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2019

Panda, B., Lim, J. H., & Tan, M. J. (2019). Mechanical properties and deformation behaviour of early age concrete in the context of digital construction. *Composites Part B: Engineering*, 165, 563-571. doi:10.1016/j.compositesb.2019.02.040

<https://hdl.handle.net/10356/140514>

<https://doi.org/10.1016/j.compositesb.2019.02.040>

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Mechanical properties and deformation behaviour of early age concrete in the context of digital construction

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Abstract

Digital construction is gradually opening unlimited possibilities for building and concrete industry. The key secret for a robust print process lies in our understanding of the processing technology and material fresh properties, in addition to developing novel measurement and control techniques. This paper aims to gain a better understanding of early age mechanical properties of 3D printable materials and improve it for the requirement of large scale concrete printing. Experimental investigations were carried out to measure green strength and stiffness of fresh fly ash-cement mortar with applied 3D optical metrology. The compressive green strength was linked with material yield strength evolution and later, modified with nanoclay for higher buildability properties. Nanoclay addition decreased the layer deformation due to significant increase in Young's modulus and to estimate this uncontrolled deformation, a mathematical function was formulated, which subsequently validated by comparison to printing experiments.

Keywords: Digital construction, 3D printing, nanomaterials, green strength, and stiffness.

1.Introduction

With increase in technological advancements, automation in the construction industry is becoming more common, as illustrated by advanced prefab, precast technologies and more recently, by digital construction (DC) process which is commonly known as 3D concrete printing (3DCP) [1-3]. In the construction practice, digital design using computer-aided design (CAD), building information modelling (BIM) tools are already well developed and the step from designing to digital manufacturing is now benefiting higher productivity, faster construction processes, higher geometrical freedom, efficient use of raw materials, etc. The most widespread approach of 3DCP is the contour crafting method [4], where contours of any vertical elements are produced by extruding concrete filaments in layer by layer manner with a print head linked to concrete pump. Since the print head gradually builds up the complete structure, it is thus feasible to vary the composition and filament direction according to specific local requirements. A schematic diagram of 3DCP process at Nanyang Technological University (NTU), Singapore is shown in Fig. 1 [5].

Fig. 1 (a) 4-axis concrete gantry printer (b) 3D concrete printing (3DCP) process

Albeit a steadily growing number of researchers and private enterprises active in this field, 3DCP is still in its infancy. Fundamental scientific understanding of the relations between design, material and process is slowly evolving while the material formulation has been highly explored

in the literature [6-13], describing printable properties such as extrudability, open time and buildability. With a consideration to the mechanical strength and interface condition of the 3DCP material [14-16], global attention of researchers is now drawn to the need for reinforcement for structural application. Nevertheless, there is a new phase that needs to be addressed under buildability criteria, i.e. mechanical properties of early-age concrete. While printing, layers of concrete are deposited on top of each other without any formwork. So, the deposited layer must be stiff and strong enough to hold its own weight and also the weight of subsequent layers. The measurement of early age mechanical strength [17,18] is one of the possible ways to find the stiffness of printable materials, which is sometimes difficult to obtain using commercial rheometers due to maximum torque limitation. A numerical model was recently developed in this regard [19], to predict different failure modes based on material fresh properties and Mohr-Coulomb failure criterion. Compressive and shear strengths were measured to develop this model and due to extra compaction force (during experimental testing), the result was found to be overestimated by the model. Voigt et. al. [20] investigated the evolution of the green strength using compression strength test which was later linked with microstructure of the concrete using ultrasonic techniques. Similarly, Assaad et. al. [21] used direct shear test to find the cohesiveness of the cement pastes and a good co-relation was obtained between the cohesion value and yield strength, measured by the vane method. Wolfs et al. [22] also compared the performance of destructive compression test with non-destructive ultrasonic test for (printable) concrete strength evolution and found a linear co-relation between them up to 90 mins after mixing with water.

Since concrete printing is a form-less additive manufacturing process, the early age mechanical strength needs to be tailored in such a way that the yield stress of bottom layer must increase with build height and print speed to avoid any structural failure [23]. Therefore, the first aim of this

research is to study the evolving green strength of a printable cementitious mortar within its dormant period and secondly, improve the strength with the help of nanoclay to increase the buildability properties. A custom made high volume fly ash (HVFA) mortar was designed as a “control” mix (3D printable), with open time more than one hour and its deformation behaviour was continuously monitored using optical methods to investigate the effect of evolving green strength on buildability. The performance of nanoclay modified mix was also compared to the control in terms of deformability and to predict the deformation height (also called standoff distance, SD). A mathematical formulation was expressed which satisfactorily matched with the actual measurements obtained from the 3D printing experiments.

2. Research significance and scope

Concrete printing is a complex process influenced by numerous parameters such as material parameters (rheology [24], green strength, stiffness), printing parameters (layer height, print speed) from different stages of design and construction. Among them, material design is of utmost importance and till now, least knowledge is available on the material (early-age) properties that can affect the 3D printability [25], especially the buildability. In this paper, a new approach of improving material green strength and its impact on buildability was demonstrated. The scope of this study is limited to use high volume fly ash material and its green strength modification by physical interactions of nanoclay particles, instead of any chemical changes by accelerators. We have only focused on strength-based failure criterion for the deformation study, however, in future, structural failure caused by loss of stability can be accounted as observed in largely unpublished printing experiments.

3. Materials and Methods

3.1. Materials and mix design

Ordinary Portland cement (OPC) from Buildmate (S) Pte Ltd. (Singapore), Class F fly ash (FA) from Sembcorp EOSM Ltd. (India), micro silica (SF) from Elkem Pte Ltd. (Singapore) and reagent grade sodium sulphate obtained from VWR International Ltd. (Singapore) were used to prepare printable HVFA mortar. The chemical composition and individual particle size of both OPC, FA and SF are shown in Table 1 and Fig. 2, respectively. Graded river sand (particle size up to 1.18 mm) was used as fine aggregate in all our mix designs.

Table 1 Chemical compositions of the raw materials

Chemical composition (%)									
	SiO ₂	Al ₂ O ₃	CaO	MgO	SO ₃	TiO ₂	K ₂ O	Fe ₂ O ₃	LOI
OPC	24.27	4.56	62.2	3.34	-	0.55	0.61	3.95	2.54
FA	51.18	28.84	5.83	1.16	1.07	2.52	1.20	6.41	1.60
SF	98.37	0.19	0.35	0.15	0.19	-	0.28	0.08	0.36

For the control mix (C-mix), 60% FA, 38% OPC and 2% SF (by mass) were used to formulate 3D printable mortar as mentioned in our previous study [26]. 3% Na-Sulphate (wt. of binder) was added as activator to gain early strength inhibited by the presence of high volume FA. Sand-to-binder and water-to-binder ratio were kept 0.83 and 0.30 respectively. Highly purified attapulgite clay was used to improve green strength of the HVFA mortar. To prepare the fresh fly ash-cement mortar, OPC, FA and SF were dry mixed in a three-gear planetary mixer for over 3 minutes, after which the pre-dissolved Na-sulphate solution was slowly added into the mixture. The mixing continued for an additional 2–3 min until a homogenous status was achieved, after which the sand was slowly charged into the mixer and mixed for 1 min. For clay modified mix, 0.5% attapulgite nanoclay (by wt. of binder) was first dispersed in required water and then added to the dry powder

to enhance the green strength of C-mix, referred as NC-mix from here. The percentage of nanoclay (NC) was decided according to our previous study [25] and more detailed description of clay can be found in [27,28].

Fig. 2 SEM images of (a) OPC (b) FA and (c) SF

3.2 Experimental methods

3.2.1 Measuring early age mechanical properties

Rheometers are often used in literature to measure early age properties of cementitious mixtures. However, due to maximum torque limitation or high thixotropy of the material, some researchers have preferred slump test to indirectly measure the yield stress [29]. Like slump test, green strength measurement by uniaxial compression test has been recently found to be useful in concrete printing application and therefore, in this paper, an experimental program similar to [19], was adopted to measure green strength development of the HVFA mortar up to 150 mins from the addition of the water (within dormant period). Usually, concrete properties in the dormant period changes with time and it results in a time-dependent rheology, called as *thixotropy* [23]. Thixotropy is a

reversible phenomenon caused by material flocculation and its effect is significant within the time-span of a typical printing process (several minutes up to two hours). Therefore, the preparation and testing procedures should be in such a way that unintentional breakdown of the thixotropic build-up is minimized.

(a) Uniaxial compression test

Uniaxial unconfined compression tests were performed on cylindrical samples with 70 mm diameter and 140 mm height. The dimensions were chosen to avoid impact of particle size and allow a diagonal shear failure [19]. Fresh HVFA mortar was moulded in five containers with some compaction (5s on vibration table) and tested after different resting time (5, 30, 60, 120 and 150 mins) as shown in Fig. 3.

Fig. 3 (a) Material preparation and (b) uniaxial compression test of fresh cement mortar

INSTRON 5969 test rig equipped with 50kN load cell was used for compression test at a loading rate of 0.6 N/s, chosen to mimic the loading steps in 3D printing test. Each test was conducted close to 60-70 seconds to neglect effects of thixotropic build-up and their average values were

presented in terms of force and displacement (F-d) diagram. In addition, the vertical and lateral deformation of the sample were measured using 3D optical metrology. This new lateral area was considered for area correction, while deriving stress-strain curve from the F-d diagram.

Optical techniques, based on digital photogrammetry or terrestrial laser scanning, have been found to be very effective and accurate solutions for static load test measurements [30] and therefore, in this study, a relatively inexpensive camera (Kinect V2) was used to capture dynamic measurements of changing cross section area. Fig. 4 shows the experimental set up with the calibrated Kinect taking a series of point cloud and RGB images during the compression test. Later, the point cloud was processed with a pass-through filter that retains only the region of interest and removes the rest of the points in the point cloud. The surface normal of resultant filtered point cloud was estimated using a k-neighbour estimation method. The number of neighbours used in the estimation was scaled in accordance to the density and level of detail required of the input point cloud [31].

Fig. 4 Experimental set up for measuring lateral and longitudinal deformation of fresh cement mortar

155

156 A *region growing segmentation* algorithm was then applied on the resultant point cloud, to group
157 all the points belonging to the fresh concrete into a single cluster for further processing. This
158 algorithm can selectively merge points that are close together and within a defined smoothness
159 constraint. The region growing segmentation first seed and begins its growth on the point with the
160 minimum curvature value. This initial point was located on a dominant plane, provided
161 intentionally by placing a white Styrofoam board behind the concrete sample during compression
162 testing. By growing the region on the flattest surface, this will greatly reduce the total number of
163 segments. Until every point in the point cloud has been sorted, the algorithm will go through the
164 next point with the new minimum curvature value and start the growth of a new cluster. At every
165 seed point, its neighbouring points were checked for the angle between its normal and the normal
166 of the seed point. If the angle difference is less than the defined smoothness threshold and curvature
167 threshold, it will be added to the cluster. The algorithm then loops through the point cloud and
168 grow the region until the points are exhausted. The output of the algorithm was a list of clusters of
169 points which describes disjoint regions with homogenous property. The list will be then filtered
170 by checking for a minimum cluster size that removes clusters group which are too small.

171 The resultant list of clusters was subsequently check for their centroid points and filtered off if
172 their centroid points are outside of the region of interest. This will effectively provide us with the
173 resultant cluster of points that makes up the concrete undergoing compression. A bounding box
174 was then added to the cluster for visualizing purposes (Fig. 5) and relevant information such as
175 height, maximum diameter and centroid of the fresh concrete were extracted and stored in an excel
176 sheet along with the time the point cloud and RGB image was taken, to correlated with data taken
177 from the compression test.

Fig. 5 (a) Original point cloud and (b) object of interest in a segmented point cloud

(b) Rheological measurement

Rheology of cementitious mortar is not a constant parameter, rather it changes over time due to particle interactions and ongoing cement hydration. To capture this time-dependent behaviour, yield stress of HVFA mortar was calculated with different resting times (5, 30, 60, 90, 150 mins) by applying a constant shear rate (0.1 s^{-1}) for 60 seconds [8] and the peak shear stress was defined as static yield stress. In this experiment, rotational rheometer MCR 102 from Anton Paar® was used with a square vane probe to measure the yield stress up to 60 seconds and then a modified mathematical relation was employed to predict the yield stress for 150 min sample as explained in [29].

3.2.2 3D Printing and standoff distance measuring system

Unlike plastic and metal 3D printers, concrete printers are usually large-scale system, and in this work, we have used our custom made four axis gantry printer (see Fig. 1(a)) that can print concrete components of one cubic meter volume. During printing, the printer speed and pump flow rate were optimised to ensure continuous flow and good shape retention of the extrudates [15]. For standoff distance measurement, a laser-based distance sensor (Panasonic HG-C1100) which can

perform real-time measurements, with a repeatability $10\text{ }\mu\text{m}$ (extended range of $\pm 35\text{mm}$) was mounted at the end of print head as shown in Fig. 6. The sensor was used in combination with an Arduino microcontroller, which has an in-built analog-digital converter (ADC). This feature enables the analog voltage output of the sensor to be read as a digital value. Using a serial monitor compatible with the Arduino board, the distance data and timestamp was logged and used for further data plotting and analysis.

Fig. 6 Laser distance sensor setup used for deformation height measurement

4. Results and Discussion:

4.1 Material green strength and rheology

The typical F-d curves are shown in Fig. 7 for concrete age $t = 5$ to 150 mins. It is clearly observed that the load initially increases approximately linearly as the vertical displacement increases. After this initial path, the increment of loading decreases as deformations grow. The younger specimens (i.e. $t = 5, 30$, and 60 min) show an increment in load with increasing deformations, up to a certain

plateau. The older specimens (i.e. $t = 120$ and 150 min), on the other hand, show a load decrease after the initial peak, again to a certain limit. This difference in behaviour is attributed different material failure, for example, a distinct failure plane is observed for older samples whereas younger samples fail by barrelling effect as shown in Fig. 8 [19,32].

Fig. 7 Load - deformation (F-d) diagram of fresh cement mortar age $t=0$ to 150 min

Fig. 8 Typical failure modes of fresh cement mortar at (a) $t = 30$ min (b) 150 min

218 The unconfined compressive strength (i.e green strength) was defined for each test as the
 219 maximum occurring stress after area correction and later, it was compared with yield stress of C-
 220 mix obtained from the rheology test. Fig. 9 shows the comparative results of green strength and
 221 static yield strength of C-mix mortar at different time intervals ranging from 0-150 mins. It is clear
 222 that, the yield stress evolution with time can be considered as linear for initial 30-40 mins and then
 223 it exponentially increases which can be explained based on Roussel linear model and Perrot et al.
 224 model [33]. In the early age (dormant period), yield stress of cementitious material increases
 225 linearly with time due to flocculation and C-S-H bridging [23], however after the dormant period,
 226 hydration occurs at faster rate due to ongoing chemical reaction which is reflected in terms of
 227 exponential rise of static yield stresses. Similar to yield strength evolution, green strength also
 228 increased with time, which was as expected for thixotropic fluids.

229
 230 **Fig. 9** Co-relation between yield stress and green strength of the control (c) mix
 231

4.2 Effect of nanoclay

In this section, effect of clay addition was investigated with an aim to improve the green strength which in turn will increase buildability of the printed materials. Fig. 10 (a) shows the load vs deformation curves for both C and NC-mixes which were converted to stress-strain diagram in Fig. 10(b) after cross section area correction. The slope of the curve represents stiffness (Young's modulus E) of material, indicating the NC-mix ($E = 0.06$ MPa) has higher stiffness compare to C-mix ($E = 0.03$ MPa) and therefore, it is expected to resist more deformation by the loads of layers on top of it.

Fig. 10 (a) Load-deformation (b) stress-strain curves of control (C-mix) and clay modified mix (NC-mix)

Fig. 11 shows progressive failure configurations during 3D printing of a cylinder using both C and NC-mixes. It is very clear that the C-mix material under goes elastic deformation after deposition of few layers and suddenly the bottom layer experienced plastic deformation which caused the entire structure to collapse before placing of the 13th layer. On the other hand, the NC-mix printed successfully up to 20 layers with very slow elastic deformation and on the placement of 21st layer, the whole structure started to collapse due to similar plastic deformation of the bottom layer.

Fig.11 Buildability performance of C-mix (left) and NC-mix (right)

Two competing time dependent processes determine the structural failure of a printed object: (1) the increasing green strength and (2) stiffness caused by thixotropic build-up. The role of NC for improving strength and stiffness of cementitious materials was previously studied by the authors [34, 35], which is attributed to flocculation of colloidal NC particles. Since, the NC-mix possess higher stiffness (E) value, the bottom layer was noted to be less deformed while the build height was gradually increasing. However, when the total weight exceeded the material green strength, it experienced sudden plastic failure and as a result, the bottom layer completely deformed leading to structural collapse. To avoid such failures, chemical admixtures [36] can be used to accelerate the strength gain rate in the fresh stage that will enable to withstand the load of deposited layers

without deforming its underneath layers. A schematic diagram is depicted in Fig.12, showing the requirement of potential admixtures at different stages of concrete printing.

Fig. 12 Schematic representation of admixtures requirement in 3D concrete printing process

4.3 Modelling of the layer deformation

Layer deformation during concrete printing is an indication of low stiffness of material, which has been improved in this study by adding NC to the HVFA mortar. However, there is a need to predict the deformation based on the material's Young's modulus (E), so that prior to experiment, the material can be tailored to minimize the deformation. Considering the example shown in Fig. 13(a), let's assume, a layer of concrete having length L , width w and height h ,

Fig. 13 (a) 3D printed layer configuration and (b) deformation under compression loading

where force (F) acting on unit area (A) is denoted by q and the layer counts start from $i = 1$ to n .

In order to estimate the deformation in the whole sample, let's consider the deformation of a single layer is δL_i as shown in Fig. 13 (b).

The deformation in the 1st layer ($i = 1$) will be sum of deformation induced by layer 2 ($\delta L_{1,2}$) and so on till the last layer ($i = n$) and it can be expressed as follows:

$\delta L_{1,2} = \epsilon \times \text{total height } (h) = \frac{\sigma}{E} \times h$ (ϵ is engineering strain and equals to $\frac{\sigma}{E}$ according to Hook's law)

$$\delta L_{1,3} = \epsilon \times (h - \delta L_{1,2})$$

Assuming $\delta L_{1,2}$ is much smaller than h , $\delta L_{1,3}$ can be rewritten as

$$\delta L_{1,3} = \frac{\sigma}{E} \times h$$

.

.

$$\delta L_{1,n} = \frac{\sigma}{E} \times h$$

292 Summing up all the individual deformations of layer 1 by layer 2,3,4....and n , the total deformation

293
$$\delta L_1 = \delta L_{1,2} + \delta L_{1,3} + \cdot \cdot \cdot \cdot \cdot \cdot + \delta L_{1,n}$$

294 In general, δL_i can be expressed as:

295
$$\delta L_i = \sum(n - i) \times \delta L = \sum(n - i) \times \frac{\sigma}{E} \times h \quad (1)$$

296 σ is the stress acting on a layer $= \frac{F}{A}$

297
$$\sigma = \frac{F}{A} = \frac{\text{Weight of the layer}}{\text{Area}} = \frac{\rho \times \text{volume}}{L \times w} = \frac{\rho \times L \times w \times h}{L \times w} = \rho h$$

298 Substituting the value of σ in Eq. (1), δL_i becomes,

299
$$\delta L_i = \sum(n - i) \times \frac{\rho h^2}{E} \quad (2)$$

300 The above equation for estimating deformation of a single layer is based on few following
301 assumptions:

302 (1) The “E” value, which is Young’s modulus is assumed to be constant here, which can be a
303 variable depending on printing time. Since, in this paper, the total print time was less than
304 five minutes, E is assigned as constant.

305 (2) The “ σ ” which counts the area (A) is also not a constant parameter, rather it changes 0.2
306 times of deformation (δL)

307 (3) “ ρ ” which is the fresh density of material, also changes with time due to water evaporation
308 and so, it is also a variable depending on the environmental conditions.

Considering the above assumptions, Eq. (2) can be calculated for all the layers (n) and added together to get the total deformation (δL) of the whole sample. It is very clear from the equation that the deformation is directly proportional to the density and inversely proportional to the E value of the material.

Using the properties of NC-mix ($E = 0.06$ MPa, $\rho = 2183$ Kg/m³ and layer height (h) = 15 mm), the estimated deformation for the L1 due to L2 was 0.08 mm, which is almost similar our experimental findings (15.85-15.78 = 0.07) as shown in Fig. 14. However, sometimes the experimental deformations have large standard deviation due to uncontrolled errors caused during distance measurement such as flatness of print bed, rigidity of 3D printer, sensor position and accuracy, etc. We also believe that compaction of the cylindrical sample used for “ E ” value calculation can be a cause for over estimation (by Eq. (2)), since in practice (concrete printing), there is no compaction force, except the extrusion pressure in pumping.

Fig.14 Experimental results of first (L1) and second-layer (L2) height information obtained from laser distance sensor (Note: The deformation of L1 by L2 was calculated by subtracting the avg. height of L1 from avg. L2)

It is interesting to note that, the total experimental deformation i.e. 1.44 mm in the NC-mix made cylinder is slightly higher than the predicted deformation (1.18 mm) which can be explained by analysing the equation used for prediction. The proposed Eq. (2) is based on Hook's law that only valid for elastic deformation of the printed structure and any deformation in the plastic mode is not counted, which might be a possible reason for the underestimation. The printed part (using NC-mix) initially does not deform much due to high E value, however after deposition of 20 layers, the bottom layer failed plastically due to low green strength of the material, while causing sudden increment in the deformation height. This sudden change is captured by the distance sensor, but Eq. (2) is not able to predict it, which can be significantly visible while using the C-mix mortar. The C-mix has both low E value and green strength, which resulted higher plastic deformation and therefore, 4.10 mm difference was observed between the estimated and experimental deformation values. To minimize this difference, "E" value from plastic region of the stress-strain diagram can be used instead of the elastic region and accordingly the plastic deformation can be calculated during the elastic-plastic deformation of 3D printed cylinder.

5. Discussion and concluding remarks:

In this paper, an experimental study was conducted to understand the evolution of early age mechanical properties of 3D printable concrete, before its initial setting. Early age compressive strength i.e the green strength and stiffness were measured via modified compression test and linked with respective buildability index of the structures. Experimental findings reveal that low stiffness can cause elastic deformation, whereas lack of adequate green strength may result in plastic failure, which will gradually become a more brittle failure for older age specimens. Therefore, small amount of nanoclay was introduced to improve the early age properties due to its inherent characteristics of flocculation and thixotropy modifier. Nanoclay improved the stiffness

of the control mix and higher buildability was obtained with minimum deformation. Despite of the improved buildability, there is a need of enhancing the (green) strength development rate, which can be solved by adding chemical accelerators either at the entrance of nozzle or in the mixing pump. Alternatively, the print path can be optimised to enable a perfect balance between the green strength development and build height.

Fig. 15 (a) Computer aided design model and (b) concrete printed (top section) modular toilet

The main goal of this paper was to understand the buildability of 3D printed materials and improve it for a large-scale construction application without using any chemical admixtures. 3D optical metrology was adopted in this regard to measure the deformation in fresh stage and accordingly, material design was modified with nanoclay to maximize the build height via increasing stiffness and green strength. The proposed deformation equation is also deemed suitable to analyse the elastic deformation of the material, however plastic deformations yet need to be incorporated to overcome its underestimates deformations. In order to demonstrate suitability of the proposed buildability criteria, three sections of a portable toilet (see Fig. 15) was 3D printed (print speed: 90 mm/s; layer height: 15 mm) using the clay modified mix (NC-mix), while considering the material strength development rate and tool path length. The buildability of the printed structure

is not only a strength-based parameter, but also depends on structural stability which will be optimised in our future work to obtain a robust printing process.

Acknowledgement

The authors would like to acknowledge Sembcorp Architects & Engineers Pte. Ltd. and National Research Foundation (NRF) Singapore for their funding and support in this research project. We are also thankful to architect Catherine Soderberg for the 3D design, Prof. Theo Salet (Tu/e, Netherlands) for the advice in modelling and research scholars of Singapore Centre for 3D Printing (building and construction) for assisting in concrete printing experiments.

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