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Evaluation of 3D concrete printing performance

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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. 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.

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. 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 2017, Oh 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(Bauchkar 2018, Benyamina 2019, Hwang 2007).

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Different from filament materials used for conventional 3D printing, cementitious materials are subject to diverse influences from the properties of materials such as that are the components of concrete, as well as the properties of uneven particles, their multi-dimensional properties. 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 system of their transfer, the performance itself of 3D printing construction (Buswell 2018, Le 2012, Lee 2017, Lim 2011, Lloret 2015, Roussel 2018). 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 (Malaeb2015). 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(Malaeb et al. 2015, Le 2012). Finally, bondability can be defined as the ability to bond inter-layers after extrusion in 3D concrete printing(Buswell 2018).

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.

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. 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.

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	100	-	-	-	0.3
2	0.28		-	-	-	
3	0.30		-	-	-	
4	0.28	80	20	-	-	
5		50	-	50	-	
6		90	-	-	10	

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. To examine the rheological properties of the paste, a generally used commercial rheometer (Fig. 1) 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(Ferraris 2012, Lee 2018).

Fig. 1 Rheometer used for cement paste rheology measurements

3. Results and analysis

3.1 Rheological properties of mixtures with different W/B ratios

As shown in Fig. 2, the plastic viscosity and yield stress were determined for each of the three mixtures. The values are listed in Table 3. Fig. 2 shows the tendency of a decline in the plastic viscosity and yield stress following an increase in the W/B ratio. 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.

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

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

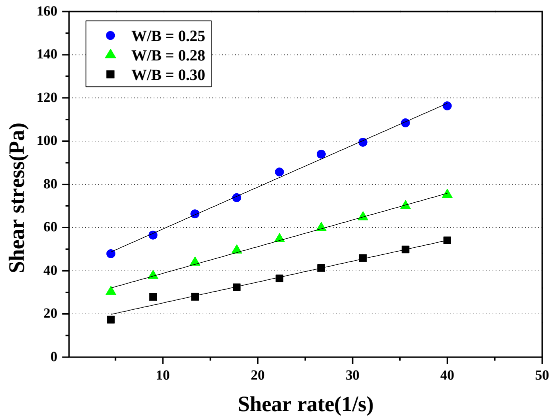

Fig. 2 Results of measuring the rheological properties of mixtures with different W/B ratios

3.2 Rheological properties of mixtures with different W/B ratios

The plastic viscosity and yield stress for binary system of W/B=0.28 mixtures with different binder mixing ratios are shown in Fig. 3, and the values are listed in Table 4. As a result of the analysis, it can be confirmed that FA, GGBS, and SF had a great influence on the plastic viscosity and yield value. Therefore, it can be said that FA and SF are relatively suitable as binders for composite materials for 3D printing.

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

No.	Mixing ratios		Plastic viscosity (Pa · s)	Yield stress (Pa)
	W/B	Binder content		
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

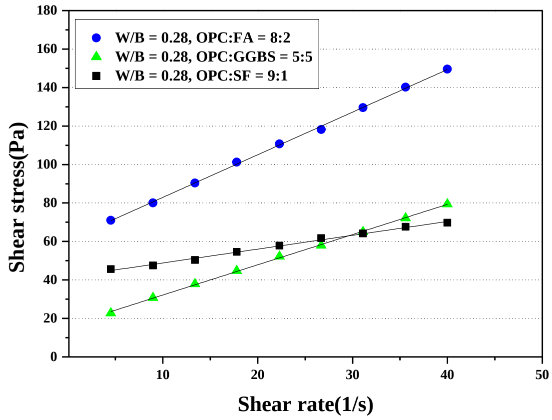

Fig. 3 Results of measuring the rheological properties of mixtures with different binders (Binary system)

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.

2) 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.

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