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Improving the 3D printability of high volume fly ash mixtures via the use of nano attapulgite clay

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Abstract:

The effect of nano-attapulgite clay (NC) addition on the fresh, hardened and microstructural properties of high volume fly ash (HVFA) mixes designed for 3D printing was investigated in this study. Experimental results showed that the addition of 0.1-0.5% (i.e. by mass of binder) NC increased the static yield stress of HVFA mortars without significantly affecting the apparent viscosity, due to particle re-flocculation and enhanced thixotropy. When compared to the control mix, the use of 0.5% NC also led to increased viscosity recovery and improved structural build-up at different resting times and shear rates. These advancements were useful for 3D concrete printing, during which the material should be extrudable and buildable layer-by-layer without any deformation. Successful implementation of mixes containing NC was demonstrated via the printing of a 20-layer structure. Further optimization of the NC content and associated HVFA mix design is recommended, depending on the geometrical and mechanical properties required.

Keywords: 3D concrete printing; nano-clay; rheology, thixotropy; hydration kinetics

1. Introduction

Digital construction has become the subject of very rapidly growing research activities on a global level due to the advantages it offers in terms of higher construction quality and productivity, higher geometrical freedom, more efficient use of natural resources, and higher cost-efficiency and universality [1-4]. Various technologies involving the 3D printing of concrete have been developed in line with the increasing number of demonstration projects and practical applications. The activities in the field of digital construction mainly focus on the development of printable materials with 3D printing systems, either utilizing a gantry printer or an industrial robotic arm.

The main challenge in the development of a printable mix is the design of a thixotropic material that can be easily extrudable during the printing process, while maintaining its original shape after deposition. Thixotropic behavior is a common rheological phenomenon that illustrates the decrease of viscosity of a colloidal suspension at a constant or increasing shear rate and the recovery of viscosity when the material is at rest. In cement-based mixes, thixotropy at rest is usually associated with the flocculation of particles and ongoing hydration. When subjected to shearing, the flocs are broken due to the rupture of the interparticle links, reducing the viscosity of the cement paste. After shearing, when the material is at rest, the links are rebuilt due to the reversible behavior of the thixotropy effect [5, 6]. Since, thixotropy is an important property for all printable materials, there is a need for appropriate testing protocol to quantitatively assess mix behavior by mimicking the 3D printing process. It is also important to measure the structural build-up rate and recovery properties over time, so that the rate of buildability (i.e. the rate of depositing layers) before failure can be estimated for different structures.

Most of the 3D printable binders involve the use of Portland cement (PC) as the prime ingredient in their formulations due to its inherent thixotropic property. Le et al. [7] presented a 3D printed high strength mortar with a sand:binder ratio of 3:2, including 70% PC, 20% fly ash (FA) and 10% silica fume (SF), along with micro polypropylene fibers. The performance of the binder and suitability for 3D printing was assessed via the measurement of its extrudability, buildability and workability. Contour Crafting (CC) research team led by Khoshnevis [8] also provided printable mix designs for the 3D printing of concrete structures using both PC and ceramic materials. Other

studies [9] have further taken the initiative to prepare this technology for large-scale construction practices.

Past work performed in this area [9] has demonstrated that a small addition of nano clay (NC) can effectively improve the thixotropy of concrete mixtures via their charged edges, which can create an attraction force to form a stable microstructure and higher viscosity at rest. Also, due to the smaller particle size and higher specific surface area of NC, it can effectively fill the gaps between cement particles [9-13], which in turn increases the Van der Waals force of attraction and hence the thixotropy. On the other hand, there is limited work on the effect of NC on the hydration and mechanical performance of cement mixes. Therefore, this study focuses on the use of highly purified attapulgite NC in high volume fly ash (HVFA) mixes. These mixes are aimed to not only reduce the environmental impact of traditional concrete mixes involving PC [14, 15], but also present a suitable formulation for 3D printing applications. The main goal of this paper is to characterize the effect of NC on the rheological properties (e.g. yield stress, viscosity and thixotropy) of HVFA mortars and improve the buildability of the prepared mixes via the thixotropic property of NC. Mechanical performance of the prepared mixes was evaluated via the measurement of compressive and tensile bond strengths. The reaction mechanisms were assessed via isothermal calorimetry and x-ray diffraction (XRD), and supported by microstructural analysis performed by field emission scanning electron microscopy (FESEM).

2. Materials and Methodology

2.1 Materials

The main materials used in this study were Class F fly ash (FA), obtained from Sembcorp Energy India Ltd, conforming to ASTM C 618; and ordinary Portland cement (OPC), obtained from LafargeHolcim Ltd, conforming to ASTM C 150 [16]. The chemical compositions of FA and OPC are shown in Table 1. Fig. 1(a) shows the particle size distribution (PSD) of these materials, which was determined by using laser diffraction. Fig. 1(b) shows the x-ray diffraction (XRD) spectra of FA and OPC, where the presence of an amorphous peak in the 2θ range of $20-30^\circ$ was observed

in FA. OPC was mainly composed of alite (C_3S), belite (C_2S) and gypsum ($CaSO_4$) phases. The SEM images of each material, shown in Fig. 2, have revealed the spherical morphology of FA particles, which had a median particle size (d_{50}) of 4-6 μm , followed by OPC at a d_{50} of 18 μm . In addition to FA and OPC, nano clay (NC), obtained from Active Minerals International (USA) in the form of a highly-purified magnesium aluminosilicate, was used as an additive in the prepared mixes [17]. The NC particles varied in terms of their morphology and presented sharp edges, as seen in Fig. 2(c). They had a diameter of ~ 3 nm, while their length varied from 1.5 to 2 microns. In addition to the dry materials, an activating agent, reagent grade sodium sulfate (SS) powder received from Sigma Aldric Ltd, was used in the prepared mixes. To produce HVFA mortars, the binder component was mixed with fine river sand with a particle size of ≤ 2 mm (i.e. determined according to the limitation in pump capability and extruder opening size).

Fig. 1 Characterization of FA and OPC, showing their (a) particle size distribution and (b) x-ray diffraction spectra (G = $CaSO_4$, P = CH, Q = SiO_2 , C = calcite, A = C_3S , B = C_2S , M = mullite)

Fig. 2 SEM micrographs of (a) FA (b) OPC and (c) NC

Table 1. Chemical composition (%) of OPC and FA

Binder	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO	Na ₂ O	K ₂ O	TiO ₂	LOI
OPC	19.7	63.1	4.8	3.2	2.5	2.1	0.2	0.4	0.1	2.8
FA	51.1	5.8	28.8	6.4	1.0	1.1	0.3	1.2	2.5	1.2

2.2 Mixing and sample preparation

Two types of HVFA mixes, one with and one without NC (control) were prepared. The HVFA control mix used in this study was composed of 70% FA and 30% OPC (by mass) for its main binder component, in line with the findings of a previous study [18]. Preliminary experiments indicated that the activator content did not influence the strength results in the range of 3-5%. Therefore, 3% SS (i.e. by mass of binder) was used in the prepared mixes. Water to binder (w/b) ratio was maintained at 0.40 and 0.45 for all pastes and mortars (sand:binder = 1:3), respectively. HVFA mortars without NC were prepared by adding water to the mix of OPC, FA and sand; and mixed until a homogenous blend was obtained. For the preparation of mixes containing NC, first NC was blended with the predetermined amount of water for 3-4 minutes, after which it was added into the OPC-FA-sand mix and mixed for another 2 minutes to ensure its effective dispersion.

2.3 Methodology

The influence of NC content within the prepared mixes was assessed to design mixes that could produce a high static yield stress without significantly affecting the mortar viscosity. An Anton Par MCR 102 rheometer was used to perform all the fresh property measurements followed by pre-shearing to ensure that all samples were at a reproducible reference state. The vane diagram and building cell geometry used during this measurement are show in Fig. 3.

Fig. 3 Vane geometry and dimensions of MCR 102 rotational rheometer

2.3.1 Rheological properties

To obtain the evolution of static yield stress, stress growth test was performed by applying deformation at a constant shear rate of 0.1 s^{-1} . The shear stress progressively developed to a maximum value and then decayed to an equilibrium value. The static yield stress was defined as the peak shear stress value [19].

After placing the mortars in the building cell, flow curve test was carried out by applying an increasing shear rate from 0 to 300 s^{-1} in 1 min, followed by a decreasing rate from 300 to 0 s^{-1} in another 1 min, as used in previous studies [20]. The obtained results from this test were useful to compare the shear stress vs. shear rate behavior of mixes with and without NC.

The structural build-up of NC modified HVFA was evaluated using the A_{thix} index, which is widely used to quantify the build-up of cement-based materials [21, 22]. For each mixture, the evolution of static yield after 0, 5, 10 and 15 minutes of rest after the initial pre-shearing was evaluated and the slope of this curve revealed the A_{thix} index.

The effect of NC on structural recovery was assessed by applying 3 different shear rates (i.e. (i) 0.01 s⁻¹ for 60 seconds (ii) 300 s⁻¹ for 30 seconds and (iii) 0.01 s⁻¹ for 60 seconds) and capturing the change in apparent viscosity values, as shown in Fig. 4. The selection of shear rates and respective time intervals were in line with the 3D printing process, during which the material was (i) initially at rest, (ii) extruded and (iii) again at rest after deposition [23].

Depending on the printing process, the values of shear rates and shearing time can be different, which affect the material behavior. Therefore, the recovery behavior of NC modified HVFA mortar was studied in the recovery stage by applying two different shear rates at 100 and 200 s⁻¹ for one and two minutes, respectively.

Fig. 4 Structural recovery test protocol

2.3.2 Heat of hydration

An isothermal calorimeter was used for measuring the heat of hydration of both the control and NC modified HVFA pastes according to ASTM C1702-15a [24]. 50 g of paste was prepared for each composition at a water/binder ratio of 0.4 and was immediately placed into the measurement

chamber within a minute. Readings were recorded for 72 hours under a constant temperature of 26 °C.

2.3.3 Mechanical performance

Compression test was performed on each sample after 28 days of curing by uni-axial loading in triplicates, in accordance with the specifications of ASTM C109 [25]. The equipment used for this purpose was a Toni Technik Baustoffprüfsysteme machine, operated at a loading rate of 100 kN/min. For tensile bond strength measurements, two layers of HVFA mortars were prepared with 5 and 30 min time intervals between each layer and their respective values were reported in line with the test setup described in [26].

2.3.4 3D printability test

Both the control and NC modified HVFA mortars were 3D printed to produce cylindrical structures with a diameter of 20 cm by using a 4-axis gantry printer equipped with a 30×15 mm rectangular nozzle and a screw pump [27]. 20 layers were printed with a time delay of 5 seconds and their deformation pattern was analyzed for each mix.

2.3.5 Microstructural analysis (XRD and SEM-EDX)

For XRD analysis, samples extracted from the crushed cubes were stored in acetone for at least 3 days to stop hydration, followed by vacuum drying for another 24 hours. The vacuum dried samples were ground down to pass through a 75-micron sieve to be used in Philips PW 1800 spectrometer using Cu Ka radiation (40 kV, 30 mA) with a scanning rate of 2° 2 θ /step from 10° to 60° 2 θ . The samples were also investigated via a field emission scanning electron microscope (FE-SEM, JOEL JSM-7600F) and energy-dispersive x-ray spectroscopy (EDX, Oxford X max 80

mm²). For SEM-EDX analysis, the powders were coated with platinum under a current of 30 mA, with a coating time of 30 seconds.

3. Results and Discussion

3.1 Static yield stress and apparent viscosity

The effect of NC content on the apparent viscosity and static yield stress of HVFA is shown in Fig. 5. With an increase in the amount of NC, apparent viscosity remains relatively constant while the static yield stress increases. Thus, the addition of NC could help with the rapid structural rebuilding of HVFA mortars, making it an ideal thixotropy modifier. Similar behavior has been investigated in other studies [28, 29], where it was postulated that at rest, the charged edges of NC tend to associate with each other via electrical attraction force, producing a highly viscous resultant structure. Alternatively, under strong pre-shearing, viscosity decreases as the particles progressively separate and align in the direction of the flow. This decrease in viscosity is associated with the electrical repulsion between the negatively charged particle surfaces, further enhancing the shear thinning behavior. Other than surface charge, fineness, dispersion force (DF) and the amount of free water are also considered as contributing factors to increasing thixotropy with the addition of NC [30]. Smaller particle sizes can result in a strong DF, which plays an important role in determining the flocculation of particles. As the mix containing 0.5% NC (i.e. referred to as 5NC) led to the highest yield stress amongst all the mixes prepared in this study, it was selected for the further analysis of its other rheological properties, in comparison with the control mix.

Fig. 5 Static yield stress and apparent viscosity as a function of NC content

The flow curve pattern in Fig. 6(a) showed that the 5NC mix had a higher static yield stress when compared to the control mix. This was associated with the flocculation of clay particles when the material was at rest. However, in the case of shearing at a constant shear rate (300 s^{-1}), the apparent viscosity went down to $< 10 \text{ Pa.s}$ and remained almost the same for both the control and clay modified mixes (Fig. 6(b)). The effect of NC on thixotropy was seen in terms of the improvements in yield stress, without affecting viscosity. This behavior is highly helpful in concrete printing applications, where there is demand for materials with high yield stress and low viscosity. An alternative common practice in increasing the yield stress involves the addition of fine aggregates [23], which is not particularly helpful as this simultaneously changes the viscosity value and thereby causes problems during the extrusion process.

Fig. 6 Fresh properties showing the (a) flow curve and (b) shear thinning behavior of the control and NC modified mix

3.2 Structural build-up

The evolution of the static yield stress of both the control mix and clay modified HVFA mortar over time is shown Fig. 7. Their relevant parameter (i.e. A_{thix}) is also summarized in Table 2. The rate of change of the A_{thix} index has an important role in 3D concrete printing as it provides an indication of the stiffness of the material, relating to the ability of an extruded layer to hold the load of subsequent layers. It can be seen in Fig. 7 that the yield stress of the prepared mixes increased linearly with time. However, when compared to the control mix, the A_{thix} index of the 5NC mix was always higher, indicating its better buildability property due to the flocculation of NC particles. These nano-sized clay particles increased the yield stress by minimizing the space between cement particles, leading to a stronger interaction and thus the yielding effect. From the perspective of concrete printing, this rapid increase in yield stress with resting time can increase the loading capacity of the deposited layers, which in turn can improve the buildability property.

It was pointed out in a previous study [31] that the yield stress of thixotropic fluids is a function of structure and time, gradually increasing in two folds. The first one of these is the dormant period, during which the yield stress increases slowly; and the second one is the accelerating stage, where

it increases rapidly. However, in this study, as the measurement was only performed for the first 20 minutes, which corresponds to the induction/dormant stage, most of the changes observed in thixotropy were reversible effects rather than the irreversible effects due to the hydration of cement [32].

Fig. 7 Evolution of static yield stress at different resting times

Table 2. Build-up indices (A_{thix} , Pa/s) of the control and NC modified mixes

Sample	Resting time (min)			
	0	5	10	15
Control	0.63	1.23	1.64	2.70
5NC	1.74	1.87	2.54	4.25

3.3 Effect of shear rate and shearing time on structural recovery

Similar to structural build-up, structural recovery is an important feature that can indicate the behavior and shape retention ability of the extruded materials. Fig. 8 shows the apparent viscosities of both mixes in three different stages, as described earlier in Section 2.3. The recovery percentage was assessed by the percentage of original viscosity in stage (i) that was recovered in stage (iii).

When compared to the control mix, recovery in the clay added (5NC) mix was more prominent at a shear rate of 300 s^{-1} . Accordingly, 5NC300 was able to recover its original viscosity 20% more than the control mix. Furthermore, the higher initial viscosity of the 5NC300 mix in stage (i) resulted in a better shape retention within the extruded samples. This rapid recovery was akin with a jammed system, where the thixotropy effect of both the NC and OPC particles built up a network that quickly increased the viscosity of the mix. The recovery kinetics after shearing were completely different from the breakdown kinetics during shearing. The van der Waals forces, which is the main cause for the agglomeration of cement particles, are weak bonds that can easily breakdown by the shearing action of the pump. Similarly, after the removal of the shear force, this network build-up rate is very fast in nature. The addition of NC increased the strength of these bonds due to their inherent charged edges. Therefore, in the case of 5NC100 and 5NC200, the recovery percentages remained almost the same as 5NC300, except for the increase in viscosity in stage (ii). This increase in viscosity was linked with the relationship between viscosity and shear rate, i.e. higher the shear rate, lower is the viscosity of the mix.

Fig. 8 Recovery behavior of the control and 5NC mixes sheared at 100, 200 and 300 s^{-1}

In concrete printing, depending on the fresh properties of the materials, pump design and its placement (i.e. in terms of distance) with respect to the printer, affects the shear rate and shearing time. The obtained results showed that the presence of NC in HVFA mixes hardly affected the recovery properties at different shear rates. However, without the inclusion of NC, the effect of

long shearing time led to delayed viscosity recovery, as shown in Fig. 9, where two scenarios involving the shearing of the control and 5NC mixes at 300 s^{-1} for 60 and 120 seconds are displayed. Increasing the shearing time from 60 to 120 seconds did not have a major influence on the 5NC sample. However, in the case of the control sample, although it could recover its original viscosity at 60 seconds, its recovery was delayed for a few seconds after the mix came to rest at 120 seconds. This delay in recovery was attributed to the breaking down of the internal structure in the lack of sufficient networking elements (e.g. NC or OPC). Linking this phenomenon with concrete printing, it can be envisaged that if a HVFA mix without NC that is sheared for a long time is used for 3D printing, a sufficient time gap must be allocated after the printing of each layer to avoid the deformation of the bottom layer due to the load applied by the subsequent layers. On the other hand, HVFA mixes including NC can be easily printed in a shorter time period as the addition of NC enables faster build-up, thereby improving the buildability property.

Fig. 9 Effect of two shearing times on the recovery behavior of the control and 5NC mixes

3.4 Heat of hydration

Fig. 10 shows the hydration kinetics for the HVFA paste samples with and without NC. Compared with the control sample, the amount of heat released by the 5NC mix was higher, as also evident

by the higher intensity of the initial hydration peak. This increased heat was an indication of the improved hydration mechanism in the presence of NC, which was associated with the nucleating effects of nanomaterials that have large specific surface areas [28]. Accordingly, the addition of NC to HVFA mixes increased the number of nucleation sites and thereby enhanced the hydration process. An opposite effect can be observed in the presence of high contents of NC, in which hydration can be negatively influenced via the agglomeration of NC particles, thereby hindering mobility inside the matrix [34]. Therefore, adjusting the NC content within HVFA mixes is important for achieving improved hydration without leading to the agglomeration of particles within the matrix.

Fig. 10 Hydration kinetics of the control and 5NC mixes showing the (a) heat flow rate and (b) cumulative heat release

3.5 Mechanical performance

The 28-day compressive and tensile bond strengths of the two mixes are shown in Fig. 11. The tensile bond strength was measured at 5- and 30-min delay intervals in between the two successive layers. In terms of compressive strength, a value of 28.5 MPa was recorded for the control mix, whereas the addition of NC led to a slight increase in strength to 31.3 MPa. Alternatively, the tensile bond strength of the 5NC mortar was lower than that of the control sample when the time

interval between the two layers was 30 min. This was associated with the thixotropic property of the NC mortar that quickly built up the yield stress in the bottom layer, before a second layer was placed over it. According to [33], a higher structural build rate can increase the apparent yield stress above a critical value, which may result in a weak interface between two layers of concrete. Comparing the structural build-up rates presented earlier in Table 2, it can be clearly seen that the addition of NC resulted in a poor bond strength between adjacent layers as the time interval between layers increased. One possible solution to this can be via the implementation of continuous mixing as opposed to batch mixing, during which each layer can exhibit homogenous fresh properties.

Similar to the findings reported earlier [33], the bond strengths of both the control and 5NC mixes was found to be higher for the 5 min time gap, in comparison to the 30 min gap. This could be due to the change in the surface moisture content and rate of structuration with resting time [34]. Accordingly, longer delay times can cause moisture loss from the substrate and if proper printing conditions are not maintained, may result in a poor adhesion between the deposited layers.

Fig. 11 28-day compressive and tensile bond strengths of the control and 5NC mixes

3.6 3D printing performance

Both HVFA mortars with and without 0.5% NC addition were prepared for 3D printing to assess their buildability in the form of 20 adjacent layers, as shown in Fig. 12. It was clearly observed that the control sample started deforming after the deposition of the 10th layer, during which its bottom layer almost crushed and widened from 30 mm to up to 65.1 mm as printing progressed. On the other hand, the 5NC mix was able to hold 20 layers without any issues with shape stability. The bottom layer expansion of this mix was also found to be limited after the deposition of 20 layers. This behavior was attributed to the improved thixotropy of the mix in the presence of NC. Nevertheless, it is important to note that while the 5NC mix presented here can be considered as a suitable mix for the 3D printing of 20 layers in cylindrical form, the NC content and the overall mix design should be further optimized depending on the 3D design and targeted layer deposition rate [35].

(a) (b)

Fig. 12 Buildability of the 3D printed (a) control and (b) 5NC mixes, highlighting their bottom layer deformation

3.7 Microstructural analysis

The XRD patterns of the control and 5NC samples at different curing ages are shown in Fig. 13. All the patterns indicated the presence of C-(A)-S-H ($2\theta = \sim 29^\circ$; PDF #00-033-0306), as Al_2O_3 from FA was also involved in the hydration process. Other than C-(A)-S-H, other hydrate phases such as ettringite ($2\theta = \sim 16^\circ$; PDF #41-1451) and portlandite ($\text{Ca}(\text{OH})_2$, $2\theta = \sim 17^\circ$ and $\sim 47^\circ$; PDF #04-0733) were also observed in the XRD patterns. The presence of calcite ($2\theta = \sim 30^\circ, \sim 38^\circ, \sim 48^\circ$;

PDF #02-0623) was also confirmed due to the carbonation of Ca-based hydrates (e.g. portlandite and C-S-H) over time. These were in line with the findings reported in [18, 36]. When mixes with and without NC were compared, it was seen that the incorporation of NC did not change the composition of the final mix by mainly acting as a filler, which could be associated with its low content (i.e. 0.5% of the binder) within the prepared mixes. For both mixes, most of the hydration took place within the first 7 days, as evident by the early formation of the hydrate phases, after which the composition did not drastically change at 14 or 28 days.

Fig. 13 X-ray diffractograms of the control and 5NC pastes at 7, 14 and 28 days of curing (E: Ettringite, P: Portlandite, Q: Quartz, G: Gaylussite, C: Calcite, A: C-(A)-S-H, M: Mullite)

In line with the XRD patterns presented earlier, the SEM image of the 5NC mix at 28 days, shown in Fig. 14(a), indicated the presence of portlandite ($\text{Ca}(\text{OH})_2$), ettringite ($\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$) and C-(A)-S-H. Along with these hydrate phases, spherical unreacted FA particles were also observed among the matrix. The selected area (black frame) was selected for EDX analysis, at the end of which the elemental spectra displayed in Fig. 14(b) was

obtained. The spectra showed the presence of C due to the formation of calcite (CaCO_3). Within these mixes, calcite was intermixed with C-S-H, showing that C-S-H was partially carbonated over time. The element Al was also observed in the spectra, indicating the formation of C-A-S-H with a Ca/Si ratio of 1.53, which is within the Ca/Si ratio of C-S-H (1.2-2.3) [37,38]. Besides these phases, the spectra also reported the presence of element S, confirming the identification of the fibrous phases shown in the SEM images as ettringite.

Fig. 14 Microstructural analysis showing the (a) SEM micrograph and (b) EDX results (selected area) of the 5NC mix

4. Conclusions

This paper investigated the effect of nano-clay (NC) addition on the fresh properties, mechanical performance and microstructure properties of high volume fly ash (HVFA) mixes designed for 3D

printing. Results showed that the addition of NC significantly improved the thixotropic property of HVFA mixes, thus increasing its suitability for concrete printing applications. The use of NC increased the flocculation strength of the material, which in return resulted in a higher yield stress without significantly affecting the viscosity. This high yield stress enabled the higher buildability and lower deformation of the prepared mixes during the 3D printing process. The presence of NC also significantly accelerated the rate of viscosity recovery, in spite of the different shearing rates and durations utilized. Mixes containing NC revealed higher heats of hydration, which was associated with the acceleration effect of NC due to its role as additional nucleation sites in the matrix. However, the low NC contents used in this study did not change the final chemical composition of the prepared mixes, revealing the formation of similar hydrate phases as the control mix. While the incorporation of NC was helpful in improving the 3D printability of HVFA mixes presented in this study, its content and the associated mix design should be further optimized, depending on the geometrical and mechanical requirements.

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