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Development of extrudable high strength fiber reinforced concrete incorporating nano calcium carbonate

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ABSTRACT

The use of extrudable (3D printable) concrete in construction has attracted increasing attention, whilst the major obstacles to its wider application lie in the difficulties in materials design, particularly when fibers are added as an alternative to reinforcement. In this study, high strength fiber reinforced concrete (HSFRC) mixtures for extrusion were developed, and the influences of nanoparticles and carbon, steel and glass fibers on their extrudability, buildability and strength properties were investigated. It was found that the addition of nanoparticles and fibers would enhance the rheological properties for shape retention. It was also found that the addition of steel fibers would be more effective in improving the strength but less effective in improving the interlayer bond compared to the addition of carbon or glass fibers, whereas a suitable amount of nanoparticles would generally favor the strength and interlayer bond. Lastly, a conceptual model for the design of extrudable concrete mixtures and some explanations from the perspective of thixotropy were presented. This study shall advance the development of extrudable HSFRC.

1. Introduction

Extrudable (3D printable) concrete, including extrudable (3D printable) cementitious mortar, enables formwork-free, low-cost, safe and speedy construction with more flexible architectural design [1–3]. Such concrete can be used for sequential placement layer by layer controlled by a digital model, the method of which has long been used in the manufacturing industry [4]. Undoubtedly, the pursuit of new freeform construction exhibiting both aesthetic and functional attributes stimulates the birth of extrusion-based construction technology using extrudable concrete [5–7]. It is advocated that this technology would greatly benefit the construction industry and would even stimulate an upcoming construction revolution. However, apart from launching of pilot projects, applications of extrusion technology have been hindered mainly by the difficulties in the design of extrudable mixtures and the related robustness control.

Extrudable concrete mixtures should exhibit adequate thixotropic behavior required by both buildability in static state and fluidity in dynamic state for achieving extrudability (and pumpability in the case of long pumping distance) [8–10]. The thixotropy is a time and rate dependent shear thinning property that governs the finite time taken for micro-structural destruction and rebuilding [10,11]. The driving force is the result of competition between break-down due to flow stresses and build-up due to in-flow collisions and Brownian motion [12]. Thus, layer-structured clay and flocculated suspensions would be favorable to the thixotropic behavior, but somehow mechanical properties and durability might be impaired [13]. A better solution for achieving adequate thixotropic behavior is the provision of fibers [14–18]. The fibers, which tend to increase cohesiveness, would be more or less aligned with each other in the flow state of the mixture, thus leading to decreased shear resistance.

Meanwhile, treatment of the matrix using nanoparticles for improving the rheological and mechanical properties has gained popularity in recent years [19,20]. The nanoparticles added to the matrix have ultra-fine particle size and ultra-large specific surface area, which can increase the packing density of the particle system and greatly emaciate the water film thickness of the mixture [21], and thus may produce rheological properties favoring the pumpability, extrudability and buildability of the extrudable mixture. However, test methods for evaluating these properties varied widely, causing difficulties in the interpretation of the test results. For instance, Kazemian [22] applied compressive load to test the buildability, Panda and Tan [23] used a

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rheometer to test the extrudability and buildability, whilst Ogura et al. [24] adopted a ram-extruder to test the extrudability. Perhaps the most straight forward test method is the existing slump-flow test, but modifications are required to incorporate the time effect so as to better reflect the extrusion properties.

The tensile strength and ductility requirements of the completed structures provoke the need of integrating reinforcing bars into the extrudable concrete [8,25]. However, little progress has been made in this challenging task. As a promising alternative, addition of reinforcing fibers to turn the extrudable concrete into a fiber reinforced concrete (FRC) or even high strength FRC (HSFRC), which can be designed to have high tensile strength and ductility, provides great possibilities of replacing part or all of the reinforcing bars [26–29]. However, although research on the properties of FRC is abundant [30–33], the use of HSFRC for extrusion-based construction is yet to be explored further due to limited previous research [34–36]. Apart from the materials design, another barrier to extrusion-based construction is that the test methods for evaluating the mixture properties have not been standardized yet, thus rendering the tests results not directly comparable.

Unavoidably, the extrusion process is influenced by the features of the extrusion apparatus [37], and more specifically, the nozzle and the control system used for depositing the concrete mixture [8]. A suitable nozzle design shall take into account both the extrudability and buildability of the concrete mixture to achieve low extrusion resistance and high extrusion accuracy [38], while the control system, the design of which is definitely dependent on the materials properties, involves largely mechanical and automation issues [39–41]. Hence, unlike conventional concrete used for casting, an extrudable concrete is much more demanding. Such differences raise the need of developing additional test methods for evaluating the fresh and hardened properties of extrudable concrete. Without proper testing of the extrusion related properties, the concrete extrusion technology would not be able to develop.

Overall, the development of extrudable HSFRC incorporating nanoparticles for enhancing extrudability, buildability and strength, and the testing methods for measuring their fresh and hardened properties are yet to be explored further. In this study, various extrudable concrete mixtures with nano calcium carbonate and various types of fibers added have been developed based on a comprehensive series of trial mixing and extrusion. For the fresh properties, some existing test methods were slightly modified and employed to evaluate the extrudability and buildability. For the hardened properties, a standard compressive strength test method and a specially designed direct tension interlayer bond test method were employed to evaluate the compressive strength and interlayer bond strength. The tests results were then used to reveal the effectiveness of the fibers and nano calcium carbonation added. As a start, in order to present the background, a brief state-of-the-art review of the extrusion technology and extrudable concrete mixtures is presented in the following section.

2. Literature review

Among various 3D printing technologies, namely, stereolithography, fused deposition modeling, inkjet powder extrusion, selective laser sintering and contour crafting, the last one has been prevalent in extruding concrete or ceramic materials [39]. Pioneering works had been done by a number of researchers [39,40,42–45]. Since 1998, concrete extrusion gained increasing attention as Khoshnevis and Dutton [42,44] conducted a series of research on contour crafting by concrete extrusion, which demonstrated the versatility and effectiveness of 3D printing construction technology in the fabrication of freeform structures with intricate surface geometries, such as containers and sculptures. The high flexibility in design, together with other advantages of high construction speed and less materials wastage, fueled further research on extrusion and related robotic technologies [42,46].

Subsequently, concrete extrusion technology has advanced further to enable high resolution deposition for better control of architectural geometries. Such high resolution deposition poses even stricter requirements on the materials design. In 2012, Lim et al. [45] presented a comprehensive review of various construction scale additive manufacturing processes, focusing mainly on the extrusion technology. They pointed out that, despite many advantages, the disadvantage of high sensitivity of extrusion performance to the ambient conditions would hamper on-site application while off-site prefabrication in a factory could overcome this problem. The limitations mentioned by them necessitate further research on the robustness of the materials design which is important for on-site construction.

Nevertheless, after then, several full-scale 3D printed construction projects had been attempted, including one building in Shanghai constructed in 2014 by a Chinese company, Winsun, and another one in Amsterdam also in 2014 by an Amsterdam-based company, DUS Architects [34]. However, questions about the possible uses of extrusion technology never stop as challenges to the materials design are growing. In recent years, concrete extrusion has gained increasing attention [1,2,4,10,39,45,47,48], but the emphasize is now put on the materials design. In 2017, Hambach and Volkmer [49] added fibers into the extrudable mixture for improved mechanical performance. In 2019, Lu et al. [47] used fly ash chemosphere and air entraining agent to attain rheological properties for improved dimensional accuracy. In same year, Zhang et al. [48] found the relationship between flowability of paste and optimum aggregate content, and suggested that the flowability of paste is a useful parameter for the mixture design. Also in same year, Panda et al. [50] added 0.1% to 0.5% nano attapulgite clay by mass of binder content into high volume fly ash mixtures to impart thixotropic behavior for improved fresh performance [51].

It is advocated herein that taking advantage of the pioneering works, a conceptual model for the design of extrudable mixtures based on a closed-loop system could be derived. In fact, the materials design involves basically two major aspects, one is the rheological properties and the other is the hardened (mechanical, interlayer bond, etc.) properties. To vividly and systematically elaborate the materials design approach, a conceptual model for the design of extrudable mixtures, as illustrated in Fig. 1, is introduced. As illustrated in the figure, the rheological properties, i.e., pumpability, extrudability and buildability, are mainly governed by the thixotropy of the mixture and have a great impact on the strength and interlayer bond while the latter aspect could reversely give feedback for rheological design of the extrudable mixture [52]. Hence, the rheological design of the extrudable mixture should be guided by the required rheological, mechanical and interlayer bond properties.

3. Experimental program

3.1. Materials

Ordinary Portland cement CEM I 52.5N, silica fume, and metakaolin were used as the cementitious materials. Their specific gravities were measured as 3.11, 2.20 and 2.50, respectively. Quartz sand with a maximum nominal size of 1.18 mm was used as the fine aggregate. Moreover, nano calcium carbonate (NC) of particle size around 150 nm was added as a filler to improve the mixture performance. Three types of fibers, namely, carbon fibers (CF), steel fibers (SF) and glass fibers (GF), were tried to evaluate their effectiveness. Their properties are summarized in Table 1. To disperse the fine particles and achieve good rheology properties, a polycarboxylate ether-based superplasticizer (SP) was added and the SP dosage was expressed as a percentage by mass of all cementitious materials and nanoparticles.

3.2. Experimental design

An extrusion apparatus, with an elaborated extrusion head, as illustrated in Fig. 2, was designed and made. It consists of four parts: a piston, a square tube, a rectangular nozzle, and a track on which the

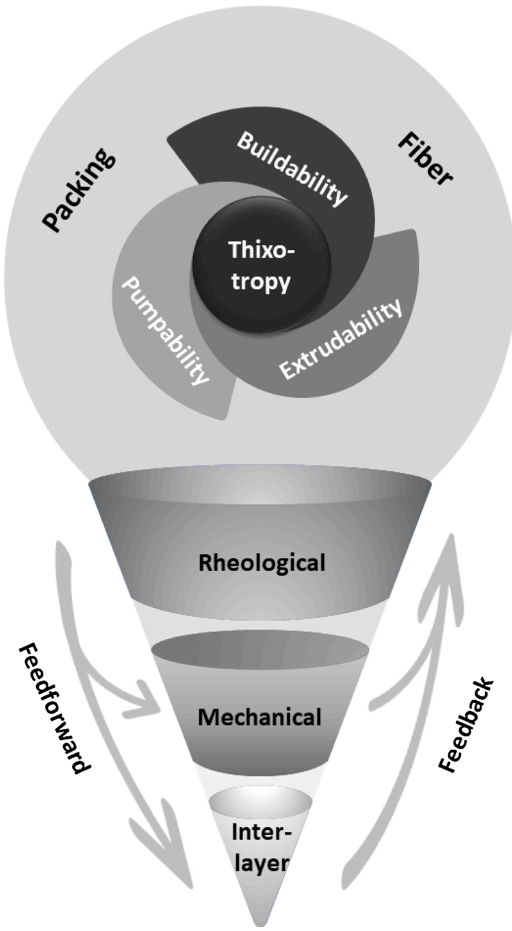

Fig. 1. Conceptual model for design of extrudable mixtures.

Table 1
Properties of fibers.

Fiber type	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)	Young's modulus (GPa)	Specific gravity
Carbon	6	0.007	857	>3000	250	1.80
Steel	13	0.20	65	>2000	210	7.85
Glass	12	0.007	1714	>1700	75	2.68

nozzle moves. The nozzle has a dimension of 40 mm width × 25 mm height, which is the same as that designed by Bos et al. [53]. During the extrusion process, a dead weight was applied to the piston which exerted pressure to the mixture in the tube. Such pressure drove the mixture to flow out of the nozzle and onto the track. Before the main test program, a series of trial mixing with the mix parameters varied was conducted to develop extrudable mixtures. It was found that a mixture with 50% sand volume and 50% paste plus fiber volume exhibited the most desired extrudability for the particular combination of materials used. Therefore, the sand volume was set as 50%. This implied that the paste plus fiber volume was also set as 50%.

After developing the extrudable mixtures, the main test program, as presented in Table 2, was lunched to evaluate their properties. To achieve as high performance as possible while maintaining good extrudability, the water/cementitious materials (W/CM) ratio was set at 0.25. The supplementary cementitious materials (silica fume and metakaolin) were added to replace 20% by mass of the cement. To exploit their synergistic effect [54], the silica fume and metakaolin were added at the same time at a mass ratio of 1 to 1, or in other words, each added to replace 10% by mass of the cement. Additionally, the nano filler NC was

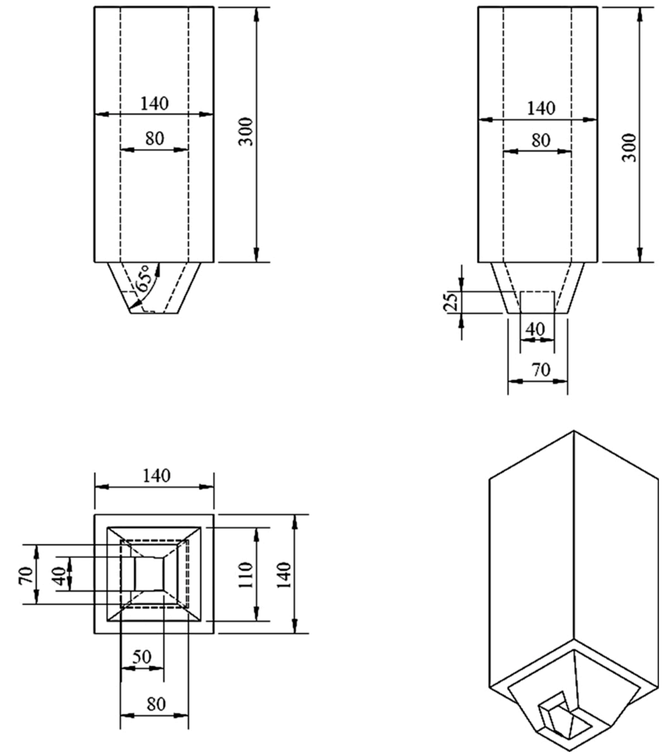

Fig. 2. Design of the extrusion apparatus.

added to replace 0, 2% and 4% by mass of the cement [55]. Finally, each of the three types of fibers was added to the mixture at a constant fiber volume of 0.5%. On the other hand, the SP was not fixed but adjusted to attain a consistent workability in terms of slump.

3.3. Mixing procedure and curing

To obtain a uniform mixture and avoid fiber balling, the paste was first mixed to achieve good consistency, and then the quartz sand and fibers were added bit by bit during mixing. The total mixing time was controlled at about 8 min. Immediately after mixing, the mixture was transferred to a mini-slump cone for buildability test which would be elaborated later. Meanwhile, the mixture was cast into steel molds for making three 40 mm cube specimens which were demolded one day after casting. To minimize the adverse effect of workability loss with time, the mixing procedure was repeated to produce another batch of mixture for the trial extrusion. Immediately after mixing, the mixture was loaded into the tube of the extrusion apparatus for extrusion. All of the specimens were cured in air at a temperature of 27± 3℃.

3.4. Extrudability test

The extrudability was measured in terms of the extrusion pressure needed to initiate the extrusion. To conduct the test, dead weight was added bit by bit to the top of the piston until the mixture in the tube started to flow out through the nozzle. The maximum dead weight recorded divided by the area of the piston was then taken as one extrusion pressure result. To achieve good accuracy, three repeated tests were carried out for each mixture and the average result was taken as the extrusion pressure of the mixture tested. It should be noted that the extrusion pressure so determined is the static extrusion pressure, which is not the same as the dynamic extrusion pressure needed to maintain a certain extrusion rate.

Table 2
Mixture proportions.

Mix no. (NC-fiber type and volume)	Cement (kg/m^3)	Silica fume (kg/m^3)	Meta-kaolin (kg/m^3)	NC (kg/m^3)	Water (kg/m^3)	Quartz sand (kg/m^3)	Fiber volume (%)
0-Plain	806	101	101	0	236	1040	0.00
0-CF0.5	806	101	101	0	234	1027	0.50
2-CF0.5	782	100	100	20	232	1027	0.50
4-CF0.5	758	100	100	40	229	1027	0.50
4-SF0.5	758	100	100	40	230	1027	0.50
4-GF0.5	758	100	100	40	230	1027	0.50

3.5. Buildability test

Although buildability is an important property, it is often evaluated just qualitatively [9]. To quantitatively evaluate the buildability, slight modifications were made to the mini-slump-flow test by considering the time effect. The mini-slump cone developed by Okamura and Ouchi [56] was adopted. The slump and flow diameter were measured every 5 min after the slump cone was lifted until the slump-flow became stable. For each measurement, four values of flow diameter were recorded in equal angles and averaged as the flow diameter result. To further quantify the buildability, the shape retention factor, defined as the ratio of the base area of the mixture while still inside the slump cone to that of the mixture after the slump-flow test, was also determined. The determination of the shape retention factor involved no additional test and needed only the flow diameter results.

3.6. Interlayer bond test

In the actual extrusion process, the time taken for the nozzle to reach the same point of two adjacent layers would significantly affect the extrusion quality [34,57], as a longer time gap would exacerbate the anisotropic behavior of the mixture, especially in the presence of fibers, and give rise to larger pores at the interface. To evaluate such time gap effect, the second layer was extruded at time gaps of 1, 10 and 30 min after the first layer was extruded. The total extruded length for each time gap was controlled at around 300 mm to make an extruded specimen comprising of two layers. After 28 days of curing, each 300 mm long extruded specimen was vertically cut into three numbers of 40 mm × 40 mm interlayer bond test specimens.

The bending test, which measures the interlayer bond indirectly by applying a compression load, is commonly adopted by other researchers [58–60]. In this study, a new test setup for measuring the interlayer bond directly by applying a tension load was designed, as shown in Fig. 3. Each interlayer bond test specimen was glued using epoxy at each face to a steel block welded with a steel bar at the center in the axial direction. To avoid misalignment, two ball joints were installed at the two ends of the setup. Then the set up was mounted into a 50 kN MTS machine. An initial load of 0.3 kN was applied first and then tension load was applied under displacement control at 0.5 mm/min until tension failure occurred. Finally, the interlayer bond strength of the extruded specimen was taken as the average tensile strength (tension load divided by sectional area of 1600 mm^2) of the three interlayer bond test specimens.

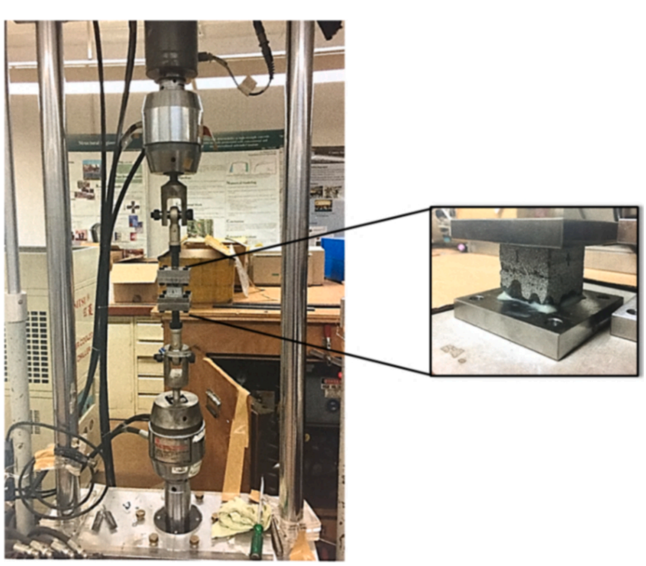

Fig. 3. Photographs of the interlayer bond test.

3.7. Compressive strength test

Compressive strength was conducted in accordance with BS EN 12390−3: 2009 at the age of 28 days. The mean strength of the three specimens tested at the same time was taken as the strength result. To make it clear, all of the above tests are summarized in Table 3.

4. Results and discussions

4.1. Extrusion pressure

The extrusion pressures results are plotted in Fig. 4. From the figure, it can be seen that with the SP dosage adjusted to maintain consistent workability, the addition of fibers and NC slightly decreased the extrusion pressure and thus had no adverse effect on the extrudability. The different types of fibers had different effects. Relatively, the addition of steel fibers (rigid fibers) yielded the lowest extrusion pressure whilst the addition of carbon or glass fibers (flexible fibers) yielded higher extrusion pressures. These results agree well with the theoretical prediction by Wu and Aidun [61] that the viscosity increases as the fiber stiffness decreases. Actually, there may be two possible reasons for this phenomenon. First, the flexible fibers have lower fiber stiffness and thus are more prone to entangle with each other. Second, the flexible fibers used in this study have smaller fiber diameters and thus at the same fiber volume, there are a larger number of fibers entangling with each other.

4.2. Buildability

Since the SP dosage was adjusted so that a consistent workability as measured by the slump-flow test was achieved, the workability results

Table 3
Testing details.

Test	Mixtures evaluated	No. of samples/ repetitions	Measurable parameter
Extrudability test	All (0-Plain, 0-CF0.5, 2-CF0.5, 4-CF0.5, 4-SF0.5, 4-GF0.5)	3	Extrusion pressure
Buildability test		5	Shape retention factor
Interlayer bond test		3	Interlayer bond strength
Compressive strength test		3	Compressive strength

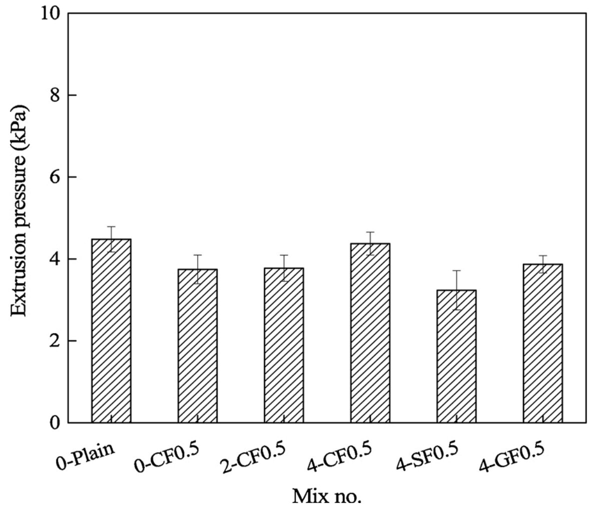

Fig. 4. Extrusion pressure for various mixtures.

would not truly reflect the effects of the fibers and NC on the workability. The SP dosage needed, i.e. the SP demand, would better reflect the effects of the fibers and NC on the workability, as presented in Fig. 5. It is seen that on the whole, the addition of fibers (regardless of the fiber type) and/or NC had significantly increased the SP demand from 2.0% for the plain mixture to a maximum of 2.5% for the mixture containing 0.5% carbon fibers and 4% NC. The observed phenomenon that the addition of nanoparticles would decrease the workability and increase the SP demand had also been observed by previous researchers [62]. This is reasonable because the addition of nanoparticles would greatly increase the specific surface area of the particle system and thus demand more SP to disperse the fine particles.

As for the effects on the extrudability, the different types of fibers appeared to have different effects on the SP demand. Comparing the SP dosages of the three mixtures with the same fiber volume of 0.5% and the same NC content of 4% but different types of fibers added, it is evident that the mixture with carbon fibers added had the highest SP demand. However, as can be seen from Table 1, the carbon fibers do not have the highest aspect ratio (the glass fibers have the highest aspect ratio). Hence, the fiber aspect ratio seems not the governing factor. It should be noted however that although the three mixtures have the same fiber volume, they do not have the same fiber number, i.e., the number of fibers per unit volume of mixture. From the fiber volume per unit volume of mixture and the volume of each fiber, the fiber number of each mixture can be calculated as 2.17×10^{10}, 1.22×10^{7} and $1.08 \times 10^{10}\,\text{m}^{-3}$ for the mixtures containing carbon fibers, steel fibers and glass fibers, respectively. Evidently, the mixture with carbon fibers added has the highest fiber number. It is postulated herein that it was the high fiber number that caused the mixture with carbon fibers added to have the highest SP demand. Apparently, the fiber number has greater effects on the fresh properties than the fiber aspect ratio.

During the slump-flow tests, the time needed for the slump and flow diameter to be stabilized was also recorded. It was found that for all the mixtures tested, the slump and flow diameter became stable within 5 min after the slump cone was lifted, indicating that the stabilizing time was short enough for the nozzle to deposit the next layer of mixture after a few minutes. The slump and flow diameter values obtained after 5 min are plotted in Fig. 6, where it can be seen that all the slump values fell within the narrow range of 6.5–9.0 mm while all the flow diameter values fell within the narrow range of 101.5–107.0 mm. Such small ranges indicated that all the mixtures had been successfully controlled by adjusting the SP dosage to have a consistent workability and the desired buildability for extrusion based on the abundant trial tests and the valuable lessons learned from the previous research [59].

The above slump and flow diameter values are not high. However, it should be noted that a high workability is not desired for extrusion and 3D printing because a high workability could lead to excessive drop in

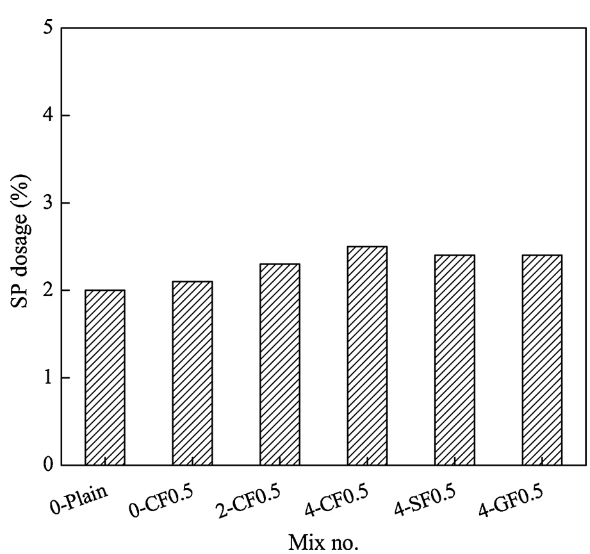

Fig. 5. SP dosage for various mixtures.

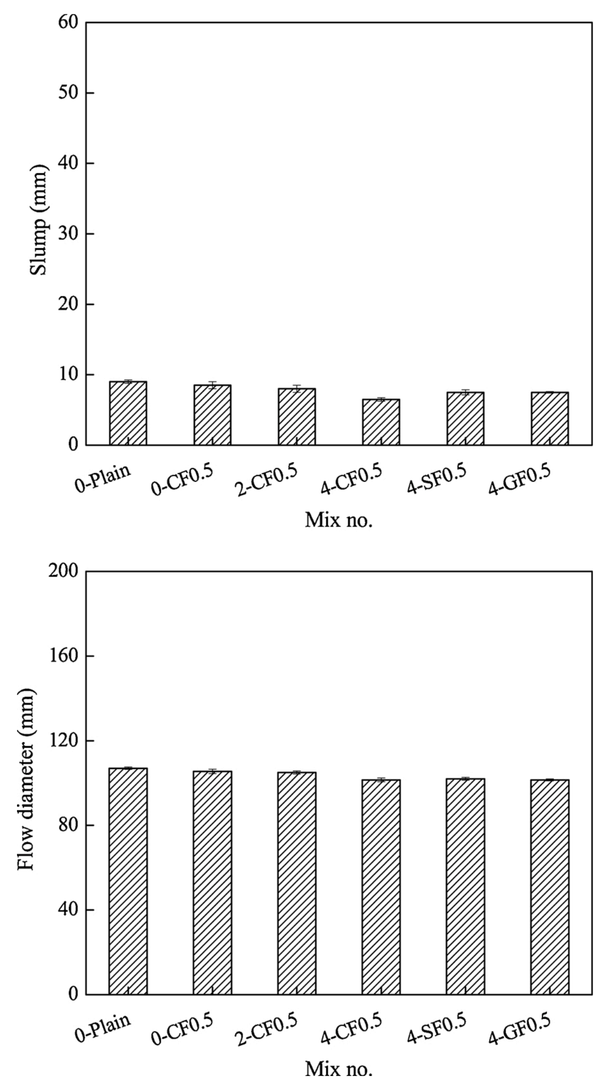

Fig. 6. Slump and flow diameter for various mixtures.

height and belly cross-section after the subsequent layer is deposited. What is more important is whether the addition of fibers and nanoparticles would lead to an excessively high SP dosage. In this series of mixtures, the maximum SP dosage was only 2.5%, which is still acceptable because no adverse effects due to excessive SP dosage had been observed.

Apart from the extrudability requirements for the extrudable mixture to be easily, smoothly and steadily extruded, there are also buildability requirements for the extrudable mixture to retain its shape after being extruded [23,59]. To further assess the buildability, the shape retention factor of each mixture is plotted in Fig. 7. Evidently, the addition of fibers and/or NC had significantly enhanced the shape retention ability. For instance, regardless of the fiber type, the addition of 0.5% fibers and 4% NC increased the shape retention factor from 0.873 to around 0.961−0.971. Relatively, the carbon fibers and glass fibers had slightly better enhancing effect than the steel fibers, but the difference was not large. Such observed enhancing effect of the fibers is consistent with the findings in literature that the addition of fibers would increase the shape retention ability [59].

4.3. Interlayer bond strength

The interlayer bond strength results at an extrusion time gap of 10 min are depicted in Fig. 8. From these results, it can be seen that the addition of NC significantly improved the interlayer bond. This observed phenomenon is consistent with the findings by Kruger et al. [63]. One probable reason was the denser microstructure caused by the filling effect of the NC particles. On the other hand, the addition of fibers hardly improved and sometimes even impaired the interlayer bond probably because the fibers in the two consecutive layers had not penetrated through the interface to develop any tie-up forces there. Relatively, the addition of carbon fibers or glass fibers tended to produce slightly higher interface bond strength than the addition of steel fibers, but the difference was not large.

The time gap effect is also a critical issue affecting the quality of the extruded structure because a certain time is required to extrude the next layer on top of the previous layer. To evaluate such time gap effect, the 4-CF-0.5 mixture was selected for extrusion at different time gaps. The test results so obtained, together with those published in the literature for comparison, are presented in Fig. 9. All the results in the present study and those in the literature show that the interface bond always decreased as the time gap increased. Moreover, the comparison reveals that the interlayer bond achieved in the present study is substantially higher than those obtained by other researchers while the rate of decrease of interlayer bond is much slower, due to the innovative use of HSFRC as the extruding material. Anyway, despite the slower rate of decrease of interlayer bond of the HSFRC developed herein, it is still considered advisable to limit the time gaps at about 10 min.

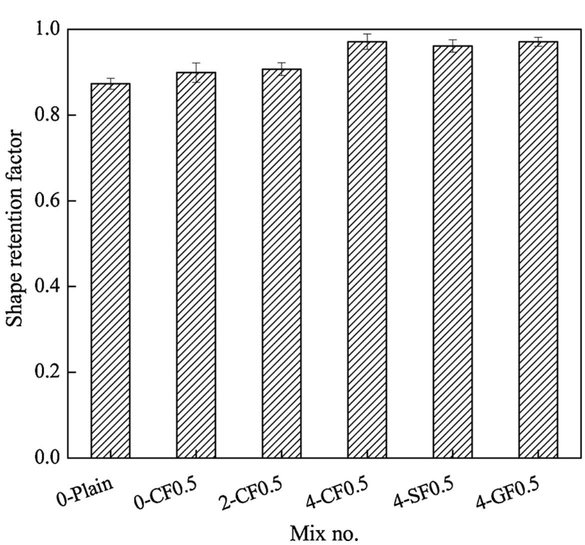

Fig. 7. Shape retention factor for various mixtures.

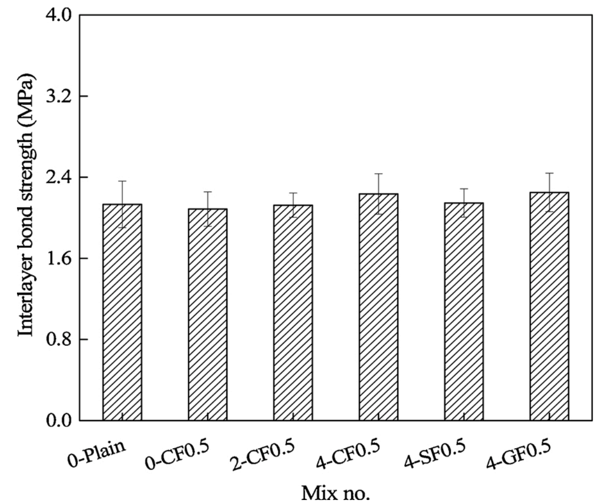

Fig. 8. Interlayer bond strength for various mixtures.

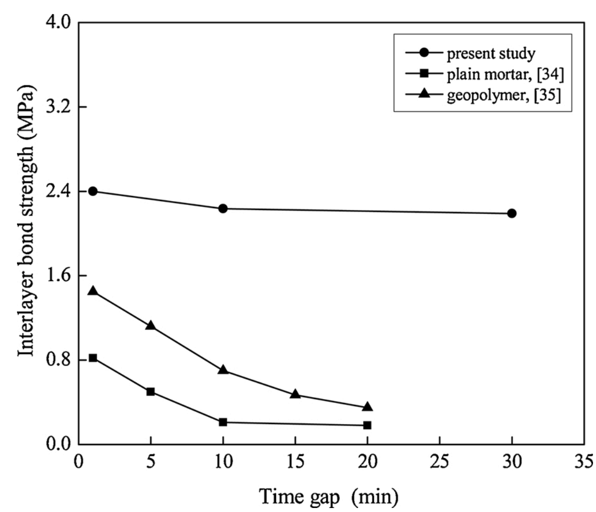

Fig. 9. Interlayer bond versus printing time gap from the present study and literature.

A previous study reported that the addition of polypropylene fibers may impair the interlayer bond [59]. A closer look at these particular test results revealed that as the fiber volume increased from 0 to 1.0%, the flow diameter as measured by the shape retention ability test decreased. Such impaired workability as evidenced by the smaller flow diameter might have adversely affected the interlayer bond strength. Nevertheless, the test results showed that the interlayer bond strength did increase from 2.6 to 3.1 MPa after the addition of 0.25% fibers but then started to decrease upon further addition of fibers [59]. In the present study, the interlayer bond strength has not been adversely affected by the addition of fibers because the SP dosage was increased to maintain similar workability after the addition of fibers.

4.4. Compressive strength

The compressive strength results are plotted in Fig. 10. As shown in the figure, the addition of fibers and NC had increased the strength to over 120 MPa, which meets the criterion for an ultra-high strength concrete or ultra-high strength FRC (UHPFRC) proposed by many

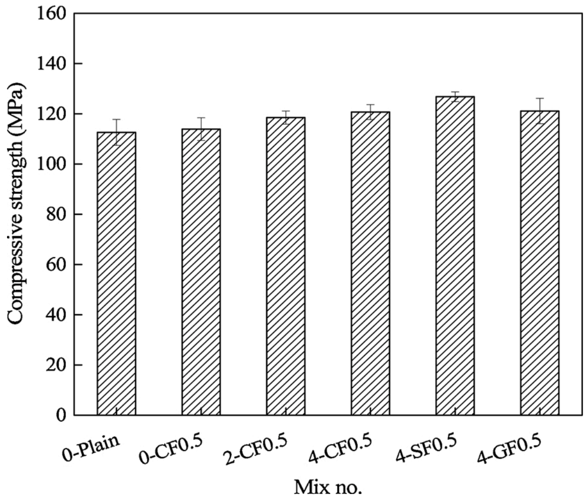

Fig. 10. Compressive strength for various mixtures.

researchers [64–66]. With no NC added, the addition of 0.5% carbon fibers slightly increased the strength by 1.2%. However, with 0.5% carbon fibers added, the addition of 4% NC significantly increased the strength by 6.0%. Hence, the increase in strength was due mainly to the addition of NC. For comparison, the increase in strength due to the addition of 3% NC reported by Liu et al. [67] was 7.7%. Similar increases in strength due to the addition of NC were also reported by Camiletti et al. [68], who explained that the NC particles would provide nucleation sites and increase contact points during hydration process. On the other hand, at the same fiber volume of 0.5%, the use of steel fibers showed greater strength enhancement effect on the strength compared with carbon fibers and glass fibers.

The optimum use of NC deserves further in-depth studies. Li et al. [62] added different contents of NC to replace cement and reported that the addition of 3% NC would best enhance the compressive strength. Likewise, Liu et al. [67] investigated the effects of NC at different contents of 0, 1%, 2%, 3% and 4% by mass of cement on the mechanical properties of UHPFRC and concluded that the optimum dosage of NC for the highest compressive and tensile strengths should be at around 3%. It had also been found by Camiletti et al. [68] that an excessive dosage of NC might lead to negative effects as it would decrease the particle packing. In the present study, the NC content was only varied among 0, 2% and 4%, and thus the optimum NC content could not be determined. However, it should be noted that the optimum content for strength and that for extrudability may not be the same.

5. Further discussions

The aforementioned pumpability, extrudability and buildability are competing attributes in that improving one of them might impair the others. For instance, when the mixture is designed to exhibit high extrudability, the buildability might be difficult to guarantee, while when the mixture is designed to exhibit high buildability, the pumpability, extrudability and the interlayer bond might be jeopardized. Therefore, a balance should be struck between the key attributes of pumpability, extrudability, buildability and interlayer bond by identifying and tailoring the fundamental governing factors. In fact, the rheological properties are mainly governed by the thixotropy of the mixture and existing methods to improve the thixotropy include addition of nanoparticles, adjustment of the SP dosage, and so on [69]. However, few attentions have been paid to the use of different types of fibers for the enhancement of both thixotropy at fresh state and strength at hardened state.

Based on the test results in this study, it is worth mentioning that the inclusion of fibers might be conducive to the thixotropy as demonstrated by the widened differences in viscosity at low to high shear rate after the addition of fibers, as shown in Fig. 11. These preliminary results were produced by using a R/S Brookfield rheometer (serrated rotating vane) to test two mixtures, a plain mixture with no fibers added and an FRC mixture with carbon fibers added. It is speculated that the observed thixotropy is highly associated not only with the reconstruction of the microstructure but also with the alignment of the fibers in the flow direction. This may also help to explain why the HSFRC mixtures developed herein exhibit a higher shape retention factor and at the same time a similar or even lower extrusion pressure compared with the plain mixture. In this regard, more systematic research is recommended.

The prospect of applying extrusion technology in the construction industry has been optimistic as evidenced by the increasing numbers of research projects and large-scale extruded concrete structures [2,70]. From laboratory-scale prototypes, to low-rise, less-ornate buildings, to medium-rise, ornate buildings, the ways forward necessitate the development of various extrudable materials exhibiting both low-environmental impact and high overall performance in the fresh and hardened states. The environmental impact may be further reduced by considering the life cycle of the extruded structure, the materials design and the structural design. Regarding the desired high performance, the extrudable materials should at least enable the extrusion of horizontal components which are quite often free of reinforcing bars. Innovative uses of fillers and fibers should be the promising ways of improving the sustainability and tailoring the rheological properties for optimizing the pumpability, extrudability and buildability, and achieving the desired strength, ductility and interlayer bond. Yet, there has been lack of comprehensive research at the present stage.

Meanwhile, challenges remain, such as the inclusion of steel reinforcement in the extruded structures, extrusion of larger scale buildings, adaptive design of the nozzle and exploration of better extrusion methods. To cope with these challenges, particularly that caused by the difficulty in including steel reinforcement, the use of an extrudable HSFRC, which exhibits much-enhanced tensile strength and ductility, should enable a more reliable structural design of the extruded structures. Apart from this, the digitalization of the extrusion process in the present study to become a 3D printing process, which has been demonstrated using the materials in the present study, as shown in Fig. 12, is worthy of further systematic investigation. Nevertheless, it is believed that the feasibility and commercial success of extrusion construction lie mainly in the robustness design of the materials and the extrusion process [2]. Besides, it is worth mentioning that by designing the extrudable mixture to exhibit anti-wash property, the extrusion technology might also be applied to constructions in marine and submarine environments.

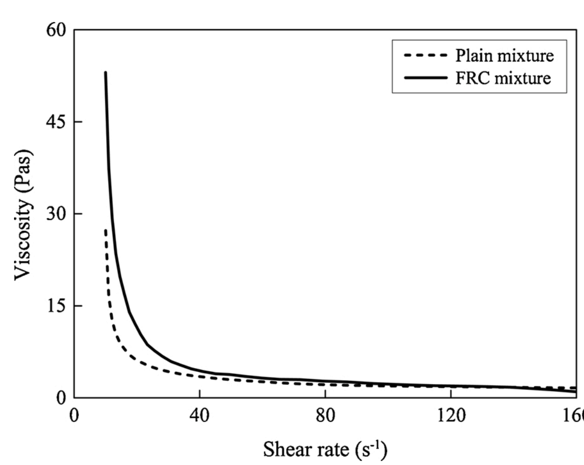

Fig. 11. Viscosity versus shear rate for plain and SHCC mixtures.

(a) (b)

Fig. 12. Photographs of (a) extruding process in the present study; and (b) 3D printing process at The University of Hong Kong.

6. Conclusions

In this paper, a brief literature review of the concrete extrusion (3D printing) technology and extrudable (3D printable) mixtures has been presented followed by a conceptual model for the design of extrudable mixtures. Extrudable HSFRC mixtures with tailored slump and flow diameter values were developed through numerous trials. In addition, a series of methods for testing the extrudable HSFRC mixtures were developed based on pioneering works by earlier researchers. A total of six mixtures, including one plain mixture and five HSFRC mixtures, were tested to evaluate their SP demand, extrudability, buildability, interlayer bond and compressive strength. Based on the test results and some general discussions, the following conclusions are drawn.

1 The extrusion pressure of the mixtures with their workability maintained at a consistent level by adjusting the SP dosage decreased slightly after adding 0.5% fibers and 4% NC. Hence, the fibers and NC added had no adverse effect on the extrudability. Relatively, the addition of the steel fibers yielded lower extrusion pressure than the addition of the carbon or glass fibers.
2 The addition of 0.5% fibers and 4% NC slightly increased the SP demand to 2.5%, which is not particularly high and still acceptable. More importantly, the addition of the fibers and NC significantly enhanced the shape retention ability for better buildability. Relatively, the carbon and glass fibers had slightly better enhancing effect than the steel fibers.
3 A new test setup for measuring the interlayer bond directly by applying a tension load was designed. Test results obtained using this setup showed that the addition of NC significantly improved the interlayer bond. However, the addition of fibers hardly improved the interlayer bond. Relatively, the carbon and glass fibers tended to produce slightly higher interface bond than the steel fibers. And, the interface bond always decreased as the time gap increased.
4 Comparison with the data in literature revealed that the interlayer bond achieved in the present study is substantially higher than those obtained by other researchers while the rate of decrease of interlayer bond is much slower, due to the innovative use of HSFRC as the extruding material.
5 The addition of fibers and NC had increased the compressive strength to over 120 MPa, which meets the criterion for an UHPFRC. However, the increase in compressive strength was due mainly to the addition of NC. Lastly, the use of the steel fibers showed greater enhancement effects on the compressive strength compared with the carbon and glass fibers.

Overall, the research works presented herein should be helpful in advancing the development of extrudable HSFRC from the materials design and testing points of view. Further research works are needed to address the issues that have not been covered yet, such as an in-depth investigation on the thixotropy and its quantitative relation with the packing of extrudable HSFRC mixtures incorporating various types of fibers and nanoparticles.

CRediT authorship contribution statement

S.H. Chu: Conceptualization, Methodology, Formal analysis, Visualization, Writing - original draft. **L.G. Li:** Investigation, Writing - review & editing. **A.K.H. Kwan:** Resources, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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