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MIX DESIGN OF STRUCTURAL SELF-COMPACTING CONCRETE USING VOID-BULK DENSITY METHOD

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ABSTRACT

Self Compacting Concrete (SCC) was firstly developed in Japan in 1987. (Alternative: Pioneering works on Self Compacting Concrete returns to 1980s in Japan) In recent years, much research has been conducted in other to achieve a reasonable and also suitable mix design method for controlling the compaction experiment and determination of the compliance particular trait of SCC. But, just a few researches have been done in to propose a mix design method that can have both of highly fluid state and good viscosity, simultaneously. SCC is a special kind of concrete that can flow through and fill the gaps of reinforcement and corners of molds without any need for vibration and compaction during the placement process. In this paper Void-Bulk Density mix design method for structural SCC is investigated. In this method, firstly, the relationship between the void volume (or density of combined aggregates) and coarse-to-total aggregate volume ratio is established by packing different amounts of coarse and fine aggregates following ASTM C 29/C 29M, using the void volume of the dry binary aggregate (fine and coarse), is determined. Then, based on the optimum ratio that results from minimum void of aggregate and minimum bulk density, mix design is accomplished and finally in order to increase the flowability of the concrete have been added, some excess paste via reducing ratio of volume aggregate in unit volume concrete. Obtained results of the experiments on fresh concrete (Slump flow, L-box, V-funnel) and hardened concrete (compressive strength, tensile strength, elastic moduli and durability) show that this method is appropriate for SCC. In this study nine different SCC mixtures having the volume of paste and the ratio between sand and gravel as variables were compared with eight different mixtures of conventionally vibrated concrete (CVC).

Keywords: Self-compacting concrete, compressive Strength, Durability, elastic moduli, Mix design

1. INTRODUCTION

The development of Self-Compacting Concrete (SCC), also referred to as ‘‘Self-Consolidating Concrete’’ and ‘‘High-Performance Concrete’’, has recently been one of the most important developments in the building industry. It is a kind of concrete that can flow through and fill gaps of reinforcement and corners of moulds without any need for vibration and compaction during the pouring process. It can be used in pre-cast applications or for concrete placed on site. SCC results in durable concrete structures, and saves labour and consolidation noise. Pioneering work in the development of SCC was carried out by Okamura [1] and Okamura and Ouchi [2], which will henceforth be referred to as Japanese Method. The method suggests that the gravel content in the concrete mix corresponds to 50% of its packed density, and that in the mortar the sand content corresponds to about 50% of its packed density (Figure 1).

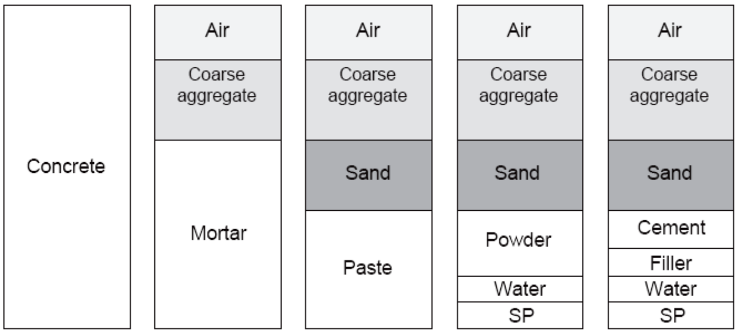

Figure 1. Schematic Composition of SCC [5]

This independent consideration of gravel and sand, results in SCC that has a relatively high content of paste. Many SCC mixes therefore attain a higher strength than actually required [3,4]. In the Netherlands, and many other European countries, the Japanese Method has been adopted and used as a starting point for the development of SCC [5]. More recently, Su et al. [6] and Su and Miao [7] developed an alternative method for composing SCC, henceforth referred to as Chinese Method. The Chinese Method starts with the packing of all aggregates (sand and gravel together), and later with the filling of the aggregate voids with paste. The method is easier to carry out, and results in less paste. This saves the most expensive constituents, namely cement and filler, and concrete of ‘‘normal’’ strength is obtained. This will also favour the technical performance of the concrete, as the largest possible volume of aggregate is advantageous in regard to strength, stiffness, permeability, creep and drying shrinkage.

Self-consolidating concrete (SCC) is a highly flowable, yet stable, concrete that can spread readily into place, fill the formwork, and encapsulate the reinforcement, if present, without any mechanical consolidation and without undergoing any significant separation of material constituents. The introduction of the modern SCC is associated with the drive towards better quality of concrete pursued in Japan in late 1980s, where the lack of uniform and complete compaction had been identified as the primary factor responsible for poor performance of concrete structures. SCC has many advantages over conventional concrete such as:

- Eliminating the need for vibration;
- Decreasing the construction time and labor cost;

2. MIXTURE DESIGN PROCEDURES FOR SCC

Several design procedures based on scientific theories or empirical experiences have been proposed for SCC [7-8]. In general, these procedures fall into the following two categories: 1) combination of high-range water-reducing admixture and high content of mineral powders, and 2) combination of high-range water-reducing admixture and viscosity-modifying admixture (VMA) with or without defoaming agent. Figure 2 illustrates the general principles for the design of SCC, as considered from the excess paste theory. The conventional concrete design method begins with the determination of the amounts of water and cement, and ends with the calculation of the amount of aggregates. Because aggregates are much less expensive and more stable than cement pastes, a quality concrete should contain as much aggregate and less cement paste as possible. Thus, the most reasonable approach to determine the amounts of cement pastes for the concrete should be based on the characteristics of the aggregates used and of the concrete designed. In this paper, a procedure has been developed to design SCC using a combination of the least void volume for a binary aggregate mixture, excess paste theory [9-10] and ACI 211.2,"Standard Practice for Selecting Proportions for Structural Concrete [11].

Figure 2(a) shows compacted aggregate particles. In order to obtain a concrete mixture with proper workability, it is necessary to have not only sufficient amount of cement paste to fill the voids among aggregate particles, but also enough paste to form a thin layer of coating on the surface of aggregates to overcome some frictions between aggregate particles, as shown in Figure 2(b). Without a film of cement paste around aggregates as a lubricant, the movement between aggregates would be difficult. To further increase the workability of the concrete mixture to become a self-consolidating concrete, it is necessary to increase the volume of excess paste or the distance between aggregate particles, as shown in Figure 2(c). The required volume of excess paste is dependent on gradation, shape, and surface texture of the aggregates used, and can be determined through laboratory experiments for concrete mixtures with desired properties.

To determine the volume of filled paste and excess paste, the void volume of the dry binary aggregate (fine and coarse) mixtures should be determined first. The relationship between void volume or density of combined aggregates and coarse-to-fine aggregate volume ratio can be established by packing different amounts of coarse and fine aggregates following ASTM C 29/C 29M,19 as shown in Figure 3. It can be seen from Figure 3 that the lowest void volume for the combined coarse and fine aggregates used in this project is around 280 L/m3 when the coarse-to-fine aggregate volume ratio is 0.4.

The target compressive strength fc′ of the designed SLC was 28 MPa (4000 psi) at 28 days using ASTM Type I Portland cement. Because no statistical strength data are available for this concrete, ACI 318 "Building Code Requirements for Structural Concrete" requires that an average strength of the tested concrete at 28 days be fc′ + 8 MPa (1200 psi), or 36 MPa (5200 psi). ACI 211.2 provides guidelines on relationships between compressive strength and cement content, and relationship between compressive strength and water cement ratio (w/c). Based on the strength requirement and ACI 211.2, a cement content of 420 kg/m3 and a w/c of 0.48 were used in this study. The volume of excess paste was determined by experiments.

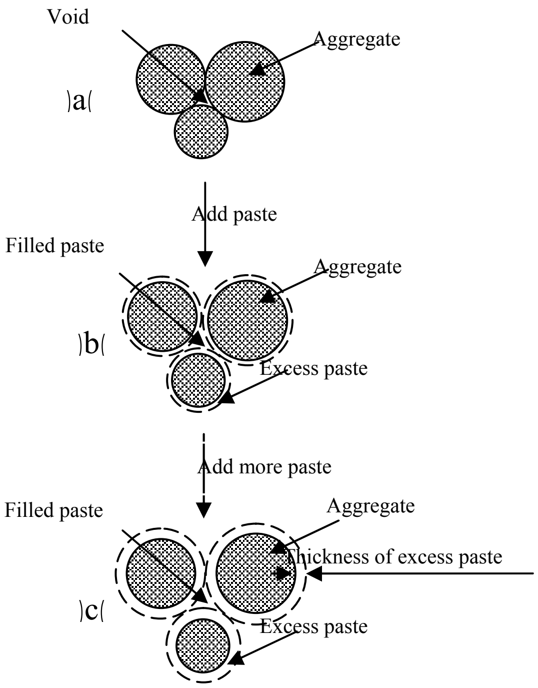

Figure 2. Scheme of compacted aggregate and concrete mixtures.

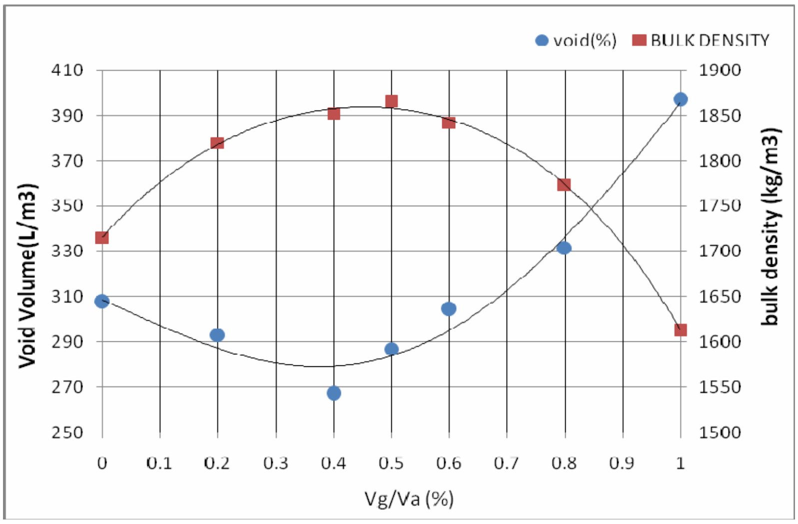

Figure 3. Effect of coarse-to-total aggregate volume ratio on bulk density and void volume of binary aggregate mixture consisting of coarse lightweight aggregate and fine natural siliceous sand

Different volumes of combined aggregates were replaced by cement paste with the same property. It was found that a replacement of 20% aggregate (by volume) by excess paste would give the concrete the required flowability and segregation resistance. The workability of the concrete mixture was adjusted by using a high-range water-reducing admixture. During the mixture proportioning, the cement content was fixed at 420 kg/m3; the rest of the paste was made from powders, such as Limestone and Silica fume.

Bulk Density ("Unit Weight") and Voids in Aggregate

Bulk Density-calculate the bulk density for the rodding, jigging, or shoveling procedure as follows:

$$M = (G - T)/V$$

Or

$$M = (G - T) \times F$$

Where:

M = bulk density of the aggregate, (kg/m^3),

G = mass of the aggregate plus the measure, kg ,

T = mass of the measure, kg ,

V = volume of the measure, m^3 , and

F = factor for measure, m^{-3}.

Figure 4. Cylindrical metal measure with Tamping Rod and piece of plate glass

Void Content-Calculate the void content in the aggregate using the bulk density determined by either the rodding, jigging, or shoveling procedure, as follows:

$$\%Void = \frac{100 \times [(S \times W) - (M)]}{S \times W}$$

Where:

M = bulk density of the aggregate, (kg/m^3) ,

S = bulk specific gravity (dry basis) as determined in accordance with Test Method C 127 or Test Method C 128, and

W = density of water, 998 (kg/m^3).

Relative Density (Specific Gravity) (OD)—Calculate the relative density (specific gravity) on the basis of oven-dry aggregate as follows:

Relative density (specific gravity) (OD) $= A/(B-C)$

Where:
A = mass of oven-dry test sample in air, g,
B = mass of saturated-surface-dry test sample in air, g, and
C = apparent mass of saturated test sample in water, g.

Powder Volume-Calculate the powder volume as follows:

$$V_P = V_W + V_C - V_{EXP} - Void$$

Where:
$V_P =$ Powder Volume (lit)
$V_W =$ Water Volume (lit)
$V_C =$ Cement Volume (lit)
$V_{EXP} =$ Excess Paste Volume (lit)
$Void =$ Void Volume (lit)

3. MIX DESIGN OF STRUCTURAL SCC USING VOID-BULK DENSITY METHOD

Nine batches of concrete were designed using the same mixture proportions, as shown in Table 1.

Concrete mixtures were mixed in a high-speed shear mixer. The properties of freshly mixed concretes were determined as described in the following. For each batch, two 100x200mm cylinders were cast for splitting strength testing and six 100x100x100mm cube were cast for compressive and elastic moduli testing. The specimens were cast in one layer without any compaction or vibration. After casting, all the molded specimens were taken to a fog room at 23±2°C. The curing and testing of these specimens for measurement of different properties are described in the following.

Table 1: Mixture proportions of SCC

Mixture No.	Coarse ggregate	Sand	Water	Cement	silicafume	limestone	sp
SCC1	684	884	191	458	46	149	6.8
SCC2	686	886	190	459	48	149	7.15
SCC3	699	907	169	429	36	165	7.01
SCC4	709	918	165	443	71	83	10.10
SCC5	711	924	180	444	63	107	9.8
SCC6	712	925	188	455	134	0	10.40
SCC7	705	917	186	451	87	61	9.47
SCC8	683	917	190	397	92	110	9.38
SCC9	692	900	205	439	116	33	10.10

3.1. Slump Flow Test

The slump flow test measures the horizontal free flow of SCC by using a regular slump cone. It was first developed in Japan for use in assessment of flowability of underwater concrete. This is a simple, rapid test procedure and is suitable for construction site use. The slump cone was filled with concrete mixtures without rodding, and then lifted up vertically. The diameters of spread mixtures in four directions after unconfined lateral spread were measured, and the average of the four measurements was used as the flowability of the concrete mixture. The slump flow of the mixtures was measured at 30, 60, and 90 min after the addition of mixing water to examine how the flowability of SCLC mixtures changed with time. Between measurements, the SCC mixtures were stored in a bucket covered with a damp cloth to avoid moisture loss.

3.2. V-funnel test

A V-funnel, as shown in Figure 5, was used to determine the flowability of the concrete. The funnel was filled with a concrete mixture without rodding or tamping, then the trap door at the bottom was opened to allow concrete to flow out under gravity. The time from opening the trap door until complete discharge of the concrete mixture was recorded as an indication of the flowability of the concrete.

Figure 5. Schematic illustration of V-funnel

3.3. L-box test

L-box tests assess the filling and passing ability of SCC. Serious lack of stability (segregation) can also be observed easily during the testing. The testing apparatus is shown in Figure 6. The vertical section was filled with a concrete sample without rodding or tamping, and then the sliding door was lifted. The time for concrete mixture to flow to the end of the horizontal section was recorded, and the distance H1 and H2 were measured. The flow time can give an indication of flowability. The ratio H2/H1 is called the blocking ratio. Obvious blocking of coarse aggregates behind the reinforcing bars can be visually observed easily.

Figure 6. Schematic illustration of L-box

Table 2: Properties of freshly mixed SCLC mixtures

Mixture no	Slump flow (mm)	Slump flow (s)	V-funnel (s)	L-Box H2/H1,%	L-Box flow t1 (s)	Segration resistance	Density kg/m3
SCC1	615.0	2.75	7.10	0.900	0.73	GOOD	2416.67
SCC2	625.0	2.65	6.70	0.910	0.54	GOOD	2425.00
SCC3	610.0	3.31	12.42	0.785	1.01	GOOD	2412.50
SCC4	655.0	4.05	9.25	0.875	0.68	GOOD	2400.00
SCC5	710.0	1.18	6.12	0.895	0.51	GOOD	2439.38
SCC6	585.0	2.25	6.45	0.805	0.74	GOOD	2424.38
SCC7	690.0	1.29	6.02	0.835	0.46	GOOD	2416.67
SCC8	670.0	1.28	5.88	0.885	0.43	GOOD	2397.78
SCC9	600.0	1.19	5.94	0.825	0.45	GOOD	2400.00

Table 3: Mixture proportions of CVC

Mixture no.	Coarse aggregate	Sand	Water	Cement	silicafume	limestone	sp
CVC1	691	895	176	393	81	180	5.86
CVC2	1062	806	159	413	36	0	6.88
CVC3	1042	877	148	385	38	0	7.16
CVC4	1041	914	138	352	39	0	7.45
CVC5	1001	849	165	447	23	0	7.9
CVC6	1038	886	146	426	22	0	8.80
CVC7	1040	823	167	437	22	0	7.05
CVC8	1071	884	156	372	20	0	7.16

ine different SCC mixtures, using the volume of paste and the relative amount of sand and gravel as variables, and four different mixtures of CVC were made (Tables 1 and 3). Natural sand and gravel with a high percentage of well rounded particles was used with a maximum grain diameter of 12.5 mm for SCC and 19.5 mm for CVC.

4. RESULT

The compressive strengths of SCC and CVC showed similar values for an identical w/b ratio (Figure 7).

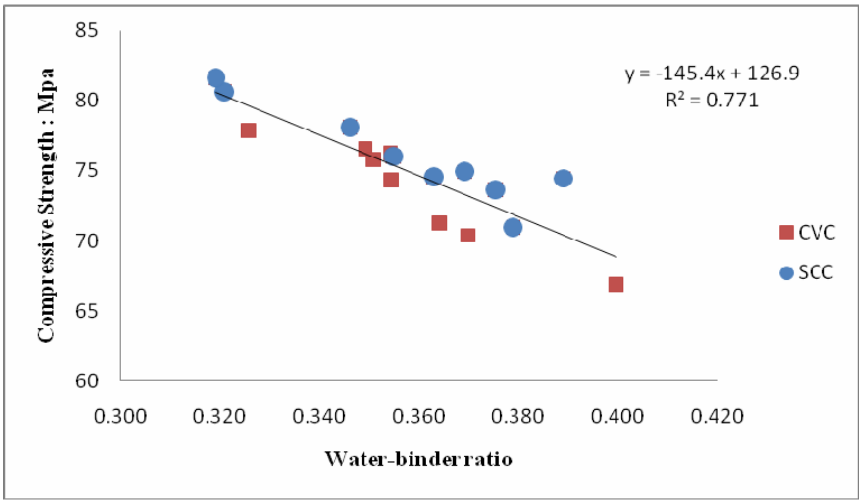

Figure 7. Compressive Strength at 28 days versus w/b ratio

The average E-modulus of SCC was about 8% lower than that of CVC for an identical compressive strength (Figure 8).

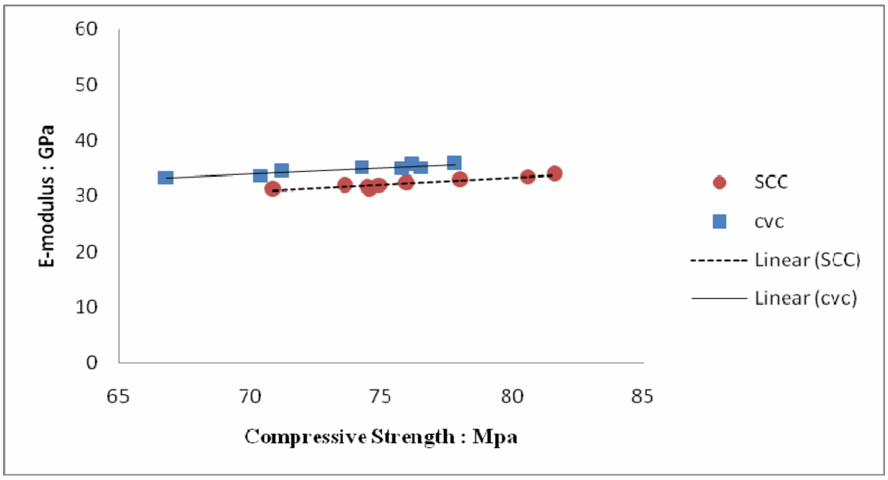

Figure 8. E-modulus versus Compressive Strength, both at 28 days

There was no significant difference in the relation between compressive and splitting tensile strength of SCC in comparison with CVC although the values for SCC showed a relatively high standard deviation (Figure 9).

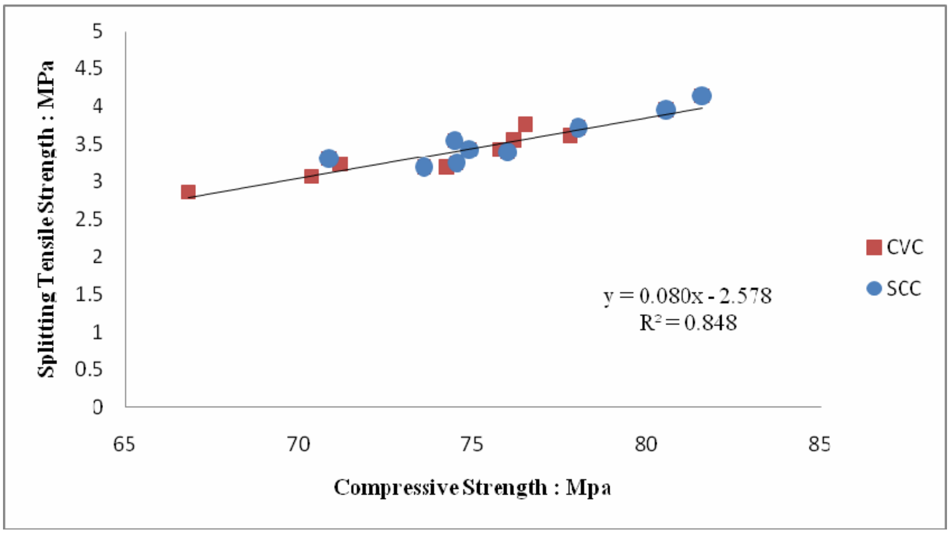

Figure 9. Splitting tensile strength versus Compressive Strength at 28 days

5. CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

1. SCLC can be designed using a combination of the least void volume for a binary aggregate mixture, excessive paste theory, and ACI standard practice for selecting proportions for structural concrete. Both ground Limestone powder and Silicafume can be used satisfactorily as powder for making up the excessive paste for SCC.
2. Differences in the properties of SCC and CVC used in this study were mainly caused by their relative volume of paste:
3. The E-modulus of SCC was about 8% smaller than that of CVC for an identical compressive strength.
4. At the age of 28 days SCC and CVC displayed the same compressive and splitting tensile strength with a constant w/b ratio.

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