Effect of superabsorbent polymers on the interlayer bonding properties of 3D printing mortar

Taiqi Zhao [1,a], Wujian Long[1,b], Qiling Luo[1,c], Wei Chen [2,d,*]

[1]College of Civil and Transportation Engineering, Shenzhen University, Shenzhen, Guangdong, PR China;

[2] Guangzhou Guangjian Construction Engineering Testing Center Co., Ltd, Guangzhou, 518060, Guangdong, PR China;

[a] 1026278259@qq.com, [b] longwj@szu.edu.cn, [c] luoqiling@szu.edu.cn, [d] 190654992@qq.com

Abstract. To investigate the impact of internal curing using superabsorbent polymers (SAPs) on the interlayer bonding properties of 3D printed mortar, this study examined the interlayer bonding properties of 3D printed mortar with different types of SAPs incorporated. The experimental results demonstrated that the addition of SAPs could enhance the interlayer bond strength of 3D printed mortar to a certain extent, with the maximum split tensile strength increased by 48.78%. The study employed the layered casting tensile method, which is simple and efficient, to assess the interlayer bond strength of the printed mortar.

To investigate the influence of internal curing using superabsorbent polymers (SAPs) on the interlayer bond strength of 3D printed mortar, this study examined the interlayer bond strength of 3D printed mortars with different types of SAP added. The experimental results show that the addition of SAP can enhance the interlayer bond strength of 3D printed mortar to a certain extent, with a maximum splitting tensile strength increase of 48.78%. In order to evaluate the interlayer bond strength of printed mortar, this study used the layer casting tensile method, which is simple and efficient.

Keywords: 3D printing; superabsorbent polymers (SAPs); internal curing; interlayer bonding properties.

1. Introduction

In recent years, 3D printing has emerged as a cutting-edge manufacturing technology that utilizes computer-controlled layer-by-layer material deposition to create a variety of objects. The significant advantages of the technology, such as cost-effectiveness, high flexibility, and shortened production cycles, have led to rapid growth and widespread adoption. In the traditional construction sector, 3D printing technology has been driving advancements in automation and smart practices. The importance of 3D printing for mortar is increasing, driven by the national demand for smart building solutions.

The major methods used for 3D printing mortar include contouring, D-shape, and slide molding processes. Of these, the contouring process stands out due to its simplicity, ease of handling, and cost-effectiveness, making it a relatively well-established process for mortar printing. However, a noteworthy problem arises during the layer-to-layer stacking of mortars. Interlayer bonding lacks sufficient friction and chemical adhesion, resulting in a significantly weaker interlayer interface. The presence of an interlayer interface adversely affects the homogeneity and structural integrity of the material, leading to compromised mechanical and durability properties of the printed structure. Therefore, an in-depth study of the interlayer bonding properties of 3D printed mortars is necessary.

However, there are limited methods to enhance the interlayer mechanical properties of 3D printed mortar. Wang et al. [1,2]used epoxy resin and neoprene latex modified mortar as an interlayer interface reinforcement by preparing. Meanwhile, they also proposed a new method to enhance the interlayer bond by using a U-shaped peg inserted into the cementitious material during the printing process. Although these methods effectively enhance the interlayer bonding performance of 3D printed mortar, the operation is relatively complicated and difficult to apply in the field.

Superabsorbent polymers have a strong ability to absorb and retain water, and can affect a variety of properties of freshly mixed or hardened cementitious materials. By purposefully regulating the water absorption and release of SAPs, the formation of internal hydration products in cementitious materials can be promoted to achieve the effect of internal curing. As 3D printed mortar are extruded, excessive surface water shrinkage and evaporation can lead to weakened interlayer bonding. Therefore, the incorporation of SAPs as an internal curing material to enhance the interlayer bonding properties of 3D printed mortar is of research interest. Van Der Putten et al.[3]showed that SAPs were able to enhance the interlayer bond strength of 3D printed mortar and were attributed to less plastic shrinkage, self-shrinkage, and a higher surface water content. However, Van Der Putten et al.[4] in another study noted that SAPs reduced the interlayer bond strength even with increased surface water content.

The main focus of this study was to assess the interlayer bonding properties of 3D printed mortar using the split-tensile strength test method. However, this method requires the use of a 3D printing device to produce printed specimens, followed by cutting and conducting strength tests, which involves a complex operation and cannot evaluate the interlayer bonding properties during the mortar mixture design phase before printing. Currently, there is still a lack of an effective testing method to assess the interlayer bonding properties of mortar before the printing process.

To elucidate the influence of internal curing using SAPs on the interlayer bonding properties of 3D printed mortar, this study compared the impacts of different types and dosages of SAPs on the interlayer bonding properties, providing a theoretical basis for the application of SAPs in 3D printed cementitious materials. Additionally, a novel method for indirectly evaluating the interlayer bonding strength of 3D printed mortar was proposed, which offers an efficient and simple way to assess the interlayer bonding strength of printed materials and provides technical support for evaluating the interlayer bonding strength of 3D printable mortar.

2. Experimen

2.1 Raw materials and mixing ratios

The binder materials used in this study consist of P·O 525 Portland Ordinary Portland Cement (OPC), Class I Fly Ash (FA), and Grade 95 Silica Fume (SF). The chemical compositions of these three binder materials are presented in Table 1.

Table 1. Chemical Compositions of Binder Materials

%	CaO	SiO_2	Al_2O_3	MgO	K_2O	SO_3
OPC	67.00	18.62	5.41	1.30	0.46	3.10
FA	6.69	52.45	29.35	0.83	1.07	0.74
SF	0.16	99.23	0.32	0.12	0.15	0.62

The fine aggregate used is Chinese ISO standard sand. The admixture employed is a high-efficiency polycarboxylate superplasticizer with a water reduction rate ranging from 35% to 39%. By adjusting the dosage of the superplasticizer, different mix proportions of 3D printed cementitious materials with similar initial slump flow values can be achieved. Two types of SAPs were used: the first type is a non-ionic covalently cross-linked acrylamide polymer, denoted as S1; the second type is an anionic covalently cross-linked acrylamide/sodium acrylate copolymer, denoted as S2. The water absorption and release of the two SAPs in simulated pore solutions were determined through tea bag experiments, and the experimental results are shown in Figure 1. The mix proportions of the 3D printed cement mortar are presented in Table 2.

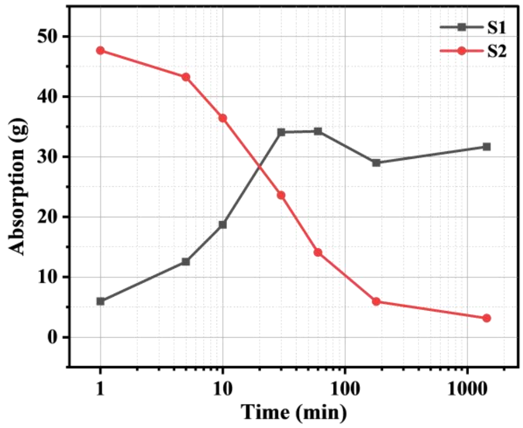


Fig. 1 The experimental results of the tea bag method

Table 2. Mix Proportions of 3D Printed Cement Mortar

groups	R0	S1-1	S1-2	S2-1	S2-2
w/b	0.3	0.3	0.3	0.3	0.3
OPC	600	600	600	600	600
FA	171.4	171.4	171.4	171.4	171.4
SF	85.7	85.7	85.7	85.7	85.7
Sand	1286	1286	1286	1286	1286
SP	0.30	0.40	0.50	0.30	0.40
SAP1	-	0.08	0.16	-	-
SAP2	-	-	-	0.08	0.16

2.2 Testing of Fresh Properties for 3D Printed Mortar

The fresh properties of the 3D printed mortar were tested using a rheometer from French company Lamy Rheology. The rheometer was used to measure the rheological behavior of the fresh mortar. The obtained data of shear rate and shear stress were then fitted using the Bingham model to determine the yield stress and plastic viscosity, among other rheological parameters. This comprehensive analysis ensures that the mortar's rheological properties meet the requirements for 3D printing.

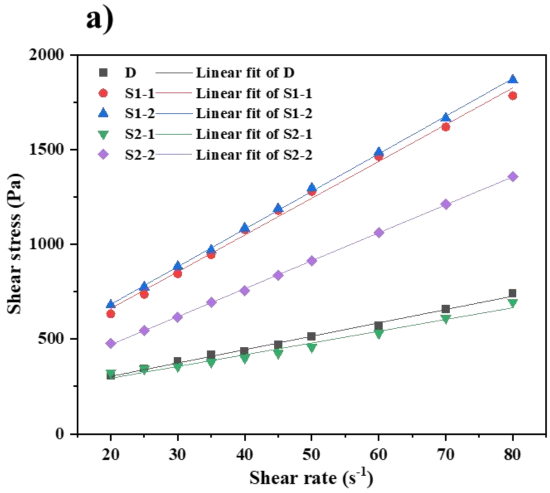
2.3 Printing and interlayer mechanical properties test

In this study, a extrusion-based 3D printer developed by JIAN YAN HUA CE and Research Institute was used to print cement mortar. The constructability of the printed mortar was verified by stacking printed layers. The extrusion length of each printed layer was set to 4000mm, with a width of 300mm and a height of 10mm per layer. A total of 15 layers were printed, and the final shape of the printed framework was observed to assess the constructability of the 3D printed cement mortar.The conventional method for evaluating interlayer bonding strength involves printing the specimens using the 3D printer, cutting the printed samples, and then conducting strength tests. However, this process is complex and time-consuming[5,6]. To address this issue, this study proposed an indirect method to assess the interlayer bonding strength of 3D printed cement mortar - the Layered Casting Tensile Test.For this method, the mold used was the 8-shaped mold specified in GB/T 16777-2008 Test Methods for Building Waterproof Coatings. The freshly mixed 3D printable cement mortar was poured into the mold twice, with a 10-minute interval between pours. An intermediate insert was placed before the first pour, and it was removed before the second pour, simulating the layered printing of cement mortar. After curing the cement mortar specimens at room temperature (20±1°C, 50±5% humidity) for 7 days, the tensile strength was tested. The measured tensile strength indirectly evaluated the interlayer bonding strength of the 3D printed cement mortar.This Layered Casting Tensile Test provides a simpler and more efficient method to assess the interlayer bonding strength of 3D printed cement mortar, avoiding the need for extensive cutting and testing of printed samples. The results obtained from this method can still provide valuable insights into the bonding performance of the printed mortar and its suitability for construction applications.

3. Results and Discussion

3.1 The fresh properties of 3D printed mortar

By adjusting the dosage of the water-reducing agent, the consistency of mortar expansion was controlled to be within 210±20 mm, meeting the requirements for the extrudability of the printing mortar and ensuring its constructability after extrusion. To simultaneously satisfy these two requirements, besides expansion, the rheological properties of the printing mortar also played a crucial role. Yield stress and plastic viscosity are commonly used parameters to characterize the rheological properties. Yield stress represents the minimum shear stress required for the flow of the mortar, which is generated by the formation of a flocculated structure from solid particles and the friction between particles. A higher yield stress indicates poorer flowability of the mortar. As shown in Figure 2, the addition of S1 significantly increased both the yield stress and plastic viscosity of the printable mortar, attributed to the ability of S1 particles to fill and reduce micropores between cementitious particles. Additionally, the water-absorbing and swelling properties of SAPs induced physical interactions between particles, enhancing the probability of particle collisions and thus leading to increased yield stress and plastic viscosity. In contrast, in the S2-1 group, the early water release of S2 had little effect on the flowability and rheological properties of the mortar.



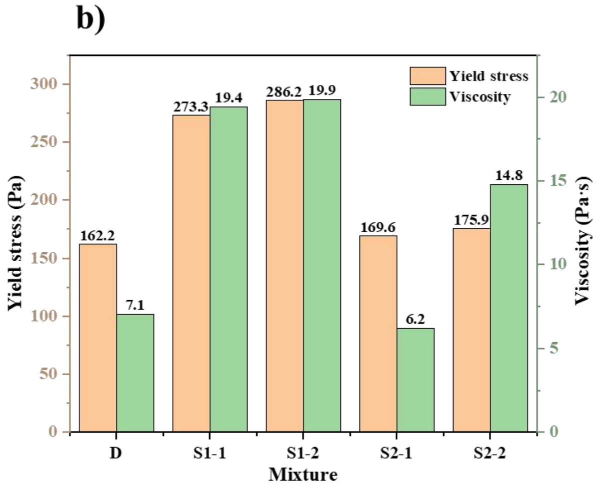


Fig. 2 illustrates the rheological behavior of different mortar mixtures: (a) depicting the flow curves, (b) presenting the rheological parameters

3.2 Buildability of 3D printed mortar

The 3D printed structure of the cementitious mortar is shown in Figure 3. From the figure, it can be observed that except for a slight sinking and deformation in the right side of the D group, all other groups of printed mortars maintain a complete structure with consistent layer height. The overall height is 150 mm, and no significant deformation or collapse is observed, indicating that the printed mortars meet the design requirements and demonstrate good constructability. The printed mortars within the specified slump range exhibit excellent constructability and fulfill the printing requirements.

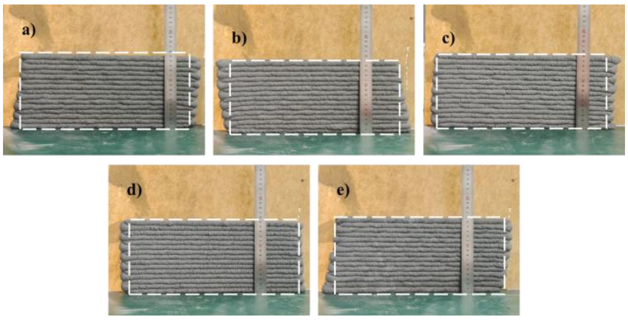


Fig. 3 3D printed cement mortar specimens: (a) Group D; (b) Group S1-1; (c) S1-2; (d) Group S2-1; (d) Group S2-2

3.3 Effect of SAPs on the interlayer strength of 3D printed cement mortars

The interlayer properties of 3D printed cementitious materials are crucial factors that significantly influence their final structural mechanical performance. Therefore, investigating the interlayer bonding strength is of paramount importance.

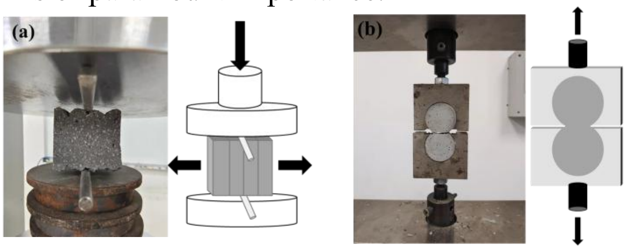


Fig. 4 Test setup and schematic diagram for measuring interlayer strength: (a) interlayer split tensile strength test, (b) layered casting tensile test

This study primarily characterizes the interlayer bonding strength of 3D printed cementitious materials through the split-tensile strength of printed mortars (Figure 4a). As depicted in the column chart of split-tensile strength in Figure 5, the addition of S1 cementitious mortar resulted in an increase of 34.2% and 48.78% in split-tensile strength, compared to the control group D without SAPs. The split-tensile strength increased with the increase in S1 content. However, excessive SAP content could introduce excessive porosity, thereby affecting the mechanical properties of the cementitious materials [16-18]. Thus, the SAP content was not further increased in this study.Furthermore, Figure 5 demonstrates that the proposed layer-by-layer pouring tensile test (as shown in Figure 4b) effectively reflects the interlayer bonding strength of cementitious materials. The test results exhibit a certain correlation with the split-tensile strength test. Compared to the control group D, the tensile strength of the cementitious mortar with S1 increased by 85.19% and 122.70%, respectively. Although the split-tensile strength test directly reflects the interlayer bonding performance of 3D printed cementitious materials, it requires the printing and cutting of cementitious specimens, and it is difficult to precisely split the specimens between layers, leading to considerable measurement errors. In contrast, the layer-by-layer pouring tensile test offers a more convenient and effective means of assessing the interlayer bonding properties of 3D printed cementitious materials, ensuring improved accuracy in the test results.

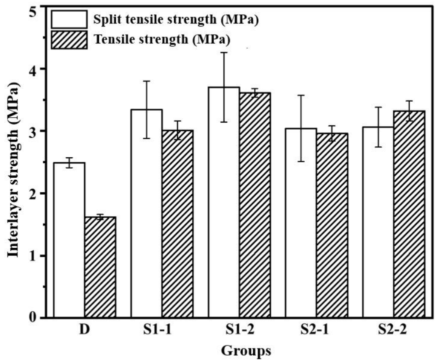


Fig. 5 Interlayer strength of 3D printed cement mortar

4. Summary

This study investigated the effect of SAPs' internal curing on the interlayer bonding properties of 3D printed mortar. By comparing the interlayer properties of mortar with two different types of SAPs, the enhancing effect of SAPs on the interlayer bonding properties of 3D printed mortar was elucidated. The conclusions are as follows:

(1) The addition of S1 particles fills and reduces the micro-pores between cementitious particles, while the water absorption and expansion of SAPs particles promote physical interactions between particles, increasing the probability of particle collisions, resulting in the enhancement of the yield stress and plastic viscosity of 3D printed mortar. Moreover, the addition of a small amount of S2 has minimal effect on the flow and rheological properties of the mortar.

(2) For the specific 3D printer used in this study, mortars with a slump range of 190-230mm exhibit favorable constructability, as they can be printed into a 15-layer bar-shaped structure without deformation or collapse, meeting the requirements for 3D printing.

(3) The inclusion of SAPs introduces pores after water release, significantly reducing the compressive strength and slightly lowering the flexural strength of mortar. However, for 3D printed materials, the interlayer bonding properties are more critical as they represent a weak link in the material's performance. Incorporating SAPs can improve the interlayer bonding strength of 3D printed mortar to some extent. Among them, the split-tensile strength of mortar with added S1 showed the highest improvement, reaching up to 48.78%. Additionally, this study proposed a new method, the layer-by-layer pouring tensile test, which can be used to indirectly evaluate the interlayer bonding properties of 3D printed mortar. This method effectively measures the interlayer bonding strength of mortar, and the test results correlate to a certain extent with the split-tensile strength test.

References

[1] Wang L, Ma G, Liu T, et al. Interlayer reinforcement of 3D printed concrete by the in-process deposition of U-nails[J]. Cement and Concrete Research, 2021, 148: 106535.

[2] Wang L, Tian Z, Ma G, et al. Interlayer bonding improvement of 3D printed concrete with polymer modified mortar: Experiments and molecular dynamics studies[J]. Cement and Concrete Composites, 2020, 110: 103571.

[3] Van Der Putten J, Snoeck D, Van Tittelboom K. 3D Printing of cementitious materials with superabsorbent polymers[C]. Durable Concrete for Infrastructure under Severe Conditions-Smart Admixtures, Self-Responsiveness and Nano-Additions, 2019: 86-89.

[4] Van Der Putten J, Snoeck D, De Coensel R, et al. Early age shrinkage phenomena of 3D printed cementitious materials with superabsorbent polymers[J]. Journal of Building Engineering, 2021, 35: 102059.

[5] Zareiyan B, Khoshnevis B. Effects of interlocking on interlayer adhesion and strength of structures in 3D printing of concrete[J]. Automation in Construction, 2017, 83: 212-221.

[6] Momayez A, Ehsani M R, Ramezanianpour A A, et al. Comparison of methods for evaluating bond strength between concrete substrate and repair materials[J]. Cement and Concrete Research, 2005, 35(4): 748-757.