PREDICTING THE YIELD STRESS OF 3D PRINTING MORTAR BASED ON THE FLOWABILITY OF PASTE AND EXCESS PASTE THICKNESS

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Abstract

This paper develops an empirical model to predict the static yield stress of 3D printing mortar based on the flowability of paste and excess paste thickness. The components of the mortar are divided into paste and aggregate. The relation between the yield stress of mortar and the yield stress of paste and the excess paste thickness is investigated. It is found that there is a linear relationship between the yield stress of mortar and that of paste, and the yield stress of mortar also is proportional to the reciprocal of excess paste thickness. Additionally, the yield stress of paste is related to its flowability when the rheological behavior of mortar is modified with different types and dosage of thixotropic agents. Based on the experimental data, an empirical model is built to predict the static yield stress of mortar in accordance with the flowability of paste and excess paste thickness.

Keywords: 3D printing mortar, yield stress, flowability of paste, excess paste thickness

1. INTRODUCTION

With a great success the 3D printing manufacturing achieves in the field of food, biology, aerospace, and so on, this technology also shows excellent prospects in concrete construction. Compared to conventional concrete construction, 3D printing concrete (3DPC) possesses many advantages, like formwork free, less consumption of raw materials, flexible design of structure, etc. [1].

Since the different way of fabricating concrete structure, the workability requirements for 3DPC are also different from conventional concrete. In the processes of printing, 3DPC should be extruded smoothly and continuously through the nozzle of a printer, and meanwhile, have the ability to maintain self-shape stable and sustain subsequently printed concrete layers. Hence, extrudability and buildability are basic printable performance of 3DPC [2]. In fact, the printability of 3DPC is largely dependent on its rheology [3]. For meeting these contradictory performance requirements of extrudability and buildability, 3DPC needs to possess thixotropy and proper yield stress. There is static and dynamic yield stress in the context of thixotropic materials. Only when the shear stress applied on 3DPC exceeds its static yield stress, 3DPC can start to flow and be extruded, which means the static yield stress of 3DPC cannot be too high. In the meanwhile, the printable height of printed structure is related to the static yield stress of 3DPC as well. High static yield stress is conducive to the buildability of 3DPC. Thus, the static yield stress is a critical rheological parameter, and possessing suitable static yield stress is a precondition for concrete being printable [4]. The preparation of printable concrete is a process of designing the concrete with proper static yield stress. According to the previous researches [5,6], the concrete with the static yield stress in the range of 500 ~ 2500 Pa can basically satisfy the requirements of printability.

Concerning the 3DPC mix design, there is still a lack of relevant criterions to guide the mix design of 3DPC. Researching the influence rule of different raw materials on the printable performance of concrete is a common method to find out the optimum mix proportion of 3DPC, which is a direct and effective method, but with lots of workloads simultaneously, considering that concrete consists of kinds of raw materials. Therefore, it will be very helpful in the mix design of 3DPC if the static yield stress could be predicted in advance just according to some simple parameters regarding the concrete mix. For fixing this problem in the mix design of 3DPC, this paper develops an empirical model in accordance with the investigation on the influence of the yield stress of paste and aggregate content on the static yield stress of mortar respectively, which is verified successful in predicting the static yield of mortar when the static yield stress of mortar is in the range of 500 ~ 2500 Pa.

2. EXPERIMENT

2.1 Materials

In this study, the materials for 3D printing mortar consisted of Portland cement (P. Ⅱ. 42.5 R), China ISO standard sand and one of the two types of rheological modifiers: nano-silica (NS) or micro-attapulgite clay (MAC). Besides, some other kinds of rheological modifiers, including silica fume (SF) and metakaolin (MK), were used in the preparation of cement paste to investigate the relationship between flowability and yield stress of paste. Polycarboxylate superplasticizer (SP) was used to adjust the workability of fresh paste and mortar.

2.2 Mix proportion

In this research, five groups of 3D printing mortar and corresponding cement paste with different content of NS were prepared to investigate the relationship between the yield stress of paste and that of mortar, as shown in Table 1 and Table 2.

Two series of 3D printing mortar with different amount of NS and sand were designed to study the effect of aggregate content on the yield stress of mortar, as listed in Table 3. Each series of mortar had the same content of NS to ensure that the paste of this series of mortar possessed the same yield stress.

Table 1: Mix of paste with different content of NS

Labels	Cement/g	Water/g	W/C	NS
J-NS1.2R0.3	1000	300	0.3	1.2%
J-NS1R0.3	1000	300	0.3	1.0%
J-NS0.8R0.3	1000	300	0.3	0.8%
J-NS0.6R0.3	1000	300	0.3	0.6%
J-NS0.4R0.3	1000	300	0.3	0.4%

Table 2: Mix of mortar with different content of NS

Labels	Sand (g/L)	Cement (g/L)	Water (g/L)	NS (%)	Superplasticizer (%)
B850NS1.2R0.3	1196	849	255	1.2	0.68
B850NS1.0R0.3	1196	849	255	1.0	0.68
B850NS0.8R0.3	1196	849	255	0.8	0.68
B850NS0.6R0.3	1196	849	255	0.6	0.68
B850NS0.4R0.3	1196	849	255	0.4	0.68

Table 3: Two series of 3D printing mortar with different amount of NS and sand

Labels	Sand (g/L)	Cement (g/L)	Water (g/L)	Superplasticizer (g/L)	Nano-silica (g/L)
S-NS0.4R30-1	1247	810	243	5.5	3.24
S-NS0.4R30-2	1277	787	236	5.4	3.15
S-NS0.4R30-3	1307	764	229	5.2	3.06
S-NS0.4R30-4	1337	741	222	5.0	2.96
S-NS0.4R30-5	1367	718	215	4.9	2.87
S-NS1.0R30-1	1082	937	281	6.37	9.37
S-NS1.0R30-2	1112	914	274	6.21	9.14
S-NS1.0R30-3	1142	891	267	6.06	8.91
S-NS1.0R30-4	1172	868	260	5.90	8.68
S-NS1.0R30-5	1202	845	253	5.74	8.45
S-NS1.0R30-6	1232	822	246	5.59	8.22
S-NS1.0R30-7	1262	798	240	5.43	7.98

2.3 Static and dynamic yield stress measurement

In this study, given that 3D printing mortar and corresponding cement paste are thixotropic, yield stress of cement paste and mortar was measured under a constant rotating speed in a Brookfield rheometer. As for static and dynamic yield stress of cement paste test, firstly, about 450 ml of specimen was poured into a 500 ml beaker with a diameter of 95 mm and a depth of 115 mm, and the specimen was sheared with a 30 mm × 60 mm vane spindle. Since the measurement of yield stress usually required a low fixed shearing speed, a constant rotating speed 0.2 s^{-1} was applied in the test; the test duration was 90 s. As for static yield stress of 3DPM measurement, testing processes were similar to the yield stress measurement procedure for cement paste. The distinctions were that the 30 mm × 60 mm vane spindle was replaced by 10 mm × 20 mm one due to the torque limitation of the rheometer, and the test duration was 120 s.

3. RESULTS AND DISCUSSES

3.1 The relationship of yield stress between mortar and paste

The performance, like buildability and extrudability, of 3DPC is relevant to its yield stress. The yield stress of mortar is highly dependent on the yield stress of paste and aggregate content. To quantificationally analyze the relationship between the yield stress of paste and mortar, the five groups of paste with different NS content and the corresponding mortar were prepared to investigate rheological behaviors. Figure 1 shows the rheological behaviors of paste and corresponding mortar with different ns content under a constant shear rate. It can be seen that the static yield stress as well as the dynamic yield stress of paste increases obviously with the rising of NS dosage. Since the aggregate contents of the five groups of mortar are the same, the distinction of yield stress between mortars is totally derived from different properties of paste. Higher the yield stress of paste is, higher the yield stress of corresponding mortar is. Figure 2 show the fitting relationship between the yield stress of mortar and the dynamic and static yield stress of paste. The yield stress of mortar presents good linear relation to not only the static yield stress but the dynamic yield stress of paste.

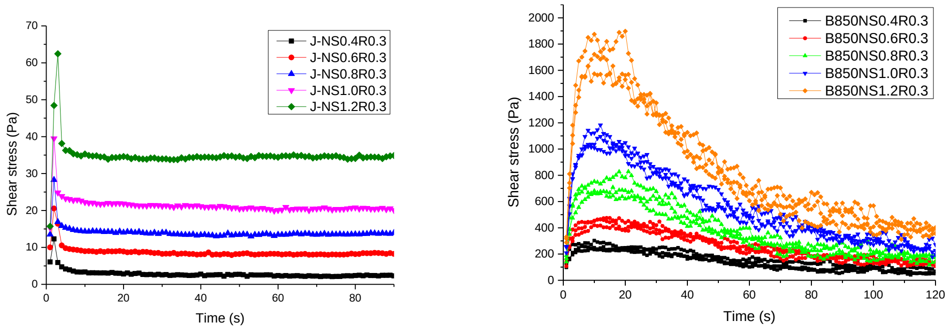

Figure 1: Rheological behaviors of paste and corresponding mortar with different NS content

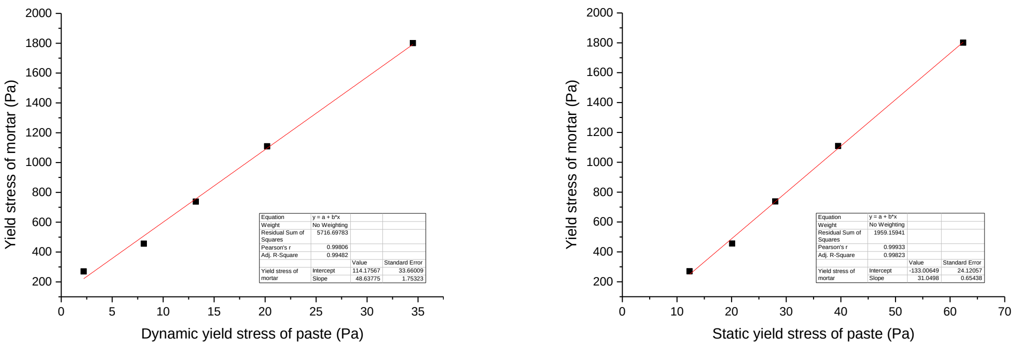

Figure 2: The fitting relationship between the yield stress of mortar and the dynamic and static yield stress of paste

3.2 The relationship between the yield stress of mortar and aggregate content

Except for the yield stress of paste, aggregate content is another crucial factor affecting the yield stress of mortar. To comprehensively investigate the effect of aggregate content on the yield stress of mortar, two kinds of paste with different yield stress, which contain 0.4% and

1.0% NS respectively, were mixed with different content of aggregate to prepare mortar for the yield stress test. Given the printability of mortar, through adjusting the aggregate content, the yield stress of mortar was controlled within 500 ~ 2500 Pa in accordance with [5,6] and the previous experimental experience by the authors. The results of rheological behavior test on mortar were shown in Fig 3. It can be observed that the rising of aggregate content is contributed to increase the yield stress of mortar, which can be explained by the excess paste model. The thickness of excess paste layer that acts as "lubrication" between the aggregate particles decreasing with the rising of aggregate content will lead to the yield stress of mortar increasing. Hence, the thickness of excess paste layer can be as a key parameter to quantificationally analyse the effect of aggregate content on the yield stress of mortar.

Considering the excess paste playing an important role to affect the yield stress of mortar, the thickness of excess paste was selected to replace aggregate content as the vital parameter to investigate the influence of aggregate on the yield stress of mortar. Fig 4 presents the fitting relation between the yield stress of mortar and the reciprocal of excess paste thickness. The yield stress of mortar is linearly related to the reciprocal of excess paste thickness as well.

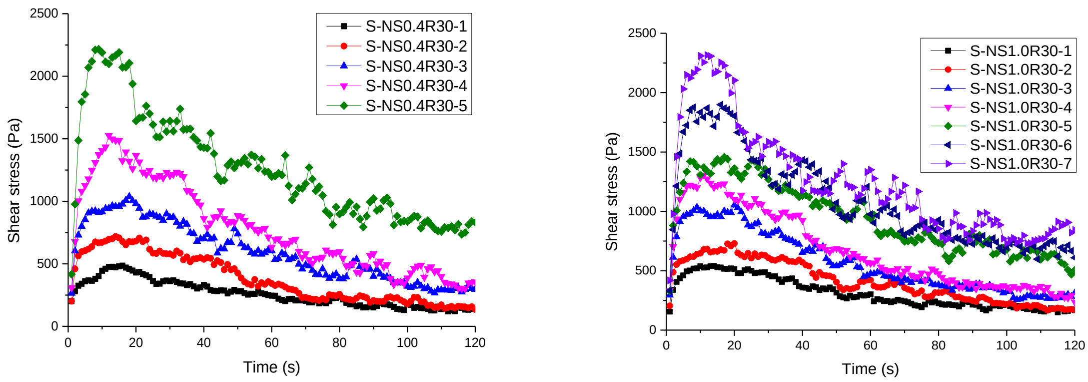

Figure 3: Rheological behaviors of mortar with different NS and sand content

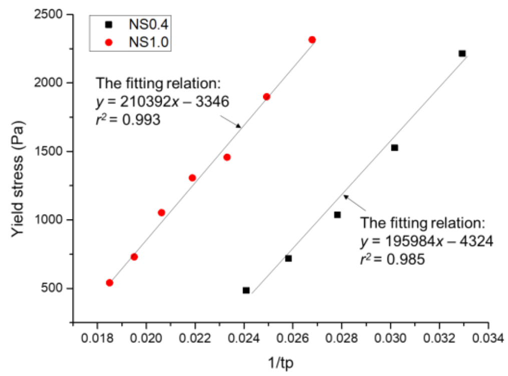

Figure 4: The fitting relation between the yield stress of mortar and the reciprocal of excess paste thickness

3.3 The empirical model to predict the yield stress of 3D printing mortar

For analyzing the slope of fitting lines, it is assumed that the slope is impacted by the yield stress of paste. According to the model of [7,8], the yield stress of mortar τ_m is equal to that yield stress of paste τ_p is multiplied by the function of aggregate fraction. It can be concluded that the τ_m-to-τ_p ratio is the function of aggregate fraction, while the reciprocal of excess paste thickness is a function of aggregate fraction, which means the τ_m-to-τ_p ratio is the function of reciprocal of excess paste thickness. However, Fig 5 shows that the τ_m-to-τ_p ratio is not the function of reciprocal of excess paste thickness due to the discontinuity of τ_m-to-τ_p ratio. Based on the said analysis to Fig 4, an empirical model can be built, shown as follows:

$$\tau_m = a \times \tau_p + b \times (1/tp) + c \quad (1)$$

This model satisfies the conclusions that the yield stress of mortar τ_m is directly proportional to the yield stress of paste τ_p and the reciprocal of excess paste thickness 1/tp, and the yield stress of paste τ_p governs the intercept rather than the slope of fitting line based on τm and 1/tp. According to the experimental data in Fig 4 and least square method, coefficients in the empirical model Eq (1) are calculated out, and the empirical model is shown as below:

$$\tau_m = 35.9\tau_p + 203188(1/tp) - 4902.6 \quad (2)$$

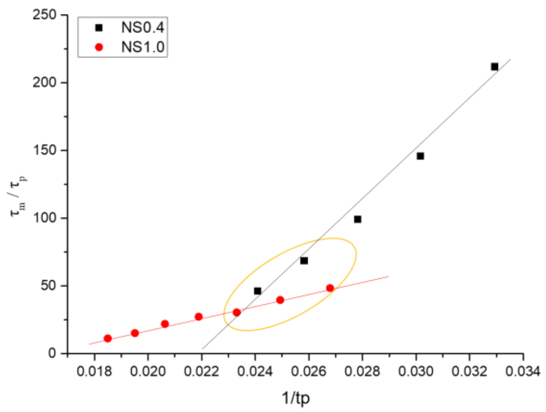

Figure 5: τ_m-to-τ_p ratio of mortar with different NS and sand content

3.4. The relationship between the yield stress and flowability of paste

In the empirical model, there are two essential parameters, the yield stress of paste τ_p and reciprocal of excess paste thickness 1/tp. The 1/tp can be figured out based on the mix proportion and physical properties of aggregate, which is easily obtained without special equipment. While the τ_p test need a rheometer that may not be a common device for some labs or construction site. Aiming to make the empirical model more convenient to use for some engineer and researcher who work in 3D printing construction field, the authors want to use an easier obtained parameter to replace τ_p in the empirical model to predict the yield stress of mortar. It was demonstrated previously that there is a relationship between the yield stress and flowability of paste. Compared to yield stress, flowability is easier to test only with simple tools. Hence, the flowability of paste was employed to take place of τ_p, and the relationship between the yield stress and flowability of paste was investigated in the context of .

So far, many kinds of rheological modifier materials have been developed in the preparation of 3D printing concrete, such as silica fume, nano silica, metakaolin and attapulgite clay. The yield stress and corresponding flowability of paste containing different type and content of rheological modifier materials were measured and presented in Fig 6. It is found that there is a relationship between the flowability of paste and not only dynamic yield stress but also static yield stress of paste which even contains different kind and content of rheological modifiers. In addition, the results of Fig 6 also demonstrate that superplasticizer dosage makes no difference to the relationship. As a consequent, we can figure out the yield stress of paste based on the flowability and the relationship between the yield stress and flowability of paste even when the paste consists of different materials.

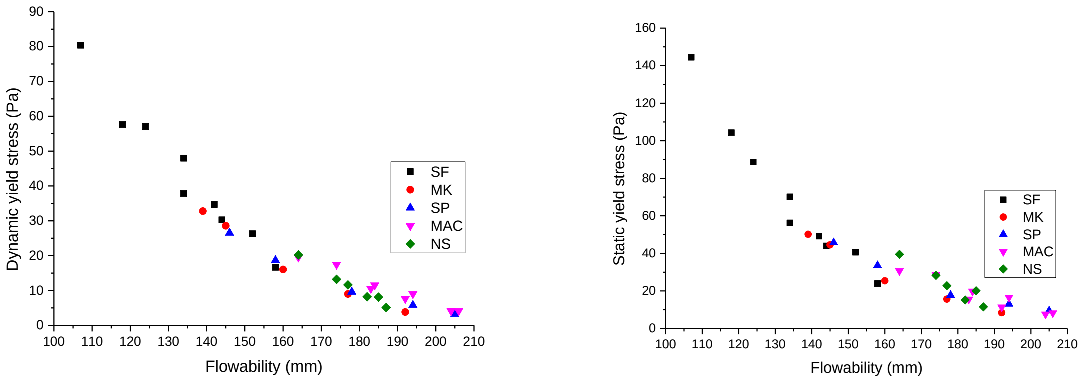

Figure 6: The relationship between the yield stress and flowability of paste

Table 4: Flowability and calculated yield stress of paste for verification

Labels	Flowability (mm)	Calculated Yield stress (Pa)
J-NS0.6R30	167	25
J-NS0.8R30	149	40
J-MAC1.0R30	129	75

Table 5: Mix and corresponding yield stress of mortar for verification

Labels	Sand (g/L)	Cement (g/L)	Water (g/L)	Tested yield stress (Pa)	Calculated yield stress (Pa)	Relative error
S-NS0.6R30-1	1202	845	253	622	729	17.2%
S-NS0.6R30-2	1262	798	240	1166	1437	23.2%
S-NS0.8R30-1	1202	845	253	1273	1269	0.3%
S-NS0.8R30-2	1262	798	240	1829	1977	8.1%
S-MAC1.0R30-1	1022	983	295	1158	1199	3.5%
S-MAC1.0R30-2	1082	937	281	1643	1551	5.6%

3.5. Verification

Some experiment was conducted to verify whether flowability is available to replace the yield stress of paste in the empirical model to predict the yield stress of mortar. The flowability of three groups of paste with 0.6% NS, 0.8% NS and 1% MAC respectively was measured. According to the value of flowability and the relationship shown in Fig 6, the corresponding yield stress of paste was computed out as presented in Table 4. Each group of paste was mixed with certain content of aggregate to make 3D printing mortar, and the mixes of mortar were shown in Table 5. The reciprocal of excess paste thickness was calculated out in accordance with aggregate content. Based on the reciprocal of excess paste thickness and calculated yield stress of paste, the predicted yield stress of mortar could be figured out by the empirical model, shown as calculated yield stress in Table 5. At the same time, the rheological behavior of mortar was detected, and the tested yield stress was listed in Table 5 as well. It can be observed that relative error between tested and calculated yield stress of mortar is less than 25%, and the relative error of most groups of mortar is within 10%. The results indict that flowability is qualified instead of yield stress of paste to predict the yield stress of mortar.

4. CONCLUSIONS

This paper investigates the effect of paste and aggregate content on the yield stress of mortar and develops an empirical model to predict the yield stress of mortar based on the experimental results. The results obtained in this study can be summarized as the following:

- There is a linear relationship between the yield stress of mortar and that of paste.
- The yield stress of mortar is linearly related to the reciprocal of excess paste thickness.
- The flowability of paste is strong linked to its yield stress and qualified instead of yield stress of paste to predict the yield stress of mortar.

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