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A simple mix design method for self-compacting concrete

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Abstract

This paper proposes a new mix design method for self-compacting concrete (SCC). First, the amount of aggregates required is determined, and the paste of binders is then filled into the voids of aggregates to ensure that the concrete thus obtained has flowability, self-compacting ability and other desired SCC properties. The amount of aggregates, binders and mixing water, as well as type and dosage of superplasticizer (SP) to be used are the major factors influencing the properties of SCC. Slump flow, V-funnel, L-flow, U-box and compressive strength tests were carried out to examine the performance of SCC, and the results indicate that the proposed method could produce successfully SCC of high quality. Compared to the method developed by the Japanese Ready-Mixed Concrete Association (JRMCA), this method is simpler, easier for implementation and less time-consuming, requires a smaller amount of binders and saves cost.

Keywords: Slump flow; Filling height; Compressive strength; Mix design

1. Introduction

Self-compacting concrete (SCC), a new kind of high performance concrete (HPC) with excellent deformability and segregation resistance, was first developed in Japan in 1986. It is a special kind concrete that can flow through and fill the gaps of reinforcement and corners of molds without any need for vibration and compaction during the placing process [1,2]. Though showing good performance, SCC is different from the HPC developed in North America and Europe, which emphasizes on high strength and durability of concrete [3,4]. In terms of workability, HPC merely improves fluidity of concrete to facilitate placing; however, it cannot flow freely by itself to pack every corner of molds and all gaps among reinforcement. In other words, HPC still requires vibration and compaction in the construction process. Comparatively, SCC has more favorable characteristics such as high fluidity, good segregation resistance and the distinctive self-compacting ability without any need for vibration during the placing process [5].

To produce SCC, the major work involves designing an appropriate mix proportion and evaluating the properties of the concrete thus obtained. In practice, SCC in its fresh state shows high fluidity, self-compacting ability and segregation resistance, all of which contribute to reducing the risk of honeycombing of concrete [6]. With these good properties, the SCC produced can greatly improve the reliability and durability of the reinforced concrete structures. In addition, SCC shows good performance in compressive strength test and can fulfill other construction needs because its production has taken into consideration the requirements in the structural design.

In 1993, Okamura proposed a mix design method for SCC [2]. His main idea was to conduct first the test on paste and mortar in order to examine the properties and compatibility of superplasticizer (SP), cement, fine aggregates and Pozzolanic materials, then followed by the trial mix of SCC. The major advantage of this method is that it avoids having to repeat the same kind of quality control test on concrete, which consumes both time and labor. However, the drawbacks of Okamura's method are that (1) it requires quality control of paste and mortar prior to SCC mixing, while many ready-mixed concrete producers do not have the necessary facilities for conducting such tests and (2) the

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mix design method and procedures are too complicated for practical implementation.

The "Standardized mix design method of SCC" proposed by the JRMCA [7] is a simplified version of Okamura's method. This method can be employed to produce SCC with a large amount of powder materials, and a water/binder ratio of < 0.30. On the other hand, the Laboratory Central Des Ponts et Chausses (LCPC), the Swedish Cement and Concrete Research Institute (CBI), research groups in both Mainland China and Taiwan all have proposed different mix design methods of HPC. The LCPC's approach is developed on the basis of the BTRHEOM rheometer and RENE LCPC software. It is difficult for others to adopt their method without purchasing the software [8]. CBI's approach makes use of the relationship between the blocking volume ratio and clear reinforcement spacing to fraction particle diameter ratio. However, it is not clear how to carry out the critical tests because concrete mixed with coarse aggregates and paste only is susceptible to severe segregation [6]. In Taiwan, the method proposed by Hwang et al. involves a densified mixture design algorithm, which is derived from the maximum density theory and excess paste theory. Nevertheless, there is no information yet concerning the relationship between their method and the ability of concrete passing through reinforcement or its segregation resistance [9]. Hon's group of Mainland China has not disclosed their mix design procedures, but just offered some useful principles. They have also shown that too low a paste volume not only impairs the passing ability of concrete, but also reduces its compression strength if no vibration is used in the mixing process [6].

To check whether the fresh properties of SCC mixed by the proposed method in this study comply with the requirements specified by the Japanese Society of Civil Engineering (JSCE) [10], laboratory tests, such as the slump flow, V-funnel, U-box and L-flow tests were conducted using indigenous materials from Taiwan. The following sections detail the procedures of the simple mix design method and discuss the results of the performance tests on SCC thus obtained.

2. Mix design procedures of the proposed method

The principal consideration of the proposed method is to fill the paste of binders into voids of the aggregate framework piled loosely. The loose unit weight of the aggregate is according to the shoveling procedure of ASTM C29, except discharging the aggregate at a height of 30 cm above to the top of the measure. Usually, the volume ratio of aggregate is about 52–58%, in other words, the void in the loose aggregate is about 42–48% according to ASTM C29. The strength of SCC is provided by the aggregate binding by the paste at hardened state, while the workability of SCC is provided by the binding paste at fresh state. Therefore, the contents of coarse and fine aggregates, binders, mixing water and SP will be the main factors influencing the properties of SCC. With the proposed method, all we need to do is to select the qualified materials, do the calculations, conduct mixing tests and make some adjustments, and SCC with good flowability and segregation resistance can be obtained with self-compacting ability as specified by the JSCE (Table 1). The procedures of the proposed mix design method can be summarized in the following steps.

2.1. Step 1: calculation of coarse and fine aggregate contents

When surface-dry coarse and fine aggregates are loosely stacked together, friction and voids exist between them. Lubrication occurs when water and binders are added to the aggregates, thus, making the pile of aggregates becomes more compact. Usually, the volume ratio of aggregate after lubrication and compaction in SCC is about 59–68%. In this study, the packing factor (PF) of aggregate is defined as the ratio of mass of aggregate of tightly packed state in SCC to that of loosely packed state. Clearly, PF affects the content of aggregates in SCC. A higher PF value would imply a greater amount of coarse and fine aggregates used, thus, decreasing the content of binders in SCC. Consequently, its flowability, self-compacting ability and compressive strength will be reduced. On the other hand, a low PF value would mean increased dry shrinkage of concrete. As a result, more binders are required, thus, raising the cost of materials. In addition, excess binders used would also affect the workability and durability of SCC. Therefore, it is important to select the optimal PF value in the mix design method so as to meet the requirements for SCC properties, and at the

Table 1
Specification of SCC proposed by JSCE [10]

		1	2	3
Class of filling ability of concrete				
Construction condition	Minimum gap between reinforcement (mm)	30–60	60–200	≥ 200
	Amount of reinforcement (kg/m^3)	≥ 350	100–350	≤ 100
Filling height of U-box test (mm)		≥ 300 (rank R1)	≥ 300 (rank R2)	≥ 300 (rank R3)
Absolute volume of coarse aggregates per unit volume of SCC (m^3/m^3)		0.28–0.30	0.30–0.33	0.30–0.36
Flowability	Slump flow (mm)	650–750	600–700	500–650
Segregation resistance ability	Time required to flow through V-funnel (s)	10–20	7–20	7–20
	Time required to reach 500 mm of slump flow (s)	5–25	3–15	3–15

same time taking economic feasibility into consideration. The content of fine and coarse aggregates can be calculated as follows (Eqs. (1) and (2)):

$$W_g = \mathrm{PF} \times W_{gL}\left(1 - \frac{S}{a}\right) \quad (1)$$

$$W_s = \mathrm{PF} \times W_{sL} \times \frac{S}{a} \quad (2)$$

where W_g: content of coarse aggregates in SCC (kg/m^3); W_s: content of fine aggregates in SCC (kg/m^3); W_{gL}: unit volume mass of loosely piled saturated surface-dry coarse aggregates in air (kg/m^3); W_{sL}: unit volume mass of loosely piled saturated surface-dry fine aggregates in air (kg/m^3); PF: packing factor, the ratio of mass of aggregates of tightly packed state in SCC to that of loosely packed state in air; S/a: volume ratio of fine aggregates to total aggregates, which ranges from 50% to 57%.

The Japanese Architecture Society [11] specifies three categories of maximum size of aggregate: 15, 20 and 25 mm. The most commonly used size is 20 mm. It is also suggested that the content of coarse aggregates should be about 50% of the dry packed unit weight (JIS A1104, ASTM C29). Since the winter temperature in Japan is below 0°C, the amount of air required in the concrete is about 4.5%. In contrast, Taiwan is in the subtropical region and has no freezing and thawing problems; so the air content in SCC is about 1.5%, depending on the construction method as well as the type and dosage of SP.

2.2. Step 2: calculation of cement content

To secure good flowability and segregation resistance, the content of binders (powder) should not be too low. According to the "Guide to Construction of High Flowing Concrete" [10], the minimum amount of cement to be used for producing normal concrete and the high durability concrete are 270 and 290 kg/m^3, respectively. However, too much cement used will increase the drying shrinkage of SCC. Generally, HPC or SCC used in Taiwan provides a compressive strength of 20 psi (0.14 MPa)/kg cement. Therefore, the cement content to be used is (Eq. (3)):

$$C = \frac{f'c}{20} \quad (3)$$

where C: cement content (kg/m^3); $f'c$: designed compressive strength (psi).

2.3. Step 3: calculation of mixing water content required by cement

The relationship between compressive strength and water/cement ratio of SCC is similar to that of normal concrete. The water/cement ratio can be determined according to ACI 318 or other methods in previous studies. The content of mixing water required by cement can then be obtained using (Eq. (4)):

$$W_{wc} = \left(\frac{W}{C}\right)C \quad (4)$$

where W_{wc}: content of mixing water content required by cement (kg/m^3); W/C: the water/cement ratio by weight, which can be determined by compressive strength.

2.4. Step 4: calculation of fly ash (FA) and ground granulated blast-furnace slag (GGBS) contents

Large amounts of powder materials are added to SCC to increase flowability and to facilitate self-compacting. However, an excess amount of cement added will greatly increase the cost of materials and dry shrinkage. Moreover, its slump loss would become greater, and its compressive strength will be higher than that required in the design. In view of this, the proposed mix design method utilizes the appropriate cement content and W/C to meet the required strength. To obtain the required properties such as segregation resistance, FA and GGBS are used to increase the content of binders. When the flow values (ASTM C230) of the FA and GGBS pastes are equal to that of the cement paste and let W/F and W/S be the ratios of water/FA and water/GGBS by weight. Then the volume of FA paste (V_{Pf}) and GGBS paste (V_{PB}) can be calculated as follows:

$$V_{Pf} + V_{PB} = 1 - \frac{W_g}{1000 \times G_g} - \frac{W_s}{1000 \times G_s} - \frac{C}{1000 \times G_C} - \frac{W_{wc}}{1000 \times G_w} - V_a \quad (5)$$

where G_g: specific gravity of coarse aggregates; G_s: specific gravity of fine aggregates; G_c: specific gravity of cement; G_w: specific gravity of water; V_a: air content in SCC (%).

If the total amount of Pozzolanic materials (GGBS and FA) in SCC is W_{pm} (kg/m^3), where the percentage of FA is A% and the percentage of GGBS is B% by weight, the adequate ratio of these two materials can be set according to the properties of local materials and previous engineering experience.

$$V_{Pf} + V_{PB} = \left(1 + \frac{W}{F}\right) \times A\% \times \frac{W_{pm}}{1000 \times G_f} + \left(1 + \frac{W}{S}\right) \times B\% \times \frac{W_{pm}}{1000 \times G_B} \quad (6)$$

where G_f, G_B, G_c, W/F and W/S can be obtained from tests, A% and B% are given, and $V_{Pf} + V_{PB}$ can be obtained from

Eq. (5). Hence, W_{pm} can be calculated using Eq. (6). Also, W_f (FA content in SCC, Kg/m^3) and W_B (GGBS content in SCC, Kg/m^3) can be calculated (Eqs. (7) and (8)),

$$W_f = A\% \times W_{pm} \quad (7)$$

$$W_B = G\% \times W_{pm} \quad (8)$$

Mixing water content required by FA paste is (Eq. (9)):

$$W_{wf} = \left(\frac{W}{F}\right) W_f \quad (9)$$

Mixing water content required by for GGBS paste is (Eq. (10)):

$$W_{wB} = \left(\frac{W}{S}\right) W_B \quad (10)$$

2.5. Step 5: calculation of mixing water content needed in SCC

The mixing water content required by SCC is that the total amount of water needed for cement, FA and GGBS in mixing. Therefore, it can be calculated as follows (Eq. (11)):

$$W_w = W_{wc} + W_{wf} + W_{wB} \quad (11)$$

According to the Japanese Architecture Society [11]: $W_w = 160-185$ kg/m^3.

2.6. Step 6: calculation of SP dosage

Adding an adequate dosage of SP can improve the flowability, self-compacting ability and segregation resistance of fresh SCC for meeting the design requirements. Water content of the SP can be regarded as part of the mixing water. If dosage of SP used is equal to n% of the amount of binders and its solid content of SP is m%, then the dosage can be obtained as follows (Eq. (12) and (13)):

$$\text{Dosage of SP used } W_{SP} = n\%(C + W_f + W_B) \quad (12)$$

$$\text{Water content in SP } W_{wSP} = (1 - m\%) W_{SP} \quad (13)$$

2.7. Step 7: adjustment of mixing water content needed in SCC

According to the moisture content of aggregates at the ready-mixed concrete plant or construction site, the actual amount of water used for mixing should be adjusted.

2.8. Step 8: trial mixes and tests on SCC properties

Trial mixes can be carried out using the contents of materials calculated as above. Then, quality control tests for SCC should be performed to ensure that the following requirements are met.

1. Results of slump flow, U-Box, L-flow and V-funnel tests should comply with the specifications of the JAS.
2. The segregation phenomenon of materials should be satisfactory.
3. Water–binders ratio should satisfy the requirements of durability and strength.
4. Air content should meet the requirement of the mix design.

2.9. Step 9: adjustment of mix proportion

If results of the quality control tests mentioned above fail to meet the performance required of the fresh concrete, adjustments should be made until all properties of SCC satisfy the requirements specified in the design. For example, when the fresh SCC shows poor flowability, the PF value is reduced to increase the binder volume and to improve the workability.

3. Sample calculation of the proposed method

In the following, an example of a mix proportion of SCC with $f'c = 27.5$ MPa (4000 psi) for 28 days, and a compaction ability of rank R2, as specified by the JSCE (Table 1), was illustrated. The maximum size of coarse aggregates is 25 mm, specific gravity of coarse aggregates is 2.65, and bulk density of loose coarse aggregates is 1500 kg/m^3. The specific gravity of fine aggregates is 2.64, and the bulk density of loose fine aggregates is 1404 kg/m^3. The specific gravity of cement is 3.15, specific gravity of FA and GGBS are 2.15 and 2.92, respectively. The ratio of FA to GGBS is 7:3 by weight, the volume ratio of fine/coarse aggregates is 58/42, the SP used is naphthalene-based sulfonates with a specific gravity of 1.064, and air content in SCC is 1.5%.

3.1. Step 1: determine the coarse and fine aggregate contents

Assume PF = 1.18.

Table 2
Mix proportion of SCC (kg/m^3)

$f'c$ (MPa)	Coarse aggregates	Fine aggregates	Cement	FA[a]	GGBS[b]	Water	SP[c]
27.5	743	961	200	157	67	176	7.6
34.3	731	945	250	154	66	173	8.5
41.2	718	928	300	148	63	172	8.2
48.0	706	912	350	142	61	170	8.8

[a] FA: fly ash.
[b] GGBS: ground granular blast-furnace slag.
[c] SP: superplasticizer.

Table 3
Composition and physical properties of binders

Binders	SiO_2[a]	Al_2O_3	Fe_2O_3	CaO	MgO	LOI[b]	SSA (m^2/kg)[c]	SG[d]
Cement	20.49	6.57	3.27	62.40	1.91	1.57	305.4	3.14
FA	55.5	27.9	6.3	6.27	1.6	5.01	(86.95% < 45 μm)	2.15
GGBS	34.81	13.63	0.32	40.51	6.96	0.40	422	2.92

[a] Percent by weight.
[b] LOI: loss on ignition.
[c] SSA: specific surface area.
[d] SG: specific gravity.

Amount of fine aggregates needed per unit volume of SCC:

$$W_s = 1404 \times 1.18 \times 58\% = 961 \text{ kg/m}^3$$

Amount of coarse aggregates needed per unit volume of SCC:

$$W_g = 1500 \times 1.18 \times (1 - 0.58) = 743 \text{ kg/m}^3$$

3.2. Step 2: determine the cement content

Assume each kg of cement can provide a compressive strength of 20 psi for SCC at 28 days.

Amount of cement needed per unit volume of SCC:

$$C = \frac{4000}{20} = 200 \text{ kg/m}^3$$

3.3. Step 3: determine the mixing water content required by cement

According to the experience of the Ready-Mixed Concrete in Taiwan, the water/cement ratio of SCC produced with FA and GGBS is about 0.43 for obtaining $f'c = 4000$ psi for 28 days.

Table 4
Properties of aggregates

Sieve size	Coarse aggregates	Fine aggregates
1 in.	100[a]	–
3/4 in.	87.13	–
1/2 in.	38.43	–
3/8 in.	25.78	100
#4	0.95	95.87
#8	0	82.2
#16	–	59.8
#30	–	29.8
#50	–	6.73
#100	–	1.0
Specific gravity	2.65	2.64
Absorption (%)	1.33	2.16
Unit weight (kg/m^3)[b]	1500	1404

[a] Percentage of passing.
[b] Bulk density at loosely packed state.

Amount of mixing water needed for cement:

$$W_{wc} = 0.43 \times 200 = 86 \text{ kg/m}^3$$

3.4. Step 4: determine the FA and GGBS contents

According to the flow table tests (ASTM C230) with Ottawa sand and the same dosage of SP, the *W/S* ratio of GGBS mortar is 0.36, and *W/F* ratio of FA mortar is 0.45 for obtaining the same consistency of cement mortar with *W/C* ratio = 0.43. Since FA:GGBS (by weight) = 7:3, the total volume of FA paste and GGBS paste can be obtained using the following equation:

$$V_{Pf} + V_{PB} = 1 - \left(\frac{743}{1000 \times 2.65} - \frac{961}{1000 \times 2.64} - \frac{200}{1000 \times 3.15} - \frac{86}{1000 \times 1} - 0.015\right) = 0.191 \text{ m}^3/\text{m}^3$$

$$\frac{0.7 \times W_{pm}}{1000 \times 2.15} + \frac{0.45 \times 0.7 \times W_{pm}}{1000 \times 1} + \frac{0.3 \times W_{pm}}{1000 \times 2.92} + \frac{0.36 \times 0.3 \times W_{pm}}{1000 \times 1} = 0.191$$

Amount of FA and GGBS (W_{pm}) needed:

$$W_{pm} = 224 \text{ kg/m}^3$$

FA content $W_f = 0.7 \times 224 = 157 \text{ kg/m}^3$

GGBS content $W_B = 0.3 \times 224 = 67 \text{ kg/m}^3$

3.5. Step 5: determine the mixing water content required for FA and GGBS

Water content for FA $W_{wf} = 0.45 \times 157 = 70.7 \text{ kg/m}^3$.

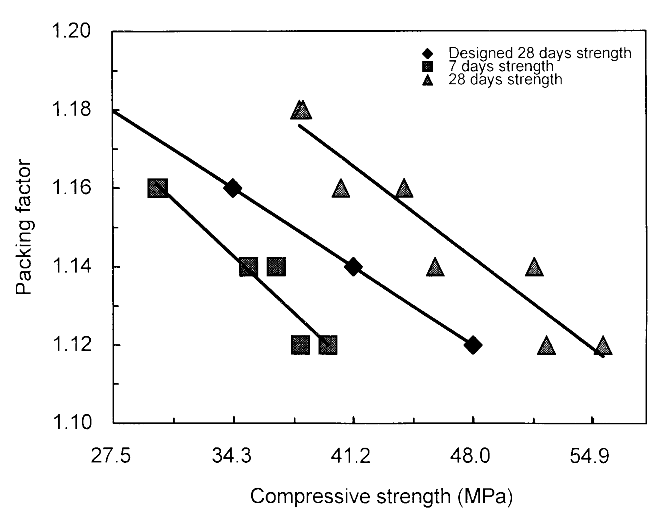

Fig. 1. Effect of aggregate packing factor on compressive strength of SCC.

Table 5
Effect of packing factor on flowability and passing ability of SCC

Packing factor	Binders volume (1/1000 m^3)	Slump flow (cm × cm)	L-flow test (cm)	V-funnel flow time (s)	Segregation resistance
1.12	198	71 × 72	74	14	Excellent
1.14	186	70 × 71	72	12	Excellent
1.16	174	69 × 70	68	11	Good
1.18	160	60 × 60	57	7	Good

* The channel length of L-flow test is 75.5 cm.

Water content for GGBS $W_{wB} = 0.36 \times 67 = 24.1$ kg/m^3.

3.6. Step 6: determine the SP dosage

The solid content of SP is 40%. According to previous engineering experience, the dosage of SP is 1.8% of the content of binders for meeting the SCC requirements specified in Table 1.

Dosage of SP:

$$W_{SP} = 0.018 \times (200 + 157 + 67) = 7.6 \text{ kg/m}^3$$

3.7. Step 7: adjustment of mixing water content needed in SCC

Amount of water in SP:

$$W_{wSP} = (1 - 0.4) \times 7.6 = 4.6 \text{ kg/m}^3$$

Amount of mixing water needed in SCC:

$$W = W_{wc} + W_{wf} + W_{wB} - W_{wSP} = 86 + 70.7 + 24.1 - 4.6$$
$$= 176.2 \text{ kg/m}^3$$

3.8. Step 8: trial batches and tests on SCC properties

Trial batches are made using the contents of materials determined as above. The methods and test results will be discussed in Sections 4 and 5.

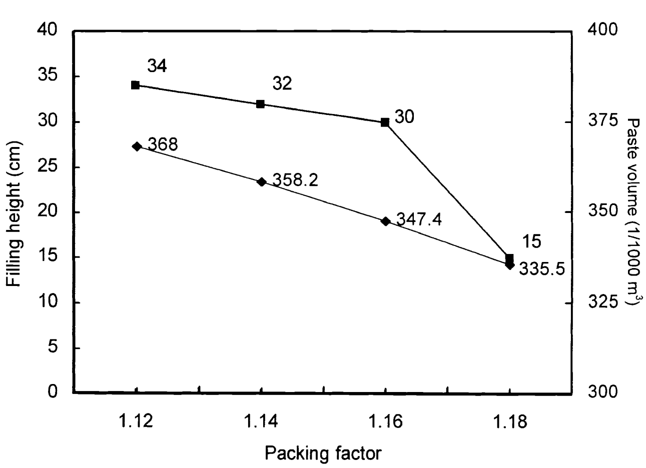

Fig. 2. Effect of packing factor on filling height of U-box and paste volume of SCC.

Not only can the above method be used to calculate the mix proportion for SCC with 27.5 MPa (4000 psi) of designed compressive strength, it can also be used to obtain the mix proportion for SCC of grade 34.3 (5000), 41.2 (6000) or 48 MPa (7000 psi). The dosages of SP are 1.8% of the binders content by weight and fine/coarse aggregates by volume = 58/42 for the examples shown in Table 2.

4. Materials and experimental methods

To verify whether the mix proportion obtained by the proposed mix design method could meet the requirements of JSCE, the following experiments were carried out.

4.1. Materials

1. Cement: Type 1 Portland cement produced by Taiwan Cement. Its specific gravity is 3.15, physical and chemical properties are listed in Table 3.
2. Coarse and fine aggregates: Gravel from Chuo-shuei River in Central Taiwan. The maximum size of aggregate is 25 mm; physical property and size gradation are shown in Table 4.
3. FA: From Hsin-Ta Power Plant of Taipower. Its specific gravity is 2.15, physical and chemical properties are listed in Table 3.

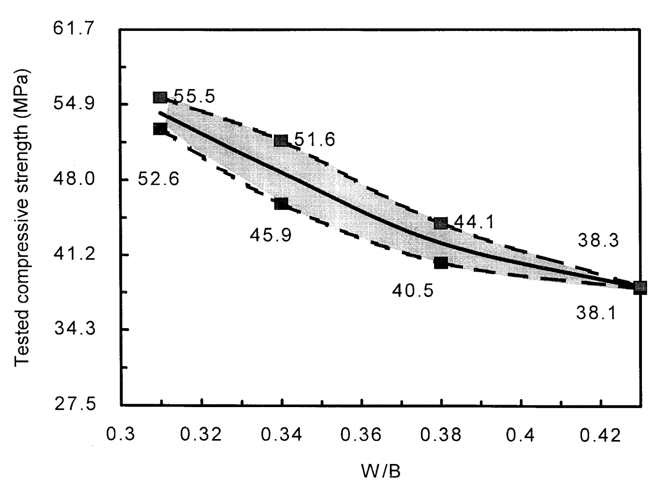

Fig. 3. Relationship between compressive strength and water to binder ratio of SCC.

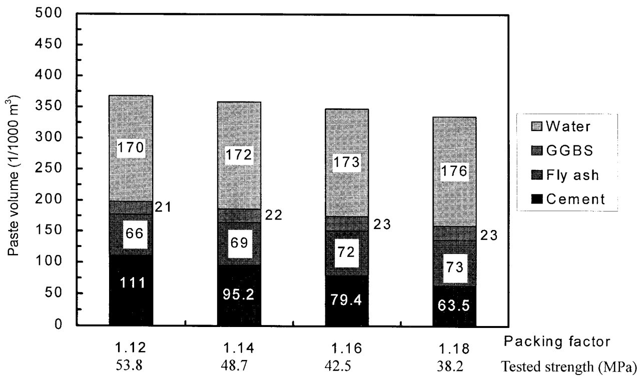

Fig. 4. Relationship between paste volume, compressive strength and packing factor.

4. GGBS: From Chung-Lien Resource. Its specific gravity is 2.92, physical and chemical properties are listed in Table 3.

5. Mixing water: From Taiwan Tap Water in Touliu.

6. SP: A commercial naphthalene-based SP (SNF) manufactured by Feng-Yo Chemical. Its specific gravity is 1.064, and 40% in solid content.

4.2. Test methods

1. Slump flow test: According to JASS T-503 in "Recommendations for Mix Design and Construction Practice of High Fluidity Concrete" of JAS [12].

2. V-funnel test: According to the "Funnel flow test method" in "Guide to Construction of High Flowing Concrete" issued by the JSCE [10]. This test measures the viscosity property of concrete, and can also detect the arching effect of aggregate. The flow time through the funnel is measured as the time taken to see daylight appearing when viewed from above. The size at the discharge end of the funnel is 65 × 75 mm.

3. U-test: According to the "Testing method of passing ability through reinforcement by U-box" in "Guide to Construction of High Flowing Concrete" issued by JSCE [10]. This test, proposed by the Taisei group and recommended by Okamura (1996), is very useful in evaluating the passing ability through reinforcement as well as self-compacting ability. The filling height of concrete (B_h), which passed through the gaps of rebars of the U-test under its own weight, indicates the degree of the self-compacting ability of the concrete. Normally, the requirement of filling height of SCC is above 30 cm according to the specification of Table 1.

4. L-flow test: According to the "L-flow test method" in "Recommendations for Mix Design and Construction Practice of High Fluidity Concrete" issued by the JAS [12]. This test has been used to assess flowability and passing ability of concrete. SCC was poured into the funnel and then released to fall under its own weight, passing through three rebars, into the trough.

5. Compressive test: According to ASTM C39. Concrete cylinders (diameter = 15 cm, height = 30 cm) with mix proportion shown in Table 3 were produced and cured in lime-water for 7 and 28 days at 23 ± 1°C for tests on compressive strength.

5. Results and discussion

Fig. 1 shows that the compressive strength of SCC decreased with increasing PF value. The specimens mixed by the proposed method and cured for 7 days showed 81–90% of the designed compressive strength. On 28 days, its strength was 6.1–10.7 MPa higher than that required in the design. Hence, it is clear that the proposed mix design method can produce concrete that meets satisfactorily the compressive strength requirement. Since PF value is closely related with compressive strength, by adjusting PF to 1.18, 1.16, 1.14 and 1.12, the SCC thus obtained could satisfy the compressive strength requirements of 27.5, 34.3, 41.2 and 48 MPa, respectively. As for slump flow, when values of PF are 1.12, 1.14 and 1.16, the slump flow values are 71 × 72, 70 × 71 and 69 × 70 cm, respectively, as shown in Table 5. This indicates that the SCC can satisfy the requirement of rank R1 shown in Table 1. When PF is 1.18, the slump flow value is 60 × 60 cm, which also meet the rank R2 requirement. When PF value is 1.12, 1.14 or 1.16, the filling height is 30–34 cm, which fulfils the requirement of $B_h > 30$ cm, specified in Table 1. Fig. 2 shows that a reduction in PF value would decrease the content of aggregates and increase the volume of paste, thus, enhancing the passing ability through reinforcement and segregation resistance of SCC. When PF are 1.12, 1.14 and 1.16, the filling heights are 34, 32 and 30 cm,

Table 6
Mix proportion of SCC by volume (0.001 m^3/m^3)

Designed strength (MPa)	Coarse aggregates	Fine aggregates	Binders			Water	SP	Total	Packing factor
			Cement	FA	GGBS				
27.5	281	364	63.5	73	23	176	7	987.5	1.18
34.3	276	358	79.4	72	23	173	8	989.4	1.16
41.1	271	351	95.2	69	22	172	8	988.2	1.14
48.0	266	345	111	66	21	170	8	987	1.12

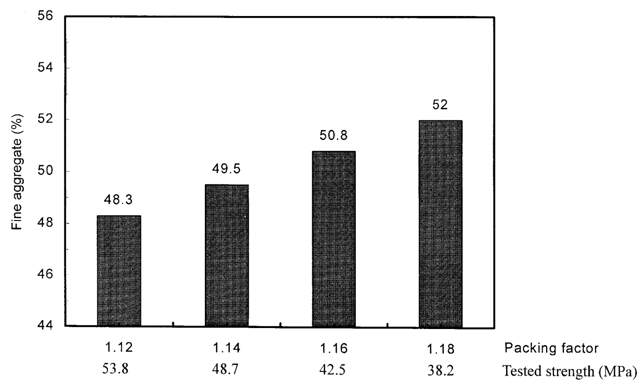

Fig. 5. Relationship between fine aggregate volume ratio, compressive strength and packing factor.

respectively. In contrast, the filling height is only 15 cm when PF = 1.18. The filling height in U-box test of SCC is found to be inversely proportional to the PF value in the calculation of mix proportion.

Although factors such as content of fine and coarse aggregates, material proportions, and curing age can affect the compressive strength of SCC, the ratio of water to binders by weight (*W*/*B*) is the most prominent determinant of compressive strength as shown in Fig. 3. As can be seen in Fig. 4, the smaller the PF value, the more the paste volume in SCC will be. As a result, the compressive strength becomes higher. Table 6 shows that with the proposed mix design method, the volume of mixing water required in SCC is 0.170–0.176 m^3/m^3, while that of binders is 0.159–0.198 m^3. The volume of binding paste has great effect on the compressive strength of SCC. In this study, the maximum content of binders used is 424 kg/m^3, which is lower than 500 kg/m^3 powder as suggested by the Japanese mix design method. On the other hand, to obtain SCC with 27.5–54.9 MPa compressive strength, the content of cement required by the proposed method is only 200–350 kg/m^3, thus, saving a lot on the cost of cement needed.

Table 1 suggests that the absolute volume of the coarse aggregates for SCC should be 0.28–0.36 m^3/m^3; however, the absolute volume of the coarse aggregates in the SCC prepared by the proposed method is only 0.266–0.281 m^3/m^3, as seen in Table 6. The mix design method proposed by Okamura suggested that the content of coarse aggregates was about of 50% of its unit weight [2,5]; however, using this method can reduce the content of coarse aggregates needed to 706–743 kg/m^3. Fig. 5 shows that the ratio of fine aggregate volume to mortar volume is 48.3–50%, which is higher than the value of 40% presented by Okamura [2,5]. Hence, the content of fine aggregates in the SCC prepared by this method will be rather high, so that it can meet the requirements of flowability, self-compacting ability, segregation resistance as well as medium compressive strength (27.5–48 MPa), thus affecting the elastic modulus of SCC. On the other hand, compressive strength of SCC is found to be inversely proportional to sand content in mortar. It is obvious that this proposed mix design method use much less binders. For example, in the case of SCC with $f'c = 34.3$ MPa, the amount of binders used is only 470 kg/m^3, while that of cement is only 250 kg/m^3. The slump flow of the fresh SCC is 69×70 cm and the filling height reaches 30 cm. As can be seen in Table 6, when PF is 1.12, 1.14 or 1.16, the V-funnel flow time is 14, 12 or 16 s, respectively, which meets the requirement of rank R1 as specified in Table 1. When PF is 1.18, the V-funnel flow time is 7 s, which satisfies the rank R2 requirement. It is also clear that when PF = 1.12, 1.14, 1.16 and 1.18, the aggregates in SCC did not segregate. In addition, when PF = 1.12, 1.14 and 1.16, the flow length of the L-flow test reaches 68–72 cm, indicating good flowability of SCC.

6. Conclusions and suggestions

1. The aggregate PF determines the aggregate content and influences the strength, flowability and self-compacting ability.
2. SCC designed and produced with the proposed mix design method contains more sand but less coarse aggregates, thus the passing ability through gaps of reinforcement can be enhanced.
3. In this design method, the volume of sand to mortar is in the range of 54–60%.
4. The water content of SCC prepared by the proposed method is about 170–176 kg/m^3 for the medium compressive strength.
5. The amount of binders used in the proposed method can be less than that required by other mix design methods due to the increased sand content.
6. This novel mix design method is simpler, requires a smaller amount of binders, and saves cost.
7. The PF value is the control factor for filling height of U-box test. The fresh properties of concrete with PF = 1.12–1.16 can meet the rank R1 requirements specified by the Japanese mix-design method.
8. Because SCC produced with this method contains less coarse aggregates, further studies are needed to evaluate its affect on the elastic modulus of concrete.
9. The optimal PF for SCC with different requirements merits further investigation.

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