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EFFECTS OF THE COMPOSING MATERIALS ON THE RHEOLOGICAL AND MECHANICAL PROPERTIES OF ULTRA-HIGH PERFORMANCE CONCRETE (UHPC)

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Abstract

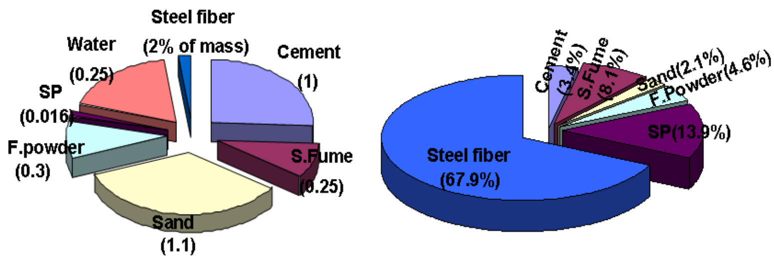
Since Ultra-High Performance Concrete (UHPC) necessitates large quantities of high-cost materials like steel fibre, silica fume and superplasticizer, its fabrication cost is known to be significantly higher than ordinary concrete. This paper investigates the use of Zr silica powder instead of silica fume to reduce the amount of superplasticizer by improving the workability. As a result, compared to the conventional UHPC using silica fume, UHPC using Zr silica powder enables to diminish the amount of superplasticizer by 50 to 70% while securing a flow of 210 to 230 mm, a compressive strength of 180 MPa, a flexural tensile strength of 35 MPa and a tensile strength of 15 MPa.

Résumé

La fabrication du béton à ultra haute performance (BUHP) nécessite de très larges quantités de matériaux coûteux comme les fibres d'acier, la fumée de silice et les superplastifiants. Cette situation rend le coût de fabrication du BUHP nettement plus cher que celle des bétons ordinaires. Cet article examine l'emploi de poudre de silicate de zirconium au lieu de fumée de silice pour réduire la quantité de superplastifiant en améliorant la mise en œuvre. En comparaison du BUHP utilisant la fumée de silice, les résultats démontrent que le BUHP utilisant la poudre de silicate de zirconium permet de réduire la demande en superplastifiant de 50 à 70 % tout en développant un étalement de 210 à 230 mm, une résistance de compression de 180 MPa, une résistance de tension en flexion de 35 MPa et une résistance de tension de 15 MPa.

1. INTRODUCTION

Ultra-High Performance Concrete (UHPC) is a material exhibiting high mechanical performances like a compressive strength and flexural strength larger than 180 MPa and 35 MPa together with an outstanding durability [1, 3, 4]. In order to achieve such performances, UHPC necessitates large quantities of steel fibre, silica fume and superplasticizer as well as a very low water-to-binder ratio (W/B) below 0.2 [2]. Since UHPC uses large quantities of expensive materials, its fabrication cost is known to be sensitively higher than ordinary concretes. Fig. 1 illustrates the results of the economic analysis per constituting materials and mix proportions of UHPC developed by the authors [6, 7]. The most cost demanding materials involved in the fabrication of UHPC are, in descending order, the steel fibre, the superplasticizer and the silica fume. It appears also that the material presenting the largest demand for the fabrication of the cement paste is the superplasticizer.



(a) Mix proportions (b) Economic efficiency

Fig. 1 Mix proportions and economic efficiency of UHPC

In view of the mechanical performances of UHPC, silica fume can be considered as indispensable [8, 10]. The specific surface area of silica fume exceeds 200,000 g/cm^3. Its grain size is thus sensitively smaller than that of the cement grain, which enables it to play the role of filler filling the pores among the cement grains. Moreover, the hydrates generated by silica fume through the pozzolanic reaction during the hydration promote the development of strength [11, 12]. Since UHPC uses large quantities of fine powders like silica fume, the viscosity of UHPC is significantly increased during its mixing. In order to secure high flowability with flow higher than 200 mm in UHPC, large quantities of superplasticizer are required, which in turn increase the fabrication cost of UHPC.

Besides, study dedicated to the use of Zr silica powder instead of silica fume in UHPC was conducted [1, 8]. The authors found out that the replacement of silica fume by Zr silica powder in the fabrication of UHPC degraded the viscosity but improved significantly the flowability [9]. This paper investigates the rheological and mechanical properties of UHPC using Zr silica powder instead of silica fume with respect to the mix ratio of Zr silica powder, the quantity of superplasticizer and the mix ratio of steel fibres.

2. TEST PROGRAMS

2.1 Materials and mix design

Table 1 lists the properties of the binder used in this study. Zr silica powder is mainly composed of SiO_2, includes approximately 3% of ZrO_2 and has practically no content in MgO and SO_3. In addition, Zr silica powder is featured by a specific surface area of 80,000g/cm^3 which is smaller than silica fume. The adopted fine aggregates present density of 2.62 g/cm^3, mean grain size smaller than 0.5 mm, and 93% of SiO_2. Filler with mean grain size of 100 µm and SiO_2 content larger than 99% is used. The superplasticizer is a polycarboxylate with density of 1.01 g/cm^3 and 30% of solid contents. The steel fiber exhibits density of 7.5 g/cm^3, length of 19 mm, diameter of 0.2 mm and tensile strength of 2,000 MPa.

Table 1: Properties of cementitious materials

Items / Types	Surface area (cm^2/g)	Density (g/cm^3)	L.O.I	Chemical composition (%)						
				SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	ZrO_2
Cement	3,413	3.15	1.40	21.0	6.4	3.1	61.3	3.0	2.3	-
Silica fume	200,000	2.10	1.50	96.0	0.25	0.12	0.38	0.2	0.3	-
Zr silica fume	80,000	2.50	0.1	94.0	-	-	-	0	0	3.0

Table 2: Mix proportions of UHPC and test parameters

Type	Cement	Zr silica powder	Silica fume	Sand	Filler powder	Super-plasticizer	W/B	Steel fiber
Super-plasticizer	1	0.25	0	1.1	0.3	Parameter 1	0.2	0
Steel fiber	1	0	0.25	1.1	0.3	0.022	0.2	Parameter 2
	1	0.25	0	1.1	0.3	0.012	0.2	
Zr silica powder	1	Parameter3		1.1	0.3	0.012	0.2	0

Parameter 1: 0.020, 0.014, 0.012, 0.010, 0.008, 0.006, 0.005, 0.004
Parameter 2: 0.0%, 1.0%, 1.5%, 2.0% (V_f)
Parameter 3: SF0.25+Zr0, SF0.2+Zr0.05, SF0.15+Zr0.1, SF0.1+Zr0.15, SF0.05+Zr0.2, SF0+Zr0.25

Table 2 presents the mix proportions and test variables of UHPC. The test variables are the mix ratios of Zr silica powder, superplasticizer and steel fibre. The mix ratio of Zr silica powder is varied by replacing silica fume by 0 %, 20 %, 40 %, 60 %, 80 % and 100 %. In such cases, the amount of superplasticizer is fixed to 0.020 and steel fibre is not used. The superplasticizer is used at ratio of 0.020, 0.014, 0.012, 0.010, 0.008, 0.006, 0.005 and 0.004 with regard to the amount of cement. In these cases, silica fume is not used and is replaced at 100 % by Zr silica powder. The volume contents of steel fiber is varied as 0.0 %, 1.0 %, 1.5 % and 2.0 % .

2.2 Test method

The fabrication of K-UHPC proceeds by introducing the binder and the fine aggregates in the 10 liter-mixer and executing dry mixing during 10 minutes at 30 to 40 rpm. Then, water and the admixtures are introduced and mixed successively at 30 to 40 rpm during 1 minute, at 70 to 80 rpm during 1 minute, at 110 to 120 rpm during 1 minute and finally at 30 to 40 rpm during 2 minutes. As shown in Fig. 1, the flowability was examined by measuring the flow using a mini slump cone. The viscosity was measured using a DV-III™ ultra rheometer and a vane spindle (length: 2.534 cm, diameter: 1.267 cm) as shown in Fig. 2. The mechanical properties including the compressive strength, the flexural strrength and the direct tensile strength were evaluated on specimens that experienced 2 days of wet curing at ambient temperature, followed by 48 hours of steam curing at high temperature of 90°C and air-dry curing at 20°C until 7 days (Fig. 3).

Figure 1: Mini slump cone test

(a) Brookfield viscometer (b) Vane spindle

Figure 2: Viscometer and spindle

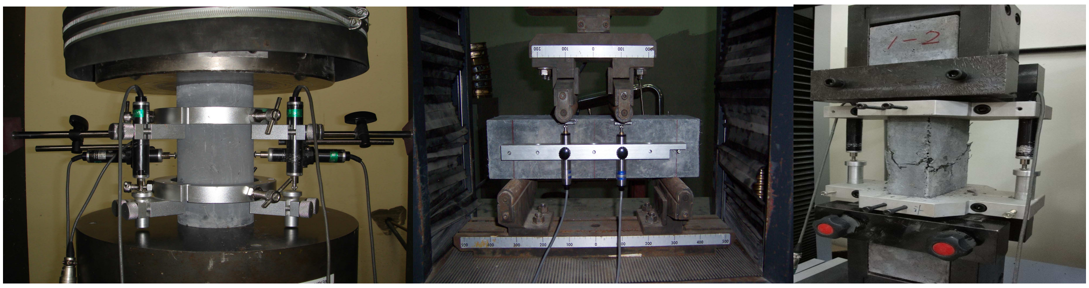


Figure 3: Mechanical performance test of UHPC

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Effect of the amount of Zr silica powder

Fig. 4 plots the results of the evaluation of the rheological characteristics of UHPC according to the amount of Zr silica powder. The flowability is seen to increase with larger amount of Zr silica powder whereas the viscosity shows a tendency to decrease. The flowability appears to increase practically linearly with respect to the augmentation of the amount of Zr silica powder so that an increase of about 23% in the flowability is achieved when replacing silica fume at 100% by Zr silica powder. Moreover, the viscosity experiences steep decrease until replacement at 60% by Zr silica powder and its variation nearly disappears for replacement ratio larger than 60%. These results indicate that the increase of the flowability provided by larger amount of Zr silica powder is caused by the loss of viscosity due to its small specific surface area. Fig. 5 plots the results of the evaluation of the compressive strength according to the amount of Zr silica powder. The results verify that the amount of Zr silica powder has no influence on the compressive strength. As shown in Table 1, Zr silica powder plays the role of filler filling the pores among the cement grains owing to its smaller grain size. Since Zr silica powder presents similar composition to silica fume, it seems that it also experiences the pozzolanic reaction. In view of these results, the use of Since Zr silica powder instead of silica fume in the fabrication of UHPC improves significantly the flowability without loss of strength, which will enable economic fabrication by reducing the use of superplasticizer.

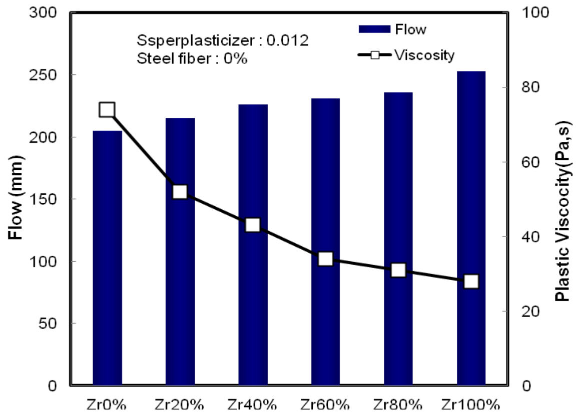


Figure 4: Rheological properties of UHPC according to the amount of Zr silica powder

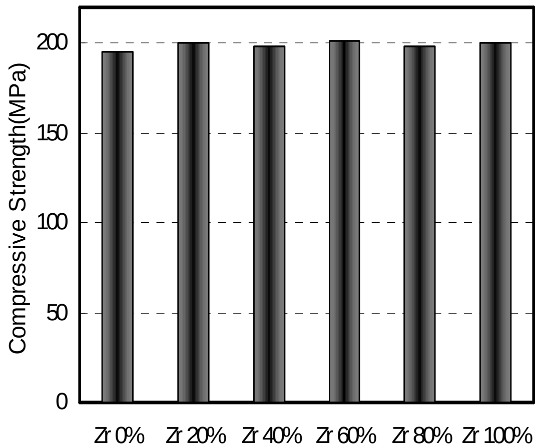


Figure 5: Compressive behavior of UHPC according to the amount of Zr silica powder

3.2 Effects of the amount of steel fibres

Fig. 6 plots the rheological properties of UHPC using silica fume as reactive powder measured with respect to the volume contents of steel fiber. The flowability appears to degrade with larger volume contents of steel fiber but this can be explained by the diminution of the paste caused by the increase of the amount of fibre. In addition, the viscosity tends to increase with larger mix ratio of steel fibre. Especially, the viscosity shows clear increase for volume contents of steel fiber larger than 1.5 %.

Fig. 7 plots the rheological properties of UHPC using Zr silica powder measured according to the volume content of steel fiber. It can be observed that there is practically no change in the flowability and viscosity even when the mix ratio of steel fibre is increased. A comparison with respect to the type of reactive powder reveals that the UHPC using silica fume and thus using larger quantity of superplasticizer experiences significant loss of workability than the UHPC using smaller quantity of superplasticizer. Accordingly, it can be stated that the use of Zr silica powder instead of silica fume is appropriate for the fabrication of UHPC.

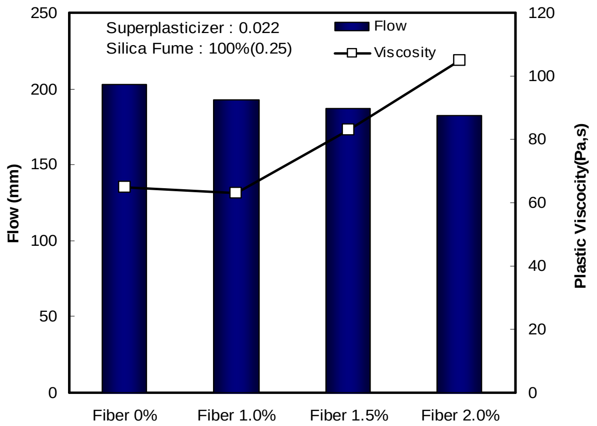


Figure 6: Rheological properties of UHPC using silica fume according to the volume contents of steel fibres

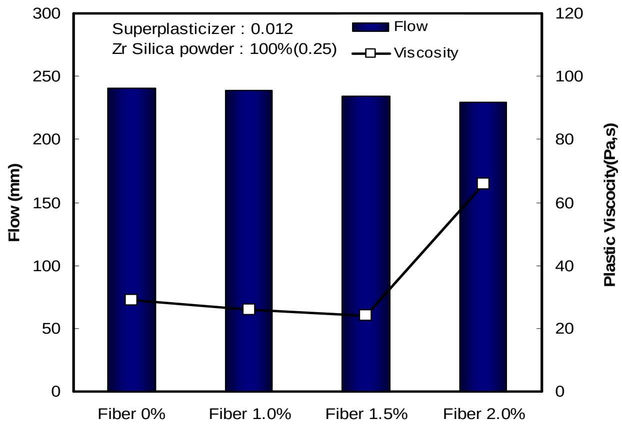


Figure 7: Rheological properties of UHPC using Zr silica powder according to the volume contents of steel fibres

3.3 Effects of the amount of superplasticizer

Fig. 8 plots the flowability of UHPC measured with respect to the amount of superplasticizer. It can be seen that the flowability is sensitively improved by adopting Zr silica powder instead of silica fume. Even if the UHPC using Zr silica powder utilizes 60 to 70 % less superplasticizer, its flow reaches 230 to 220 mm which demonstrates enhanced workability compared to UHPC using silica fume. Such result indicates that UHPC using Zr silica powder makes it possible to reduce the amount of superplasticizer by maximum 70 % than UHPC using silica fume and will enable to realize economically efficient fabrication of UHPC.

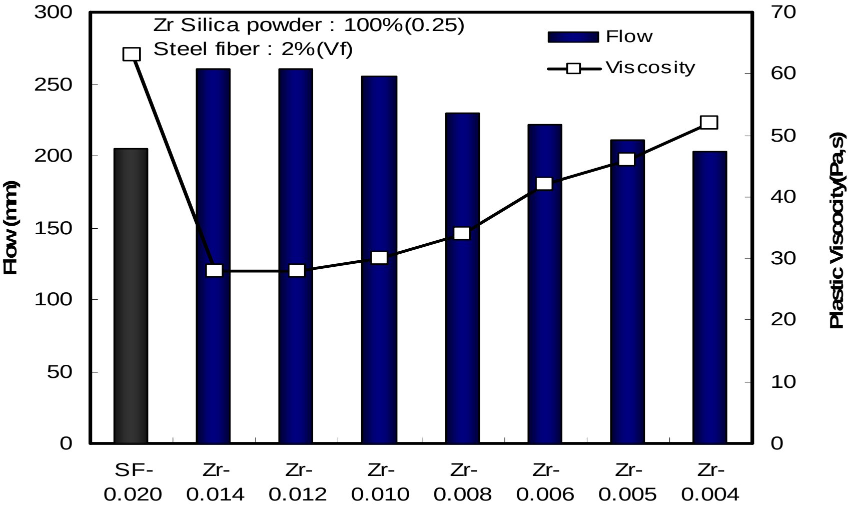


Figure 8: Rheological properties of UHPC according to the amount of superplasticizer

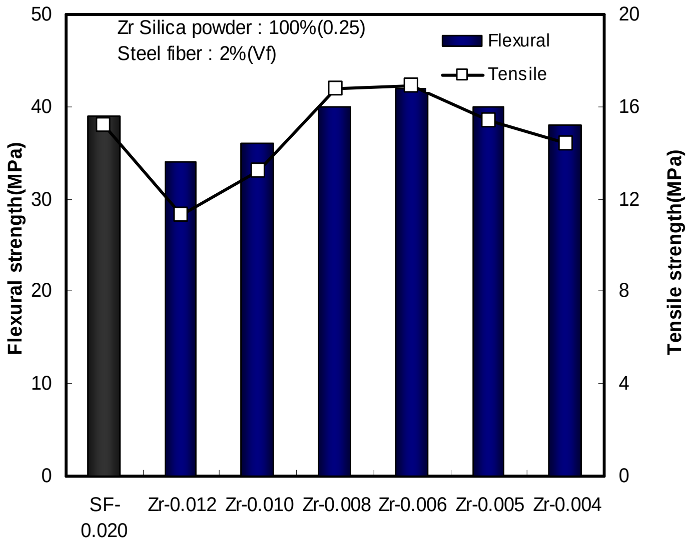


Figure 9: Mechanical properties of UHPC according to the amount of superplasticizer

Fig. 9 plots the flexural tensile strength and direct tensile strength of UHPC measured with respect to the amount of superplasticizer. The flexural tensile strength and the direct tensile strength of mixes Zr-0.012 and Zr-0.010 show degradation. Such loss of the flexural tensile strength and direct tensile strength can be explained by the significantly degraded distribution of the steel fibers following the segregation of materials and the loss of dispersion of the fibers caused by the excessively large flow. To demonstrate this statement, the UHPC mixes Zr-0.008 and Zr-0.006 securing identical flowability to UHPC using silica fume show increase of their flexural tensile strength and direct tensile strength. This indicates that an adequate flowability enables to even the distribution of the fibers inside the paste so as to let them develop their strengthening effect. Moreover, the flexural tensile strength and direct tensile strength display degradation for the mixes beyond Zr-0.004. Such degradation can be attributed to the disorganization of the structure of the cement paste caused by the lack of selfcompacting ability. In view of these results, it appears that UHPC using Zr silica powder and securing a flow ranging between 210 and 230 mm is able to develop mechanical properties equivalent or superior to the conventional UHPC using silica fume.

4. CONCLUSIONS

The effects of the mix ratio of Zr silica powder, the amount of superplasticizer and the mix ratio of steel fiber on the rheological and mechanical properties of UHPC using Zr silica powder instead of silica fume have been examined. It appeared that, compared to the conventional UHPC using silica fume, UHPC using Zr silica powder enables to diminish the amount of superplasticizer by 50 to 70% while securing a flow of 210 to 230 mm, a compressive strength of at least 180 MPa, and a flexural tensile strength and tensile strength larger than of 35 MPa and 15 MPa, respectively. Consequently, the use of Zr silica powder in the fabrication of UHPC is believed to realize substantial reduction of the fabrication cost and to contribute significantly to the applicability of UHPC in the future.

ACKNOWLEDGEMENTS

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