MIXTURE PROPORTIONING METHOD FOR SELF-COMPACTING HIGH PERFORMANCE CONCRETE WITH MINIMUM PASTE VOLUME

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Abstract

This paper presents a mix design method from the view point of high durability, economic efficiency and application for different materials for self-compacting high performance concrete. Concrete is considered as two-phase material, namely solid and liquid phases. Based on proposed criteria for solid and liquid phases, minimum paste volumes can be estimated. Experimental results show that the method can be useful for mix design of self-compacting concrete, resulting in less superplasticzer dosage, less paste volume and low drying shrinkage. Also, the method can be applicable for different materials.

Keywords: mix design method, self-compacting concrete, minimum paste volume, criteria for solid and liquid phases

1. Introduction

Self-compacting concrete (SCC) is a relatively new type of concrete that has been developed in recent years. The main properties of interest in its fresh state are deformability, segregation resistance and blocking property when the concrete flows through clear spacing between reinforcement bars. Good deformability or flowability is necessary to ensure adequate flow under self-weight of SCC. Adequate segregation resistance is required to ensure that components, especially coarse aggregate, are uniformly distributed in SCC when it is in a static or fl.owing condition, particularly through and around reinforcement. In addition, SCC should not block around reinforcements. It is therefore necessary to apply appropriate mix design procedures for SCC in order to achieve these properties. This paper presents a mix design method for self-compacting high performance concrete aimed at producing high durability and economic efficiency, while being applicable for different materials. The paper describes the proposed criteria for the paste phase of the concrete. Using procedures relevant to the criteria of aggregate and paste phases, minimum required paste volume and optimum coarse to total aggregate ratio are determined. Experimental results and analytical data relating to the proposed criteria are also discussed in the paper.

2. Background

A method for the optimum proportioning of the aggregate phase for self-compacting high performance concrete was first proposed by the first author and co-workers in 1993 (1). In this proposed method, concrete is considered as a two-phase material, namely solid and liquid phases. The solid phase consists of fine and coarse aggregates. The liquid phase includes powder (cement, fillers), water, admixtures and air. The paste fills the voids in the aggregate matrix and provides a lubricating layer around each aggregate particle. The author and co-workers initially focused on the solid phase (the aggregate phase), and the blocking criteria for the aggregate phase in SCC was developed based on the condition that the concrete does not segregate and has sufficient deformability (1, 2, 3). From the blocking criteria, a minimum required paste volume (or maximum allowable aggregate volume) can be calculated in order to obtain self-compaction of concrete without causing blocking around the reinforcement. For a certain coarse to total aggregate ratio (Nga) (by mass), the maximum allowable aggregate volume can be computed as follows:

$$Vabmax = \frac{\rho g + (\rho s - \rho g) * Nga}{\sum \frac{Pvgm * Nga * \rho s}{Vabm} + \sum \frac{Pvsn * (1 - Nga) * \rho g}{Vabn}} \quad \text{(Eq. 1)}$$

where Vabmax is the maximum allowable aggregate volume in SCC. ρg and ρs are specific gravities of coarse and fine aggregates, respectively. Pvgm is volume ratio of coarse aggregate group m to total coarse aggregate, and Pvsn is volume ratio of fine aggregate group n to total fine aggregate. Vabm and Vabn are the blocking volumes of group m and n in coarse and fine aggregates, respectively. Vabm and Vabn can be calculated as follows:

$$Vabm = Nabm*Vt \quad \text{(Eq. 2)}$$

$$Vabn = Nabn*Vt \quad \text{(Eq. 3)}$$

where Vt is total concrete volume, and from test results, for crushed coarse aggregate, the values of Nabm and Nabn can be calculated as follows:

a) For $1 \le Dca \le 2.6$

$$Nabm \equiv Nabn = \frac{Ck}{1.6} Dca - \frac{Ck}{1.6} \quad \text{(Eq. 4)}$$

b) For $2.6 \leq Dca \leq 15$

$$Nabm \equiv Nabn = \frac{0.84 - Ck}{12.4} Dca + 1.2097\, Ck - 0.1761 \qquad \text{(Eq. 5)}$$

c) For $Dca > 15$

$$Nabm \equiv Nabn = 0.84 \qquad \text{(Eq. 6)}$$

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

$$Daf = M_{i-1} + 3/4 * (M_i - M_{i-1}) \qquad \text{(Eq. 7)}$$

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

Ck is a coefficient dependent on ratio (K) between reinforcement diameter and maximum aggregate size:

$$Ck = -0.0875\, K + 0.55 \qquad \text{(Eq. 8)}$$

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

Test results which were reported in a number of publications (1, 2, 3, 4) showed that the blocking criteria is useful in predicting minimum paste volume (Vpwmin) required for SCC when it flows through clear spacing between reinforcement bars without blocking. Therefore, the blocking criteria (solid-phase criteria) together with the liquid-phase criteria, which is described in the following sections, are used to design mix proportions for self-compacting concrete.

3. Liquid-Phase Criteria

3.1. Concept

In a previous study (1), the author also proposed a formula to calculate the average spacing (Dss) between particle surfaces in concrete as follows:

$$Dss = Dav \left\{ \sqrt[3]{1 + \frac{Vpw - Void}{Vt - Vpw}} - 1 \right\} \qquad \text{(Eq. 9)}$$

where Dss is average spacing between particle surfaces (particles are assumed to be spherical); Vpw is paste volume; Void is volume of voids in the densely compacted aggregate; Vt is total concrete volume; and Dav is the average particle diameter, which is given by:

$$Dav = \frac{\sum Di * Mi}{\sum Mi} \qquad \text{(Eq. 10)}$$

where Di: Average size of aggregate fraction i

Mi: Percentage of aggregate mass retained between upper and lower sieve sizes (obtained from sieve analysis) in fraction i

As stated above, previous studies by the author and co-workers (1, 2, 3) focused mainly on the solid phase, e.g. the aggregate phase when considering blocking behaviour, based on the condition that concrete does not segregate and has sufficient deformability. In this study, major emphasis has been concentrated on the liquid phase, e.g. the paste phase that includes water, cement, mineral powder, admixtures and air in concrete. From this, a comprehensive mix proportioning method has been developed. The method is based on the concept of:

- high durability (control of strength and drying shrinkage),
- economic efficiency (as low a paste volume and superplasticizer dosage as possible),
- capacity to be applied for many types of materials,
- enhancing quality control (as little sensitivity as possible to quality control), and
- reducing necessity for extensive laboratory testing (less trial mixes, use of computer program and rapid tests for deformability, blocking behaviour and segregation resistance of self-compacting concrete).

In order to produce SC-HPC conforming to the above requirements, the concrete should have the following characteristics:

- Slump flow diameter (Fd) should be larger than 650 mm in order to have good flow or deformability and good surface appearance, as Shiba et al. (5) have reported that SCC with slump flow diameter larger than 650 mm is of better surface appearance;
- Penetration depth (Pd) should not be larger than 8 mm in order to ensure that concrete has satisfactory segregation resistance (6);
- The flow time T50 should not be greater than 12 seconds (T50 is the time for concrete to flow to a diameter of 50 cm, when it is tested for slump flow) because flow time relates to speed of construction;
- Superplasticizer dosage should be less than 15 kg per m^3 in dry form to reduce the cost of concrete, and also to limit any undesirable effects due to concrete containing excessive amounts of certain types of superplasticizer (5);
- As low a paste volume as possible in order to control drying shrinkage (as low paste volume usually leads to lower drying shrinkage), and to lower the cost of SCC.

3.2. Materials Used in Experimental Program

Two types of shrinkage limited portland cements (SC1 and SC2), ordinary portland cement (OP), two blast furnace slag cements together with three sources of milled limestone and fly ash (FA) were used. The two blast furnace slag cements, identified as BC1 and BC2, contain 30% and 65% of blast furnace slag, respectively. The three sources of milled limestone, identified as LS1, LS2 and LS3, had different degrees of fineness that are classified as coarse, fine and very fine, respectively. The fineness and specific gravities of cements and mineral admixtures are indicated in Table 1. Six sources of coarse aggregates and two sources of river sand (RS1 and RS2) were used in the concrete mixes. The six sources of coarse aggregate, identified as A, B, C, D, E and F, had maximum size of 20mm, 20mm, 14mm, 14mm, 10mm and 10mm, respectively. The specific gravities of river sands and coarse aggregate are indicated in Table 2. Coarse aggregates A and E, with mass ratio of 62 : 38, and aggregates C and E, with mass ratio of 70:30 were blended and used together with river sand RS1 were used in mixes containing milled limestone. Aggregates B and F, with mass ratios of 62 : 38, and aggregates D and F, with mass ratio of 73:27 were blended and used together with river sand RS2 in mixes containing fly ash and blast furnace slag cements.

Table 1: Specific gravity and fineness of cements and mineral admixtures

	SC1	SC2	OP	BC1	BC2	LS1	LS2	LS3	FA
Specific Gravity	3.14	3.18	3.15	3.03	2.89	2.65	2.69	2.69	1.9
Fineness (Blaine) (m^2/kg)	336	357	370	405	410	380	870	1680	-
Passing 45μm (%)		-	-	-	-	-	-	-	91

Table 2: Maximum size and specific gravity of coarse aggregates

Identification	A	B	C	D	E	F	RS1	RS2
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

3.3. Minimum Required Value of Average Aggregate Spacing (Dssmin)

To date, no recommendations have been put forward to predict a required value of Dss for self-compacting concrete. Thus, in this study, a model for predicting the required value of Dss for self-compacting high performance concrete (SC-HPC) was developed.

The minimum required value of Dss is dependent on a number of factors, namely:

- Properties of cement (chemical composition and fineness);
- Properties of aggregates (particle size distribution, specific gravity, surface texture and shape);
- Properties and content of supplementary materials and admixtures (chemical reactivity, fineness, particle shape and size distribution);
- Properties of superplasticizer
- Water to binder ratio
- Characteristics of binary mixture of fine and coarse aggregate (void content);
- Interaction between components such as reaction between cement and superplasticizer, or between cement and mineral admixtures.

The values of Dss with respect to different values of Dav for experimental concretes containing 20-mm and 14-mm aggregates and water to binder ratios of 0.30, 0.32 and 0.35 were calculated. Due to limited space of this paper, only two typical cases are illustrated in Fig. 1 and 2 for SCC containing 20-mm and 14-mm coarse aggregates. Test results show that higher values of average aggregate particle diameter (Dav) generally require higher average spacing (Dss) between particle surfaces in order to achieve a sufficient slump flow diameter greater than 650 mm without producing segregation. However, for certain mixes when the average diameter, Dav, was low, the superplasticizer requirement and flow time of the respective concrete was high. The superplasticizer requirement and flow time can be reduced by increasing the paste volume (e.g. increase average spacing Dss) for mixes with the same average aggregate diameter (Dav). Also, for concrete containing similar superplasticizer dosage, lower water to binder ratio requires higher paste volume (Vpw) (e.g. higher Dss) in order to achieve similar slump flow diameters without causing segregation. In addition, different coarse aggregates with different maximum sizes can have an affect on flow velocity, tendency for segregation and required paste volume (i.e. average spacing Dss). Concretes containing coarse aggregate of higher maximum size tends to have higher flow velocity and higher risk of segregation.

As discussed above, the minimum required values of Dss depend on a number factors, and there would no formula that can calculate exactly the minimum required value of Dss for all materials. Therefore, in this study, effort was made to propose a model that ultimately can be used to specify the approximate minimum required value of Dss. The model is useful for estimating an initial value to be used in trial mix designs. The proposed model is based on consideration of :

- Water to binder ratio (W/B) (or water to powder ratio, in the case of large proportions of very fine particles in aggregates);
- Particle size distribution and particle shape of aggregate binary mixtures by incorporating average aggregate diameter (Dav) and void content in the formula estimating the minimum required value of Dss;
- Aggregate maximum sizes of 20 mm and 14 mm as, for the same coarse to total aggregate ratio, 20-mm aggregate can lead to higher risk of segregation and higher flow velocity of SCC in comparison with 14-mm aggregate; and
- Different coarse to total aggregate ratios (Nga) that relate to average aggregate diameter, Dav and void content.

The analytical values of Dssmin in SCC containing 20-mm and 14-mm coarse aggregates with different water to binder ratios are illustrated in Fig. 1, 2 and 3. These are generated based on experimental results by considering pairs of points (having corresponding values of Dav and Dss) where the values of Dav are divided into three ranges ($Dav \leq 5.0$ mm, 5.0 mm $< Dav \leq 6.5$ mm and $Dav > 6.5$ mm) for SCC containing 20-mm coarse aggregate and two ranges ($Dav \leq 6.5$ mm and $Dav > 6.5$ mm) for SCC containing 14-mm coarse aggregates, respectively. Linear relationships are considered to exist in the respective ranges for Dav.

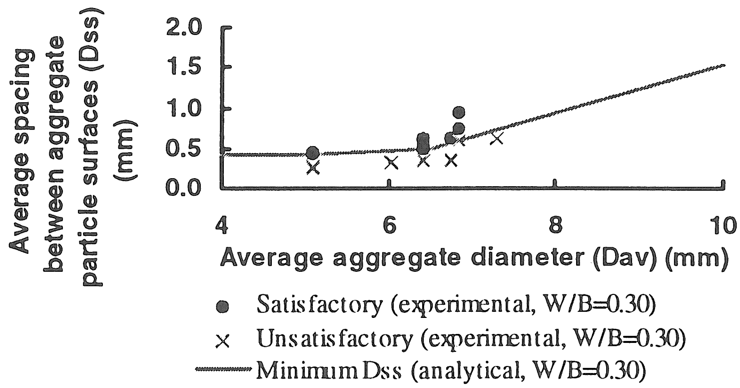

Fig. 1: Analytical values of Dssmin and average aggregate spacing (Dss) (experimental) for SCC containing 20-mm coarse aggregate with water to binder ratio of 0.30

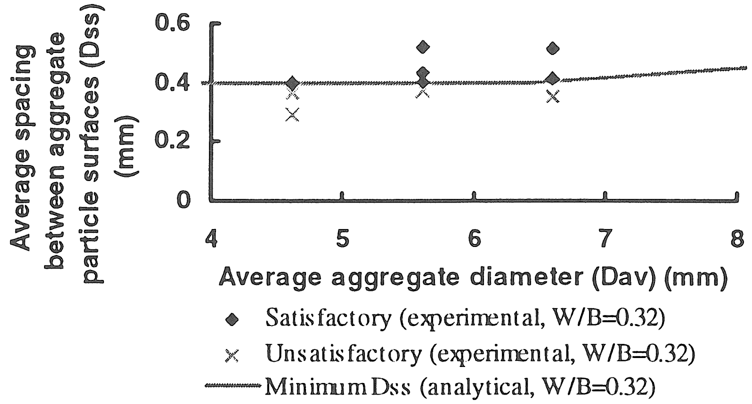

Fig. 2: Analytical values of Dssmin and average aggregate spacing (Dss) (experimental) for SCC containing 14-mm coarse aggregate with water to binder ratio of 0.32

For low average aggregate diameter, Dav (i.e. low coarse to total aggregate ratio), the required values of Dssmin for SCC containing 14-mm coarse aggregate are generally higher than those for SCC containing 20-mm coarse aggregate (Fig. 3). This is due to the fact that, for low value of Dav, low flow velocity and high requirement of superplasticizer dosage are generally problematic; therefore, increase in paste volume (Vpw) (i.e. increased Dssmin) is necessary in order to achieve satisfactory flow velocity for SCC containing 14-mm coarse aggregate. On the other hand, when average aggregate diameter (Dav) is high (larger than 6.5 mm), SCC containing 20-mm coarse aggregate has higher risk of segregation than that containing 14-mm coarse aggregate;

thus, in order to reduce the risk of segregation, the value of Dssmin in SCC containing 20-mm coarse aggregate needs to be larger than for SCC containing 14-mm coarse aggregate.

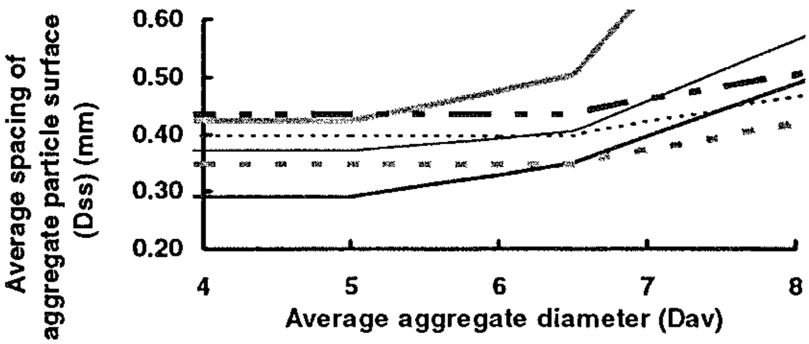

Fig. 3: Analytical values of Dssmin for SCC containing 20-mm and 14-mm coarse aggregate with water to binder ratios of 0.30, 0.32 and 0.35

As can be seen from Fig. 1, 2 and 3, the required value of Dssmin depends on water to binder ratio (W/B) and average aggregate diameter (Dav). Lower water to binder ratio requires higher value of Dssmin, and generally, higher average aggregate diameter Dav requires higher value of Dssmin. Fig. 1, 2 and 3 also show that the required value of Dssmin is dramatically increased when the average aggregate diameter is larger than 6.5 mm. This is due to the fact that too large a value of Dav, i.e. too large a proportion of coarse aggregate, causes high sensitivity to segregation control for SCC. The high value of Dssmin is necessary to reduce the sensitivity and increase the deformability of SCC without causing segregation. For certain types of fine and coarse aggregates, the average aggregate diameter, Dav, depends on the coarse to total aggregate ratio (Nga). Therefore, it is better to choose a coarse to total aggregate ratio (Nga) with an average aggregate diameter smaller than or equal to 6.5 mm.

3.4. Minimum Paste Volume (Vpdmin) of SCC Considering Liquid-Phase Criteria

By substituting Dssmin instead of Dss in Eq. 9, the minimum required paste volume (Vpdmin) of SCC, when considering the liquid phase, can be calculated as follows:

$$\text{Vpdmin} = \text{Vt} - \frac{\text{Vt} - \text{Void}}{\left[\dfrac{\text{Dssmin}}{\text{Dav}} + 1\right]^3} \qquad \text{(Eq. 11)}$$

where Vpdmin is minimum required paste volume (l/m^3) for certain coarse to total aggregate ratio (Nga); Void is aggregate void content (l/m^3) of compacted aggregate matrix, measured according to ASTM C29/C29M (7); Dssmin is minimum required average spacing (mm) between aggregate particle surfaces, calculated from criteria for liquid phase (illustrated in Fig. 3); Dav is average aggregate particle diameter (mm) that is calculated from Eq. 10.

Test results and analytical values (from Eq. 11) of paste volumes for SCC containing milled limestone with 20-mm coarse aggregate and water to binder ratios of 0.30 and 0.35 are given in Fig. 4 and 5. Test results and analytical values of paste volume for SCC containing fly ash (FA) and blast furnace slag cements (BC1 and BC2) with 20-mm and 14-mm coarse aggregates and water to binder ratios of 0.32 are shown in Fig. 6 and 7.

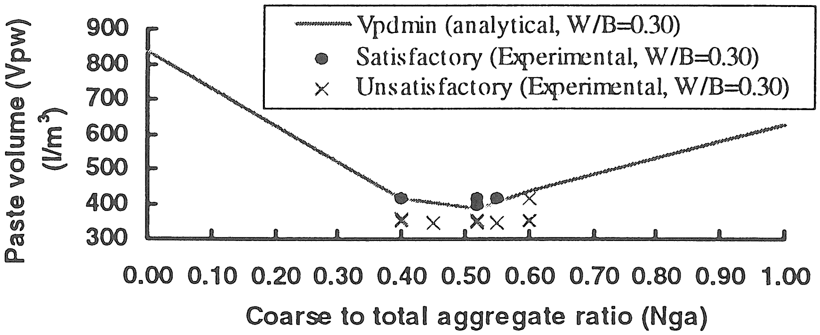

Fig. 4: Minimum required paste volume (Vpdmin) (analytical) and experimental results for SCC containing milled limestones and 20-mm coarse aggregate (W/B=0.30)

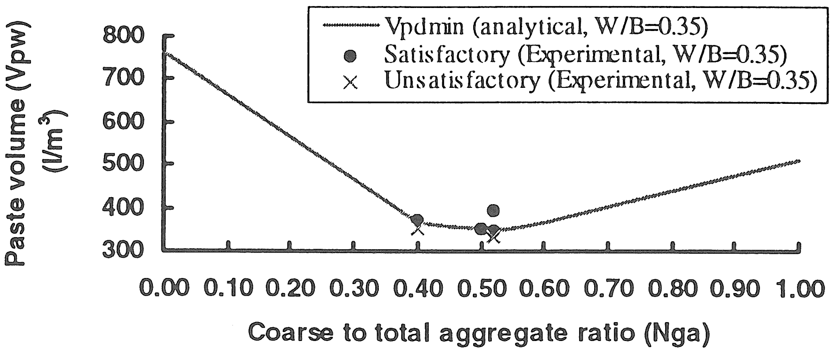

Fig. 5: Minimum required paste volume (Vpdmin) (analytical) and experimental results for SCC containing milled limestones and 20-mm coarse aggregate (W/B=0.35)

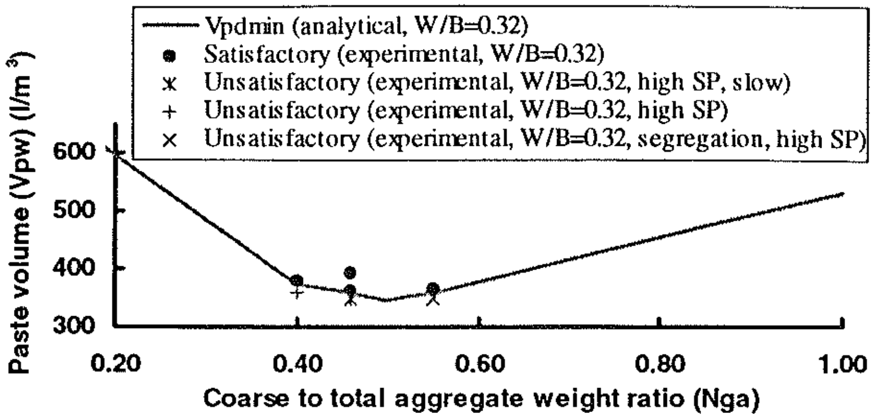

Fig. 6: Minimum required paste volume (Vpdmin) (analytical) and experimental results for SCC containing fly ash and 20-mm coarse aggregate (W/B=0.32)

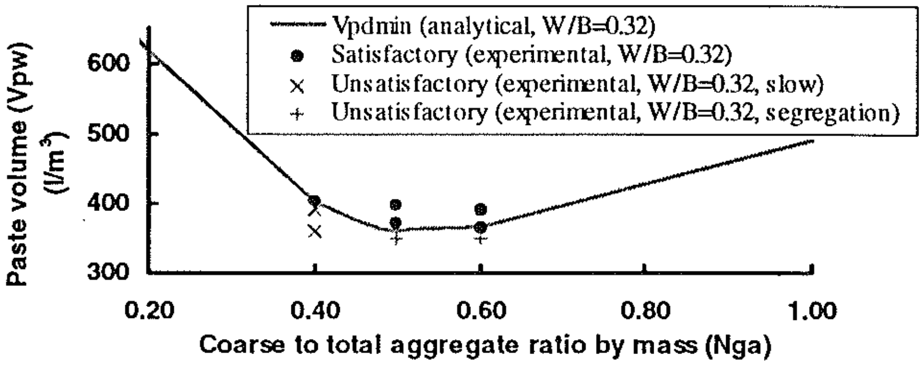

Fig. 7: Minimum required paste volume (Vpdmin) (analytical) and experimental results for SCC containing blast furnace slag cements and 14-mm coarse aggregate

If deformability and segregation resistance of SCC only are considered, then for low coarse to total aggregate ratio and/or low maximum size of coarse aggregate, SCC sometimes requires less paste volume than that computed from the proposed criteria of liquid phase. However, when other parameters are considered, namely flow velocity and superplasticizer dosage, it is necessary to increase paste volume to a level which is not less than that computed from the criteria (Fig. 6 and 7). As can be seen from Fig. 1 to Fig. 7, inclusive, the analytical lines, which illustrate the values computed from the proposed liquid-phase criteria, clearly divide the zones of satisfactory and unsatisfactory experimental results. Therefore, the liquid-phase can be used to predict the minimum required paste volume (Vpdmin) for SCC in order to have satisfactory deformability, segregation resistance and flow velocity, and to require less superplasticizer.

4. Mixture Proportioning Steps

The steps in the mix design procedure are as follows:

a) Construction criteria such as clear spacing between reinforcement bars, diameter of reinforcement bars and requirement of compressive strength are specified;

b) Determine material characteristics for mineral admixtures, cement and aggregates, (such as specific gravity, particle size distribution, maximum size, average diameters (Dav) of different coarse to total aggregate ratios (Nga) (values of Nga between 0.40 and 0.60 are recommended)), void contents corresponding to different Nga that have Dav $\leq$ 6.5 mm;

c) Calculate maximum allowable aggregate volume (Vabmax) (or minimum paste volume (Vpwmin)) with respective Nga, according to blocking criteria (using Eq.1);

d) Determine water to binder ratio and mineral admixture to total binder ratio in considering the required compressive strength;

e) Calculate minimum required values of Dssmin for different Dav (with respective value of Nga) and minimum required paste volumes (Vpdmin), according to liquid-phase criteria;

f) Select the optimum Nga that requires the lowest paste volume according to the liquid-phase criteria, provided that its respective Dav is not larger than 6.5 mm; otherwise, choose the Nga which has Dav of 6.5 mm. The paste volume (Vopt) at optimum coarse to total aggregate ratio (Nopt), which satisfies both blocking criteria (solid phase) and liquid-phase criteria, is selected as follows:
   - (f1) Vopt $\geq$ Vpdmin, if Vpdmin $>$ Vpwmin; or
   - (f2) Vopt $\geq$ Vpwmin, if Vpdmin $<$ Vpwmin, and Vpwmin is not too high from the view point of economic efficiency (Vopt $\leq$ 420 l/m^3 is recommended);
   - (f3) In the case of very narrow clear spacing between reinforcement bars and Vpwmin is too high (Vpwmin $>$ 420 l/m^3), the use of the coarse aggregate with smaller maximum size should be considered;

g) Estimate superplasticizer dosage, and carry out trial mixing and testing;

h) If required superplasticizer dosage is very high (SP $\geq$ 15 kg per m^3 concrete) or if the mix is unsatisfactory, it is necessary to increase paste volume (Vpw) or adjust water to binder ratio and admixture, accordingly.

4. Conclusions

Criteria for liquid phase that include minimum average aggregate spacing (Dssmin) and minimum paste volume (Vpdmin) were developed. The minimum average aggregate spacing (Dssmin) depends on water to binder ratio, maximum size of coarse aggregate and average aggregate diameter (Dav). The minimum required paste volume (Vpdmin) can be calculated from a formula that relates to Dssmin, Dav and void content of aggregates. Test results have shown that an analytical line, which corresponds to the computed minimum required paste volume, divides zones of satisfactory and unsatisfactory experimental results. Therefore, the proposed criteria for liquid phase can be useful in estimating the required minimum paste volume in order to achieve SCC having satisfactory deformability, segregation resistance and flow velocity, and requiring reasonable dosage of superplasticizer.

The proposed mix design method combines the criteria for aggregate blocking and liquid phase (deformability, segregation resistance and flow velocity as well as superplasticizer requirement), criteria for selection of optimum coarse to total aggregate ratio and construction criteria. The method can be used to design SCC having high durability, economic efficiency and application for different materials. The developed criteria should also reduce the need for repeated mixing trials, while economising on the time and extent of laboratory procedures and practices.

5. References

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