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Rheological Properties of Binder Pastes for Self-Compacting Concrete

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Abstract

This paper investigated rheological properties of binder pastes for self-compacting high performance concrete. Six mixtures of self-compacting concrete were initially prepared and tested to estimate self-compacting property. Then, the binder pastes used in self-compacting concrete were tested for rheological properties using a rotary type rheometer. Binder pastes with different water-binder ratios and flow values were also examined to evaluate their rheological characteristics. The binders were composed of ordinary Portland cement, fly ash, two types of pulverized blast-furnace slag, and limestone powder. The flow curves of binder pastes were obtained by a rotary type rheometer with shear rate control. Slump flow, O-funnel time, box, and L-flow tests were carried out to estimate self-compacting property of concrete. The flow curves of binder pastes for self-compacting concrete had negligible yield stresses and showed an approximately linear behavior at higher shear rates beyond a certain limit. Test results also indicated that the binders incorporating fly ash are more appropriate than the other types of binders in quality control of self-compacting concrete.

keywords : binder paste, rheology, self-compacting concrete, yield value, plastic viscosity, flow curve

1. Introduction

Self-compacting concrete makes it possible to construct durable and highly reliable concrete structures without consolidation efforts although the structures are heavily reinforced and have intricate shapes. Therefore, many problems caused by vibrating, such as insufficient or excessive consolidation, vibration noise, and difficulties of vibration can be eliminated by using self-compacting concrete. Futhermore, it enabled to be placed into structures that would otherwise have been impossible to be constructed with concrete, and realized dramatic improvements in construction efficiency of very large scale structures.

Since the concept of self-compacting high performance concrete was firstly proposed by Ozawa et al.[1], many studies and field applications have been carried out. Meanwhile, a wide range investigations[2~5] for evaluating rheological properties of binder pastes are being carried out. However, the studies for self-compacting concrete are very limited.

Three most important factors for producing self-compacting concrete are rheological properties of binder paste, volume ratio of paste and coarse aggregate(V_p/V_g), and unit volume of coarse aggregate(V_g) as far as the materials are not changed. In the previous studies[6,7], the method for determining these factors were presented. As well known, the rheological properties of fresh concrete are largely influenced by those of binder pastes, and the rheological properties are much more important in self-compacting concrete than in normal concrete. Therefore, to quantify rheolgical properties of binder pastes is very important to efficiently produce self-compacting concrete.

In this study, using the previously developed method[6,7], six self-compacting concretes were prepared and tested to confirm the self-compacting property with four apparatuses. The flow curves of binder pastes in self-compacting concrete were obtained from a rotary rheometer. In addition, the flow value and the J-funnel time of binder pastes were measured. Binder pastes with different ratios of water to binder were also examined to evaluate rheological properties.

2. Experimental Work

2.1 Materials

A single source of ordinary Portland cement was used in this study with the physical properties as shown in Table 1. The fly ash used in this study is produced from combustion of bituminous coal at Boryong thermal power plant in Korea, and meets with the quality requirement specified in KS L 5405 and Class F requirements of ASTM C618-80. Two types of blast-furnace slag with specific surface of 4900 and 6000 cm^2/g were used. Limestone powder was also used for binder. The physical properties and chemical composition of the fly ash, two kinds of blast-furnace slag, and limestone powder are shown in Table 2. Nineteen-mm nominal maximum size crushed stone from a single source was used for coarse aggregate, and sea sand was used for fine aggregate to produce self-compacting concrete. The physical properties of aggregates are illustrated in Table 3. A sulphonated naphthalene formaldehyde condensate superplasticizer, which meets ASTM C 494 requirements for Type G admixture, was used. Table 4 shows the properties of admixture.

2.2 Mixture Proportions of Self-Compacting Concrete and Paste

Flow and J-funnel(KS F 2432) tests were carried out to determine mixture proportions(water-binder ratio, replacement ratios of mineral admixtures, and superplasticizer content) for the binder paste. The method used for flow test is similar to flow test method of mortar consistency(KS L 5111) skipping the consolidation and the impact procedures. The volume ratio of binder paste to coarse aggregate, and the volume of coarse aggregate were selected properly within the limit suggested in the previous work[7]. Throughout these procedures, six mixture proportions of self-compacting concrete were selected with different binders,

Table 1 Physical properties of ordinary portland cement

Specific gravity	Specific surface (cm^2/g)	Time of set (hour:min.)		Compressive strength (MPa)		
		Initial	Final	3 days	7 days	28 days
3.14	3250	2:55	6:10	25	38	40

Table 3 Physical properties of aggregates

Type	Max. size (mm)	Specific gravity	Water absorption (%)	Fineness modulus
Fine aggregate	-	2.60	1.27	2.64
Coarse aggregate	19	2.64	0.64	6.92

Table 4 Properties of admixture

Type	Form	Solid content (%)	Main ingredient	Specific gravity
ASTM C 494 Type G	liquid	46.5	sulphonated naphthalene formaldehyde condensate	1.26

and were tested to evaluate the self-compacting property. Usually in normal concrete, the air content is controlled to 4.5±1.5% with air entraining admixture to have good durability. However, in this test, the air entraining admixture was not used to reduce the experimental errors due to different air contents and air losses, and the air content was assumed to 1%. The mixture proportions are shown in Table 5.

Binder pastes used for the evaluation of rheological properties were prepared and mixed with a mortar mixer under similar conditions(same source, combination of binders, water-binder ratio, superplasticizer content, and temperature) with the binder pastes of tested self-compacting concrete. To compare rheological properties with variations of water-binder ratio and flow value, binder pastes with different water-binder ratios and flow values were also prepared and tested. The mixture proportions of binder pastes are shown in Table 6.

2.3 Test Method

Flow test, O-funnel test, box test, and L-type flow test were carried out to estimate self-compacting property of fresh concrete. Flow test is almost the same procedure as slump test. The flow test evaluates the flowability and workability of fresh concrete by the spread diameters of the concrete specimens after removing slump cone, while the slump test evaluates them by the difference of the height of concrete specimens between before and after removing slump cone. O-funnel test measures the time that fresh concrete flows out from a funnel (Fig. 1(a)). The concrete with

Table 2 Physical properties and chemical composition of mineral admixtures

Kind	Specific gravity	Specific surface (cm^2/g)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)	Loss on ignition(%)
Fly ash	2.2	3790	57.19	23.07	5.04	4.08	1.19	0.24	0.89	0.73	4.30
Slag A	2.90	4900	33.24	13.52	0.30	41.04	6.65	2.49	0.46	0.15	0.73
Slag B	2.90	6060	32.72	13.59	1.09	41.06	7.66	1.65	0.53	0.12	0.78
Limestone	2.84	6000	2.27	0.61	0.53	31.67	19.21	0	0.21	0	45.31

Table 5 Mixture proportions of self-compacting concrete

Mixture No.	W/B (%)	S/a (%)	Unit contents (kg/m³)								Superplasticizer (%)
			Water	Cement	Fly ash	Slag A	Slag B	Limestone	Fine agg.	Coarse agg.	
CF	35.0	51.1	181	362	155	-	-	-	828	805	1.40
CSA	30.0	51.0	175	321	-	263	-	-	826	805	1.15
CSB	30.0	51.0	175	321	-	-	263	-	826	805	1.10
CS	25.0	50.7	160	384	-	-	-	256	814	805	1.40
CFSA	35.0	51.0	182	182	104	234	-	-	825	805	1.00
CFSB	33.0	51.1	176	187	107	-	240	-	828	805	1.10

Table 6 Mixture proportions of binder pastes

Mixture No.	W/B	Unit contents (kg/m³)					Superplasticizer(%)
		Water	Cement	Fly ash	Slag	Limestone	
F-1	0.35	494	988	423	-	-	1.50
F-2	0.35	494	988	423	-	-	1.40
F-3	0.35	494	988	423	-	-	1.15
F-4	0.32	472	1031	442	-	-	1.60
F-5	0.38	514	947	406	-	-	1.20
SA-1	0.30	476	873	-	715(A)	-	1.25
SA-2	0.30	476	873	-	715(A)	-	1.15
SA-3	0.30	476	873	-	715(A)	-	1.03
SA-4	0.27	450	917	-	750(A)	-	1.30
SA-5	0.33	500	834	-	682(A)	-	0.95
SB-1	0.30	476	873	-	715(B)	-	1.25
SB-2	0.30	476	873	-	715(B)	-	1.10
SB-3	0.30	476	873	-	715(B)	-	1.00
SB-4	0.27	450	917	-	750(B)	-	1.15
SB-5	0.33	500	834	-	682(B)	-	1.00
LS-1	0.25	430	1032	-	-	688	1.48
LS-2	0.25	430	1032	-	-	688	1.40
LS-3	0.25	430	1032	-	-	688	1.35
LS-4	0.22	399	1088	-	-	726	1.65
LS-5	0.28	458	981	-	-	654	1.15
FSA-1	0.35	495	495	283	636(A)	-	1.05
FSA-2	0.35	495	495	283	636(A)	-	1.00
FSA-3	0.35	495	495	283	636(A)	-	0.90
FSA-4	0.32	473	517	295	665(A)	-	1.10
FSA-5	0.38	515	475	271	610(A)	-	0.80
FSB-1	0.33	480	509	291	655(B)	-	1.20
FSB-2	0.33	480	509	291	655(B)	-	1.10
FSB-3	0.33	480	509	291	655(B)	-	1.00
FSB-4	0.30	456	533	304	685(B)	-	1.18
FSB-5	0.36	502	486	279	627(B)	-	0.92

good flowability would take short time (shorter than 15 seconds[7]) to flow out. For the evaluation of self-compactable performance, L-type apparatus shown in Fig. 1(b) was used, and four grades such as excellent(when the apparatus is fully filled with concrete in short time without segregation), good(fully filled but, with a little segregation), average(partially not filled with concrete) and poor(the fill-ing ratio is lower than 70%) were applied. In box test, as shown in Fig. 1(c), fresh concrete is put in left box and opens the gate. When flow is stopped, self-compactable performance is estimated by measuring height difference of fresh concrete in the left and right boxes.

A computer-operated controlled strain and stress rheometer is used, in which strain or stress is applied, and stress or deflection of inner cylinder is measured automatically as shown in Fig. 2. In this study, the shear rate(strain rate) was controlled, while shear stress was measured in plotting flow curves. The applied shear rate was continuously increased with a constant increment of shear rate from 0 s^{-1} to 100 s^{-1} during 120 second. The measurement was started at 6 minutes after mixing.

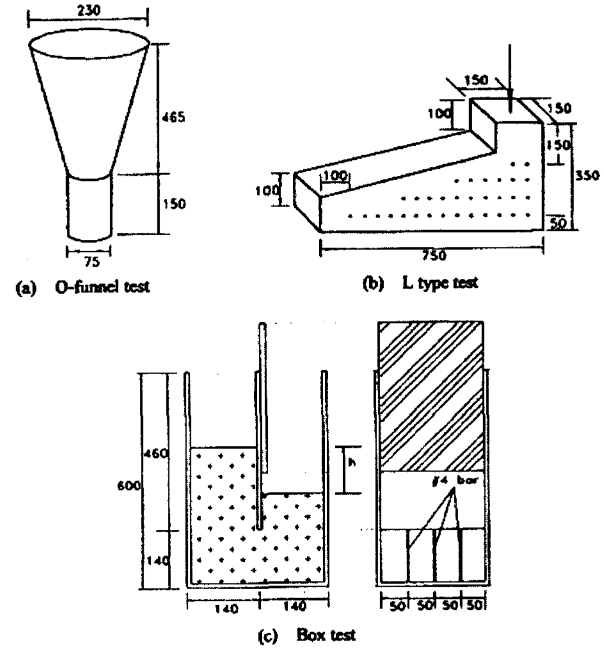

Fig. 1 Test apparatuses for self-compacting concrete(unit:mm)

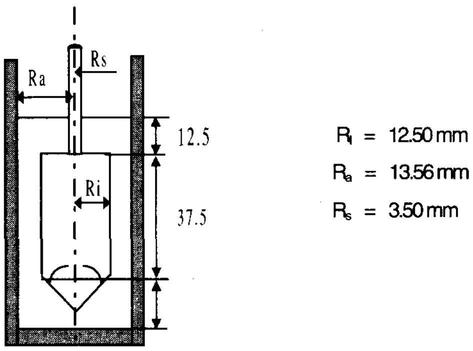

Fig. 2 Diagram of rheometer

3. Test Results and Discussion

3.1 Properties of Self-Compacting Concrete

Table 7 shows the results of slump flow test, O-type funnel test, box test, and L-type flow test. It can be observed that all mixtures have good self-compactability regardless of the binders used, implying that the self-compacting concrete can be produced successfully regardless of binder type if proper rheological properties of the binder paste are achieved.

Meanwhile, it was observed from the preliminary tests that the increase of bleeding and degree of segregation are more pronounced in the mixtures containing cement and blast-furnace slag only as the binder than the other mixtures when slump flow and water binder ratio were not controlled properly. The reason is considered that the water absorption capacity of blast-furnace slag is lower than that of the other binders. This means that the combination of cement and blast-furnace slag is not good as a binder for the self-compacting concrete in the view point of quality control compared to other binders.

Table 7 Test results of self-compacting concrete

Mixture No.	Slump flow (mm)	O-funnel time (sec.)	Difference of height (Box test;mm)	L-flow
CF	650	.5	48	excellent
CSA	675	9.7	68	excellent
CSB	633	8.5	47	good
CS	641	170.5	37	excellent
CFSA	685	7.6	18	good
CFSB	665	11.3	43	excellent

3.2 Rheological Properties of Binder Pastes for Self-Compacting Concrete

Table 8 shows flow values, J-funnel time, and plastic viscosities of the binder pastes. Flow curves of six binder pastes for self-compacting concrete are shown in Fig. 3. All curves show the approximately linear behavior like Bingham's plastic materials at higher shear rates beyond a certain limit. However, within a certain limit, binder pastes behave like pseudo-plastic materials rather than Bingham's plastic materials with negligible yield stresses.

Table 8 Test results of binder pastes

Mixture No.	Flow (mm)	J-funnel time (sec.)	Plastic viscosity (Pa · s)
F-1	257	52	0.68
F-2	215	71	0.72
F-3	180	blockage	0.71
F-4	218	135	0.81
F-5	219	41	0.52
SA-1	248	52	0.74
SA-2	216	60	0.83
SA-3	180	blockage	0.89
SA-4	220	118	1.19
SA-5	200	50	0.66
SB-1	241	53	0.79
SB-2	201	96	0.84
SB-3	171	blockage	0.93
SB-4	215	blockage	1.20
SB-5	219	38	0.62
LS-1	250	49	0.78
LS-2	200	61	0.86
LS-3	180	67	0.86
LS-4	205	109	1.21
LS-5	201	37	0.61
FSA-1	242	53	0.70
FSA-2	219	55	0.70
FSA-3	180	94	0.72
FSA-4	219	55	0.95
FSA-5	208	45	0.58
FSB-1	256	50	0.76
FSB-2	219	65	0.82
FSB-3	179	blockage	0.82
FSB-4	201	blockage	1.07
FSB-5	208	45	0.64

Chung et al.[8] reported that the cement paste of anti-washout concrete showed pseudo-plastic behavior with high plastic viscosity contrary to cement pastes of normal concrete, and it is the main factor to have high anti-segregation and self-leveling properties. As well known, the theoretical concept and the technical background of self-compacting concrete were developed from anti-washout concrete, and the roles of pastes in two concretes are almost same. Test results in this study also indicate that the rheological behavior of binder pastes for self-compacting concrete are similar to that of the paste for anti-washout concrete tested by Chung et al..

As shown in Fig. 3, each binder paste for self-compacting concrete has similar plastic viscosity each other beyond shear rate of 20 s^{-1}. However, the shear stresses under same shear rate are somewhat different, and binder pastes incorporating fly ash show relatively low shear stresses compare to the other binder pastes. This indicates that the plastic viscosity of binder paste in producing self-compacting concrete is almost identical regardless of binder paste if mixture proportions of the concrete are identical. But, within a certain limit of shear rate, there are some differences according to binders. A reason for the differences can be explained by that although the rheological properties of the

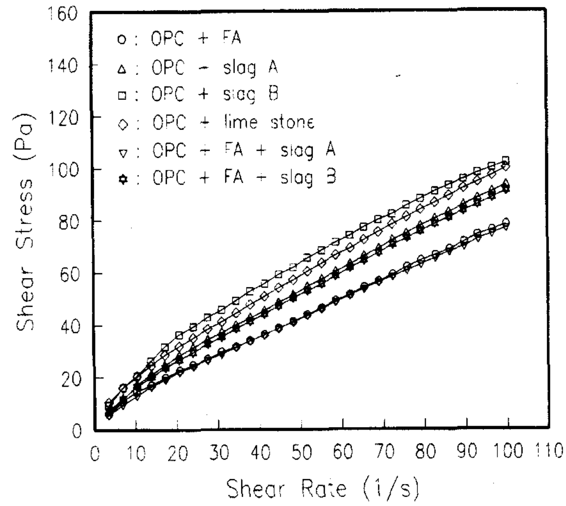

Fig. 3 Flow curves of binder pastes for self-compacting concrete

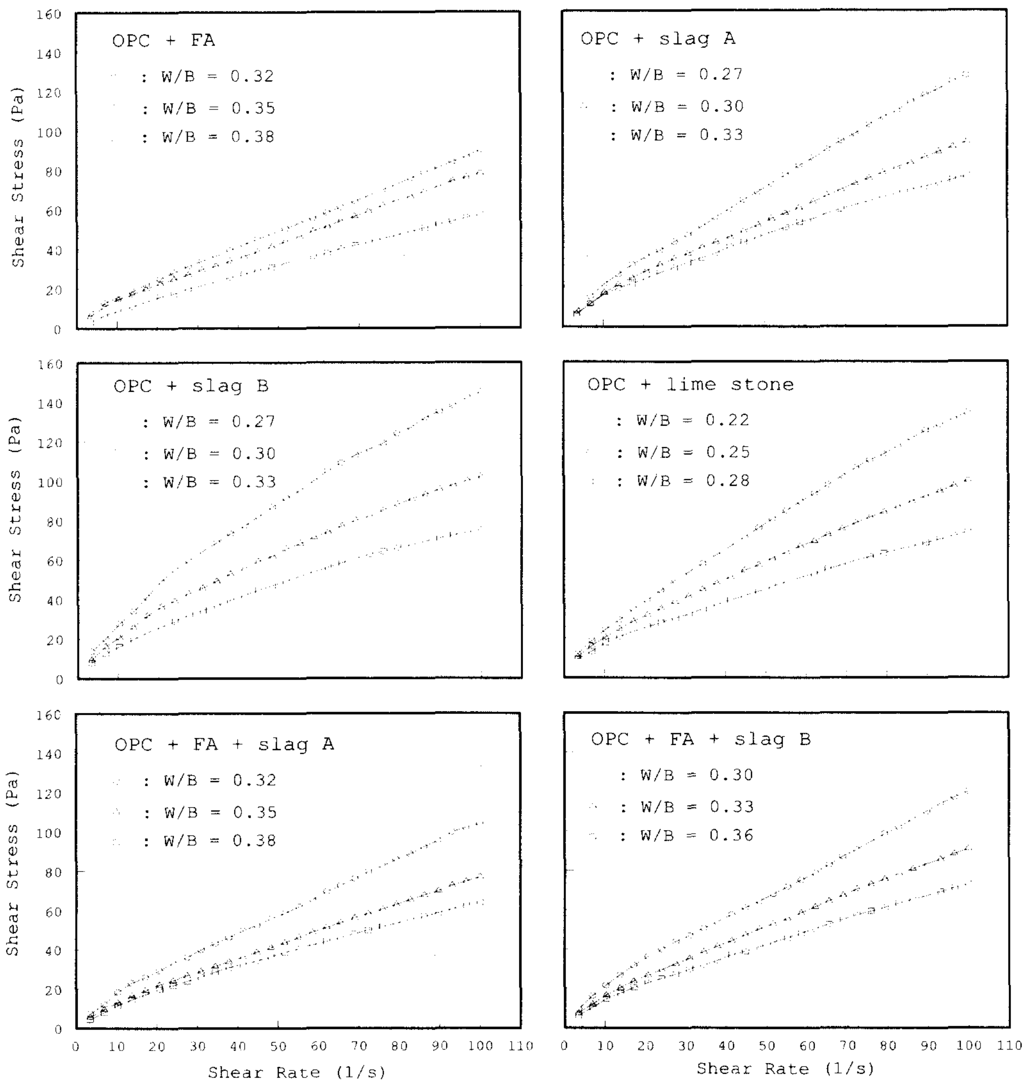

Fig. 4 Effect of water-binder ratio on rheological properties of binder pastes

binder paste used are identical, those of concrete can be changed if the combination and the type of binders are different.

3.3 Effect of Water-Binder Ratio and Flow on Rheological Properties of Binder Paste

Fig. 4 shows flow curves of binder pastes with different water-binder ratios and flow value of 210±10 mm. From this figure, it can be seen that the plastic viscosity is greatly influenced by water-binder ratio. On the other hand, if the type of flow behavior is assumed to be Bingham's plastic, the yield stress is less influenced, whereas the plastic viscosity is more largely influenced by water-binder ratio.

The ratios between maximum and minimum plastic viscosity (between minimum and maximum water-binder ratios) are lower in the binders which incorporate fly ash, and fly ash plus blast-furnace slag(type A, B). This can be explained by that the fly ash particles are spherical shape. This phenomenon can add some beneficial effects to the use of fly ash for the binder of self-compacting concrete since there may be some errors on the water-binder ratio in practice, like an actual concrete mixing plant, therefore, the difference of the plastic viscosity between target and actual values caused by the error of water-binder ratio may be reduced. However, the larger quality variance of fly ash compared to the other binders must be considered.

Fig. 5 shows flow curves of binder pastes with different flow values of 170±10, 210±10, 250±10 mm, and same water-binder ratio of 0.35. Contrary to the variation of water-binder ratio, the plastic viscosity is little influenced with increasing flow value. Similar observations were also made by Banfill[5]. Meanwhile, especially in the binders which incorporate fly ash(with or without blast-furnace slag), there are no clear differences in plastic viscosity with increase of flow value.

According to this investigation, there may be some beneficial effects in the use of fly ash for producing self-compacting concrete in practice similar to the case of variation of water-binder ratio.

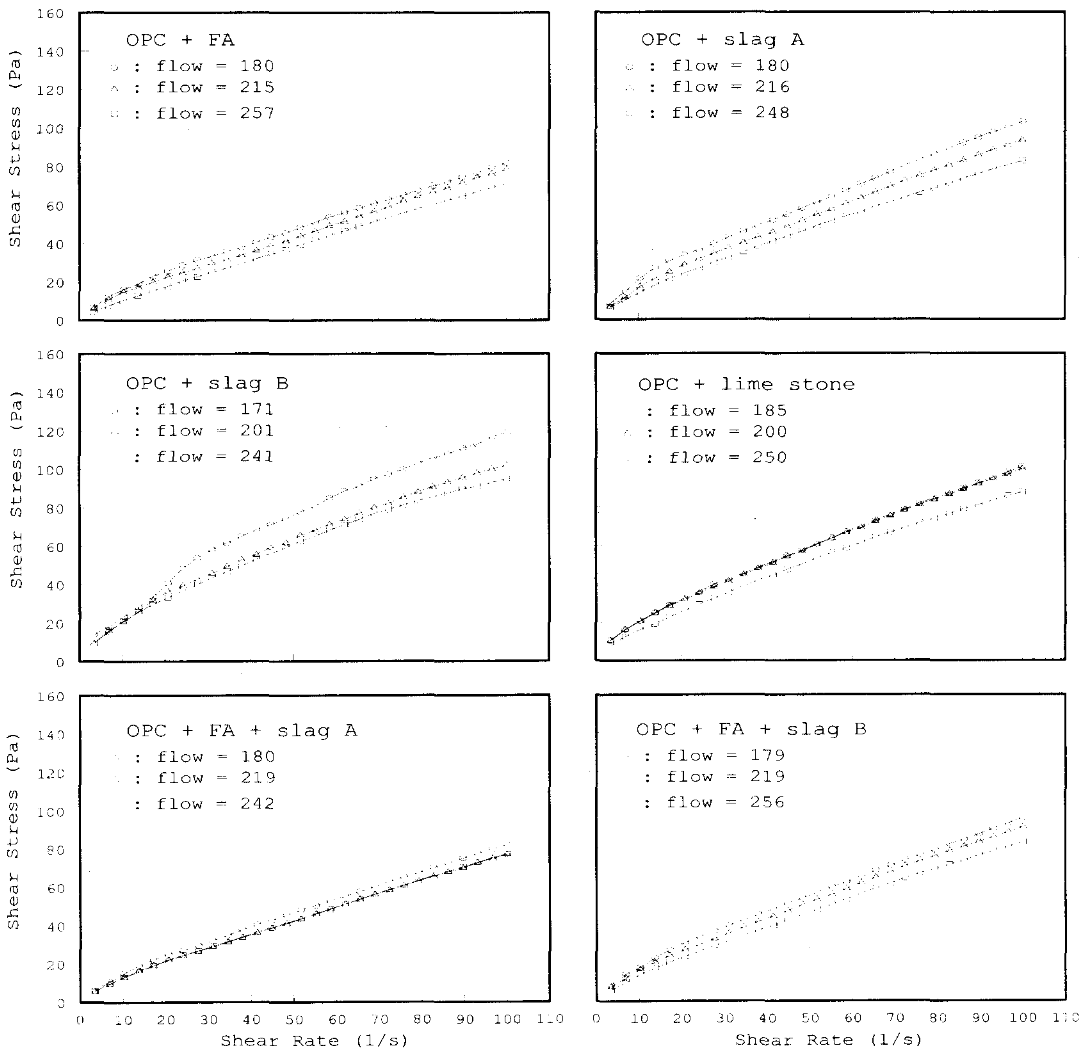

Fig. 5 Effect of flow on rheological properties of binder pastes

4. Conclusions

The rheological properties of binder pastes for self-compacting concrete were investigated experimentally. On the basis of the results obtained from this study, the following conclusions was drawn.

1) The mixture proportions of binder pastes for self-compacting concrete may be determined by using flow and J-funnel tests.
2) The flow behavior of binder pastes for self-compacting concrete is similar to pseudo-plastic behavior especially at lower shear rates regardless of binder type, while the flow curves tend to be linear at higher shear rates beyond a certain limit.
3) The plastic viscosity of binder pastes for self-compacting concrete is similar each other regardless of binder type. However, the shear stresses under the same shear rate are somewhat different.
4) The plastic viscosity of binder pastes is largely influenced by water-binder ratio, however, little influenced by flow value.
5) If the quality variance of fly ash is not considered, it is shown that the binder pastes incorporating fly ash are more appropriate than the other type binder pastes in producing self-compacting concrete for quality control in practice.

References

1. Ozawa, K., Maekawa, K., and Okamura, H., "Development of the High Performance Concrete," Proceedings of the Japan Concrete Institute, Vol. 11, No. 1, 1989, pp. 699-704.
2. Struble, L.J., and Schultz, M.A., "Using Creep and Recovery to Study Flow Behavior of Fresh Cement Paste," Cement and Concrete Research, Vol. 23, 1993, pp. 1369-1379.
3. Ferraris, C.F., and Gaidis, J.M., "Connection between the Rheology of Concrete and Rheology of Cement Paste," ACI Materials Journal, Vol. 89, No. 4, July-August, 1992, pp. 388-393.
4. Papo, A., and Caufin, B., "A Study of the Hydration Process of Cement Pastes by Means of Oscillatory Rheological Techniques," Cement and Concrete Research, Vol. 21, 1991, pp. 1111-1117.
5. Banfill, P.F.G., "A Viscometric Study of Cement Pastes Containing Superplasticizers with a Note on Experimental Techniques," Magazine of Concrete Research, Vol. 33, No 114, March 1981, pp. 37- 47.
6. Park, Y.D., Cho, I.H., Kwon, Y.H., and Park, C.L., "Development of Fly Ash Super-Flowing Concrete," Proceedings, Korea Concrete Institute Conference, Vol. 6, No. 2, November 1994, pp. 121-126.
7. Noh, J.H., Han. C.H., Baeg, M.J., Lee, B.G., and Park, K.C., "Effect of Mix Proportion on the Flowing Characteristics of Super-Flowing Concrete," Proceedings, Korea Concrete Institute Conference, Vol. 6, No. 2, November 1994, pp. 115-120.
8. Chung, Y.S., Tsurumi, T., Asaga, K., and Daimon, M., "Rheological Property and Segregation Resistivity in Water of Cement Paste with Methyicellulose," Proceedings of the Cement & Concrete, No. 44, 1990, pp. 216-221.