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<th>Develop cementitious materials incorporating fly ash cenosphere for spray-based 3D printing</th>
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<td><strong>Author(s)</strong></td>
<td>Lu, Bing; Li, Mingyang; Qian, Shunzhi; Leong, Kah Fai; Tan, Ming Jen</td>
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ABSTRACT: Developments of 3D printing in building and construction have attracted a lot of research focus during recent years. While the mainstream 3D printing of cementitious material adopts extrusion method, the limitation in vertical applications such as overhanging structures calls for further investigation of printing method with suitable materials. In this paper, spray-based 3D printing of cementitious material is proposed. The influence of incorporating fly ash cenosphere is studied for spray-based 3D printable cementitious material development. Rheological tests and robotic arm-controlled spray tests illustrate that the incorporation of fly ash cenosphere significantly reduces the spray splash, improves sprayed material distribution of sprayed material while impairs the pumpability of the material.

KEYWORDS: 3D printing, cementitious material, fly ash cenosphere, pumpability, spray performance

1. Introduction

3D printing, as a fast-evolving technology in building and construction, has attracted a lot of attention for research studies and engineering applications recently (Bos et al., 2016; Lu, Tan and Qian, 2016; Chua and Leong, 2017). However, conventional 3D printing of cementitious material is extrusion-based process, which has limitations in vertical applications such as decorative overhanging structures. This issue is proposed to be solved by altering the current spray system with suitable spray-based 3D printable cementitious materials (Lu, Tan and Qian, 2016). However, there is little research carried out in this specific field, especially for suitable spray printing materials.
cementitious materials. Therefore, it is necessary to develop suitable cementitious material for spray-based 3D printing. Fly ash cenosphere is one of the byproducts from coal-fired power plants. It has low density (around 0.8 g/cm³) with spherical hollow shape, as can be seen in Figure 1. Although fly ash cenosphere has similar chemical compositions as fly ash, its reactivity is limited and treated as an inert aggregate (Hanif, Lu and Li, 2017). The incorporation of fly ash cenosphere in cementitious composites greatly decreases the density and improve the sustainability of the material, while its mechanical properties still meet the requirements of structural applications. Till now, little research has been carried out to investigate the incorporation of fly ash cenosphere in the spray-based cementitious material.

Figure 1 Scanning Electron Microscope (SEM) image of fly ash cenosphere

This paper introduces the exploration of substituting silica sand by fly ash cenosphere in spray-based 3D printable cementitious materials. Based on previous studies, three mixes with different incorporation percentage of fly ash cenosphere were designed. Then the rheological experiments were conducted to further assess pumpability and estimate the maximum build-up thickness. After that, robotic arm-controlled spray tests were implemented to study the spray performance of the developed material. Based on these aspects, the feasibility of utilizing fly ash cenosphere in spray-based 3D printable cementitious materials has been clarified.

2. Information of raw ingredients and mix design

The raw ingredients in this research study were cement, fly ash, silica sand, fly ash cenosphere, silica fume, air-entraining agent and superplasticizer. Fly ash is used as a supplementary cementitious material for cement. It is pointed out that addition of silica fume and air-entraining agent (AEA) reduce the rebound of sprayed material (Neville, 2002), contributing to better spray performance. Therefore, silica fume and AEA were included in the raw ingredients. Chemical composition and particle size distribution can be referred in the previous related work from the authors’ group (Weng et al., 2018).

The mix design table is shown as Tab.1. Mix A does not contain fly ash cenosphere, which was designed as the control set. Silica sand was substituted by fly ash cenosphere in Mix B and Mix C with different substitution mass percentages (50% and 100% respectively). Other parameters, i.e., water/binder ratio, fly ash/cement ratio, silica fume/cement ratio, air-entraining agent and superplasticizer usage, were kept as constant.

Table 1 Mix design

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<th>Mix</th>
<th>FAC / Agg.</th>
<th>Agg. / b</th>
<th>FA / b</th>
<th>W / b</th>
<th>Sf / b</th>
<th>Superplasticizer</th>
<th>AEA</th>
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<tr>
<td>A</td>
<td>0%</td>
<td>0.29</td>
<td>0.5</td>
<td>0.4</td>
<td>0.05</td>
<td>3 g/L</td>
<td>0.1 g/L</td>
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During experiments, AEA was put into the weighed water to get fully dissolved. Powder ingredients were mixed in Hobart mixer 200HL at stir speed for three minutes, then the water with dissolved AEA was added and mixed at stir speed for another three minutes. Superplasticizer was added thereafter, followed by 1.5 minutes of mixing at stir speed and 1.5 minutes of mixing at a faster speed. Then the fresh cementitious material was taken for rheological tests or robotic arm-controlled spray tests.

3. Pumpeability assessment

Bingham model is one of the widely accepted rheological models for cementitious materials (Austin, Robins and Goodier, 1999). The relationship between the applied shear stress and shear rate can be described as follows:

$$\tau = \tau_0 + k\dot{\gamma}$$

where \(\tau_0\) is yield stress (Pa), which describes the minimum shear stress the material needed to maintain the flow; \(k\) is plastic viscosity (Pa·s), which describes the increment of shear stress with variable shear rates. Fluid dynamics points that lower yield stress and lower plastic viscosity contribute to less required pumping pressure under the same equipment setup (Chhabra and Richardson, 2008), indicating better pumpeability. The pumping pressure \(p\) (Pa) for the material with different rheological parameters under flow rate \(Q\) (m³/s) can be decided by the following equation:

$$Q = \frac{\pi R^4}{8k} \left[ 1 - \frac{4}{3} \left( \frac{2\tau_0 L}{pR} \right)^3 + \frac{1}{3} \left( \frac{2\tau_0 L}{pR} \right)^4 \right]$$

where \(R\) and \(L\) are the radius (m) and length (m) of the hose respectively.

Rheological tests were conducted for each mix respectively, in which a rotational rheometer Viskomat XL was used. After mixing procedure, the fresh material was poured into the sample container of the rheometer. The sample container rotated as per programmed to generate a linear variation in rotation speed. The yield stress and the plastic viscosity can be calculated afterwards according to the equipment dimension and measured torque–rotation speed curve of the material. Table 2 gives yield stress and plastic viscosity of each mix. To better describe the pumpeability of each mix, the pumping pressure using specific hose and flow rate for each mix is also calculated and shown in Table 2. It can be found that substituting silica sand by fly ash cenosphere greatly increases yield stress and plastic viscosity of the material. The increments become smaller with the increasing percentage. With increasing rheological parameters, the substitution of silica sand by fly ash cenosphere impair the pumpeability. However, as the required pumping pressure is quite low (less than 2 Bar), the pumping of all the three mixes can be achieved by the lab asset.

Table 2 Rheological parameters, theoretical fresh density and pumping pressure calculation

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<tr>
<th>Mix</th>
<th>Yield stress (Pa)</th>
<th>Plastic viscosity (Pa·s)</th>
<th>Theoretical fresh density (g/cm³)</th>
<th>Pumping pressure with 2 m long 1 inch diameter hose and 1 L/min flow rate (Bar)</th>
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<tr>
<td>Mix A</td>
<td>23.85</td>
<td>6.22</td>
<td>1.96</td>
<td>0.61</td>
</tr>
<tr>
<td>Mix B</td>
<td>102.06</td>
<td>9.00</td>
<td>1.71</td>
<td>1.16</td>
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</table>
4. Spray performance assessment

A simplified build-up model of sprayed material was proposed by Beaupre (Beaupre, 1994). In this model, the maximum build-up thickness $t$ (m) can be estimated as:

$$t = \frac{\tau_0}{\rho g}$$  \hspace{1cm} (3)

where $\rho$ (kg/m$^3$) is the fresh density of the material; $g$ (m/s$^2$) is the gravitational acceleration. From Eq. (3), higher yield stress and lower density contribute to larger maximum build-up thickness. The rheological experiments in the previous section reveal that Mix C possesses the highest yield stress. In addition, the increasing percentage of fly ash cenosphere further decreases the density of the material. Therefore, it should have the largest build-up thickness theoretically, which should be checked through spray tests. Nevertheless, the relationship between sprayed material distribution and rheological parameters is also needed to be investigated through spray tests. Thus, robotic arm-controlled spray tests are performed to assess the spray performance of Mix A to Mix C. Spray process includes many process-related parameters, e.g. nozzle size, nozzle moving speed, the distance between nozzle and substrate. These process-related parameters may affect the sprayed profile and should be kept constant for material investigation. Therefore, robotic arm is introduced in the spray performance assessment (Pham, Lim and Pham, 2016). The setup of robotic arm-controlled spray tests can be referred in Figure 2. The spray nozzle is connected to the hose and gripped by the coupling of the robotic arm. Therefore, the movement and orientation of spray nozzle can be controlled by the robotic arm with programmed settings.

In the experiment, the flow rate of the material was kept at 2.5 L/min; the round nozzle of 8.5 mm in diameter was used, of which moving speed was kept at 100 mm/s; the initial distance between nozzle and substrate was 50 mm; the injected air pressure was kept at 0.05 MPa. The hose was 2 m in length and 1 inch in diameter. The material sprayed in 5 cycles, each was comprised of 300 mm straight line profile. After completion of each cycle, the nozzle shifted backwards of 10 mm. Figure 3 shows the sprayed profile of each mix. From the figure, it is noticed that both sprayed profiles of Mix A and Mix B presented large shift from the height of sprayed nozzle axis. In addition, the sprayed profile of Mix C shows distinctively less splash width compared with Mix A and Mix B. The differences can be attributed to the insufficient yield stress of Mix A and Mix B to resist the injected air pressure and the pressure brought by the impact of successive sprayed material. The maximum build-up thickness in 5 cycles of spray was measured to be 26.64 mm,
28.74 mm and 29.51 mm for Mix A to Mix C respectively. Hence Mix C shows the largest build-up thickness in the 5 cycles among all the three mixes.

The sectional material distribution was further studied for Mix B and Mix C specifically, which is shown in Figure 4. Samples were cut from sprayed material and measured their height at certain points of the intersection. As can be seen from Table 2 and Figure 6, the increase of 24.5% yield stress and the decrease of density contribute to significantly improved section material distribution. In Mix B, the maximum thickness value is more than twice of the minimum. As a comparison, all the thickness values measured in Mix C are within 8.4% range of the average. The standard deviation of thickness values in Mix B and Mix C are 5.23 mm and 1.67 mm, respectively. Considering the maximum buildup thickness and section material distribution, Mix C shows the best spray performance among all the three mixes.

5. Feasibility of developing cementitious material incorporating fly ash cenosphere for spray-based 3D printing

With the data regarding pumpability and spray performance assessment, it is accessible to carry the feasibility study of developing cementitious material incorporating fly ash cenosphere for spray-based 3D printing. Accuracy is always required in the 3D printing process, otherwise the printed profile will deviate from the designed profile. Among the three mixes, Mix C has little offset from the height of spray nozzle axis. In addition, the relatively uniform distribution of sprayed material can alleviate the accumulated deviation in the material build-up direction. Thus, Mix C is adopted for a simplified 3D printing with a controlled crane, which shows good performance in the spray-based 3D printing (see Figure 5). Hence the feasibility is clarified.
6. Conclusion

In this paper, the feasibility of developing cementitious materials incorporating fly ash cenosphere for spray-based 3D printing was studied. Rheological tests and robotic arm-controlled spray tests show that increasing the substitution percentage of silica sand by fly ash cenosphere can greatly improve the spray performance. Though it also reduces the pumpability of the material, the application was not affected as the material can still be easily pumped with the reduced pumpability. The full substitution mix showed little offset and more uniform sectional material distribution compared with the other two mix designs. Studies of further improving material distribution and ameliorating the pumpability of the material should be implemented in the future.

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