The influence of fine aggregates on the 3D printing performance

J C Lin, X Wu, W Yang, R X Zhao and L G Qiao

National Enterprise Technology Center, China State Construction Ready Mix
Concrete CO., LTD, Wuhan, China

E-mail: Sillybear@yeah.net

Abstract. Influences of nature Particle, size, grain shape and fineness modulus of fine aggregates on the 3D printing performance of cement-based mortar were investigated. Results showed that the working performance of the mortar is not only dependent on the fineness of the aggregate, but also the gradation and grain size of the aggregate. And the mechanical properties of the mortar are increasing with the increase of Mx in the same test condition. The research shows that it is effective to choose different properties of materials for different design requirements, and the fluidity of mortar must be decreased under assuring construction quality and the pumpability of 3D printing materials.

1. Introduction

3D printing technology, as a rapid prototyping technology, fabricates three-dimensional entity structure using layer-by-layer superimposed method based on 3D digital model. As one of the most promising manufacturing technology in the 21st century, it is known as the core of the "third industrial revolution".

The application of 3D printing originated from 20th century in US in the building field. A new construction method of free form component that accumulative building structures layer by layer with selective solidification of cementitious materials was proposed by Joseph Pegnain1997 [1].

According to the diversity of building materials, the current 3D printing construction methods can be divided into three categories: 1st, the construction method of stratified squirting superimposed with cement-based material, 2nd, the construction method based on gravel powder Layered bonding, 3rd, Three-dimensional construction method with large manipulator [2].

3D printing technology puts forward more special requirements for the workability of building materials. At the same time, the printing process also has great influence on the structural performance and material hardening performance. Therefore, the effect of 3D printing is dependent on not only the rheological properties, plasticity and self-condensation properties of cement-based materials, but also with matching between the 3D printing equipment and construction process. For now, 3D printing test and application in the building field mostly use pumping technique with mortar, the aggregate accounted for more than 70% of the total volume in the cement-based materials, so the performance of the aggregate has a significant impact on the extrusion performance, printing performance, mechanical property, durability of 3D printing.
Therefore, this paper explored the major characteristics of 3D printing materials and their applications based on the research of nature Particle, size and grain shape of micro-aggregates on workability, mechanical property and the 3D printing performance of the cement-based mortar.

2. Raw materials

2.1. Raw materials

2.1.1. Cementitious material. P·O42.5 cement produced by Hubei Yadong Cement Plant, whose basic performance is shown in table 1. S95 mineral powder is produced in Xinzhou, Wuhan. microspheres produced by Tianjin ZHUXIN New Material Technology Co., Ltd. was used. Their basic performance indexes and particle size distribution are shown in table 2 and table 3.

| Table 1. Basic performance of concrete. |
|----------------------------------------|
| Standard Consistency/g | Flexural Strength/MPa | Compressive Strength/MPa | Density/g·cm⁻³ | Stability |
|------------------------|-----------------------|--------------------------|----------------|-----------|
| 127                    | 5.23                  | 8.72                     | 23.30          | 48.10     | 3.20 | Qualified |

| Table 2. Physical properties of cement and mineral admixtures. |
|---------------------------------------------------------------|
| Raw Materials | Density/g·cm⁻³ | Specific Surface Area/m²·kg⁻¹ | Water Requirement/% | Fluidity Ratio/% | 28d Compressive Strength Ratio/% |
|----------------|----------------|-------------------------------|--------------------|-----------------|-------------------------------|
| Cement         | 3.20           | 350                           | 100                | 100             | 100.0                         |
| S95 Slag Powder| 2.80           | 425                           | 105                | 100             | 90.1                          |
| Microsphere    | 2.73           | 710                           | 95                 | 105             | 83.5                          |

| Table 3. Particle size distribution of raw materials. |
|-----------------------------------------------------|
| RawMaterials | D₁₀/μm | D₅₀/μm | D₂₅/μm | D₇₅/μm | D₉₀/μm |
|--------------|--------|--------|--------|--------|--------|
| Cement       | 15.00  | 2.63   | 5.85   | 21.42  | 37.47  |
| S95 Slag Powder | 16.00  | 2.44   | 5.55   | 25.06  | 41.52  |
| Microsphere  | 1.00   | 0.61   | 0.78   | 1.42   | 1.99   |

2.1.2. Aggregate. The test uses river sand 1# with 3.1 fineness modulus; river sands 2# with 2.84 fineness modulus; river sand 3# with 1.84 fineness modulus; river sand 4# with 1.68fineness modulus; quartz sand 7# with 1.0 fineness modulus; manufactured sand 7# with 3.5 fineness modulus. Their clay lump content, silt content are less than 1%,apparent density are 2600±30kg/m³;

2.1.3. Admixture. Polycarboxylate superplasticizer was used, whose solid content of 25% and water-reducing rate of 28%.

3. Test methods

3.1. Mortar compressive strength test

Concrete strength test is performed according to the Standard for Method of testing cements-determination of strength(GB/T 17671-1999).The mortar specimen dimensions in this paper are 40mm×40mm×160mm.
3.2. Mortar workability test
Concrete fluidity test is performed according to the Standard for Methods of testing uniformity of concrete admixture (GB8077-2012), Test method for fluidity of cement mortar (GB / T 2419-2005) test.

3.3. 3D printing test
3D printing Test process: 3Dprinter builds φ30cm circular components based on the medium-sized 3D printer, print layer height 1.4cm, flat print speed 8cm / s.

4. Results and Discussion
Based on the design of C70 concrete mixing proportion, the research analyses workability, mechanical property and the 3D printing performance with the component quality of the mortar, Cement: Microsphere: Slag Powder: Sand: Water=40:9:5:74:15.

4.1. Workability of 3D print material
In the mixing proportion invariable situation, the fluidity of fresh mortar usually increase and the viscosity decrease with the increasing of the fineness modulus (Mx) as following of fine aggregate [3]. Figure 1 presents the result is in accordance with the expected except the trial group of manufactured sand. When Mx of sand less than 2.2, the fresh mortar has poor fluidity and high viscosity, the reason is that the specific surface area increased significantly, the sands require more cement slurry to fill the space. When Mx of sand more than 2.8, with decreasing of the percentage of voids in fine aggregate, flowable slurry in the mortar is more opulent because of the accumulation effect of sand particles, the workability of fresh mortar is effectively improved. Meanwhile that segregation and weeping of fresh mortar is serious .And with the increased angularity index of the manufactured sand which has a high fineness modulus, the fluidity and workability retention of the fresh mortar is becoming bad relatively. Also by contrast it find that the group of river sand has more excellent fluidity and thixotropy properties than the group of quartz sand in the 1.68~1.84 range of Mx .This is because the river sands have continuous gradation and less surface area.

![Figure 1. Effect of fineness modulus on Fluidity.](image1)

![Figure 2. Effect of fineness modulus on amount of additives.](image2)

As shown in figure 2, it can also be found than the change trend of amount of additives gradually decreases with the increase of the fineness modulus of the sand. But in the same Mx range, poor granulation or poor gradation of the fine aggregate increases significantly the amount of additives. Therefore, the working performance of the mortar is not only dependent on the fineness of the aggregate, but also the gradation and grain size of the aggregate.

4.2. Mechanical property of 3D print material
The results are shown in figure 3, the compressive strength of the mortar are increasing with the increase of Mx in the same test condition. Compared with Mx 1.0 group, the 28d strength of Mx 3.5 group increase 8% .This is due to the mortar with a larger fineness modulus offers lower viscosity and higher uniformity, the strength is improved with decreasing porosity and surface area.
But the Mechanical performance of the mortar leveled off after \( M_x \) more than 2.2, there is a 5% increase of strength of manufactured sand group only. And compared with natural one, manufactured sand has the characteristics of poor graduation, high fine modulus, rugged surface and sharp particle, so the intensity and contractibility of the mortar is improving after the hardening process [4-6].

![Figure 3. The Mechanical Properties of Mortar.](image)

At the same time, in the experimental groups with the ratio of \( M_x \) between 1.68 ~ 1.84, it is found that the strength of quartz sand group is about 2% higher than that of continuous graded sand group, and that's related to the higher hardness and angular shape of quartz sand.

### 4.3. 3D printing performance of 3D print material

According to the 3D printing process (3D printer builds with diameter of 30cm circular components with the fluidity of \( 220 \pm 10 \) mm and \( 240 \pm 10 \) mm of the mortar, print layer height 1.4cm, flat print speed 8cm / s), the experiments test the effect of 3D print quality on the various mortars workability. As shown in table 4. It is found that there is no significant difference in the extrusion volume of the mortar under the same pumping conditions. In addition to manufactured sand group which has higher resistance of pipeline because of the heat generated by the screw is with rugged surface and sharp particle of fine aggregate. The extrusion force of the other groups is gradually reduced with the fine aggregate increased, but at the same time the loss of working performance is gradually increased, that is good agreement with the peculiarity of poor bleeding are consistent and lower viscosity of the manufactured mortar.

| NO . | The Variety of Sand | Fineness Modulus | Number of Layers | Layer Height/cm | Single Layer Width/cm | Difficulty of Transport | Effect of Surface | Fluidity/mm |
|------|---------------------|------------------|-----------------|-----------------|------------------------|-----------------------|-----------------|-------------|
| 1    | river sand          | 3.1              | 26              | 1.4             | 4                      | medium                | good            | 220         |
| 2    | river sand          | 3.1              | 20              | 1.4             | 4                      | medium                | excellent       | 230         |
| 3    | river sand          | 2.84             | 25              | 1.4             | 4                      | medium                | good            | 220         |
| 4    | river sand          | 2.84             | 15              | 1.4             | 4.2                    | low                   | excellent       | 240         |
| 5    | river sand          | 1.84             | 22              | 1.4             | 4.7                    | low                   | excellent       | 210         |
| 6    | river sand          | 1.84             | 13              | 1.4             | 5.6                    | low                   | excellent       | 230         |
| 7    | quartz sand         | 1.68             | 16              | 1.4             | 5.2                    | low                   | excellent       | 210         |
| 8    | quartz sand         | 1.68             | 12              | 1.2             | 5.6                    | low                   | excellent       | 235         |
| 9    | quartz sand         | 1                | 15              | 1.4             | 5.2                    | low                   | excellent       | 210         |
| 10   | quartz sand         | 1                | 10              | 1.1             | 6                      | low                   | excellent       | 230         |
| 11   | manufactured sand   | 3.5              | 42              | 1.4             | 4                      | hard                  | tiny crack      | 210         |
| 12   | manufactured sand   | 3.5              | 32              | 1.4             | 4                      | medium                | excellent       | 230         |
Moreover, as the fineness modulus decreases, the number of stable print layers decreases and the single-layer printing width gradually increases, at the same time the apparent effect of the member is improved (figure 5- figure 6). That is due to the reduction of Mx improve the mortar thixotropic performance, the structure has the higher tendency to deformation when 3D printing. When the Mx of the test group is less than 1.68, the single layer height of the mortar is less than the set value with the same condition. After forming only several layers, the structure begin lateral collapseing as shown in figure 7, it is relative to mismatch between the default parameters and material properties. When the Mx of the test group is higher than 2.86, the print layers and the single layer width of the mortar are stable, and the average number of layers is more than 15 layers, and the maximum is more than 40 layers, as shown in figure 8.

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Figure 4. Effect of fineness modulus on Number of Layers.  
Figure 5. Effect of fineness modulus on Single Layer Width.

Figure 6a. Single Layer Width of Mx 1.84.  
Figure 6b. Single Layer Width of Mx 2.84.

Figure 7. The phenomenon of Lateral Collapseing.  
Figure 8. Maximum Layers of 3D Printing.

Meanwhile, all that mortar pumping takes a lot of effort with larger aggregate, due to the operation of the friction between the metal screw and rubber bushing will produce a certain degree of friction heat. So for the avoidance of rigidity impact of mortar pump in movement, it is necessary to optimize slurry viscosity and water retention to counteract the effects of rough particle and angular.

5. Summary  
In summary, according to the different 3D printing construction conditions and design requirements, it is necessary to choose different specifications of the fine aggregate: for the excellent appearance effect
of small components with low requirement of construction speed, the fineness modulus of sands less than 1.68 of 3D printing materials is an appropriate choice; for medium-sized components, the fine aggregate with fineness modulus during 1.6 ~ 2.86 should be selected for 3D printing materials; for large volume components, it is suggested to select the mortar with mechanism sand which the fineness modulus is more than 2.86 to ensure the building speed and stability.

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