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Optimal Mixture Proportion for High Performance Concrete Incorporating Ground Granulated Blast Furnace Slag

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Abstract

In this study, a mix design for self compacting concrete was based on Okamura's method and concrete incorporated just a ground granulated blast furnace slag. Replacement ratio of slag is in the range of 20-80% of cement matrix by volume. For the optimal self compactability in mixture incorporating ground granulated blast furnace slag, the paste and mortar tests were first completed. Then the slump flow, elapsed time of 500mm slump flow, V funnel time and filling height by U type box were conducted in concrete. The volume of coarse aggregate in self compacting concrete was in the range of 50-60% to the solid volume percentage of coarse aggregate. Finally, the compressive and splitting tensile strengths were determined in the hardened self compacting concrete incorporating ground granulated blast furnace slag. From the test results, it is desirable for self compacting concrete that the replacement of ground granulated blast furnace slag is in the range of 40-60% of cement matrix by volume and the volume of coarse aggregate to the solid volume percentage of coarse aggregate with a limit of 55%.

Keywords : self compacting concrete, ground granulated blast furnace slag, mixture proportion

1. Introduction

In general, asphalt is melted through any heating For several decades, the durability of concrete structures has been a major topic of interest. The creation of durable concrete structures requires adequate compaction by skilled workers. One solution to achieve durable concrete structures independently to the quality of construction work is to employ self compacting concrete(SCC), which can be compacted into every corner of a formwork, purely by its own weight without vibrating compaction. The necessity of this type of concrete was proposed by Okamura.[1)]

Originally developed to offset the growing shortage of skilled labor, it has proved beneficial economically because of a number of factors, including faster construction, reduction in site manpower, better surface finishes, easier placing, improved durability, greater freedom in design, thinner concrete sections, reduced noise levels, absence of vibration and safer working environment.

The workability of SCC is higher than the conventional concrete and can be characterized by the following properties: filling ability, passing ability and segregation resistance.[2-4)] A concrete mix can be classified as self compacting concrete only if all requirements for three characteristics are fulfilled. As a result, many different test methods have been developed in attempts to characterize the three properties of SCC.[5,6)] So far no single method or combination of methods has achieved universal approval and most of them have their adherents. Alternative test methods for the different parameters are given in Table 1.[7)]

Generally mix procedures on self compacting concrete are divided into Okamura's method and JSCE method.[8)] In this research, mix design for self compacting concrete is based on Okamura's mix procedure. In mix design for self compacting concrete, however, Okamura recommended that the volume of coarse aggregate to the solid volume percentage of coarse aggregate of 50% is appropriate for self compacting concrete regardless of the volume of

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Table 1 Test methods for fresh SCC

Requirement	Test methods
Filling ability	Slump flow
	Elapsed time of 500mm slump flow(T_{500mm})
	V-funnel
Passing ability	J-ring
	L-box
	U-box
	Fill-box
Segregation resistance	V-funnel after 5 minutes($T_{5min.}$)
	GTM screen stability test

ground granulated blast furnace slag. However, in this study, the optimal ground granulated blast furnace slag and the limit of the volume of coarse aggregate to the solid volume percentage of coarse aggregate had to be calculated.

2. Mix procedure on SCC

The mix procedure is based on Okamura's method.[9] The required preliminary examinations concerning paste and mortar are described as follows. In designing the mix, it is most useful to consider the relative proportions of the key components by volume rather than mass.

2.1 Paste examination

To test the suitability of a powder in SCC, the water retaining capacity is examined. Therefore, pastes composed of cement and admixture are produced. The water powder volume ratio is gradually increased from 1.1 to 1.4 and evaluated with the flow cone.

$$\Gamma_p = \left(\frac{F_p}{F_0}\right)^2 - 1 \qquad (1)$$

where, Γ_p : the relative flowing area ratio
F_p : the flow value of cement paste (mm)
F_0 : the initial diameter of flow cone (100mm)

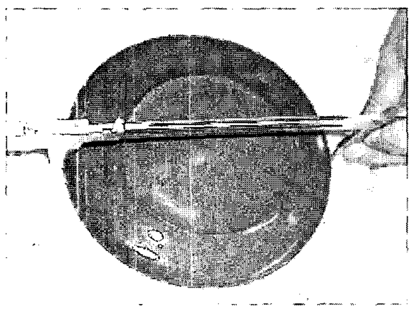

Photo 1 Flow test of paste

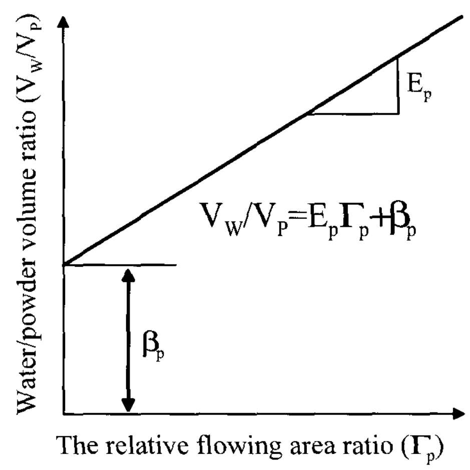

Fig. 1 The relationship between the relative flowing area ratio and water powder volume ratio

The relative flowing area ratio of cement paste is measured by equation (1).

Water powder volume ratio has the relation of Fig.1 with the relative flowing area ratio. From the regression, the water powder volume ratio for zero flow is called the water retaining capacity(βp). This value is used mainly for the quality control of water demand with new batches of cement and fillers.

2.2 Mortar examination

Investigations of the mortar are performed with the common approach in the Japanese literature to determinate the flow with the flow cone and the funnel time with V funnel.[10] Water powder volume ratio is set to about 0.8-0.9 times the water retaining capacity from the result of paste. Volume ratio of fine aggregate to total solid volume of mortar in mortar is set on 0.4. Variety is given to the addition of high range water reducing(HRWR) agent in mortar. V funnel for funnel time in Photo 2 corresponds to the

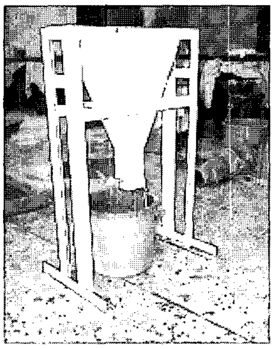

Photo 2 V funnel for flowability

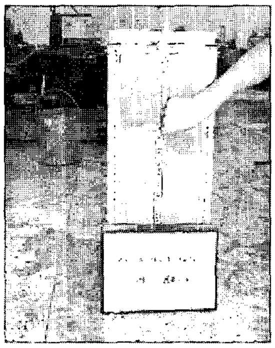

Photo 3 U type box for compactability

Table 2 Specification of SCC proposed by JSCE

Class of filling ability of concrete		1	2	3
Construction condition	Minimum gap between reinforcement (mm)	35-60	60-200	≥200
	Amount of reinforcement (t/m^3)	≥0.35	0.10-0.35	≤0.10
Filling height of U box (mm)		≥300(rank R1)	≥300(rank R2)	≥300(no rank)
Absolute volume of coarse aggregates per unit volume of SCC (m^3/m^3)		0.28-0.30	0.30-0.33	0.32-0.35
Flowability	Slump flow (mm)	600-700	600-700	500-680
Segregation resistance ability	Elapsed time through V funnel	9-20	7-13	4-11
	Elapsed time of 500mm slump flow	5-20	3-15	3-15

measurement of efflux time.

The relative flowing area ratio is calculated with the same as the paste and expressed with Γ_m instead of Γ_p. The relative funnel time is calculated with the following equation of (2).

$$R_m = \frac{10}{t} \tag{2}$$

where, R_m : the relative funnel time of mortar
t : the efflux time by V funnel

Flow and funnel tests for mortar and paste have been proposed to characterize the materials of powder material, sand and HRWR agent used for SCC. The relative funnel time and the relative flowing area ratio represent the viscosity and the deformability of matrix, respectively.

2.3 Concrete examination

By examining the mortar and paste, concrete with suitable mortar can be produced. Okamura proposed that the water powder volume ratio in concrete is optimum, when the relative flowing area ratio and the relative funnel time are 5 and 0.9-1.1 from the test results of mortar respectively.[1] The volume of coarse aggregate to the solid volume percentage of coarse aggregate(SVPCA) varies in 0.5, 0.55 and 0.6 respectively.

SCC is investigated on its properties by measuring the slump flow for flowability, the funnel time and elapsed time of 500mm slump flow for segregation resistance, and the filling height of U type box for filling capacity. The good flowability, filling ability and segregation resistance of SCC are specified in Table 2 proposed by the JSCE.[10]

Table 3 Chemical composition of binders (wt., %)

Items / Types	SiO_2	Al_2O_3	TiO_2	P_2O_5	Fe_2O_3	CaO	MgO	Na_2O	SO_3	K_2O
OPC	20.36	5.77	-	-	2.84	64.33	2.05	-	2.51	1.30
Slag	35.10	14.55	1.12	0.35	0.42	42.65	6.33	0.19	-	0.41

3. Experimental test

3.1 Materials

3.1.1 Cementitious material

Ordinary portland cement(OPC) and ground GGBF slag have the chemical compositions as shown in Table 3. Specific gravity and specific surface area of GGBF slag are 2.90 and 450m^2/kg respectively. In this study, the volume ratios of GGBF slag incorporating OPC are 0, 20, 40, 60 and 80% in volume.

3.1.2 Aggregate

River sand is a fine aggregate immune to most chemical agents and has little organic compounds. This is entirely passed from the sieve of 5mm. The specific gravity, absorption and fineness modulus of fine aggregate are 2.59, 1.18% and 2.46, respectively.

Crushed stone, which is a coarse aggregate, has properties of following: G_{max} of 20mm, specific gravity of 2.70, absorption of 0.50%, solid volume of 57% and fineness modulus of 6.70.

3.1.3 Chemical admixture

In order to obtain suitable workability, superplasticizer, which was selected from several available products after an evaluation of their workability, is a polycarbonic acid-based chemical admixture. Air entraining(AE) agent is used for making the entrained air in matrix.

3.2 Test methods

3.2.1 Test for cement paste

Cement pastes were mixed by the mortar mixer. The water powder volume ratios were selected with 1.1, 1.2, 1.3 and 1.4. The mixing sequence was as follows: mixing for

0.5 minute, rest for 1.5 minute, and remix for 1 minute. No vibrated flow test was examined by this cone on the flat plate shown in Photo 1. The flow value was measured from average diameter vertically.

3.2.2 Test for mortar

Flow test for mortar was performed as cement paste. The relative flowing area ratio was obtained from this test. In order to investigate the flowable behavior in mortar, efflux time was measured with V funnel[10] as shown in Photo 2. The efflux time in mortar was converted into relative funnel time by equation (2)

3.2.3 Test for concrete

The pan type mixer was used for concrete. The order of materials charging for concrete is explained below. First, concrete mixer was charged with cement and fine aggregate for the dry mix for 30 seconds. Then the mixture was blended for 90 seconds after mixing water threw into mixer. Finally the mixture in mixer goes round with HRWR agent, AE agent and coarse aggregate for 90 seconds.

Slump flow, air content, efflux time with V funnel and filling ability test with U type box(Photo 3) were observed with fresh concrete. A deformed bar was made into an obstacle in U type box. The bottom of U type box divided by obstacle was flat.[11] The efflux time with V funnel for concrete is the same for the mortar test.

The hardened concrete characteristics were examined according to KS F 2405 (for compressive strength) and KS F 2423 (for splitting tensile strength).

4. Results and discussion

4.1 The water retaining capacity from paste test

To test the suitability of GGBF slag as powder composition in SCC, the water retaining capacity(βp) has to be examined. In order to obtain the water retaining capacity, it has to be seen that the water powder volume ratio has the relation with the relative flowing area ratio. The results of flow test for the cement paste are shown in Fig. 2. The intercept points with the y-axis are the water retaining capacity of GGBF slag. The water retaining capacity of cement powder containing GGBF slag is presented in Table 4.

The more slag, the lower the water retaining capacity. The low water retaining capacity indicates a high packing density of powder and low C_3A. βp decrease gradually. It is concluded that the cementitious material is improved in the flowability if the replacement of GGBF slag is increased.

4.2 Optimum water powder volume ratio from mortar test

The relative flowing area ratio has relations with the relative funnel time of mortar using only ordinary portland cement in Fig. 3.

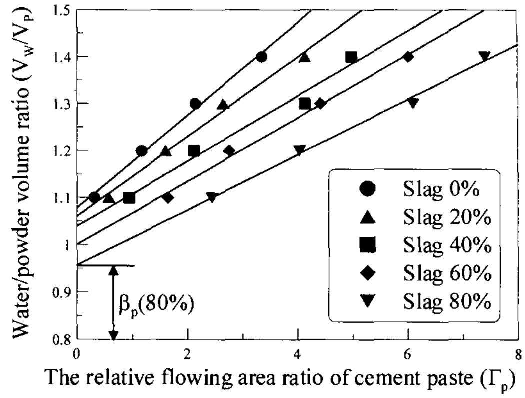

Fig. 2 The relationship between the relative flowing area ratio and water powder volume ratio in paste

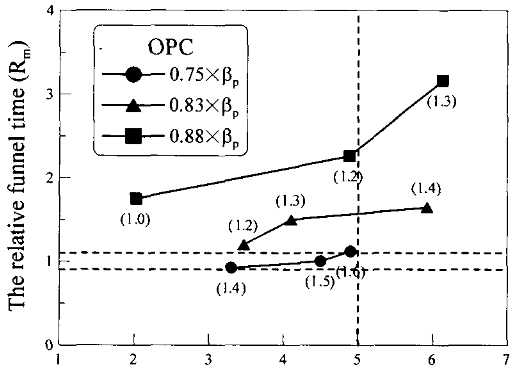

Fig. 3 The relationship between the relative flowing area ratio and the relative funnel time in mortar(OPC)

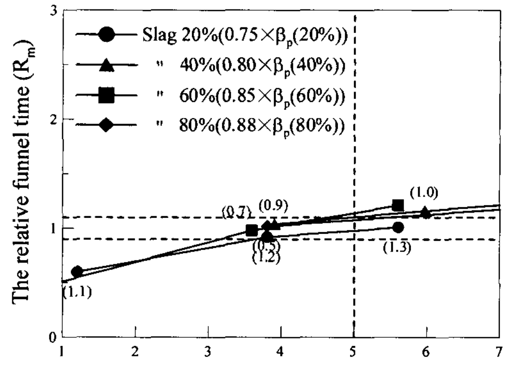

Fig. 4 The relationship between the relative flowing area ratio and the relative funnel time in mortar(GGBF slag))

Okamura recommended that the water powder volume ratio in concrete is decided from the relative flowing area ratio and the relative funnel time in mortar test. If the relative flowing area ratio of 5 can not be obtained from the range of 0.9-1.1 in the relative funnel time, the water powder volume ratio has to be altered. At target mortar flow, if relative funnel time is higher than 1.1, the water powder volume ratio should be decreased. On the other hand, if the relative funnel time is lower than 0.9, the water powder volume ratio should be increased.[9,11)] The values in bracket are the dosage of HRWR agent. The optimum water powder volume ratio of mixture without GGBF slag is 0.81(=0.75 × β p) from the previous mortar test.

In Fig. 4 the relationship between relative funnel time and the relative flowing area ratio of mortar incorporating GGBF slag is shown. The greater the volume of slag, the higher the coefficient of β p. When GGBF slag is used in mixture of 20, 40, 60 and 80 percent, the water powder volume ratio in concrete gets 0.75, 0.80, 0.85 and 0.88 times β p, respectively.

4.3 Properties of self compacting concrete

4.3.1 Mixture proportion

Table 5 shows the mixture proportion of SCC. The volume of coarse aggregate in SCC is fixed at 50, 55 and 60% to solid volume percentage of coarse aggregate respectively, so that self-compactability can be easily achieved by adjusting the water powder volume ratio and HRWR agent dosage only. The water powder volume ratio in concrete can be obtained from the results of paste and mortar tests in Table 4. On the whole, the required air content(5 ± 0.5%) and the required slump flow(650 ± 50mm) meet air contents and slump flows of concrete from the experimental results.

In Fig. 5 and Fig. 6, the dosage of HRWR agent for the target slump flow of 650 ± 50mm, and the dosage of AE agent for the target air content of 5 ± 0.5% are represented respectively. Regardless of the volume of aggregate to the solid volume percentage of coarse aggregate, dosage of

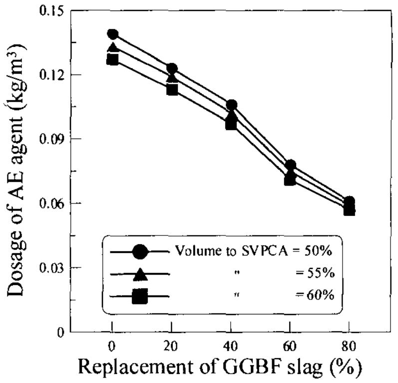

Fig. 5 Dosage of AE agent in GGBF slag concrete

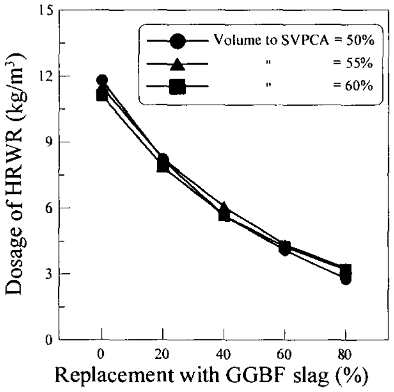

Fig. 6 Dosage of HRWR agent in GGBF slag concrete

Table 4 The water retaining capacity and water powder volume ratio of GGBF slag

Replacement of GGBF slag(%)	0	20	40	60	80
β_p	1.08	1.06	1.04	1.00	0.96
Water powder volume ratio in concrete	0.81	0.80	0.83	0.85	0.84

Table 5 The mixture proportions of self compacting concrete

No.	Replacement (%)	Volume to SVPCA (%)*	Unit weight (kg/m³)						
			W	C	GGBF slag	S	G	HRWR	AE agent
1	0	50	179	694	-	689	770	11.80	0.139
2		55	171	665	-	659	846	11.50	0.133
3		60	163	635	-	630	923	11.11	0.127
4	20	50	177	547	137	689	770	8.20	0.123
5		55	169	528	132	659	846	8.25	0.119
6		60	162	504	126	630	923	7.88	0.113
7	40	50	181	399	266	689	770	5.65	0.106
8		55	173	382	255	659	846	6.05	0.102
9		60	166	365	243	630	923	5.66	0.097
10	60	50	183	260	389	689	770	4.09	0.078
11		55	175	248	373	659	846	4.35	0.075
12		60	168	237	356	630	923	4.25	0.071
13	80	50	183	128	513	689	770	2.78	0.061
14		55	175	123	491	659	846	3.27	0.059
15		60	167	117	469	630	923	3.20	0.057

* : the volume of coarse aggregate to the solid volume percentage of coarse aggregate

HRWR and AE agent are decreases with the slag replacement. It can be seen that the coarse aggregate volume to the solid volume percentage of coarse aggregate doesn't affect the dosage of HRWR and AE agent for the target slump flow and air content, respectively.

4.3.2 Properties of fresh SCC

First, the slump flow from the experimental of SCC is converted into the relative slump flow by the equation (3). The relative slump flow is arranged in Fig.7.

$$\Gamma_c = \left(\frac{F_c}{F_0}\right)^2 - 1 \qquad (3)$$

where, Γ_c : the relative slump flow

F_c : the slump flow of SCC (mm)

F_0 : the initial diameter of flow cone (200mm)

The relative slump flow has been proposed for deformability of SCC.[11] A larger Γc indicates higher deformability. High deformability means good filling ability. From this concrete test results, the more the replacement of GGBF slag, the lower the relative slump flow Γc in SCC. The relative funnel time in concrete has been proposed for testing viscosity of SCC. The formula is same as equation (2) and the index of equation (2) is changed from Rm to Rc meaning concrete.

A smaller Rc indicates higher viscosity while a larger Rc indicates a higher risk of segregation. Therefore, Okamura recommended that the relative funnel time be between 0.5 and 1, represented with dotted line in Fig. 8.[9] If the volume of coarse aggregate is over 60% to the solid volume percentage of coarse aggregate, generally the relative funnel time is out of recommended range. In this case, SCC may have higher viscosity than the reference mixture containing filling and passing ability.

The elapsed time of 500mm slump flow is shown in Fig. 9. The lower elapsed time of 500mm slump flow indicates the greater flowability. Generally a time of 3 to 15 seconds is acceptable in specification of JSCE, Table 2. All the mixture is accepted in SCC, but the mixture of volume 60% shows more slow than other mixtures in elapsed time of 500mm slump flow. The head loss of SCC from the U type box test is shown in Fig. 10. The degree of compactability can be indicated by the concrete reaches after flowing through an obstacle in box, so called head loss. Therefore, the nearer this head loss is to zero, the better the flow and passing ability of the concrete.

All the SCC mixed with the volume of coarse aggregate 60% to the solid volume percentage of coarse aggregate is not compactable and could be caught by reinforced area. Especially the higher volume of GGBF slag has a tendency

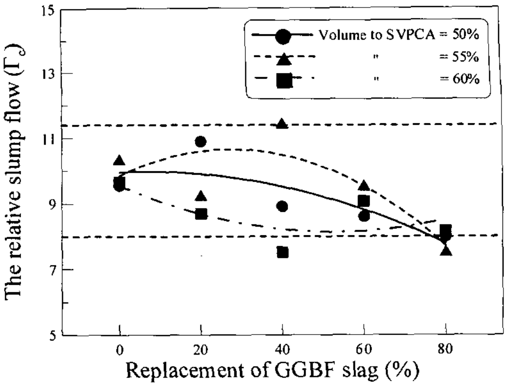

Fig. 7 The relative slump flow in GGBF slag concrete

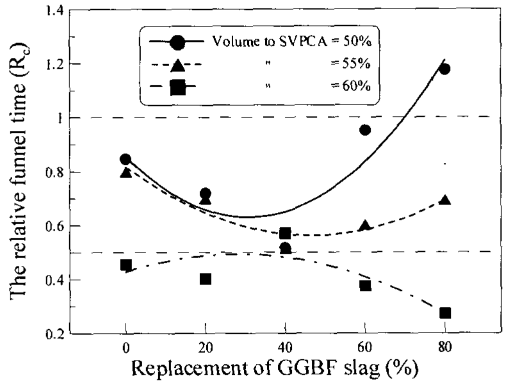

Fig. 8 The relative funnel time in GGBF slag concrete

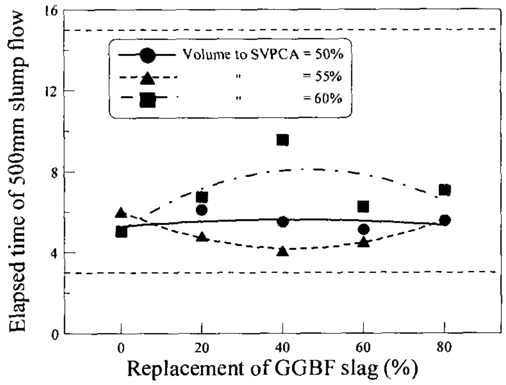

Fig. 9 Elapsed time of 500mm slump flow in GGBF slag concrete

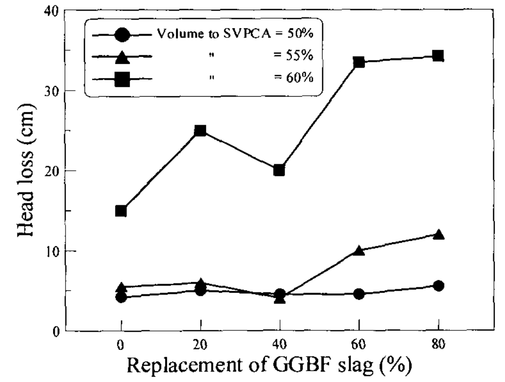

Fig. 10 Head loss by U-type box in GGBF slag concrete

to be remarkable in SCC. It is desirable that the volume of coarse aggregate to the solid volume percentage of coarse aggregate is limited to 55% in SCC.

The results of the relative slump flow, the relative funnel time and head loss show that the volume of coarse aggregate to the solid volume percentage of coarse aggregate has to be the limit of 55% and the optimal replacement of slag is in the range of 40-60% in SCC.

4.3.3 Properties of hardened SCC

Table 6 shows the compressive and splitting tensile strengths of SCC at the age of 7 and 28 days respectively.

Standard cylinder for compressive and splitting tensile strength measuring Ø 100×200mm are demoulded one day after casting. Specimens are then cured in water until the test is carried out at 7 and 28 days.

As expected, the compressive strength is strongly affected by the water cement ratio and filler types. With the similar water cement ratio in Table 5, mixtures of SCC using GGBF slag have a lower strength than the corresponding reference mix(slag 0%) at 7 days, but developed higher strength at 28 days in Table 6. This is due to the slower, but prolonged reaction(hydraulic and pozzolanic) between cement hydration products and GGBF slag which contributes significantly to strength.

The splitting tensile strengths at 28 days for the Ø 100×200mm cylinder specimens are given in Table 6. For easy comparison, the tensile/compressive strength ratios are also included. It is worth noting that each result in Table 6 is the average of only three specimens. Results in Table 6 indicate that the relationships of the tensile strength to the compressive strength are of similar orders for all the mixes studied. Generally the higher strength concrete gets the lower tensile/compressive strength ratio in conventional concrete. In this table, the strength ratios of concrete incorporating GGBF slag from 20 to 40% have no difference with the concrete using only ordinary portland cement. In GGBF slag of 80% volume, however, the strength ratio makes a rapid progress. Therefore, the tensile/compressive strength ratios indicate that there is no significant difference in the pattern of conventional concrete.

5. Conclusions

From the fundamental study based on the Okamura's method, the properties of self compacting concrete incorporating GGBF slag are as follows:

1) The water retaining capacity in ordinary portland cement is 1.08. The water retaining capacity in matrix decreases inversely proportional to the amount of GGBF slag.
2) The optimum water powder volume ratio of self compacting concrete without GGBF slag is 0.81(=0.75 × β p) with the mortar test. When GGBF slag is used in mixture of 20-80%, the optimum water powder volume ratio of mixture is 0.8-0.85.
3) From the U type box test, V funnel test and slump flow test, the optimal replacement ratio of GGBF slag in fresh self compacting concrete is in the range of 40-60% of cement matrix by volume.
4) It is desirable to set up the absolute volume ratio of coarse aggregate up to a limit of 55% for self compacting concrete incorporating GGBF slag.

Table 6 Compressive strength and splitting tensile strength

Replacement (%)	Volume to SVPCA (%)	Compressive (MPa)		Splitting tensile (MPa)	Tensile/Compressive strength ratio (%)
		7 days	28 days	28 days	
0	50	52	64.8	4.1	6.3
	55	52.5	64.3	4.0	6.2
	60	53.1	65.5	4.0	6.1
20	50	48.6	61.4	4.1	6.7
	55	48	64.6	4.2	6.5
	60	50.1	63.1	4.2	6.7
40	50	37.7	58	3.9	6.7
	55	39.5	60.6	4.1	6.8
	60	37.2	59.5	4.0	6.7
60	50	27.3	49	3.8	7.8
	55	28.9	54.4	3.9	7.2
	60	30.3	50.7	3.9	7.7
80	50	19.1	31.5	3.2	10.2
	55	20.3	31.5	2.8	8.9
	60	21	33.1	3.0	9.1

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