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Rapid testing method for segregation resistance of self-compacting concrete

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Abstract

A simple apparatus and a rapid method for testing the segregation resistance of self-compacting concrete (SCC) were developed. Extensive test programs of SCC with differences in water–binder ratios, paste volumes, combinations between fine and coarse aggregates and different types as well as different contents of cements and mineral admixtures were carried out. The test results showed that the developed apparatus and method are useful in rapidly assessing the segregation resistance of SCC in both vertical and horizontal directions.

Keywords: Self-compacting concrete; Segregation resistance; Rapid testing method; Penetration apparatus

1. Introduction

Self-compacting concrete (SCC) is a new type of concrete that can fill all corners of formwork without vibration. In order to achieve this property, SCC must have good deformability, high segregation resistance and no blocking around reinforcements. Good segregation resistance means that the distributions of aggregate particles in the concrete are relatively equivalent at all locations and at all levels. It also means that concrete should not segregate in vertical and horizontal directions. Segregation resistance plays an important role for SCC because poor segregation resistance can cause poor deformability, blocking around reinforcement and high drying shrinkage as well as nonuniform compressive strength of concrete. Therefore, it is important to have an appropriate method to assess segregation resistance of this new type of concrete. However, there are few publications devoted to testing methods for segregation resistance of SCC. In Australia, research and development of SCC has been carried out at the University of Wollongong for several years. One of the R&D activities has been focused on rapid testing methods for segregation resistance, deformability and blocking behavior, which are the main properties of SCC in its fresh state. The test results of the testing methods for deformability, blocking behavior and segregation resistance in vertical direction were partially reported elsewhere [1]. This paper presents the testing method for rapid assessment of segregation resistance of SCC not only in the vertical direction, but also in the horizontal direction. The laboratory test results on segregation resistance of concrete containing various mineral admixtures, different types of aggregates and different kinds of cements are discussed in the paper.

2. Materials

Five types of cement, namely, two types of shrinkage limited (also called shrinkage reducing) Portland cement, one type of normal Portland cement and two types of blast furnace slag cement, were used. In this paper, two types of shrinkage limited Portland cement and ordinary Portland cement are identified as SLC1, SLC2 and OPC, respectively. Two types of blast furnace slag cement, which contain

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Table 1
Specific gravity, fineness and chemical analysis of the cements and mineral admixtures

	SLC1	SLC2	OPC	BFC1	BFC2	LS1	LS2	LS3	FA
Specific gravity	3.14	3.18	3.15	3.03	2.97	2.65	2.69	2.69	1.9
Fineness index (Blaine) (m^2/kg)	336	357	370	405	410	380	870	1680	–
Mean particle size (μm)	18.2	17.5	–	–	–	27.4	6.3	3.8	–
Passing 45 μm (%)	–	–	–	–	–	–	–	–	91
Chemical compositions:									
SiO_2	20.5	20.4	20.0	25.3	28.3	10.0	1.9	1.3	68.0
Al_2O_3	4.4	4.7	4.7	8.1	10.4	2.1	0.8	0.2	23.0
Fe_2O_3	5.5	4.7	4.7	2.3	1.8	2.8	0.3	0.1	3.0
CaO	64.5	65.0	65.0	55.4	48.4	45.7	53.2	53.6	1.0
SO_3	2.1	2.6	2.6	2.80	2.6	0.09	0.03	0.0	–
MgO	1.5	1.0	0.8	3.05	4.7	0.98	0.55	1.5	0.7
K_2O	0.36	0.57	0.56	0.46	0	0.3	0.1	0.0	1.4
LOI	0.8	0.8	1.0	–	0.5	35.83	40.9	41.1	1.4

SLC1 and SLC2: shrinkage limited (shrinkage reducing) cements; OPC: ordinary Portland cement; BFC1 and BFC2: blast furnace slag cement containing 30% and 65% blast furnace slag, respectively; LS1, LS2 and LS3: milled limestone; FA: fly ash.

30% and 65% of blast furnace slag, are identified as BFC1 and BFC2, respectively. Four types of mineral admixtures, namely, three sources of milled limestone and fly ash were also used in laboratory tests. The three sources of milled limestone and fly ash are specified as LS1, LS2, LS3 and FA, respectively. The specific gravity, fineness and chemical analysis of the cements and mineral admixtures are shown in Table 1.

Six types of crushed basalt coarse aggregate and two types of river sand were used in the concrete testing program. Six types of the coarse aggregates, which include two types with a maximum size of 20 mm, two types with a maximum size of 14 mm and two types with a maximum size of 10 mm are identified as A, B, C, D, E and F, respectively. Two types of river sand are specified as RS1 and RS2. Particle size distributions and specific gravity of the coarse aggregates and river sands are given in Table 2. Naphthalene sulphonate-based superplasticizer in dry form was used in all mixes.

3. Apparatus and testing procedures

3.1. Apparatus

In this study, a mold (mold type M) with a height of 420 mm and a cross-section of 100 × 100 mm was used in conjunction with the conventional apparatus used for testing the compacting factor of normal concrete [2] (Fig. 1), in order to cast specimens for evaluating segregation resistance of SCC in the vertical direction. A set of small cylinder molds (mold type N) with a height of 70 mm and a diameter of 80 mm was used to assess segregation resistance of concrete in horizontal direction (Fig. 2).

A simple apparatus (Fig. 3), called the penetration apparatus (PA), was also developed and used for rapid testing of segregation resistance of SCC. The structure of the apparatus is indicated in Fig. 3 and consists of a Frame F, Slot E, Reading scale M, Screw D and a penetration head. The penetration head, which has a mass of 54 g, is

Table 2
Particle size distribution, maximum size and specific gravity of coarse aggregates and river sands

Screen size (mm)	A (%p)	B (%p)	C (%p)	D (%p)	E (%p)	F (%p)	Screen size (mm)	RS1 (%p)	RS2 (%p)
19.0	99.0	93.5	100.0	100.0	100.0	100.0	2.36	99.0	99.4
13.2	34.0	4.9	90.0	84.2	100.0	99.9	1.18	90.0	84.2
9.5	4.0	0.0	10.0	11.1	90.0	86.7	0.600	60.0	62.2
4.75	1.0	0.0	0.0	0.0	3.0	0.5	0.300	16.0	34.5
2.36	–	–	–	–	–	–	0.150	1.0	8.2
Maximum size (mm)	20	20	14	14	10	10		4.75	4.75
Specific gravity	2.88	2.67	2.87	2.66	2.82	2.69		2.62	2.57

A, B, C, D, E, F: crushed coarse aggregates; RS1 and RS2: river sands.
%p = percentage of passing.

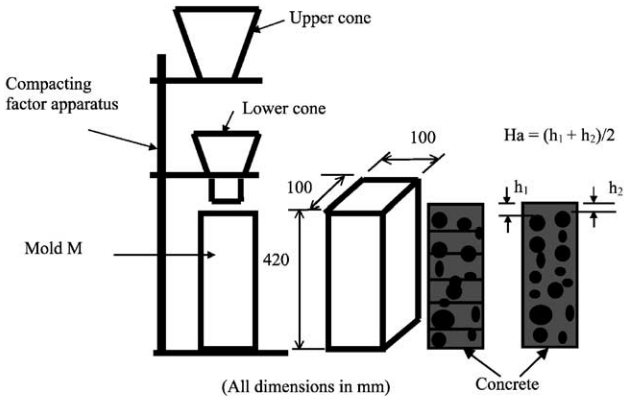

Fig. 1. Mold M and conventional compacting factor apparatus.

assembled from a Cylinder C and Rod K. The inner diameter, height and wall thickness of the cylinder is 75, 50 and 1 mm, respectively.

The L-box apparatus (Fig. 2) was used together with the above-described PA to rapidly test segregation resistance, deformability and blocking behavior of SCC. The set of bars of the L-box apparatus was manufactured in such fashion as to permit: adjustment of the clear spacing between the reinforcement bars; replacement of the bars with different diameters; and easy removal of the reinforcement bars from the box.

3.2. Testing procedure

The testing procedure is carried out with the following steps:

(1) With gate A of the L-box closed, place concrete into the vertical leg of the L-box without any consolidation such as rodding or vibration. Level the top of the placed concrete immediately. Before measuring penetration depth (Pd), care must be taken in order to avoid segregation caused by external impacts (such as L-box moving). Also, care must be taken in order to fill all parts of the mold with a representative sample of concrete (be careful to avoid blocking of coarse aggregate in the upper section of the mold which may occur if the concrete in this region of the mold is nonrepresentative of the whole sample of concrete due to excessive coarse aggregate content in the material filled last).

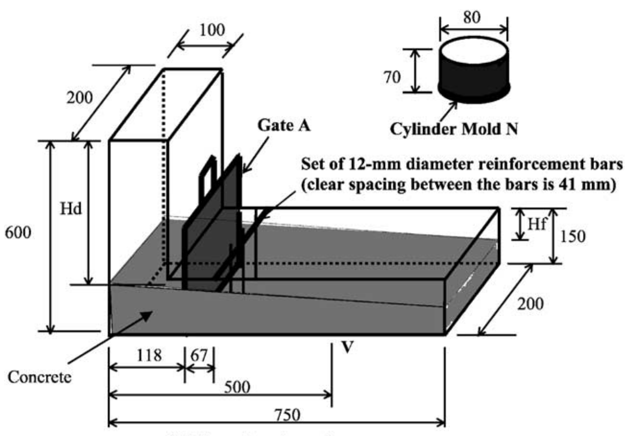

Fig. 2. L-box apparatus and small cylinder mold N.

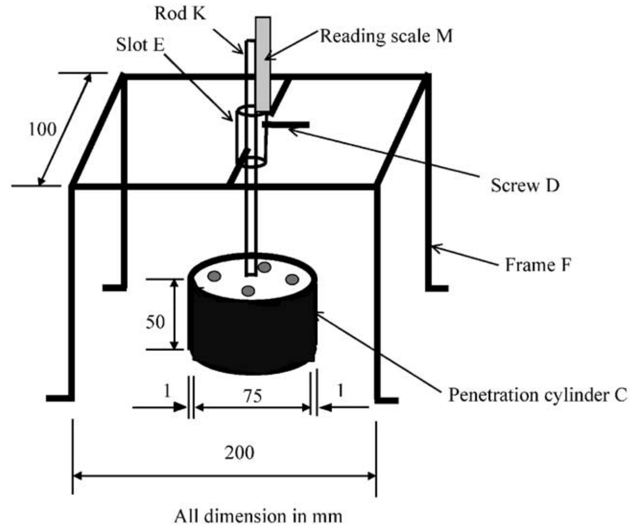

Fig. 3. PA for segregation tests.

(2) After 2 min, locate the PA on the top of the vertical leg of the L-box, adjust the penetration cylinder to just touch the upper surface of concrete, then allow the cylinder to penetrate freely into the concrete. After 45 s, the Pd of the cylinder head is recorded from the scale. The average Pd of three measurements at two sides and the center is calculated and is used together with data from Steps 4, 7 and 8 to assess the segregation resistance of SCC.

(3) Lift gate A in a vertical direction to allow the concrete to flow through the clear spacings between the reinforcement bars.

(4) When the concrete stops flowing, take fresh concrete from the region in front of the reinforcement set and fill it into a pair of small molds (type N). Similarly, take fresh concrete at the end of the horizontal leg of the L-box and again fill the concrete into the other pair of small molds (type N). Immediately, wash out the concrete from the small molds (type N), and coarse aggregate particles larger than 9.5 mm are separated, dried and weighed. The average mass of the coarse aggregate, for each pair of the small molds, is calculated and compared in order to assess segregation resistance of concrete in horizontal direction. Concrete is of satisfactory segregation resistance if the difference (specified as Rh) of average masses of coarse aggregate from the front of the reinforcement set and at the end of the L-box is smaller than 10%.

(5) The difference Rh and the Pd are compared to determine the optimum range of Pd, which can be used to rapidly evaluate the segregation resistance of SCC in the horizontal direction.

(6) Separately, fresh concrete, having a volume of 4.3 l, is placed into the upper cone of the compacting factor

Table 3
Mix proportions and test results related to segregation resistance of SCC

Mix no.	Nga	Vpw (l)	W/B	SP (kg)	Ad. type	Ad. (%)	AC	Fl (mm)	Pd (mm)	Ha (mm)	Rh (%)	Rv (%)	As.
S1	0.40	414	0.30	5.719	LS3	20	T1	710	15	14.8	–	–	Seg
S2	0.52	413	0.30	4.438	LS3	20	T1	685	1	3	–	–	No
S3	0.55	413	0.30	4.428	LS3	20	T1	700	2	4	–	–	No
S4	0.60	413	0.30	3.438	LS3	20	T1	660	1	2	–	–	No
S5A	0.40	353	0.30	15.63	LS3	20	T1	655	1	3	–	–	No
S5B	0.40	355	0.30	18.44	LS3	20	T1	645	2	5.0	–	–	No
S6A	0.52	391	0.30	8.619	LS3	20	T1	720	20	27.0	–	–	Seg
S6B	0.52	390	0.30	6.616	LS3	20	T1	700	15	19.5	–	–	Seg
S6C	0.52	389	0.30	4.594	LS3	20	T1	695	2	4.5	–	–	No
S6D	0.52	393	0.30	5.169	LS3	20	T1	690	1	1	–	4.5	No
S6E	0.52	393	0.30	5.652	LS3	20	T1	710	27	35	–	23.9	Seg
S7A	0.52	346	0.30	5.000	LS3	20	T1	655	1	4.5	–	6.8	No
S7B	0.52	403	0.41	4.745	LS3	20	T1	730	40	48	–	34.7	Seg
S7C	0.52	346	0.30	5.250	LS3	20	T1	660	1	2.5	–	–	No
S7D	0.52	346	0.30	5.625	LS3	20	T1	705	15	19.5	–	–	Seg
S8A	0.52	415	0.30	4.328	LS2	20	T1	670	1	5	–	–	No
S8B	0.52	415	0.30	5.595	LS2	20	T1	725	15	26	–	–	Seg
S9A	0.52	413	0.30	4.438	LS2	20	T1	670	1	0	–	–	No
S9B	0.52	413	0.30	4.508	LS2	20	T1	700	2	3	–	–	No
S10A	0.52	395	0.30	4.465	LS2	20	T1	705	2	4.5	–	–	No
S10B	0.52	395	0.30	4.390	LS2	20	T1	690	1	2.0	–	–	No
S10C	0.52	395	0.30	4.379	LS2	20	T1	680	1	4	–	–	No
S10D	0.52	400	0.32	5.691	LS2	20	T1	715	12	7	–	10.9	Seg
S11	0.52	395	0.30	6.600	–	0	T1	700	3	6	6.2	8.6	No
S12	0.52	346	0.30	6.588	LS2	20	T1	685	1	2	2.0	–	No
S13	0.55	346	0.30	6.587	LS2	20	T1	680	1	2	3.4	–	No
S14A	0.40	352	0.36	7.192	LS2	20	T1	670	3	5	5.5	–	No
S14B	0.40	355	0.37	9.625	LS2	20	T1	680	8	6.0	9.2	5.2	No
S14C	0.52	351	0.36	4.714	LS2	20	T1	690	8	6.5	8.8	7.7	No
S14D	0.60	351	0.36	4.959	LS2	20	T1	640	10	18.5	11.3	11.2	Seg
S15	0.52	393	0.30	5.672	LS2	10	T1	690	1	4	3.4	–	No
S16A	0.52	397	0.30	5.883	LS2	30	T1	720	15	9	13.5	12.2	Seg
S16B	0.52	397	0.30	4.655	LS2	30	T1	690	4	6.5	5.3	4.5	No
S16C	0.52	397	0.30	6.125	LS2	30	T1	725	30	37	–	–	Seg
S17A	0.52	365	0.32	5.456	LS2	20	T2	690	1	2.0	2.7	6.7	No
S17B	0.52	366	0.32	6.592	LS2	20	T2	730	18	17.5	13.8	12.4	Seg
S18A	0.52	365	0.34	7.988	LS2	20	T3	680	2	4.5	5.4	5.4	No
S18B	0.52	365	0.34	8.502	LS2	20	T3	675	11	13.5	12.7	13.2	Seg
S19	0.52	395	0.30	8.717	LS1	20	T1	700	2	4	2.5	–	No
S20	0.52	395	0.30	4.379	LS2	20	T1	680	1	3	3.9	–	No
S21	0.52	395	0.30	4.316	LS2	20	T4	720	4	5	6.8	–	No
S22	0.48	380	0.30	19.83	–	0	T5	610	2	–	4.8	–	No
S23	0.48	380	0.30	15.83	–	0	T5	640	3	1	–	–	No
S24	0.48	380	0.30	13.09	FA	30	T5	655	3	5.5	1.1	–	No
S25	0.48	380	0.30	6.016	FA	65	T5	660	5	5	2.3	–	No
S26	0.48	380	0.35	2.383	–	0	T5	660	1	1	3.6	–	No
S27	0.48	380	0.35	2.485	FA	30	T5	725	4	4	5.3	–	No
S28	0.50	380	0.30	7.406	FA	0	T6	652	3	6.0	4.8	–	No
S29	0.50	380	0.30	5.714	FA	30	T6	655	7	–	9.0	–	No
S30	0.50	380	0.30	8.509	FA	65	T6	690	8	6.0	1.0	–	No
S31	0.50	416	0.30	2.314	FA	30	T6	665	0	0.5	–	–	No
S32	0.50	458	0.30	2.283	FA	65	T6	670	0.5	1.5	–	–	No
S33	0.40	381	0.32	4.800	FA	30	T6	685	2.0	3.5	–	–	No
S34	0.40	360	0.32	23.94	FA	30	T6	660	1.7	1.5	–	–	No
S35	0.50	360	0.32	5.424	BFS	30	T5	715	6.7	4.5	–	–	No
S36	0.50	350	0.32	6.276	BFS	30	T5	658	9.7	7.0	–	–	Seg
S37	0.50	370	0.32	5.484	BFS	30	T5	715	7.0	5.5	–	–	No
S38	0.50	397	0.32	2.708	BFS	30	T5	700	4.5	1.0	–	–	No
S39	0.60	365	0.32	2.768	BFS	30	T5	680	2.0	2.5	–	–	No
S40	0.60	350	0.32	3.164	BFS	30	T5	660	9.7	11.0	–	–	Seg
S41	0.48	380	0.30	4.494	BFS	30	T5	660	3.7	0.5	7.2	–	No
S42	0.48	380	0.35	2.800	BFS	30	T5	720	1.0	1.0	6.7	–	No

Table 3 (*continued*)

Mix no.	Nga	Vpw (l)	W/B	SP (kg)	Ad. type	Ad. (%)	AC	Fl (mm)	Pd (mm)	Ha (mm)	Rh (%)	Rv (%)	As.
S43	0.50	380	0.30	7.886	BFS	30	T6	613	6.3	5.0	6.8	–	No
S44	0.48	380	0.30	8.106	BFS	65	T5	680	5.7	5.0	6.2	–	No
S45	0.48	380	0.35	3.031	BFS	65	T5	685	3.3	3.0	7.0	–	No
S46	0.50	380	0.30	6.317	BFS	65	T6	583	9.0	16.0	8.6	–	Seg

Nga: coarse–total aggregate ratio; Vpw: paste volume for m^3 concrete; W/B: water–binder ratio; SP: superplasticizer dosage for m^3 concrete; Ad. type: mineral admixture type; Ad. (%): percentage of mineral admixture in binder; Fl: slump flow diameter of SCC; Pd: penetration depth; BFS: blast furnace slag; Ha: average depth of coarse aggregate; Rh: coarse aggregate difference in the horizontal direction; Rv: coarse aggregate variation in the vertical direction; As.: segregation assessment; Seg: segregation; No: no segregation.

Cement SLC1 was used in mixes S1–S19; Cement SLC2 was used in mixes S20–S21; Cement OPC was used in mixes S22–S34; Cement BFC1 was used in mixes S35–S43; Cement BFC2 was used in mixes S44–S46.

AC is aggregate combination. T1: aggregates consist of sand RS1 and coarse aggregates, which include 62% of Type A and 38% of Type E; T2: aggregates consist of sand RS1 and coarse aggregates, which include 50% of Type A and 50% of Type E; T3: aggregates consist of sand RS1 and coarse aggregates, which include 40% of Type A and 60% of Type E; T4: aggregates consist of sand RS1 and coarse aggregates, which include 70% of Type C and 30% of Type E; T5: aggregates consist of sand RS2 and coarse aggregates, which include 73% of Type D and 27% of Type F; T6: aggregates consist of sand RS2 and coarse aggregates, which include 62% of Type B and 38% of Type F.

apparatus (Fig. 1) (compacting factor apparatus is modified by removal of the lower cone for this test), and after 1 min, the concrete is released, falling freely into the molding box (type M). After setting, the concrete is demolded and the specimens are cut into two halves in the vertical direction. One half of 15 selected specimens are sectioned into six equal-sized pieces in the horizontal direction. Coarse aggregate particles (larger than 9.5 mm) of each piece are separated and weighed.

(7) The average mass and the variation (Rv) of the mass of the coarse aggregate in the vertical direction are calculated as follows [1,3] (Eqs. (1) and (2)):

$$V = \sum \mathrm{Vgi}/6 \tag{1}$$

$$\mathrm{Rv} = \left[\sum \left\{(\mathrm{Vgi} - V)/V \times 100\right\}^2 /6\right]^{1/2} \tag{2}$$

where Vgi and V are the mass of each piece and average mass of the coarse aggregate with particle size larger than 9.5 mm, and Rv is the variation of the mass of the coarse aggregate in the vertical direction. Segregation resistance of SCC is satisfactory if the value of Rv is smaller than 10%.

(8) The average depth (Ha) of aggregate particles [called aggregate depth (Ha) in this paper] in the upper area of the uncut half is measured (Ha=$(h_1+h_2)/2$ in Fig. 1). [The Ha is the mean of two depths which are the distances between the upper surface of the concrete specimen and the upper surface of the two coarse aggregate particles (with size not smaller than 9.5 mm) closest to the upper surface of the concrete specimen]. Ha is compared with Rv in order to determine the maximum allowable value at which the concrete specimen is of satisfactory segregation resistance.

(9) Similarly to Step 5, Rv, Ha and Pd are compared to determine the optimum range of Pd which can be used to rapidly evaluate the segregation resistance of SCC in the vertical direction.

4. Results and discussion

The mix proportions of the SCC mixtures had different water–binder ratios, different paste volumes and different combinations between fine and coarse aggregates (Table 3). Also, different contents of mineral admixtures and cements have been used. Test results for this study are shown in Figs. 4–14.

4.1. Segregation resistance in the vertical direction

4.1.1. Ha of coarse aggregate and segregation resistance in the vertical direction

Fifteen specimens, which differed in coarse–total aggregate ratio (Nga), paste volume (Vpw), type and content of mineral admixture, aggregate combination as well as water–binder ratio, were selected to measure the Rv of coarse aggregate in the vertical direction (Table 3).

Fig. 4 shows that specimens having Ha values smaller than 7 mm had Rv values of coarse aggregate in the vertical direction less than 10%; and specimens with Ha values equal to and larger than 7 mm had Rv values larger than 10%. In order to ensure that fresh SCC has satisfac-

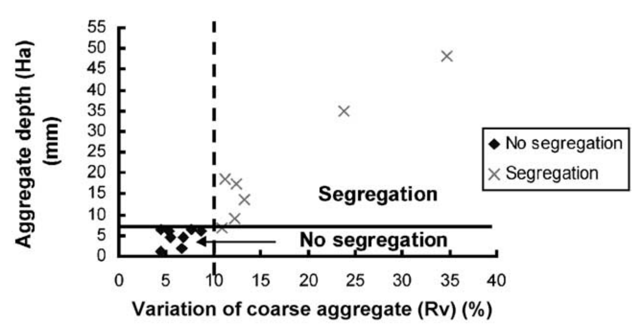

Fig. 4. Ha and different Rv of coarse aggregate by mass in the vertical direction.

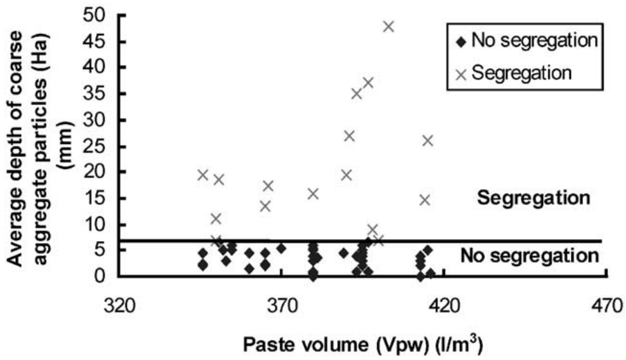

Fig. 5. Average Ha and different paste volumes (vertical direction).

tory segregation resistance, the following criteria for Ha are proposed:

- Concrete has good segregation resistance if Ha < 7 mm,
- Concrete has poor segregation resistance if Ha ≥ 7 mm.

Test results with different paste volumes showed that the zones of poor segregation resistance and satisfactory segregation resistance were clearly divided by the lines representing the proposed values as can be seen in Fig. 5, which means that there is no clear relation between Ha and paste volume.

4.1.2. Pd and segregation resistance in the vertical direction

As discussed above, the testing method using the molding box is a good method to evaluate segregation resistance of SCC. However, it is quite laborious and slow. Therefore, a PA was developed in order to carry out the test more quickly and with less labor. The structure of the apparatus has been described previously in Section 3.1 and is illustrated in Fig. 3. Testing was implemented as detailed in Step 2 of the Testing procedure. Results using the PA were compared with test results using the molding box (type M), where the specimens with Rv smaller than 10% and Ha smaller than 7 mm exhibited satisfactory segregation resistance.

As shown in Fig. 6, specimens with Pd smaller or equal to 8 mm were of satisfactory segregation resistance, because they exhibited mass variation Rv (of coarse aggregate in vertical direction) smaller than 10%. Conversely, specimens

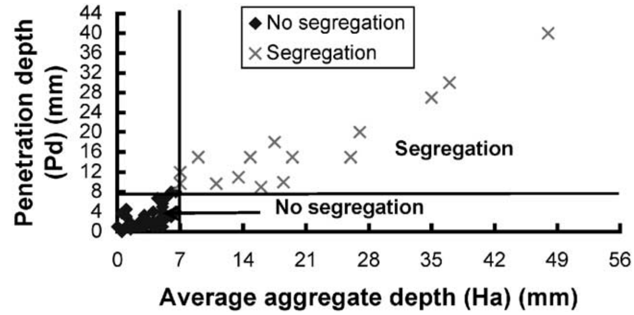

Fig. 7. Pd and Ha in the vertical direction.

with Pds larger than 8 mm exhibited unsatisfactory segregation resistance as those specimens had the mass variation Rv larger than 10%.

As can be seen in Fig. 7, the specimens with Pds smaller or equal to 8 mm had Ha values smaller than 7 mm, which can be considered as the maximum allowable value for specimens having good segregation resistance. Fig. 7 also shows that specimens having Pds larger than 8 mm had Ha values equal to and larger than 7 mm. Therefore, segregation resistance of SCC can be assessed as follows:

- Concrete has satisfactory segregation resistance in vertical direction if Pd ≤ 8 mm,
- Concrete has poor segregation resistance in vertical direction if Pd > 8 mm.

where Pd is the penetration depth measured by use of the PA.

Figs. 8, 9 and 10 show laboratory test results with different coarse–total aggregate ratios, different water–binder ratios and different paste volumes with different cement types, different mineral admixtures and different aggregate combinations consisting of different aggregate types. The results indicated that the zones of satisfactory and poor segregation resistance were clearly divided by the lines representing the proposed values stated above.

4.2. Segregation resistance in the horizontal direction

Nonequivalent distribution of coarse aggregate particles in concrete structures is caused not only by blocking around

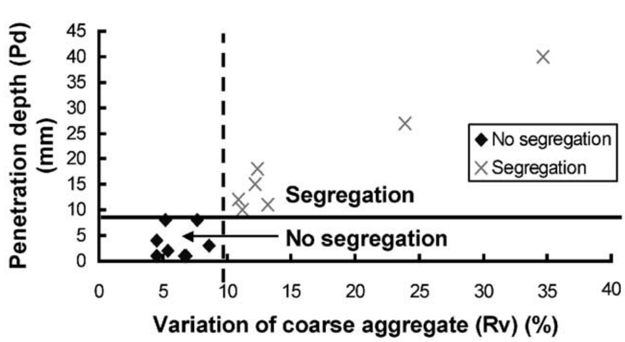

Fig. 6. Pd and Rv of coarse aggregate in the vertical direction.

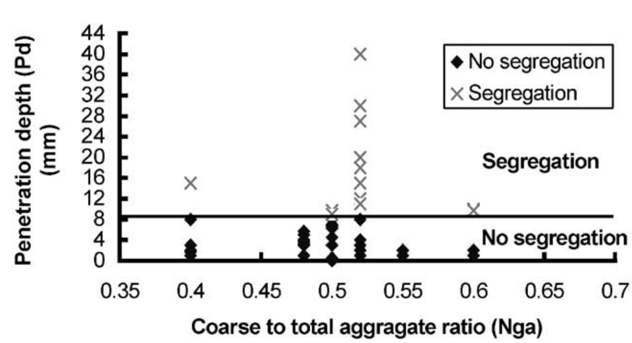

Fig. 8. Pd and different coarse–total aggregate ratios (vertical direction).

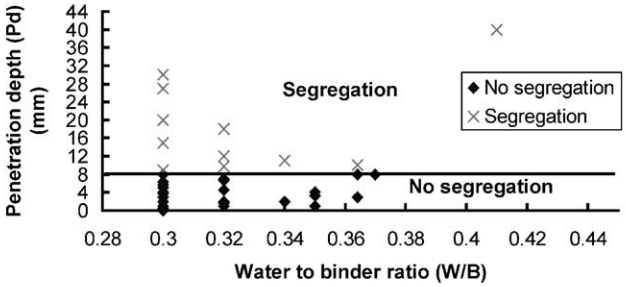

Fig. 9. Pd and different water–binder ratios (vertical direction).

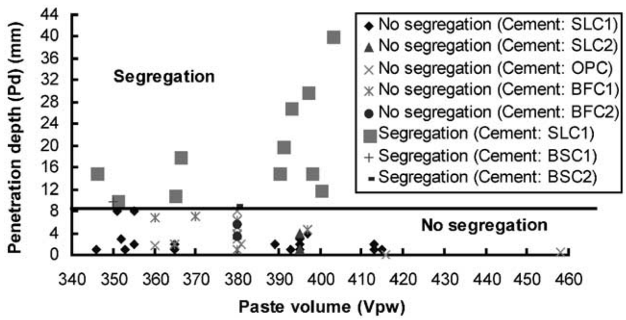

Fig. 10. Pd and different paste volume with cement types (vertical direction).

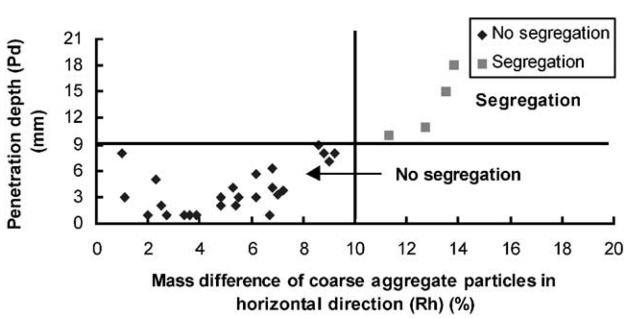

Fig. 11. Pd and mass difference of coarse aggregate in the horizontal direction.

reinforcements, but also by poor segregation resistance of concrete. This paper reports test results on segregation resistance of SCC without blocking around reinforcement, only concrete which blocks around reinforcement is expected to cause nonequivalent distribution of coarse aggregate particles in a structure.

As can be seen from Figs. 11, 12, 13 and 14, the specimens with Pds smaller or equal to 9 mm had a mass difference (Rh) of coarse aggregate smaller than 10%. Conversely, the specimens with Pds larger than 9 mm had a mass difference (Rh) of coarse aggregate larger than 10%. These findings were valid for different water–binder ratios, different paste volumes and different materials (namely, different types of cement, mineral admixtures and aggregates). Therefore, segregation resistance of SCC can be assessed as follows:

- Concrete has satisfactory segregation resistance in horizontal direction if Pd $\leq$ 9 mm,
- Concrete has poor segregation resistance in horizontal direction if Pd > 9 mm.

where Pd is the penetration depth measured by use of the PA.

4.3. Criteria for Pd in considering segregation resistance of SCC in both vertical and horizontal directions

Test results and discussions in Sections 4.1 and 4.2 showed that, for no segregation to occur in SCC in both the vertical and horizontal directions, the values of Pd should not be greater than 8 and 9 mm, respectively. These values were valid for the mixes, which differed in coarse–total aggregate

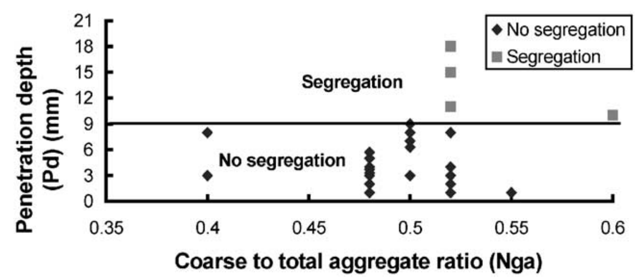

Fig. 12. Pd with different coarse–total aggregate ratios and concrete segregation resistance in the horizontal direction.

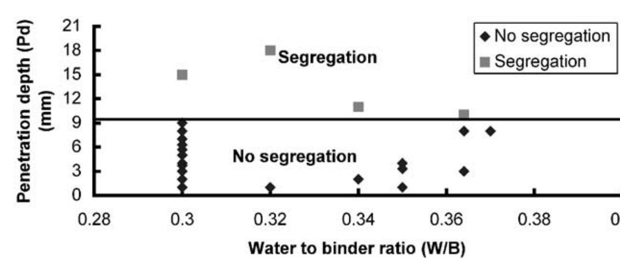

Fig. 13. Pd with different water–binder ratios and concrete segregation resistance in the horizontal direction.

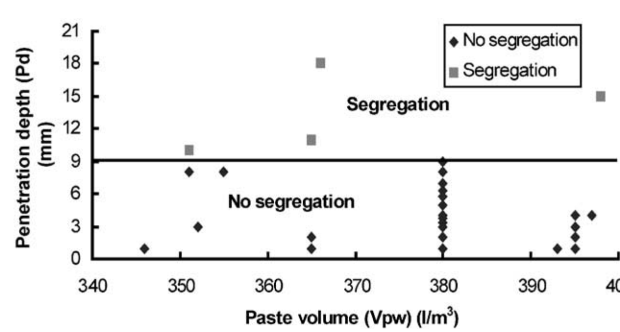

Fig. 14. Pd with different paste volumes and concrete segregation resistance in the horizontal direction.

ratio, paste volume, water–binder ratio, aggregate combination, type and content of cements and mineral admixtures as well as superplasticizer dosage. This can be explained by the fact that properties and content of all components in a mixture affect segregation resistance of SCC. Proper mix proportioning results in nonsegregated SCC, in which the coarse aggregate particles remain dispersed throughout the mortar matrix when SCC flows in the horizontal direction. Unsuitable mix proportioning causes segregation of the concrete, resulting in the coarse aggregate particles sinking down deeply in the vertical direction or becoming segregated from the mortar matrix when the concrete flows in the horizontal direction. In testing of the SCC, the penetration head of the apparatus reflects the movement of coarse aggregate particles in the SCC. Nonsegregated SCC, which has proper mix proportions (e.g., suitable rheology), is able to support the penetration head and results in low Pd. Conversely, segregated SCC, with unsuitable mix proportions (e.g., unsuitable rheology), is not capable of supporting the penetration head and causes a high Pd.

As an example, mix S16B with a paste volume of 397 l/m^3 exhibited an Ha of only 6.5 mm and Pd of 4 mm; while mix S18B exhibited the Ha of 13.5 mm and Pd of 11 mm, which were greater than that of mix S16B although mix S18B had a lower paste volume (365 l/m^3) than mix S16B (Table 3). Mix S16B had a satisfactory segregation resistance (its respective values of Rh and Rv were 5.3% and 4.5%), while mix S18B exhibited poor segregation resistance (its respective values of Rh and Rv were 13.5% and 12.7%). Another example is the case of mixes S16A and S16B, which both had the same type and content of all components except for superplasticizer dosage. Mix S16A segregated but mix S16B did not segregate. Mix S16A had excessive dosage of superplasticizer, which was considerably higher than that of mix S16B.

As stated, SCC should have good segregation resistance not only in the vertical direction, but also in the horizontal direction. From test results and discussions of the values of Pd in Sections 4.1 and 4.2, the following criteria for Pd for segregation resistance of SCC are proposed:

- Concrete has satisfactory segregation resistance if $Pd \leq 8$ mm,
- Concrete has poor segregation resistance if $Pd > 8$ mm.

where Pd is the penetration depth measured by use of the penetration head with a total mass of 54 g (the value of Pd is recorded at a time of 45 s after releasing the penetration head) [4].

5. Conclusions

A number of extensive test series were carried out. A simple PA and a rapid testing method for segregation resistance were developed. The test results showed that the proposed method and the developed apparatus are useful for the rapid evaluation of segregation resistance of concrete in both vertical and horizontal directions. The method can reduce testing time and laboratory work. The proposed method can also distinguish between different coarse–total aggregate ratios, different water–binder ratios and different materials.

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