2005)		Perrot et al. Exponentiel model (Perrot.2015)		
		A_{thix} (Pa.min ⁻¹)	$\tau_{0,0}$ (Pa)	A_{thix} (Pa.min ⁻¹)	$\tau_{0,0}$ (Pa)	t_c (min)
M1_0.38_3%SP	0.38	27.2	746.7	11.3	746.7	25.3
M1_0.39_3%SP	0.39	24.48	673.7	16.5	673.7	48.5
M1_0.40_3%SP	0.40	18.8	485.2	13.8	485.2	62.4
M1_0.39_3%SP_0.5%AWA	0.39	241.7	112.8	185.5	112.8	84.2
M1_0.40_3%SP_0.5%AWA	0.40	51.6	420.4	34.9	420.4	48.2
M1_0.41_3%SP_0.5%AWA	0.41	26.2	520.9	16.0	520.9	43.0
M1_0.42_3%SP_0.5%AWA	0.42	20.7	287.9	12.1	287.9	37.8
M1_0.39_3%SP_1%AWA	0.39	199.0	672.4	166.5	672.4	98.0
M1_0.40_3%SP_1%AWA	0.40	46.8	505.1	33.7	505.1	67.1
M1_0.41_3%SP_1%AWA	0.41	28.3	543.8	21.9	543.8	63.6
M1_0.42_3%SP_1%AWA	0.42	22.3	525.6	15.4	525.6	50.2
M1_0.39_3%SP_1.5%AWA	0.39	123.5	1142.4	107.3	1142.4	125.7
M1_0.40_3%SP_1.5%AWA	0.40	48.3	1089.3	38.9	1089.3	82.3
M1_0.41_3%SP_1.5%AWA	0.41	29.6	634.1	22.2	634.1	67.0

M1_0.42_3%SP_1.5%AWA	0.42	13.4	452.1	9.6	452.1	58.5
----------------------	------	------	-------	-----	-------	------



214

215 **Fig. 3: Evolution of the yield stress vs resting time for the materials for different W/C and 0.5% of AWA.**
 216 **Comparison of the experimental data with prediction of the Perrot et al. [35] and Roussel models [19]**

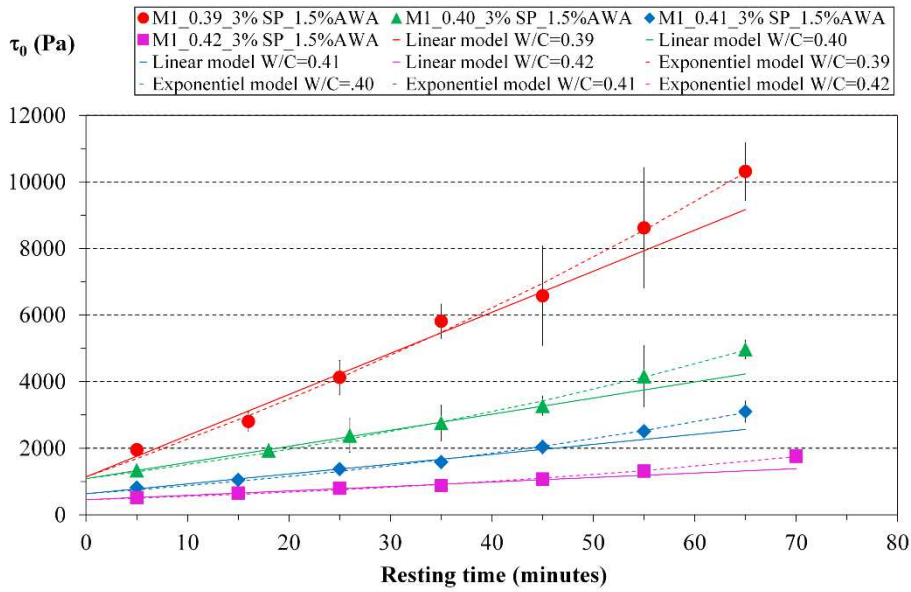


217

218 **Fig. 4: Evolution of the yield stress versus resting time for the materials for different W/C and 1% of AWA.**
 219 **Comparison of the experimental data with prediction of the Perrot et al. [35] and Roussel models [19]**

220

221



222

223 **Fig.5: Evolution of the yield stress vs resting time for the materials for different W/C and 1.5% of AWA.**
 224 **Comparison of the experimental data with prediction of the Perrot et al. [35] and Roussel models [19]**

225

226 The effect of W/C on the structural build-up rate of cement mortar with various AWA dosages is shown in
 227 Figure 6. The effects of AWA dosage on structural build-up rate of cement mortar with various W/C are
 228 shown in Figure 7.

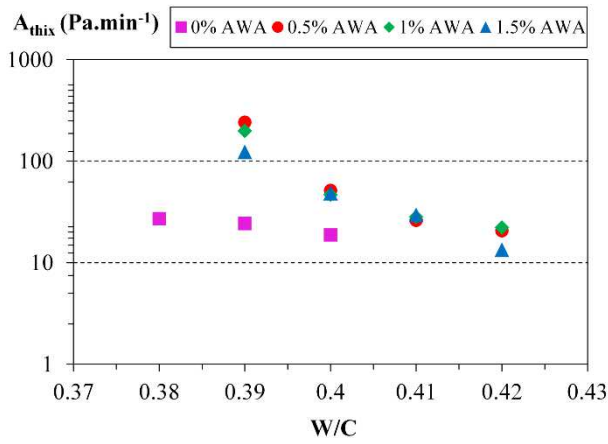
229 We first observe that the structural build-up rate decreases when the water to cement ratio is increased.
 230 Indeed, when the water to cement ratio varies from 0.39 to 0.42, the structural build-up rate decreases by
 231 91–89% depending on the dosage of AWA.

232 The mortar without AWA shows a less significant decrease of structural build-up rate with W/C ratio.
 233 Indeed, it decreases by 28% when water to cement ratio varies from 0.38 to 0.40.

234 For higher W/C, the effects of W/C on the structural build-up rate were not highly significant, as shown in
 235 Figure 6. It became more influencing at lower W/C. This is in agreement with prediction of Yodel model:
 236 the yield stress and structural build-up variation are larger when approaching the packing fraction [43,44].

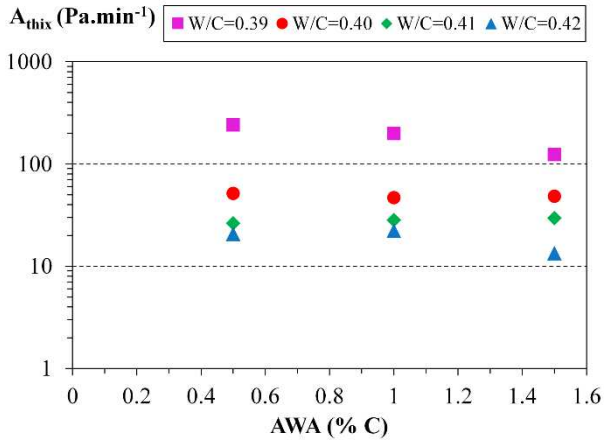
237 On the other hand, the structural build-up rate was more sensitive to AWA dosage in lower W/C than in
 238 higher W/C, as shown in Figure 7.

239 The addition of water reduces the solids concentration, resulting in less resistance to flow. Workability is
 240 improved with increasing water-to-cementitious materials ratios up to a certain point, after which bleeding
 241 and segregation can become a problem [45].



242

243 **Fig. 6: Evolution of the structural build-up rate versus the W/C ratio of cement mortar with various AWA**
 244 **contents.**



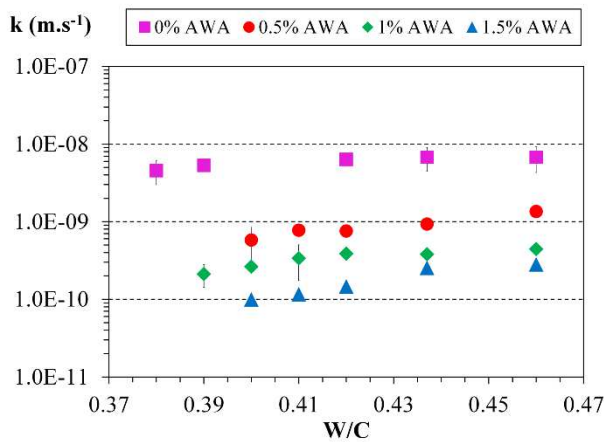
245

246 **Fig. 7: Evolution of the structural build-up rate versus the AWA contents of cement mortar with various W/C**
 247 **ratio.**

248 **3.2. Permeability**

249 The variation of fresh mortar permeability as a function of water to cement ratio is shown in Figure 8.
250 Whatever the AWA content, the permeability of fresh mortar increases with W/C. It can be explained by
251 the increase of the void ratio and porosity [33] that are both closely linked to W/C [31]. Therefore, mortars
252 with high W/C have higher porosity causing the acceleration of water flow through the tested specimen.

253 For constant W/C, the permeability decreases with increase in AWA content. For example, for the mortar
254 with W/C equal to 0.42, an augmentation in the dosage of AWA from 0% to 0.5%, 1% and 1.5% resulted
255 an decrease of permeability for 88%, 94% and 98% respectively. This can be explained by the increase in
256 the interstitial liquid phase viscosity and by changes in the cement grain assembly. In fact, this is due to
257 the mode of function of the AWA polymers bonds together, thus adsorbing and fixing part of the mixing
258 water inside an gel [46,47]. A three-dimensional gel structure is created thanks to van der Waals forces
259 and hydrogen bonds increasing the viscosity of the interstitial phase and thus reducing permeability [48].



260

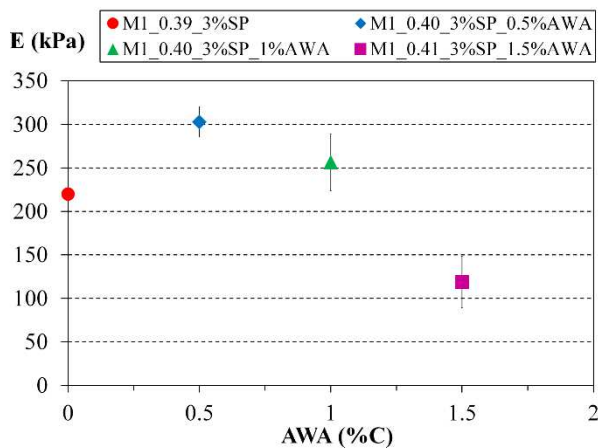
261 **Fig. 8: Permeability coefficient k ($m.s^{-1}$) vs W/C for various AWA contents.**

262 **3.3. Fresh mortar elastic modulus**

263 Concrete 3D printing carried out with the extrusion/deposit method can be seen as a multistep process. The
264 material has to be transported (often by pumping) before its deposit when the material leaves the extruder.

265 Once deposited, the material has to form a structure that remains stable over the whole printing process.
266 Then, the specification sheet for the behaviour of the freshly mixed material has to comply with all the
267 requirements defined at each step of the process. Such specifications lead to draw a mix-design window
268 that may need compromise between fluidity and strength or between fast structural build-up and long
269 workable time.

270 Figure 9 shows the effect AWA content on fresh mortar elastic modulus. We can observe that, over a critical
271 AWA content the elastic modulus of fresh mortar decreases with increasing the AWA content at a same
272 value of yield stress. This means that the AWA increase will lower the critical strain but increase the elastic
273 deformation. Further studies will be needed to accurately understand the mechanisms explaining this result
274 at the microscale.



275

276 **Fig. 9: Effect of AWA content on fresh mortar elastic modulus.**

277 **3.4. Optimized mix-design**

278 Rheological requirements of for 3D printing are dictated by the pumping stage, the extrusion/deposition
279 stage and finally by the overall stability of the structure during printing.

280 In this study, the pump presents a pressure capacity of 20 bar and the hose pipe is 6 m long with an inner
281 diameter of 35 mm. Preliminary pumping tests have allowed to validate that the shear yield stress of the

282 material must remain under 1.1 kPa in order to keep the pressure under the pump pressure capacity. To
283 maintain a safety margin during pumping, the water content of the material was adjusted in order to obtain
284 hear yield stress of 0.8 kPa for the printing test. For the mortar without AWA the W/C is equal to 0.39, for
285 the mortar with 0.5% and 1% of AWA the W/C is equal to 0.40 and for the mortar with 1.5% of AWA the
286 W/C ratio is equal to 0.41 respectively.

287 Also, in order to ensure that the printed structure remains stable, the material must build-up as fast as
288 possible and must present the highest possible elastic modulus. this last property is considered to be
289 detrimental for 3D printing because low elastic modulus can lead to self-buckling. As previously exposed,
290 highest structural build-up rate and highest elastic modulus are found at a AWA dosage of 0.5%. In order
291 to ensure the 3D printing wall stability during the process, the yield stress and the elastic modulus of the
292 first deposited layer that undergoes the heaviest load must be sufficient to sustain this load and to keep its
293 shape. Therefore, AWA dosage of 0.5% (overall stability requirements) and W/C of 0.39 (in order to have
294 a yield stress of 0.8 kPa for pumpability) were chosen in order to perform the underwater printing.

295 It is also worth noting that the dosage of 0.5% of AWA is sufficient to significantly decrease the
296 permeability of the mortar hence enhancing its anti-washout properties, as shown in Figure 8. Indeed, from
297 0 to 0.5% of AWA allows to decrease the permeability of the mortar by around one order of magnitude
298 whereas from 0.5 to 1% divide only by 2 the permeability.

299 **4. Underwater printing 3D printing materials**

300 It is important to note that the nozzle displacement velocity (printing speed in our study) can significantly
301 affect the behaviour the printed material. This is even more pronounced in the case of concrete printing due
302 to the presence of larger particles in comparison with the printing of other types of materials [49,50]. It is
303 expected that a balance can be found between pumping flow rate and nozzle velocity leading to an optimal
304 printing speed [32]. For the printed mortar, it has been noted that with a constant pump flow, the increase
305 in print speed reduces the width of the printed mortar.

306 The mechanical properties measured in this study are summarized in **Table 3**. Compressive strength of the
 307 mortar samples printed in water is plotted as a function of printing speed in Figure 10. For the studied
 308 materials, the compressive strength decreases with the studied printing speed. Results shows that the
 309 compressive strength decreases by 10.4% when the printing speed varies from 16 to 25 mm.s⁻¹. This is
 310 decrease can be explained by both size effect and strain gradients within the cross section of the filaments
 311 of mortar, caused by the differences between mortar velocity in the printhead and nozzle displacement
 312 velocity [51]. This may cause what can be called under or over-extrusion and leads to a decrease of the
 313 sample density.

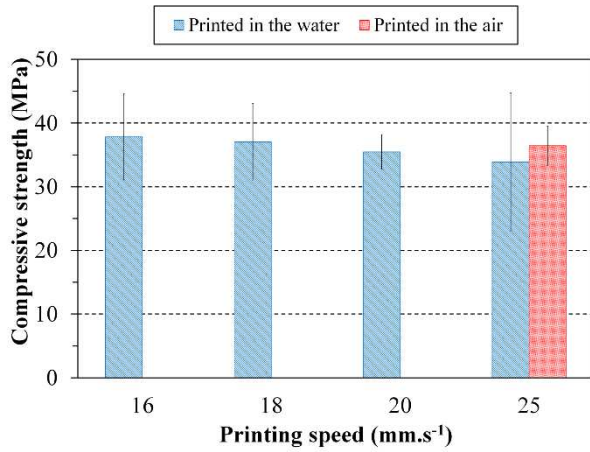
314 In contrast to compressive strength, elastic modulus displays a different trend. Figure 11 shows that below
 315 a critical printing speed, the elastic modulus of 3D printable mortar decreased with increasing the printing
 316 speed. A too fast nozzle displacement may have led to tensile stresses in the filament cross section that may
 317 have led to material micro-failure or fracture that may significantly affect the mechanical properties of the
 318 sample once hardened [49].

319 If we compare the mechanical properties obtained with the 3D printable mortar specimens in water with
 320 those printed in the air, we observe a decrease of 7% and 11% respectively for compressive strength and
 321 elastic modulus. This can be explained by washout effect at the surface of the layers.

322 **Table 3 : Densities and mechanical properties of printed samples.**

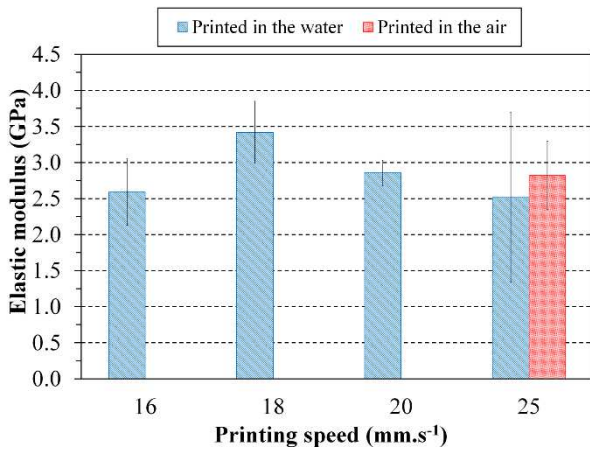
	Printing speed (mm.s ⁻¹)	Density (kg.m ⁻³)	Compressive strength (MPa)	Elastic modulus (GPa)
Water	16	2280 ± 25	37.84 ± 6.77	2.59 ± 0.46
	18	2280 ± 20	37.06 ± 6.01	3.42 ± 0.43
	20	2260 ± 24	35.49 ± 2.68	2.86 ± 0.18
	25	2240 ± 18	33.90 ± 10.84	2.52 ± 1.18
Air	25	2270 ± 32	36.45 ± 3.09	2.82 ± 0.48

323



324

325 **Fig. 10: Evolution of the compressive strength of 3D printable cement mortar versus the printing speed.**

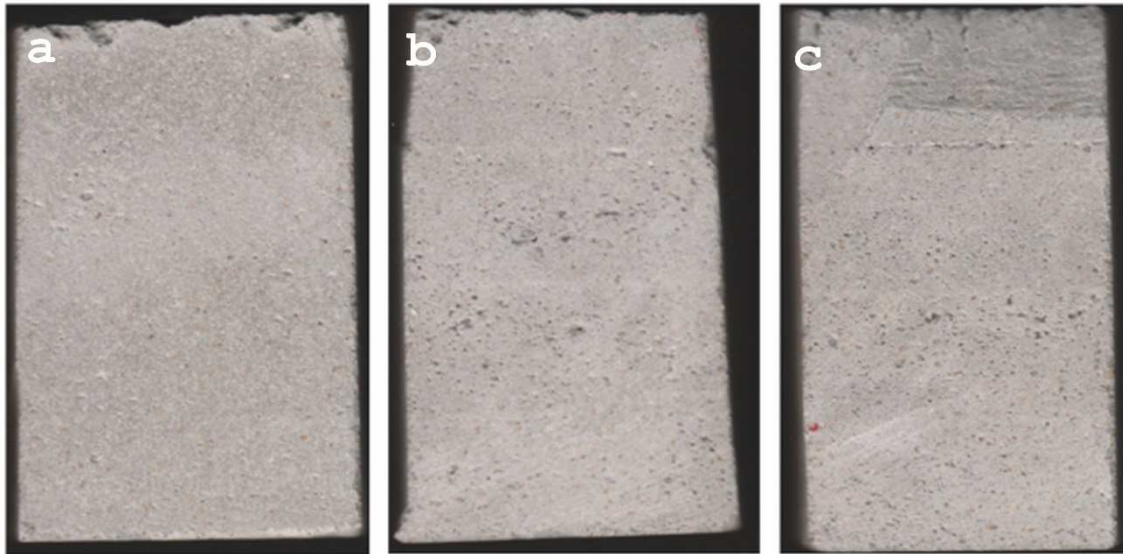


326

327 **Fig. 11: Evolution of the elastic modulus of 3D printable cement mortar versus the printing speed.**

328 Cut section of sample printed in water at different speed is shown in Figure 12. It is worth noting the absence
 329 of cold joints and adhesion defects between the extruded layers for printing speed of 18 and 20 mm/s. This
 330 means that at these printing speeds, water does not alter adhesion between layers.

331 However, it can be seen of Fig. 12c that some voids appear between layers. It can be attributed to under-
 332 extrusion: the nozzle moves too fast and creates tension in the deposited layer leading to void formation.
 333 Such results are in agreement with the measured densities presented in table 3.



334

335 **Fig.12: Cut section of printed samples in water: a) printed with a speed of 18 mm.s⁻¹ - b) printed with a speed**
336 **of 20 mm.s⁻¹ - c) printed with a speed of 25 mm.s⁻¹**

337 **5. Conclusion**

338 This study aimed to investigate the possibility of producing an underwater 3D printing material and
339 highlights the effect of printing speed on mechanical properties. Firstly, the effects of W/C and AWA
340 content on the fresh properties were studied, with the goal of designing a printable mortar.

341 Tested mortars were characterised by measuring their yield stress, structural build-up rate, water
342 permeability and elastic modulus. Literature has shown that their properties are involved during the printing
343 process and need to be fine-tuned for the successful implementation of the underwater 3D printing of
344 mortar. The experimental results show that the structural build-up rate is influenced by the AWA content
345 and W/C. In fact, the structural build-up rate decreases with the increase in W/C and AWA content.

346 Moreover, the addition of AWA decreases the permeability of the fresh mortar. This can be explained by
347 increase in the interstitial fluid viscosity and by densification of the particle network.

348 After selection of the best formulation, mortar 3D printing has been performed at different printing speed
349 (nozzle displacement velocity) and the compressive strength of the printed samples have been measured.

350 Finally, for the underwater 3D printing materials, the compressive strength decreases with the increase of
351 printing speed. In contrast to compressive strength, elastic modulus shows quite a different trend, below a
352 critical printing speed the elastic modulus of 3D printable mortar decreases with increasing the printing
353 speed.

354 **6. Acknowledgement**

355 The authors want to thank the “Pôle Homme Mer Littoral” of Université Bretagne Sud for funding this
356 research program.

357 **7. References**

- 358 [1] B. Khoshnevis, Automated construction by contour crafting—related robotics and information
359 technologies, *Autom. Constr.* 13 (2004) 5–19. doi:10.1016/j.autcon.2003.08.012.
- 360 [2] B. Khoshnevis, D. Hwang, K.T. Yao, Z. Yeh, Mega-scale fabrication by Contour Crafting, *Int. J.*
361 *Ind. Syst. Eng.* 1 (2006) 301. doi:10.1504/IJISE.2006.009791.
- 362 [3] T.T. Le, S.A. Austin, S. Lim, R.A. Buswell, A.G.F. Gibb, T. Thorpe, Mix design and fresh
363 properties for high-performance printing concrete, *Mater. Struct.* 45 (2012) 1221–1232.
364 doi:10.1617/s11527-012-9828-z.
- 365 [4] S. Lim, R.A. Buswell, T.T. Le, S.A. Austin, A.G.F. Gibb, T. Thorpe, Developments in
366 construction-scale additive manufacturing processes, *Autom. Constr.* 21 (2012) 262–268.
367 doi:10.1016/j.autcon.2011.06.010.
- 368 [5] A. Perrot, D. Rangeard, A. Pierre, Structural built-up of cement-based materials used for 3D-
369 printing extrusion techniques, *Mater. Struct.* 49 (2016) 1213–1220. doi:10.1617/s11527-015-0571-0.
- 370 [6] R.A. Buswell, R.C. Soar, A.G.F. Gibb, A. Thorpe, Freeform Construction: Mega-scale Rapid
371 Manufacturing for construction, *Autom. Constr.* 16 (2007) 224–231. doi:10.1016/j.autcon.2006.05.002.
- 372 [7] B. Nematollahi, M. Xia, J. Sanjayan, Current Progress of 3D Concrete Printing Technologies, in:
373 2017. doi:10.22260/ISARC2017/0035.
- 374 [8] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, P. Morel, Large-scale 3D
375 printing of ultra-high performance concrete – a new processing route for architects and builders, *Mater.*
376 *Des.* 100 (2016) 102–109. doi:10.1016/j.matdes.2016.03.097.
- 377 [9] T. Wangler, E. Lloret, L. Reiter, N. Hack, F. Gramazio, M. Kohler, M. Bernhard, B.
378 Dillenburger, J. Buchli, N. Roussel, R. Flatt, Digital Concrete: Opportunities and Challenges, *RILEM*
379 *Tech. Lett.* 1 (2016) 67. doi:10.21809/rilemtechlett.2016.16.

- 380 [10] A. Perrot, D. Rangeard, E. Courteille, 3D printing of earth-based materials: Processing aspects,
381 *Constr. Build. Mater.* 172 (2018) 670–676. doi:10.1016/j.conbuildmat.2018.04.017.
- 382 [11] S. Amziane, Setting time determination of cementitious materials based on measurements of the
383 hydraulic pressure variations, *Cem. Concr. Res.* 36 (2006) 295–304.
384 doi:10.1016/j.cemconres.2005.06.013.
- 385 [12] S. Amziane, C.F. Ferraris, Cementitious paste setting using rheological and pressure
386 measurements, *ACI Mater. J.* 104 (2007) 137.
- 387 [13] P.H. Billberg, N. Roussel, S. Amziane, M. Beitzel, G. Charitou, B. Freund, J.N. Gardner, G.
388 Grampeix, C.-A. Graubner, L. Keller, K.H. Khayat, D.A. Lange, A.F. Omran, A. Perrot, T. Proske, R.
389 Quattrocioni, Y. Vanhove, Field validation of models for predicting lateral form pressure exerted by
390 {SCC}, *Cem. Concr. Compos.* 54 (2014) 70–79.
391 doi:http://dx.doi.org/10.1016/j.cemconcomp.2014.02.003.
- 392 [14] A. Perrot, S. Amziane, G. Ovarlez, N. Roussel, {SCC} formwork pressure: Influence of steel
393 rebars, *Cem. Concr. Res.* 39 (2009) 524–528. doi:http://dx.doi.org/10.1016/j.cemconres.2009.03.002.
- 394 [15] G. Ovarlez, N. Roussel, A Physical Model for the Prediction of Lateral Stress Exerted by Self-
395 Compacting Concrete on Formwork, *Mater. Struct.* 39 (2006) 269–279. doi:10.1617/s11527-005-9052-1.
- 396 [16] N. Roussel, F. Cussigh, Distinct-layer casting of SCC: The mechanical consequences of
397 thixotropy, *Cem. Concr. Res.* 38 (2008) 624–632. doi:10.1016/j.cemconres.2007.09.023.
- 398 [17] E. Lloret, A.R. Shahab, M. Linus, R.J. Flatt, F. Gramazio, M. Kohler, S. Langenberg, Complex
399 concrete structures: Merging existing casting techniques with digital fabrication, *Comput.-Aided Des.* 60
400 (2015) 40–49. doi:10.1016/j.cad.2014.02.011.
- 401 [18] N. Roussel, Steady and transient flow behaviour of fresh cement pastes, *Cem. Concr. Res.* 35
402 (2005) 1656–1664. doi:10.1016/j.cemconres.2004.08.001.
- 403 [19] N. Roussel, A thixotropy model for fresh fluid concretes: Theory, validation and applications,
404 *Cem. Concr. Res.* 36 (2006) 1797–1806. doi:10.1016/j.cemconres.2006.05.025.
- 405 [20] N. Roussel, Rheological requirements for printable concretes, *Cem. Concr. Res.* 112 (2018) 76–
406 85. doi:10.1016/j.cemconres.2018.04.005.
- 407 [21] D. Lowke, T. Kränkel, C. Gehlen, P. Schießl, Effect of Cement on Superplasticizer Adsorption,
408 Yield Stress, Thixotropy and Segregation Resistance, in: K.H. Khayat, D. Feys (Eds.), *Des. Prod. Place.*
409 *Self-Consol. Concr.*, Springer Netherlands, Dordrecht, 2010: pp. 91–101. doi:10.1007/978-90-481-9664-
410 7_8.
- 411 [22] R. Ferron, A. Gregori, Z. Sun, S.P. Shah, Rheological Method to Evaluate Structural Buildup in
412 Self-Consolidating Concrete Cement Pastes, *ACI Mater. J.* 104 (2007). doi:10.14359/18669.
- 413 [23] N. Roussel, G. Ovarlez, S. Garrault, C. Brumaud, The origins of thixotropy of fresh cement
414 pastes, *Cem. Concr. Res.* 42 (2012) 148–157. doi:10.1016/j.cemconres.2011.09.004.

- 415 [24] F.P. Bos, Z.Y. Ahmed, R.J.M. Wolfs, T.A.M. Salet, 3D Printing Concrete with Reinforcement,
416 in: D.A. Hordijk, M. Luković (Eds.), High Tech Concr. Technol. Eng. Meet, Springer International
417 Publishing, Cham, 2018: pp. 2484–2493. doi:10.1007/978-3-319-59471-2_283.
- 418 [25] K.H. Khayat, M. Sonebi, Effect of mixture composition on washout resistance of highly
419 flowable underwater concrete, *Mater. J.* 98 (2001) 289–295.
- 420 [26] M. Sonebi, K.H. Khayat, Effect of mixture composition on relative strength of highly flowable
421 underwater concrete, *Mater. J.* 98 (2001) 233–239.
- 422 [27] J.J. Assaad, C.A. Issa, Mechanisms of strength loss in underwater concrete, *Mater. Struct.* 46
423 (2013) 1613–1629. doi:10.1617/s11527-012-0004-2.
- 424 [28] N. Roussel, A. Lemaître, R.J. Flatt, P. Coussot, Steady state flow of cement suspensions: A
425 micromechanical state of the art, *Cem. Concr. Res.* 40 (2010) 77–84.
426 doi:10.1016/j.cemconres.2009.08.026.
- 427 [29] N. Massoussi, E. Keita, N. Roussel, The heterogeneous nature of bleeding in cement pastes,
428 *Cem. Concr. Res.* 95 (2017) 108–116.
- 429 [30] A. Perrot, T. Lecompte, H. Khelifi, C. Brumaud, J. Hot, N. Roussel, Yield stress and bleeding of
430 fresh cement pastes, *Cem. Concr. Res.* 42 (2012) 937–944.
431 doi:http://dx.doi.org/10.1016/j.cemconres.2012.03.015.
- 432 [31] V. Picandet, D. Rangeard, A. Perrot, T. Lecompte, Permeability measurement of fresh cement
433 paste, *Cem. Concr. Res.* 41 (2011) 330–338. doi:10.1016/j.cemconres.2010.11.019.
- 434 [32] A. Perrot, D. Rangeard, V. Picandet, S. Serhal, Effect of coarse particle volume fraction on the
435 hydraulic conductivity of fresh cement based material, *Mater. Struct.* 48 (2015) 2291–2297.
436 doi:10.1617/s11527-014-0311-x.
- 437 [33] A. Perrot, D. Rangeard, V. Picandet, Y. Mélinge, Hydro-mechanical properties of fresh cement
438 pastes containing polycarboxylate superplasticizer, *Cem. Concr. Res.* 53 (2013) 221–228.
439 doi:10.1016/j.cemconres.2013.06.015.
- 440 [34] A. Pierre, A. Perrot, V. Picandet, Y. Guevel, Cellulose ethers and cement paste permeability,
441 *Cem. Concr. Res.* 72 (2015) 117–127. doi:10.1016/j.cemconres.2015.02.013.
- 442 [35] A. Perrot, A. Pierre, S. Vitaloni, V. Picandet, Prediction of lateral form pressure exerted by
443 concrete at low casting rates, *Mater. Struct.* 48 (2015) 2315–2322. doi:10.1617/s11527-014-0313-8.
- 444 [36] F. Mahaut, S. Mokéddem, X. Chateau, N. Roussel, G. Ovarlez, Effect of coarse particle volume
445 fraction on the yield stress and thixotropy of cementitious materials, *Cem. Concr. Res.* 38 (2008) 1276–
446 1285. doi:10.1016/j.cemconres.2008.06.001.
- 447 [37] T. Lecompte, A. Perrot, Non-linear modeling of yield stress increase due to SCC structural
448 build-up at rest, *Cem. Concr. Res.* 92 (2017) 92–97. doi:10.1016/j.cemconres.2016.11.020.
- 449 [38] D. Lootens, P. Jousset, L. Martinie, N. Roussel, R.J. Flatt, Yield stress during setting of cement
450 pastes from penetration tests, *Cem. Concr. Res.* 39 (2009) 401–408.
451 doi:10.1016/j.cemconres.2009.01.012.

- 452 [39] H. Sleiman, A. Perrot, S. Amziane, A new look at the measurement of cementitious paste setting
453 by Vicat test, *Cem. Concr. Res.* 40 (2010) 681–686.
454 doi:<http://dx.doi.org/10.1016/j.cemconres.2009.12.001>.
- 455 [40] S. Amziane, A. Perrot, The plate test carried out on fresh cement-based materials:How and
456 why?, *Cem. Concr. Res.* 93 (2017) 1–7. doi:[10.1016/j.cemconres.2016.12.002](https://doi.org/10.1016/j.cemconres.2016.12.002).
- 457 [41] BS ISO 13765-1:2004, Refractory mortars. Determination of consistency using the penetrating
458 cone method, (2006).
- 459 [42] L. Josserand, O. Coussy, F. de Larrard, Bleeding of concrete as an ageing consolidation process,
460 *Cem. Concr. Res.* 36 (2006) 1603–1608. doi:[10.1016/j.cemconres.2004.10.006](https://doi.org/10.1016/j.cemconres.2004.10.006).
- 461 [43] R.J. Flatt, P. Bowen, Yield stress of multimodal powder suspensions: an extension of the
462 YODEL (Yield Stress mODEL), *J. Am. Ceram. Soc.* 90 (2007) 1038–1044.
- 463 [44] R.J. Flatt, P. Bowen, Yodel: a yield stress model for suspensions, *J. Am. Ceram. Soc.* 89 (2006)
464 1244–1256.
- 465 [45] L. Shen, L. Struble, D. Lange, Modeling static segregation of self-consolidating concrete, *ACI*
466 *Mater. J.* 106 (2009) 367–374.
- 467 [46] K.H. Khayat, Viscosity-enhancing admixtures for cement-based materials—an overview, *Cem.*
468 *Concr. Compos.* 20 (1998) 171–188.
- 469 [47] L. Patural, P. Marchal, A. Govin, P. Grosseau, B. Ruot, O. Deves, Cellulose ethers influence on
470 water retention and consistency in cement-based mortars, *Cem. Concr. Res.* 41 (2011) 46–55.
- 471 [48] A. Pierre, A. Perrot, V. Picandet, Y. Guevel, Cellulose ethers and cement paste permeability,
472 *Cem. Concr. Res.* 72 (2015) 117–127.
- 473 [49] B. Panda, S.C. Paul, N.A.N. Mohamed, Y.W.D. Tay, M.J. Tan, Measurement of tensile bond
474 strength of 3D printed geopolymers mortar, *Measurement.* 113 (2018) 108–116.
475 doi:[10.1016/j.measurement.2017.08.051](https://doi.org/10.1016/j.measurement.2017.08.051).
- 476 [50] O. Lužanin, D. Movrin, M. Plančak, Experimental investigation of extrusion speed and
477 temperature effects on arithmetic mean surface roughness in FDM built specimens, *J. Technol. Plast.* 38
478 (2013) 179–190.
- 479 [51] F. Bos, R. Wolfs, Z. Ahmed, T. Salet, Additive manufacturing of concrete in construction:
480 potentials and challenges of 3D concrete printing, *Virtual Phys. Prototyp.* 11 (2016) 209–225.
481 doi:[10.1080/17452759.2016.1209867](https://doi.org/10.1080/17452759.2016.1209867).
- 482