Optimum Aggregate Phase Based on Deformability and Blocking Criteria of Self-Compacting Concrete

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Abstract

This paper summarizes a concept to proportion the aggregate phase for self-compacting concrete in order to obtain the concrete with smallest paste content and sufficient passing ability through reinforced area without aggregate blocking. The concept was based on aggregate void-surface area theory in combination with blocking criteria. The idea of maximum aggregate particle distance was used to select the optimum coarse aggregate ratio for a specified paste volume. The average particle distance of the aggregate was calculated based on the paste volume, void content and total surface area of the aggregate phase. Then the blocking criteria for aggregate phase, relating the aggregate blocking volume ratio to ratio between reinforcement clear spacing and diameter of single-sized aggregate based on sieve analysis, and ratio between reinforcement diameter and maximum aggregate size, was introduced. Then linear combination rule was applied to compute the blocking volume ratio of the multiple-sized aggregate. The computed results verified by experiments in this study indicated that with the use of blocking criteria, the maximum allowable aggregate volume, which results in minimum paste volume in SCC, can be determined. The proposed criteria will enable the mix proportion of self-compacting concrete to achieve high economic efficiency and good deformability.

1. Introduction

Self-Compacting Concrete (SCC), which is a concrete placeable without need of compaction, has been developed and used in construction for more than a decade. At the early state, it was referred to by many different names such as high performance concrete, no-vibration concrete, super workable concrete, etc [1,2]. The implementation of SCC varies among countries based on the raw materials, level of material and construction technologies including labor condition. In Thailand, SCC is effectively applied in line with the use of fly ash [3,4]. It is estimated that two to three million tons of fly ash is produced annually in Thailand with the estimated utilization of only about 10% in 1998. Due to higher CaO content which leads to higher early age strength and relatively higher SO_3 content which reduces autogenous and drying shrinkage when compared to the low lime fly ash, of some Thai fly ashes, SCC in Thailand is incorporated with the fly ashes as an important mineral admixture. Owing to the higher cost of the SCC than the conventional concrete, SCC is used as a special concrete in Thailand. This paper introduces a design concept for aggregate phase, which is defined as the combination of coarse and fine aggregates, of SCC. The design concept includes the method for selecting aggregate proportion by aiming at a mixture with minimum paste content, optimum deformability and no blocking. It is noted here that to be able to conduct a life-cycle design of self-compacting concrete, prediction models for other

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properties like deformability, strength development and durability are necessary [5, 6, 7, 8]. Due to the limitation of space, only the concept to select optimum aggregate phase will be explained in this paper.

2. Mix Proportioning of SCC

The overall quality of SCC depends not only on properties of the raw materials as ingredients, but also on their quantities. The proposed mix design concept is aimed at a mixture with economic efficiency, sufficient mechanical properties and good durability. One way to achieve this goal is to minimize the paste volume, which represents the largest proportion of total raw material cost and is normally the part causing most of the durability problems, in considering satisfactory filling ability of fresh concrete and properties of hardened concrete.

It is obvious that the modern mix proportioning method concerns the quality of concrete in all states of application i.e. fresh, plastic, early age, hardened and long term. In this paper, the concept for proportioning the aggregate phase to avoid blocking of the aggregate during the filling of the concrete in fresh state will be focussed on.

2.1 Proportioning of Aggregate Phase

The proposed mix design method is based on the concept that fresh concrete consists of two phases i.e. solid and liquid phases. The solid phase includes fine and coarse aggregates whereas the rests are liquid phase. This proportioning method is aimed at finding an optimum proportion between coarse and fine aggregates which can minimize the paste volume based on the concept of maximum inter-particle distance and blocking criteria. The optimum coarse aggregate ratio for SCC is defined as the coarse aggregate ratio (N_{ga}) that satisfies the following conditions:

1) the smallest paste volume

2) the largest average aggregate particle distance

3) no risk of blocking

2.2 Optimum Coarse and Fine Aggregate Ratio for Smallest Paste Volume and Maximum Inter-Particle Distance

Coarse to fine aggregate ratio affects the void content and total surface area of the aggregate phase. The optimum gravel-sand ratio must lead to a less required paste volume, whereas satisfying the requirement of fresh concrete and hardened concrete properties.

The paste volume (V_{pw}) is needed to fill all voids in the aggregate phase and to envelop all surfaces of the aggregate particles. Therefore, it is needed to consider not only the void content, but also the total surface area of the aggregates. Two mixtures of aggregate, even having the same solid volume, can have different surface area. Then, the paste volume required to cover the aggregate particles will be different. For the same paste quality, larger surface area of the aggregates requires larger covering paste volume in order to maintain the same deformability.

In this study, the average distance between the surfaces of aggregate particles (D_{ss}) is calculated from 2 times of the average thickness of covering paste layers around an aggregate particle (see Fig.1). It was found that for the same set of gravel and sand in the concrete with constant paste volume, the average distance, D_{ss}, is different with respect to different gravel-total aggregate ratio (N_{ga}). The gravel-total aggregate ratio, N_{ga}, is defined as

$$N_{ga} = V_g / (V_g+V_s) \qquad (1)$$

where V_g is the volume of coarse aggregate in the concrete and V_s is the volume of fine aggregate in the concrete.

Larger Dss is considered to result in higher deformability and filling ability. The average distance (D_{ss}) can be calculated from the gradation curve by first calculating

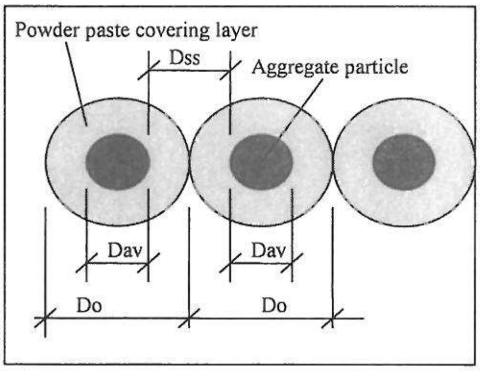

Fig.1 Spherical aggregate particles and paste layer

the average diameter of the aggregate particle (D_{av}) can be derived from

$$D_{av} = \frac{\sum_{i=1}^{n} D_i M_i}{\sum_{i=1}^{n} M_i} \quad (2)$$

where D_i is the average of sieve group dimension, $D_i = (d_i + d_{i+1})/2$ (see Fig.2), d_i is the size of the sieve i on which the aggregate particles are retained, M_i is percentage of retaining on the corresponding sieve of the aggregate group i and n is the number of size groups.

It can be realized from Eq.(2) and Fig.2 that the average diameter of aggregate particles depends on gravel-total aggregate ratio and gradation of the fine and coarse aggregate which is also influenced by the maximum size of aggregate since V_{void} changes with the change of maximum size of aggregate.

Then the average distance between aggregate particle surfaces can be derived based on the volumetric calculation as

$$D_{ss} = D_{av} \left\{ \left[\frac{V_{pw} - V_{void}}{V_t - V_{pw}} + 1 \right]^{1/3} - 1 \right\} \quad (3)$$

where D_{ss} is the average distance between aggregate particle surfaces, V_t is the total concrete volume, V_{pw} is the paste volume, V_{void} is the volume of void of the aggregates in densely compacted state and D_{av} is the average diameter of the aggregate particle.

It is noted here that aggregate particles are assumed to have spherical shape for simplicity of computing D_{ss} in Eq.(3).

The experimental and computed data indicated that different gravel-sand proportion resulted in different average particle diameter and void content of binary mixes. Analysis using Eq.(3) and experimental results show that for the same set of gravel and sand in the concrete with constant paste volume, the average distance D_{ss} is different with respect to different N_{ga}.

Fig.3 shows an example of computed relationship between gravel-total aggregate ratio and the average distance between the aggregate surfaces of concrete with aggregate mix A1 (see Experimental Investigation for properties of aggregates and their mix proportion of A1) by varying

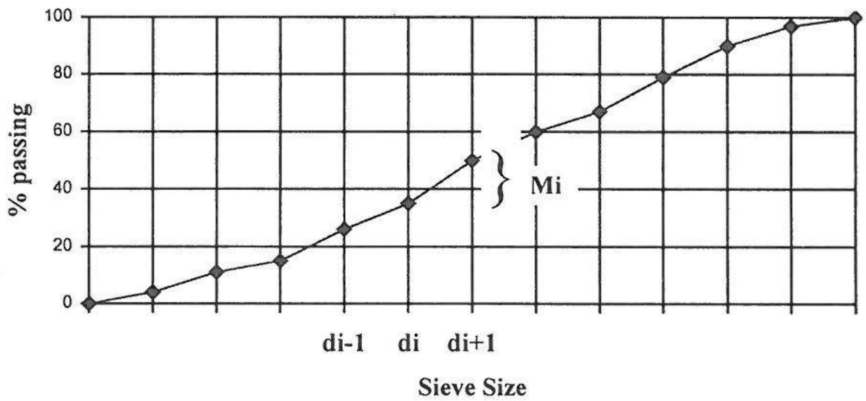

Fig.2 Typical grading curve of aggregate

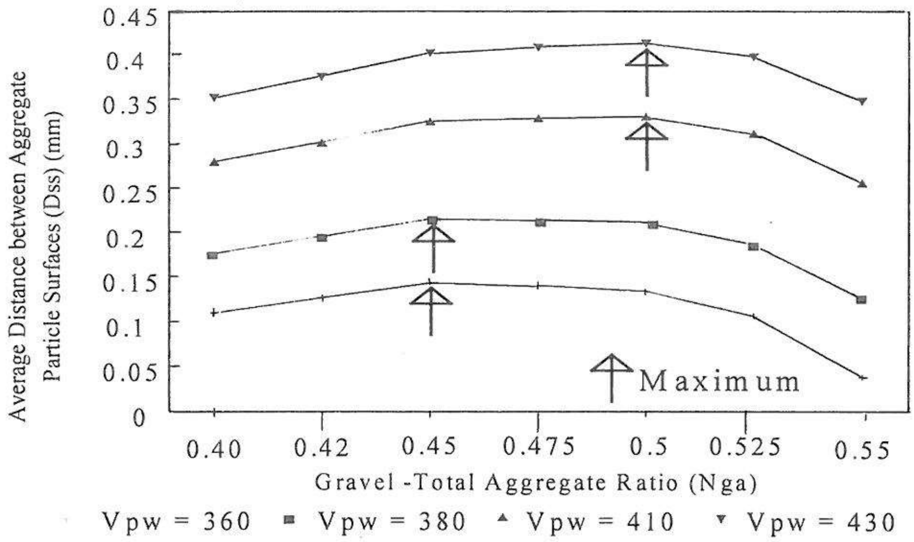

Fig.3 Relationship between computed average distance between aggregate particle surfaces and gravel-total aggregate ratio

paste volume. It is shown that with a constant paste volume, there is a gravel-total aggregate ratio which produces the maximum D_{ss} (See Fig.3). Let define this gravel-total aggregate ratio as N_{ga}'. However, N_{ga}' shifted when changing paste volume. When the paste volume is small, N_{ga}' is very closed or even at the same point as N_{ga} at the minimum void. However, when the paste volume is increased with the same set of aggregates, the N_{ga}' shifts to be the larger value, in other word, larger proportion of coarse aggregate than that of the minimum-void mixture is required for maximum D_{ss}. This can be explained using the following explanation. In the range of small paste volume, the paste is needed to fill the voids in the aggregate mixture with very small paste left for dispersing the aggregate particles, therefore, void content has great influence and then controls the behavior. On the contrary, when there is plenty of paste in the concrete, the distances among particles increases when there is smaller proportion of fine particle due to smaller surface area of the total aggregates. It may be more obvious by considering two single-size aggregates, both having the same solid volume. The one with larger size has larger distance among particles. By the explanation, it is obvious that N_{ga}' changes when changing paste volume. This behavior is taken into account in this study by introducing the effect of surface area into the calculation of D_{ss}.

Filling ability of the no-vibration concrete depends on two significant material properties which are deformability and segregation resistance of the concrete. However, external factors also affect the filling ability and the most common factor to be considered is the denseness of the reinforcement. Maximum size of aggregate and the amount of large particles in the concrete play a key role in the filling mechanisms of the concrete since they are the major factors to decide whether the concrete can flow through the reinforced area or not. Concrete with too large aggregate or too much large aggregate usually can not fill the heavily reinforced area due to blocking of the aggregate. As found in the previous section, N_{ga}' changes when changing the paste volume. Also, the larger aggregate volume and larger maximum size of aggregate result in the reduction of required paste volume, but this can lead to a higher blocking risk. So, to avoid blocking of the aggregate, the blocking criteria is needed to implement together with the concept of maximum D_{ss}.

2.3 Blocking Criteria for Self-Compacting Concrete

Ozawa, Tangtermsirikul and Maekawa [9] studied the mechanism of blocking of mortar flowing through round openings and the role of single-size sand in fresh mortar on blocking and found that the volume of sand which causes blocking depends on the mean size of the sand. Larger particle size leads to higher risk of blocking. They proposed an equation for computing the blocking risk of a multi-size aggregate as

$$\text{Risk of blocking} = \Sigma(n_{si}/n_{sbi}) \qquad (4)$$

where n_{si} is the volume ratio of an aggregate of single-size group i and n_{sbi} represents the blocking volume ratio which means the volume ratio, which causes blocking, of the aggregate of single-size group i. The volume ratio of aggregate is defined as the ratio between volume of the aggregate and the total volume of the concrete.

Moreover, they found that the ratio between size of opening and the size of sand was another factor affecting blocking of flowing mortar. The blocking volume increased linearly with the ratio of the opening diameter to the mean size of sand at initial state, however, this relationship changes when this ratio reaches about 10.

The above findings is a basis for studying the effect of size and volume of total aggregate on blocking of SCC. Generally, the blocking volume ratios are not only affected by the ratio of reinforcement clear spacing to the aggregate particle size but also by the ratio between reinforcement diameter and maximum aggregate particle size, and by the inter-particle friction and properties of the liquid phase such as viscosity. In this study, only the effect of aggregate type, aggregate size, aggregate volume and bar size are considered by assuming that the blocking volume ratios are independent on paste properties as long as the mixture has no static segregation. In order to propose the blocking criteria, the experiment with different kinds of aggregate was carried out.

a) Physical properties of aggregates and procedure of filling ability test

The physical properties of the used raw materials are given in Tables 1, 2 and 3. Table 4 shows the combined aggregates used in the tested concrete. Mix proportions were given in Table 5.

In order to measure the filling ability of self-compacting high performance concrete, a simple L-shape apparatus was developed (Fig.4). In the tests of mixtures with aggregate types A1, A2, B1, B2 and B3, the clear spacing between reinforcement bars was 40mm which was considered a very severe reinforcing condition. The test was commenced by filling the concrete into the apparatus. After 1 to 2 minutes to let the concrete undergo static segregation if there is, the gate A was lifted in order to allow the concrete to flow through the reinforcing bars. The filling ability of the concrete was evaluated by using the filling head drop (h) which was defined as the difference of the head of the concrete at the start and the end of the test. Larger filling head drop means better filling ability. It is noted here that the tests were completed in 15 minutes after finish mixing the concrete.

b) Test results and blocking criteria

The test results are recorded in Table 5. Fig.5 shows a model for deriving blocking volume of various single-size aggregates. The model was derived from the filling ability test of concrete using L-shape apparatus (Fig.4). The model relates blocking volume ratio of aggregate (n_{abi}) to

1) the ratio between reinforcement clear spacing and the three-quarter dimension of each aggregate fraction (or is called here as clear spacing to particle size ratio, Dca) and

2) ratio between reinforcement diameter and maximum size of aggregate (K).

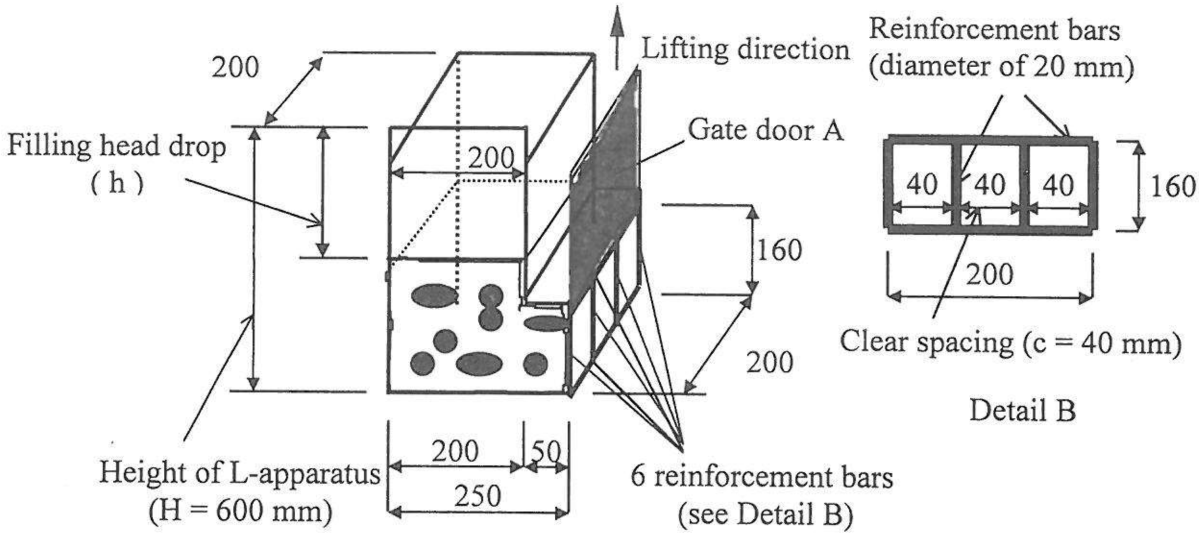

Fig.4 L - apparatus for filling ability test (all dimensions are in mm)

Table 1 Physical properties of raw materials used in the test

Raw materials	Max. Size (mm)	Fineness modulus	Specific Gravity	Absorption (%)
GA1 (crushed limestone coarse agg.)	25.0	9.40	2.68	0.61
GA2 (crushed limestone coarse agg.)	19.0	6.85	2.68	0.61
GB1 (crushed limestone coarse agg.)	12.5	6.74	2.69	0.62
GB2 (crushed limestone coarse agg.)	19.0	7.69	2.70	0.58
GB3 (crushed limestone coarse agg.)	25.0	8.16	2.70	0.52
SA1 (river fine agg.)	4.75	3.24	2.53	0.90
SA2 (river fine agg.)	4.75	2.84	2.56	1.10
SB (river fine agg.)	4.75	2.89	2.49	1.06

Table 2 Sieve analysis of the tested sand samples

Type of Sand	Percentage retained on sieve (%)							
	8mm	No.4	No.8	No.16	No.30	No.50	No.100	Pan
SA1	*0*	1.56	13.7	30.14	28.57	16.12	7.87	2.04
SA2	*0*	1.64	12.5	15.04	30.34	26.17	8.97	2.65
SB	*0*	0.10	11.94	21.75	29.44	20.58	12.5	3.69

Table 3 Sieve analysis of coarse aggregates

Type of gravel	Percentage retained on sieve (%)						
	25.0mm	19.0mm	12.5mm	9.5mm	6.3mm	4.75mm	<4.75mm
GA1	0	1.10	54.64	35.40	3.80	4.57	*0.5*
GA2	0	0	18.75	18.51	18.08	21.56	*23.1*
GB1	0	0	0	24.51	35.19	35.19	*5.12*
GB2	0	0	29.17	36.68	15.86	15.86	*2.44*
GB3	0	8.92	52.48	11.73	10.53	10.53	*5.81*

Table 4 Types of binary mixtures

Aggregate type	Combination of coarse and fine aggregates
A1	GA1 + SA1
A2	GA2 + SA2
B1	GB1 + SB
B2	GB2 + SB
B3	GB3 + SB

The parameters nabi, Dca and K are defined as follows:

$$n_{abi} = \frac{V_{abi}}{V_t} \qquad (5)$$

$$D_{ca} = \frac{c}{D_{af}} \qquad (6)$$

$$K = \frac{\Phi}{D_{max}} \qquad (7)$$

where nabi : blocking volume ratio of aggregate group i,

Vabi : blocking volume of aggregate group i,

Vt : total volume of the concrete mixture,

Dca : ratio between reinforcement clear spacing (c) and the three-quarter dimension of each aggregate fraction (Daf)

K : ratio between reinforcement diameter (Φ) and maximum size of aggregate (Dmax)

$$D_{af} = M_{i-1} + 3/4\,(M_i - M_{i-1})$$

where M_i and M_{i-1} are upper and lower sieve dimensions of aggregate group i, respectively.

Fig.5 shows that larger ratio between reinforcement diameter and maximum size of aggregate (K) gives smaller aggregate blocking volume ratio (nabi). Fig. 5 also indicates that the river coarse aggregate has aggregate blocking volume ratio (nabi) higher than that of crushed coarse limestone aggregate. This can be explained by the effect of friction among aggregate particles. (The river coarse aggregates have a smaller inter-particle friction than that of crushed coarse limestone aggregate).

Then the equation for computing maximum aggregate volume corresponding to each gravel-total aggregate ratio of each aggregate type can be derived from Eq.(4) as

$$\text{Risk of blocking} = \sum_{i=1}^{n}\left(\frac{n_{ai}}{n_{abi}}\right) = \sum_{i=1}^{n}\left(\frac{V_{ai}/V_t}{V_{abi}/V_t}\right) = \sum_{i=1}^{n}\left(\frac{V_{ai}}{V_{abi}}\right) \qquad (8)$$

where V_{ai} is volume of aggregate group i, V_{abi} is the blocking volume of aggregate group i, V_t is total volume of the concrete mixture and n is number of aggregate size groups. The maximum total aggregate volume is the volume at which the blocking risk equals to 1, so

$$\sum_{i=1}^{n}\left(\frac{V_{ai}}{V_{abi}}\right) = 1.0 \qquad (9)$$

then the maximum total aggregate volume can be obtained from

$$V_{atmax} = \sum_{i=1}^{n} V_{ai} = V_a \qquad (10)$$

where V_{atmax} is the maximum total aggregate volume and Va is total aggregate that can be obtained from Eq.(10).

Using Eq.(10), the diagrams showing the relationship between the blocking volume ratio, or maximum allowable total aggregate volume ratio, and the gravel-total aggregate ratio of different aggregate types are plotted in Fig.6. The figure also shows the effect of maximum size of aggregate on the blocking volume ratio. The figure indicates that the blocking volume ratio decreases with increasing the gravel-total aggregate ratio and also with the increase of maximum size of aggregate.

Table 5 Mix proportion and experimental results of the tested concrete

Mix	Agg. type	p (kg/m^3)	f/p	w/p	Nga	Vpw (l/m^3)	Va (l/m^3)	SP (%powder)	Slump flow (cm)	h (cm)
A1-1	A1	562	0.5	0.296	0.40	400	600	1.00	65.0	47.0
A1-2	A1	562	0.5	0.295	0.42	400	600	1.00	62.5	50.0
A1-3	A1	564	0.5	0.292	0.45	400	600	1.00	64.0	39.0
A1-4	A1	568	0.5	0.288	0.55	400	600	0.90	62.5	6.0
A1-5	A1	490	0.5	0.300	0.42	377	623	1.55	62	19
A1-6	A1	436	0.5	0.342	0.42	335	665	1.5	58	5
A2-1	A2	554	0.5	0.328	0.50	412	588	1.30	64.0	52.0
A2-2	A2	514	0.5	0.350	0.45	396	604	1.35	62.5	51.0
A2-3	A2	554	0.5	0.328	0.42	412	588	2.45	65.0	52.0
A2-4	A2	544	0.5	0.322	0.45	402	598	1.9	62.5	52.0
A2-5	A2	436	0.5	0.342	0.42	335	665	1.5	53.0	3
B1-1	B1	466	0.5	0.33	0.30	350	650	1.8	62.0	54.0
B1-2	B1	533	0.5	0.32	0.30	390	610	1.6	67	55.0
B1-3	B1	494	0.5	0.30	0.42	355	645	1.9	62	42.0
B1-4	B1	558	0.5	0.27	0.42	385	615	1.7	68	55.0
B1-5	B1	603	0.5	0.26	0.50	405	595	1.2	67	55.0
B1-6	B1	559	0.5	0.27	0.55	385	615	1.6	68	13.0
B1-7	B1	595	0.5	0.26	0.55	400	600	1.2	66	14.0
B1-8	B1	618	0.5	0.26	0.55	415	585	1.9	66	55.0
B1-9	B1	638	0.5	0.24	0.70	415	585	1.8	63	6.0
B2-1	B2	470	0.5	0.36	0.30	365	635	1.7	63	52.8
B2-2	B2	602	0.5	0.31	0.30	435	565	1.4	67	52.2
B2-3	B2	460	0.5	0.32	0.42	340	660	1.4	55	9.0
B2-4	B2	506	0.5	0.32	0.42	375	625	1.7	63	51.0
B2-5	B2	536	0.5	0.32	0.42	395	605	1.2	65	50.0
B2-6	B2	512	0.5	0.31	0.50	370	630	1.5	65	9.0
B2-6	B2	538	0.5	0.30	0.50	385	615	1.5	63	34.2
B2-7	B2	624	0.5	0.27	0.50	425	575	1.4	66	52.8
B2-8	B2	612	0.5	0.25	0.55	405	595	1.2	66	15.0
B2-9	B2	700	0.5	0.24	0.55	450	550	1.5	66	13.0
B3-1	B3	473	0.5	0.35	0.30	365	635	1.4	55	37.8
B3-2	B3	515	0.5	0.30	0.30	370	630	1.9	59	51.0
B3-3	B3	508	0.5	0.31	0.42	370	630	1.7	64	9.0
B3-4	B3	573	0.5	0.31	0.42	415	585	1.6	69	52.2
B3-5	B3	613	0.5	0.29	0.50	430	570	1.9	73	4.0
B3-6	B3	684	0.5	0.22	0.50	430	570	1.2	64	20.0
B3-7	B3	701	0.5	0.22	0.50	440	560	1.0	62	40.2
B3-8	B3	652	0.5	0.25	0.55	430	570	1.3	72	4.0
B3-9	B3	773	0.5	0.21	0.55	475	525	1.0	58	25.0

f : fly ash *p : total powder material* *w : water*
Nga : gravel to total aggregate weight ratio *Vpw : paste volume* *Va : aggregate volume*
SP : superplasticizer content *h : filling head drop*

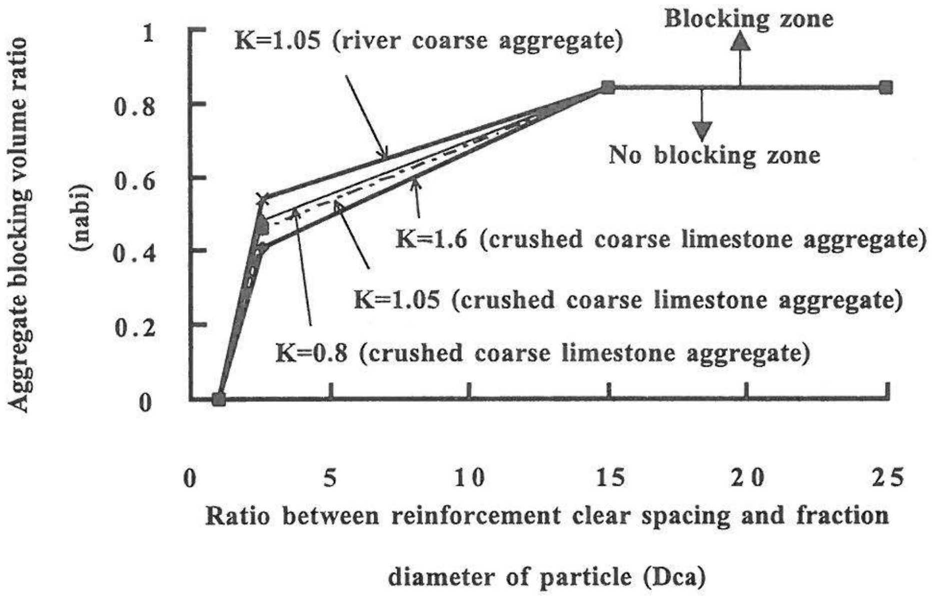

Fig. 5 Relationship between blocking volume ratio and clear spacing to particle size ratio

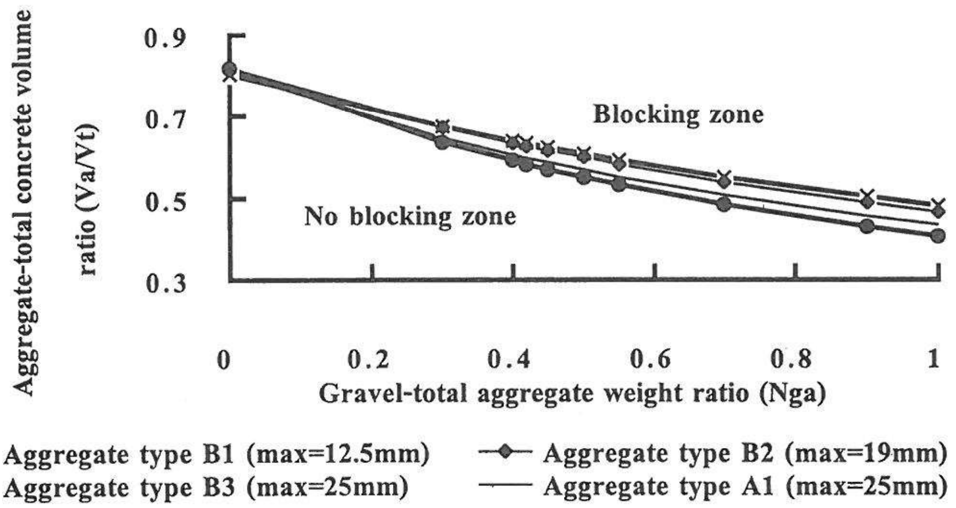

Fig. 6 Relationship between computed blocking volume ratio and gravel-total aggregate weight ratio of various aggregate types

The test results and analytical blocking volume of various aggregate types are plotted in Figs. 7, 8, 9, 10 and 11. The blocking and no blocking zones are divided by the calculated lines which are confirmed by the test results. The test results were obtained from the filling ability test of various concrete mixtures using the L-shape apparatus (see Table 5). The figures show that the proposed blocking criteria can be reasonably used to predict maximum aggregate volume which causes blocking. The blocking criteria will be utilized in combination with the proposed aggregate void-surface area theory (for determining maximum D_{ss}) to determine the best gravel to total aggregate ratio and maximum allowable aggregate volume which creates no blocking.

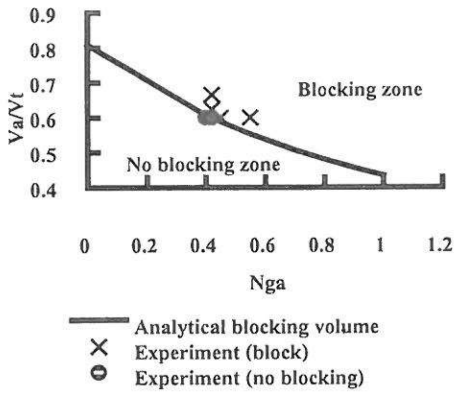

Fig. 7 Filling test results and computed blocking volume ratio of concrete (aggregate type A1 containing crushed coarse limestone aggregate with maximum size of 25 mm)

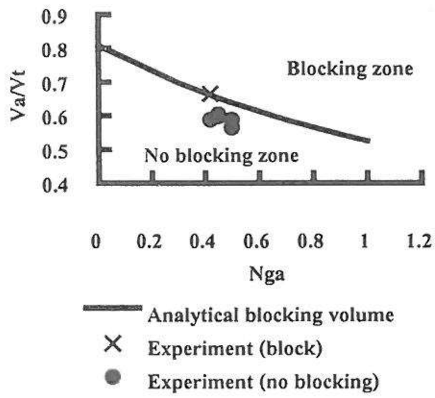

Fig. 8 Filling test results and computed blocking volume ratio of concrete (aggregate type A2 containing crushed coarse limestone aggregate with maximum size of 19 mm)

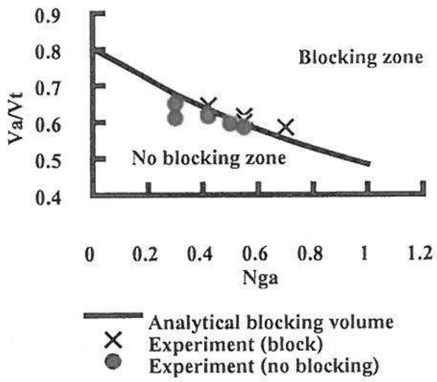

Fig. 9 Filling test results and computed blocking volume ratio of concrete (aggregate type B1 containing crushed coarse limestone aggregate with maximum size of 12.5 mm)

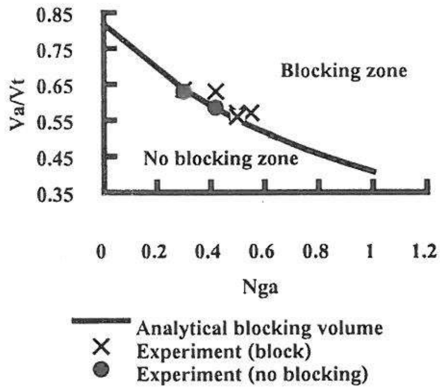

Fig. 10 Filling test results and computed blocking volume ratio of concrete (aggregate type B2 containing crushed coarse limestone aggregate with maximum size of 19 mm)

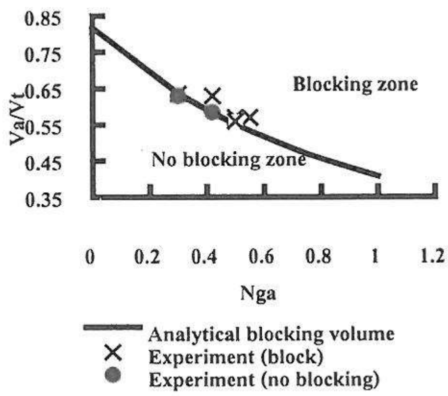

Fig. 11 Filling test results and computed blocking volume ratio of concrete (aggregate type B3 containing crushed coarse limestone aggregate with maximum size of 25 mm)

3. Concluding Remarks

1) The SCC with minimum paste volume can be achieved by using the concept of maximum aggregate particle distance based on the void ratio-total surface area of the aggregate phase.

2) The proposed blocking criteria relates the aggregate blocking volume ratio to the ratio between reinforcement clear spacing and diameter of aggregate particle fraction and the ratio between reinforcement diameter and maximum size of aggregate particle, as well as coarse aggregate type. Blocking is easier to occur when coarse aggregate content is larger, maximum size of coarse aggregate is larger, clear spacing of steel is smaller, size of steel is larger and aggregate shape is more angular.

3) The proposed blocking criteria can be used to obtain SCC which has minimum paste and has no blocking.

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