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Evaluation of 3D concrete printing performance from a rheological perspective

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Abstract. The objective of this study was to derive a cementitious material for three-dimensional (3D) concrete printing that fulfills key performance functions, extrudability, buildability and bondability for 3D concrete printing. For this purpose, the rheological properties shown by different compositions of cement paste, the most fundamental component of concrete, were assessed, and the correlation between the rheological properties and key performance functions was analyzed. The results of the experiments indicated that the overall properties of a binder have a greater influence on the yield stress than the plastic viscosity. When the performance of a cementitious material for 3D printing was considered in relation with the properties of a binder, a mixture with FA or SF was thought to be more appropriate; however, a mixture containing GGBS was found to be inappropriate as it failed to meet the required function especially, buildability and extrudability. For a simple quantitative evaluation, the correlation between the rheological parameters of cementitious materials and simplified flow performance test results-time taken to reach T-150 and the number of hits required to reach T-150—in consideration of the flow of cementitious materials was compared. The result of the analysis showed a high reliability for the correlation between the rheological parameters and the time taken to reach T-150, but a low reliability for the number of hits needed for the fluid to reach T-150. In conclusion, among several performance functions, extrudability and buildability were mainly assessed based on the results obtained from various formulations from a rheological perspective, and the suitable formulations of composite materials for 3D printing was derived.

Keywords: 3D printing; cementitious materials; rheology; extrudability; buildability

1. Introduction

The modern construction industry requires new construction technologies different from those used in the past, such as the ones for super-tall buildings and buildings in various shapes. Notably, a new market of three-dimensional (3D) printing and related services is growing on a very large scale, in accordance with the emergence of the fourth Industrial Revolution. 3D concrete printing technologies have been commercially applied to the field of construction, and new technologies that can fulfill the requirements of the fourth Industrial Revolution are being developed for construction industry (Chen *et al*. 2017, Oh *et al*. 2014). Following such trends, more systematic and quantitative technique to evaluate construction performance needs to be developed, going beyond the current qualitative performance evaluation technologies. Several studies have been conducted so far especially in the field of construction material for the quantitative and analytical evaluation. The most notable studies that attempted quantitative evaluation of construction materials include a study that examined rheological properties by applying the concept of rheology (Bauchkar *et al*. 2018, Bauchkar *et al*. 2017, Benyamina *et al* 2019, Choi *et al*. 2014, Ferraris *et al*. 2001, Goo *et al*. 2006, Hwang *et al*. 2007).

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Similarly, the 3D concrete printing technology used in the construction industry these days requires quantitative performance evaluation to secure the quality and stability of fabricated structures when 3D printing is applied to construction. Different from other materials used for 3D printing, cementitious materials are subject to diverse influences from the properties of materials such as cement, fine aggregate, and coarse aggregate that are the components of concrete, as well as the properties of uneven particles, their multi-dimensional properties, and diverse construction environment and conditions; therefore, the influences of those factors must be considered for the decision of 3D concrete printing materials. However, most of the studies on 3D concrete printing technologies that have been conducted so far were focused on the construction design and transfer process, including ones on the mix design and the system of their transfer, the performance itself of 3D printing construction (Airey *et al*. 2012, Asprone *et al*. 2018, Buswell *et al*. 2018, Cesaretti *et al*. 2013, Hojati *et al*. 2018, Le *et al* 2012, Lee *et al*. 2017, Lim *et al*. 2011, Lloret *et al*. 2015, Lowke *et al*. 2018, Marchon *et al*. 2018, Perrot *et al*. 2016, Reiter *et al*. 2018, Roussel *et al* 2018, Schutter *et al*. 2018, Schwartz *et al*. 2018, Zhang *et al*. 2013). Previous studies have mostly been insufficient to evaluate quantitative performance evaluation, which end up hard to ensure consistency in the material level used for 3D construction. Namely, there have been few researches about evaluating 3D printing performance using a rheology-based approach, i.e., a method for quantitatively evaluating the mixture of a cementitious

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material and analyzing key functions for 3D concrete printing. Therefore, research on quantitative performance evaluation in terms of rheology for the essential functions required for 3D concrete printing is necessary for development of composite materials. Among those key performance functions, the ones related with rheological properties can be largely divided into three categories: extrudability, buildability, and bondability. First, according to the existing literature, extrudability can be defined as the capacity of concrete to pass through the small pipes and nozzles at the printing head (Malaeb *et al*. 2015). This could be assessed on the basis of the distance over which the paste can be printed without blocking the nozzle. In another existing literature, extrudability is closely related to the pumping performance and the local pressure gradient is the mostly related to the plastic viscosity of the printable material (Roussel *et al*. 2018). And they suggest here that contribution of yield stress can be neglected for typical printable materials contrarily to the case of firm mortars extrusion (Roussel *et al*. 2018). Most existing studies reveal that extrudability is affected by the plastic viscosity and is one of the key factors for 3D concrete printing. Second, buildability can be defined as able to the capacity to print a certain number of layers or height in 3D concrete printing.(Jeong *et al*. 2012, Malaeb *et al*. 2015) According to the existing literature, this ability related to the yield stress of the printable material, and they suggested a certain range to meet the buildability performance by controlling yield stress values at 0.3kPa-0.9kPa in mortar mixes (Le *et al*. 2012). In addition, one study proposed a model through the relationship between yield stress and elapsed time, and evaluated the building performance by identifying the occurrence and location of collapse when concrete was overlaid (Jeong *et al*. 2019). The previous studies reveal that buildability is closely related to yield stress and is the most important key factors for 3D concrete printing. Finally, bondability can be defined as the ability to bond inter-layers after extrusion in 3D concrete printing (Zareiyan *et al*. 2017). The length of the extrusion path and the speed with which material can be placed are key factors that effect both the production time of the component and the time taken to overlay layers, which effects interlayer bond strength (Buswell *et al*. 2018). Also, bond strength between existing and new concrete typically depends on surface and moisture conditions of the existing concrete surface (Sanjayan *et al*. 2018). In other words, the previous research show that the bonding performance is most dominantly influenced by not the rheological properties but the construction conditions such as the time until one layer is overlaid and the moisture state of the contact surface. Based on the results of previous studies, extrudability and buildability among 3D concrete printing performance were found to be closely related to the rheology parameters.

Therefore, in this study, we first evaluate the rheological properties in the phase of cement paste, which is the most fundamental component of 3D concrete printing material and which is a mixture of diverse materials. Based on the measured rheological properties, we evaluate the correlation between the quantitative results for the materials and the key functions, especially, extrudability and buildability required for 3D printing. Additionally, it is not easy to derive the rheological parameter every time using the unique equipment to confirm that formulation is suitable for 3D concrete printing, we attempt to derive a correlation between simplified flow performance test and rheological parameters based on previous studies (Koehler *et al*. 2006, Lee *et al*. 2018). Through those analysis, the ultimate goal of this study is to derive the optimal formulation of 3D concrete printing that is satisfied key performance functions from a rheological perspective.

Table 1 Composition of the binders

Type	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	MgO (%)	Fe_2O_3 (%)	SO_3 (%)	L.O.I (%)	Density (g/cm^3)
OPC	61.60	19.80	4.50	3.01	3.57	2.10	1.20	3.15
GGBS	34.95	31.85	14.55	5.63	0.59	2.97	0.60	2.82
FA	5.95	52.83	18.08	1.43	7.74	0.01	6.14	2.34
SF	0.39	93.8	0.31	0.42	0.83	-	2.80	2.18

Table 2 Mixing ratios of cement pastes

No.	W/B	OPC	FA	GGBS	SF	HWRA
1	0.25		-	-	-	
2	0.28	100	-	-	-	
3	0.30		-	-	-	
4		80	20	-	-	
5		50	-	50	-	0.3
6	0.28	90	-	-	10	
7		70	20	-	10	
8		40	-	50	10	

2. Experimental design and method

2.1 Experimental design

This study investigated diverse mixing conditions for cement paste in order to select the appropriate cementitious material for 3D concrete printing and evaluated the rheological properties of different mixtures of cement paste. The following binders were used in the experiments: ordinary portland cement (OPC), fly-ash (FA), ground granulated blast furnace slag (GGBS), and silica-fume (SF). A high water-reducing admixture (HWRA) was used as the chemical admixture. Distilled water was also used. Table 1 shows the composition of the materials used for the experiment.

The cement paste experiment was conducted with the mixtures shown in Table 2 to analyze changes in rheology according to the water to binder (W/B) ratio. As a cementitious material for 3D concrete printing must have enough strength and workability, the W/B ratios were set as 0.25, 0.28, and 0.30. In addition, an HWRA that amounted to 0.3% of the weight of the binder was added to enable mixing in mixtures with low W/B ratios.

Then, to analyze the rheological properties of the mixture with different binder, the W/B ratio was fixed, and the analysis was conducted separately for binary system mixtures and ternary system mixtures. For the binary system, three mixtures were analyzed by replacing the

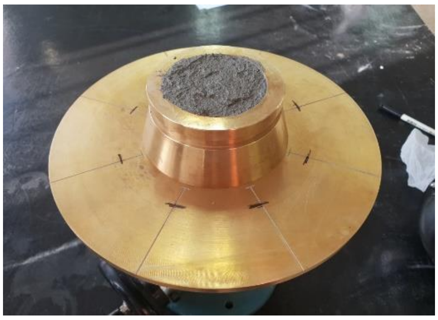


Fig. 1 Apparatus of simplified flow performance test

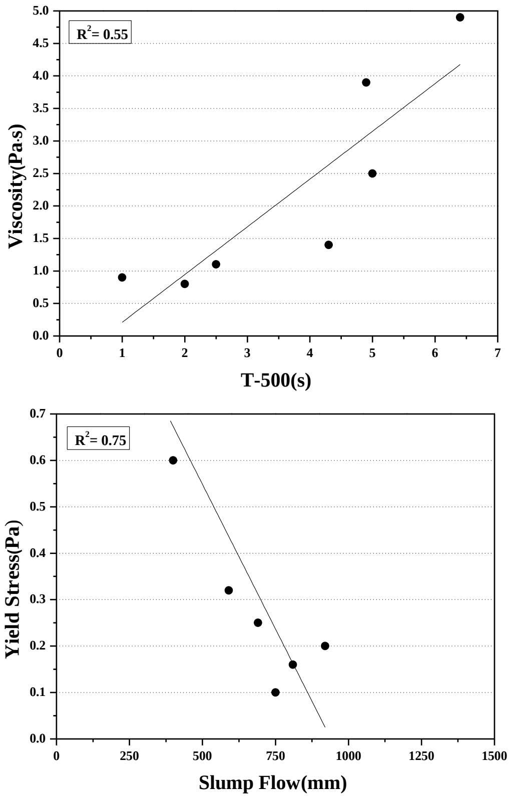


Fig. 2 Results of a previous study on correlation between concrete slump flow test and rheological parameters

100% OPC mixture with each of the following: 20% FA, 50% GGBS, and 10% SF mixtures. For the ternary system, two mixtures were analyzed by replacing the 100% OPC mixture with each of the following: 20% FA with 10% SF and 50% GGBS with 10% SF mixtures.

Lastly, a simplified flow performance test to examine the rheology parameters was performed to complement the qualitative result of an existing flow test. As shown in Fig. 1, a generally used table flow test apparatus was used for the simplified flow performance test. In the experiment, the workability of cement paste was measured by referring to the national test standards KS L 5111 and KS F 2594. Then, the result of the table flow test was analyzed by referring to other studies that determined the plastic viscosity value, time taken to move 500 mm, and correlation between the yield stress and flow length in Fig. 2 (Koehler *et al*. 2006, Lee *et al*. 2018). Firstly, the time for the cement paste to reach the 150 mm point (T-150(s)) when the cone was lifted

Fig. 3 Rheometer used for cement paste rheology measurements

in consideration of the length of the flow plate (250 mm) in the table flow test apparatus was set as one parameter. Then, the number of hits needed to reach the 150 mm point in case it did not flow naturally even after the cone was lifted was set as another parameter. The maximum number of hits (T-150(c)) was set as 25, according to the national test standard (KS F-2594. 2015, KS L-5111. 2017). Lastly, for the measurement of slump flow length in T-150(s), the length of flow at the point when the liquid stopped flowing on the flow plate after lifting the cone was measured, while the length of the flow of the liquid after hitting it 25 times was measured in T-150(c). From the result of those measurements, the correlation between slump flow value and rheological parameters was examined.

2.2 Experimental method

We conducted a rheology experiment that can assess rheological properties to examine properties required for a composite material for 3D printing. A high-speed mixer was used to prepare the materials for the experiment. First, a measured amount of distilled water and HWRA were mixed in a container of the mixer. Then, the binder was added. The mixture was allowed to mix at a low speed for 30 s, and it was made into paste by using a mixing rod. Then, it went through a minute of low-speed mixing and two minutes of high-speed mixing. To examine the rheological properties of the paste, a generally used commercial rheometer (Fig. 3) was used for the experiment under the same temperature and time conditions. Generally, the measurement of rheology is done with the shear stress-shear strain relation that acts toward the measured material. For this study, plastic viscosity and yield stress were determined by using the Bingham model, Eq. (1). In that method, the plastic viscosity value is defined as the inclination of the shear stress-shear strain curve and the

Table 3 Results of rheology parameters with different W/B ratios

No.	Mixing ratios		Plastic viscosity	Yield stress
	W/B	Binder content	(Pa · s)	(Pa)
1	0.25	OPC=100%	1.94	39.80
2	0.28		0.86	16.77
3	0.30		0.76	10.83

yield stress is the value of the y-intercept, which are determined by performing a regression analysis (Ferraris *et al*. 2012, Lee *et al*. 2018).

$$\tau = \mu\dot{\gamma} + \tau_0 \quad (1)$$

Where,

τ=Shear Stress

μ=Plastic Viscosity

$\dot{\gamma}$=Shear Rate

τ_0=Yield Stress

To control the thixotropic phenomenon and to homogenize the entire material, the material was rotated at a shear velocity of 100 s^{-1} for 90 s; then, the equilibrium state was reached by allowing the material to rest for 10 s. This was done to restrain the directivity that was generated from idling before performing the experiment. Then, the shear velocity was raised to 40 s^{-1} from 0.1 s^{-1} and then was reduced to 0.1 s^{-1} again to measure the shear resistance that was put on the spindle by the rotating speed set during the ten stages on a downward curve. In addition, the above-mentioned process was repeated three times to guarantee reliability of the measured values. A serrated spindle with a diameter of 50 mm was used to prevent separation and slip of the material.

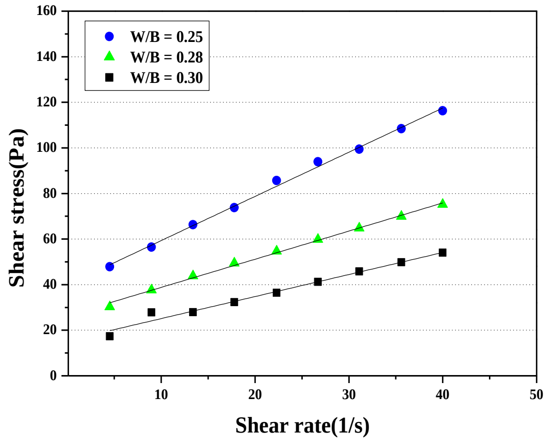


Fig. 4 Results of measuring the rheological properties of mixtures with different W/B ratios

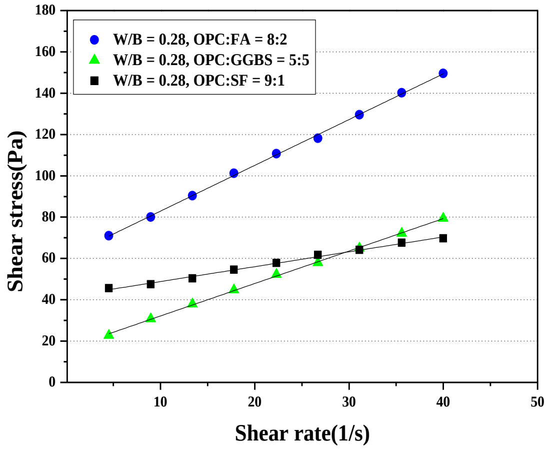


Fig. 5 Results of measuring the rheological properties of mixtures with different binders (Binary system)

3. Results and analysis

3.1 Rheological properties of mixtures with different W/B ratios

As shown in Fig. 4, the plastic viscosity and yield stress were determined for each of the three mixtures with W/B ratios of 0.25, 0.28, and 0.30 based on 100% OPC. The values are listed in Table 3. Fig. 4 shows the tendency of a decline in the plastic viscosity and yield stress following an increase in the W/B ratio. For the mixture with a W/B ratio of 0.25, proper mixing failed even though the water-reducing admixture was used when mixing the material, and the torque capacity reached the limit of the measurement apparatus, owing to a lack of moisture content; therefore, it was difficult to determine the rheological property values from it. On the contrary, for the mixtures with W/B ratios of 0.28 and 0.30, there was no difficulty in mixing, and the torque capacity did not exceed the limit; therefore, the measurement was performed as planned. The mixtures with W/B ratios of 0.28 and 0.30 showed similar levels of plastic viscosity, which indicates they can exhibit similar exturdability when considered in terms of the performance function for a composite material for 3D printing. In addition, as the mixture with a W/B ratio of 0.28 showed a slightly higher yield stress, which indicated a good manner for the buildability, it was selected as the representative mix for the analysis of rheological properties of mixtures with different binders in this study.

3.2 Rheological properties of mixtures with different binders

The tendency shown by the plastic viscosity and yield stress of cementitious materials with different binders was analyzed, and the result is shown in Fig. 5 and Fig. 6. To analyze the impact of each binder on the rheological properties of the mixture that it was added to, the mixture with a W/B ratio of 0.28 was selected as the representative mix, as mentioned above, for the design of the rheometer experiment on different mixing ratios of binder. The values of distilled water and the water-reducing admixture were fixed, and the mixing ratio for the binder was calculated based on the weight ratio of other materials added to the mixture.

3.2.1 Binary system

The plastic viscosity and yield stress for binary system of W/B=0.28 mixtures with different binder mixing

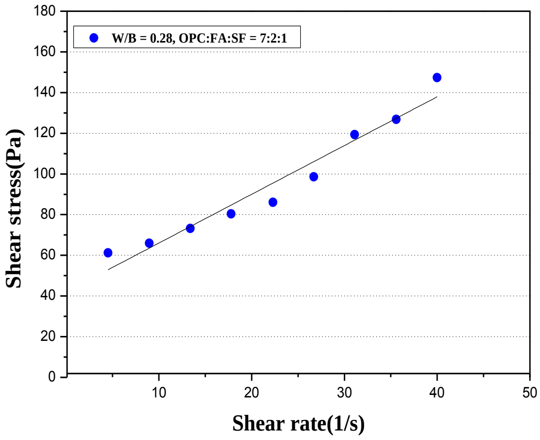


Fig. 6 Results of measuring the rheological properties of mixtures with different binders (Ternary system)

Table 4 Results of the rheology parameters for mixtures with different binders (Binary system)

No.	Mixing ratios W/B	Mixing ratios Binder content	Plastic viscosity (Pa · s)	Yield stress (Pa)
1	0.28	OPC:FA=8:2	2.21	60.73
2		OPC:GGBS=5:5	1.57	16.44
3		OPC:SF=9:1	0.72	41.63

ratios are shown in Fig. 5, and the values are listed in Table 4. First, when the plastic viscosity and yield stress of the mixture with OPC:FA = 8:2 were compared with those of a mixture with the same W/B with 100% OPC, FA was thought to increase the plastic viscosity and yield stress of the material. In terms of the buildability, the incorporation FA meant to be suitable for 3D printing composite materials. On the other hand, in terms of the extrudability, as the plastic viscosity increases, it is considered to have an adverse effect on pumping. In view of increase in value, the incorporation of FA increases the plastic viscosity by about 2.4 times and yield stress by about 3.7 times. Although the difference in effect is not large, it can be judged that the buildability improvement effect will be higher by increasing the yield value. Therefore, in view of the composite material for 3D printing, it is a relatively suitable material because the amount of increase in buildability is better than the amount of decrease extrudability. Next, when the mixture with OPC:GGBS=5:5 was compared with the material with 100% OPC, GGBS was found to play a role in increasing the plastic viscosity value and reducing the yield stress of the material. When considered from the perspective of the performance function for composite materials for 3D printing, the cement paste mixture with GGBS did not satisfy the extrudability, due to an increase in the plastic viscosity and the buildability, due to a decrease in the yield stress. In addition the mixture liquids with 20 Pa or lower yield stresses did not maintain their form, flowing in the simplified flow performance test conducted afterwards, so it is a unsuitable for 3D printing composite materials. Therefore, GGBS was excluded from ternary system experiments. Based on a comparison of the mixture with OPC:SF=9:1 with the material with 100% OPC, it was

Table 5 Results of the rheology parameters for mixtures with different binders (Ternary system)

No.	Mixing ratios W/B	Mixing ratios Binder content	Plastic viscosity (Pa · s)	Yield stress (Pa)
1	0.28	OPC:FA:SF=7:2:1	2.40	42.06

Table 6 Results of simplified flow performance test with rheology parameters

No.	Mixing ratios W/B	Mixing ratios Binder content	T-150 (s or c)	Slump flow (mm)	Plastic viscosity (Pa · s)	Yield stress (Pa)
1	0.25	OPC=100%	25(c)	150	1.94	39.80
2	0.28		0.82(s)	200	0.86	16.77
3	0.30		0.62(s)	210	0.76	10.83
4	0.28	OPC:FA=8:2	14(c)	160	2.21	60.73
5		OPC:GGBS=5:5	error	error	1.57	16.44
6		OPC:SF=9:1	15(c)	170	0.72	41.63
7		OPC:FA:SF=7:2:1	25(c)	150	2.40	42.06

found that SF reduces the plastic viscosity of a material and increases its yield stress. Therefore, a cement paste mixture with SF seems to be appropriate as a composite material for 3D printing in terms of the buildability and extrudability requirement. Therefore, it can be said that FA and SF are relatively suitable as binders for composite materials but not GGBS for 3D printing.

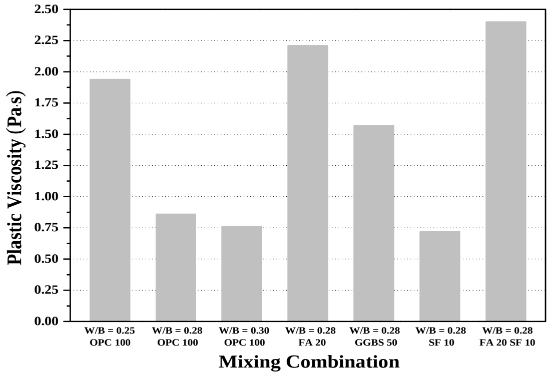
3.2.2 Ternary system

The ternary system was experimented with the combination of FA and SF. The plastic viscosity and yield stress for ternary system mixtures with a W/B ratio of 0.28 and different ratios of binder mixed in them are shown in Fig. 6 and the values are listed in Table 5. When the mixture with OPC:FA:SF=7:2:1 was compared with the mixture with OPC:FA = 8:2 and the mixture with OPC:SF =9:1 that were tested in the experiment on binary systems, its extrudability was lower because of an increase in the plastic viscosity following the addition of FA. In addition, buildability also getting lower because its yield stress was reduced slightly due to the addition of SF. However, as the fluid did not flow at 40 Pa of higher yield stresses in the simplified flow performance test conducted afterwards, it did not have a problem in terms of buildability.

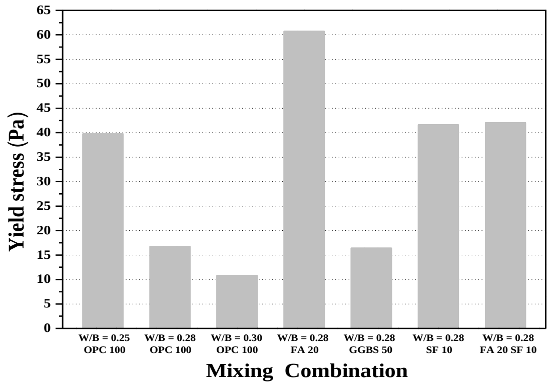
Rheological properties of mixture with various binders were performed to derived 3D printing composite materials. As a results, it was confirmed that the binders had an effect on the plastic viscosity and yield stress, and thus had an important effect on the performance of composite materials for 3D printing. Therefore, when considering the extrudability and buildability based on the experimental results, OPC:FA=8:2, OPC:SF=9:1, OPC:FA:SF=7:2:1 formulations are suitable for 3D printing composite materials.

3.3 Simplified flow performance test

In a simplified flow performance test, T-150(s) was measured when the cement paste reached T-150. When the cement paste did not reach T-150, T-150(c), which enabled

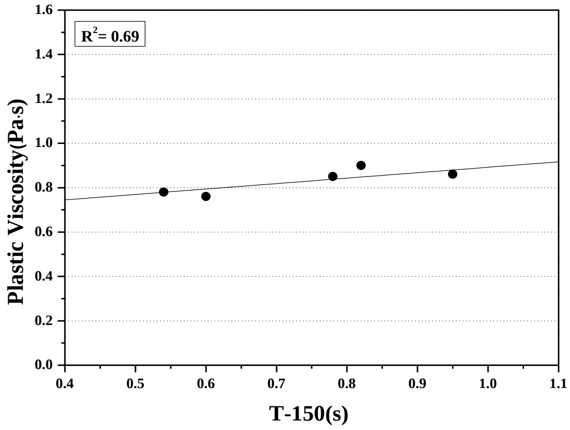


(a) Plastic viscosity

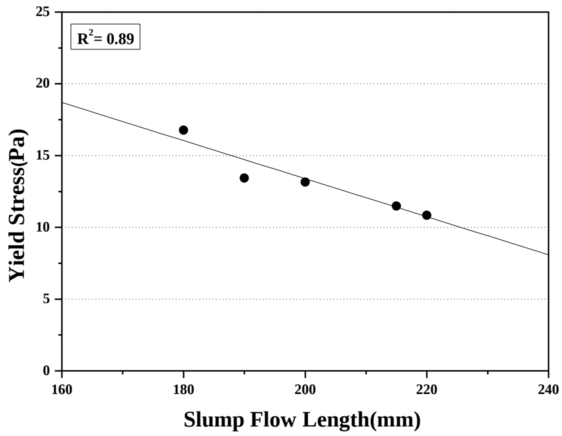


(b) Yield stress

Fig. 7 Variation of rheology parameters according to mixing combinations



(a) Plastic viscosity vs. T-150(s)



(b) Yield stress vs. Slump flow length

Fig. 8 Correlation between the rheology parameters and simplified flow performance test for the flowable materials

it to reach T-150 by hitting, was expressed as the result of the experiment. According to the results of the flow test shown in Table 6, for the two mixtures with W/B ratios of 0.28 and 0.30 that contained 100% OPC, the time needed to reach T-150 was measured, and for the other six mixtures, the number of hits needed for the paste to reach T-150 was measured. Table 6 demonstrates that T-150(c) was measured for mixtures that had yield stresses of 40 Pa or higher, as the cement paste liquid did not flow. Furthermore, T-150(s) was also measured for mixtures with yield stresses of 20 Pa or lower. These results indicate that yield stress has a greater influence on the division between T-150(s) and T-150(c) than plastic viscosity. In other words, the flow test is better suited for determining the buildability than the extrudability of cementitious materials. Regarding the mixture with OPC:GGBS=5:5, for which measurements failed, its plastic viscosity was the third highest, but it had a low yield stress, which is thought to be why it flowed over the flow plate. In conclusion, it is thought that OPC:FA=8:2, OPC:SF=9:1 and OPC:FA:SF=7:2:1 formulations with yield stresses of 40 Pa or higher met the buildability. In addition, the table flow experiment shows that the yield stress to satisfy the buildability should be at least 40 Pa.

Fig. 7 shows the variation of plastic viscosity and yield value according to the mixing combination in Table 6. In Fig. 7(a), W/B=0.28(OPC=100%), W/B=0.30(OPC=100%), W/B=0.28(SF=10%) compositions are relatively low in plastic viscosity as compared to other formulations, and thus can be considered to exhibit good extrudability performance. However, W/B=0.28(OPC=100%), W/B=0.30 (OPC=100%) were excluded because the yield stress was lower than 40 Pa, which was not satisfied in terms of buildability based on simplified flow performance test. Therefore, W/B=0.28 (SF=10%) formulation is considered to be relatively most suitable in terms of extrudability. In Fig. 7(b), the mixtures of W/B=0.28 (FA=20%), W/B=0.28 (SF=10%), W/B=0.28 (FA=20%, SF=10%) formulations had good buildability because the yield stress was 40 Pa or more. W/B=0.28 (FA=20%) and W/B=0.28 (FA=20%, SF=10%) formulations have a high yield stress at the same time as the plastic viscosity, it can be judged that the extrudability is not good. However, since the increase in yield stress is more than the increase in plastic viscosity, it is relatively suitable for 3D printing composite. Ultimately, in the 3D concrete printing composite material performance, the combinations satisfying both conditional buildability and extrudability are W/B=0.28 (FA=20%), W/B=0.28 (SF=10%), W/B=0.28 (FA=20%, SF=10%) under this study cases.

3.4 Correlation between the rheology parameters and simplified flow performance test with different compositions

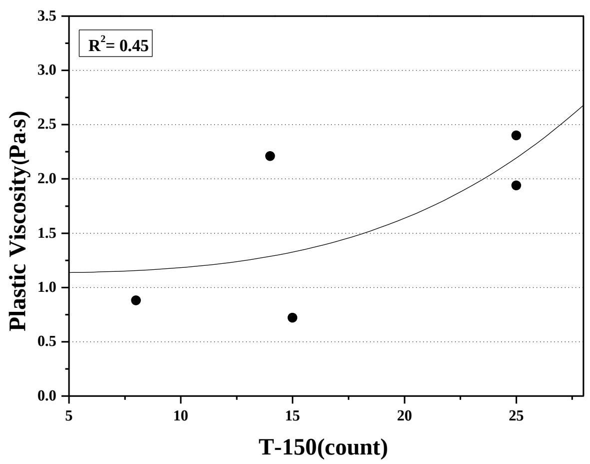


Fig. 9 Correlation between the plastic viscosity and T-150 (c) for stiff materials

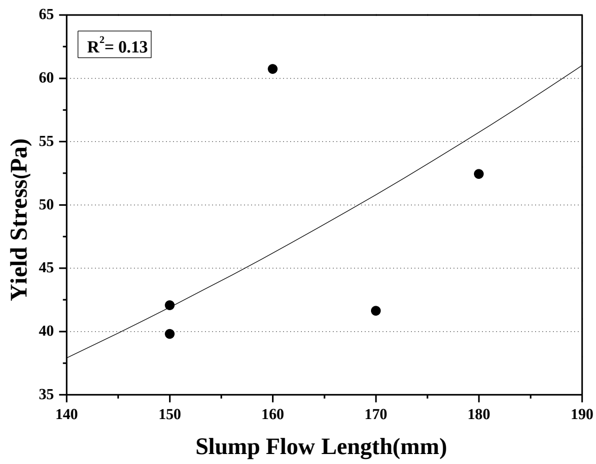


Fig. 10 Correlation between the yield stress and slump flow length after 25 strokes for stiff materials

Based on the results of the cement paste flow test described above, the correlation between the rheological parameters and simplified flow performance test of each mixture was analyzed. First, for the correlation regarding the time needed to reach T-150, a tendency of a proportional relationship between T-150(s) and plastic viscosity was revealed in the plotted graph, Fig. 8(a), as in the preceding study (Koehler *et al*. 2006, Lee *et al*. 2018). Its reliability was 0.69, which was higher than the 0.55 value obtained in the preceding study, indicating that there is a tendency of a correlation between the time needed to reach T-150 and plastic viscosity. Figure 8(b), which shows the correlation between yield stress and slump flow length, shows a reliability of 0.89, which is higher than the 0.75 value obtained in the preceding study.

However, it was difficult to find the tendency of proportional correlation between T-150(c) and plastic viscosity, in terms of the correlation according to the number of hits as shown in Fig. 9. The reliability was 0.44, which was lower than that obtained in the preceding study. In addition, the graph showing the relationship between yield stress and slump flow length showed a proportional correlation between the two parameters, contrary to the results obtained in the preceding study and the reliability was 0.13. It is believed that the slump flow length measured from the number of hits lacks reliability. The reason for low reliability in rheological results is that rheological parameters and hit measurements are inconsistent because the initial intrinsic rheological properties has been destroyed by the impact which results in measuring different flow condition.

The rheology concept was introduced for the quantitative performance evaluation of 3D concrete printing materials and the relationship was derived by using simplified flow performance test which can be easily used to derive rheological parameters. In the case of a good fluidity formulation, a satisfactory level of relationship can be derived and utilized. However, additional studies such as improving the measurement method for stiff materials with poor fluidity are necessary.

4. Conclusions

This study was to derive a cementitious material for 3D concrete printing that fulfills various key functions. We conducted experiments to quantitatively analyze the rheological properties of different cement paste mixtures and evaluated the performance functions by comparing rheology results with key functions required for 3D printing. The main conclusions from this study were as follows.

1) From the rheological measurement of cement paste with different W/B ratios, the mixture of W/B ratio of 0.28 that showed the most suitable rheological levels in terms of extrudability and buildability according to the performance functions for a cementitious material for 3D concrete printing was selected as the representative mix for the analysis of rheological properties of different mixtures of cement paste.

2) The cement paste mixture with GGBS did not satisfy the extrudability requirement, as plastic viscosity increased. In addition, the mixture liquids with 20 Pa or lower yield stresses did not maintain their form, flowing in the simplified flow performance test conducted. Therefore, the GGBS binder is inadequate as composite materials for 3D concrete printing, as they failed to fulfill the buildability and extrudability requirement.

3) When SF was added, the yield stress increased and plastic viscosity slightly decreased. It showed still good extrudability performance while maintaining good buildability performance. Therefore, it is considered that the binder including SF seems to be more suitable as a cementitious material for 3D concrete printing.

4) A simplified flow performance test conducted to determine a simplified method of rheological assessment succeeded in showing a tendency of a correlation between T-150(s) or T-150(c) and plastic viscosity, as well as a relationship between the slump flow length and yield stress. The results of the experiment revealed T-150(s) and slump flow length correlation with rheological properties along with a high reliability value for a flowable materials. However, the

reliability was low for the results of the experiment on the correlation regarding T-150(c) and slump flow length for stiff materials. Therefore, it is thought that the simplified method of measuring the rheological properties for a low slump materials needs to be improved.

5) In this study, quantitative properties of binders, as well as the mixture that is appropriate in terms of the extrudability and buildability required for a cementitious material for 3D concrete printing, were investigated and a simple but unique flow measurement was evaluated to analyze rheological properties of flowable materials. Through this investigation, we have derived a formulation that satisfies these requirements in an optimal manner.

6) Through this study, the basic foundation for deriving 3D printing composites guidelines has been obtained with cement paste level. Further research on the composite materials for 3D printing with mortar and concrete level will need to be conducted based on current study.

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