Methodology for mix design of the mortar phase of self-compacting concrete using different mineral additions in binary blends of powders

M. Nepomuceno, L. Oliveira, S.M.R. Lopes

Abstract

This paper details a comparative analysis of the results obtained in tests on mortars suitable for self-compacting concrete (SCC). The binary and ternary blends of powder materials used were combinations of two cements with four additions in different percentages: limestone powder, fly ash, granite filler and microsilica. The correlations between the mix design parameters of the mortar phase and the flow properties and compressive strength were evaluated. As a result of this evaluation, a simple methodology was proposed for the mix design of the mortar phase in binary blends of powder with the aim of simultaneously obtaining both adequate flow properties and the necessary compressive strength of the mortar. © 2011 Elsevier Ltd. All rights reserved.

1. Introduction

To achieve a suitable viscosity, self-compacting concrete can be produced using a viscosity-modifying admixture or, more commonly, using a large amount of powder materials (cement and mineral additions). A superplasticizer is also used to control the shear stress [1]. In the SCC discussed in this paper, no stabilizing agents, such as viscosity-modifying admixture, were used.

For the purpose of increasing the viscosity of SCC, the most commonly used mineral addition is limestone powder, classified as a type I addition (nearly inert or inactive). This addition has been successfully used as a partial substitute for cement and has produced improvements at the rheological level and in the substantial reduction of the amounts of superplasticizer deemed necessary when compared to cement-only mixtures with similar flow properties. In large masses of concrete, limestone powder has shown to be effective in inhibiting temperature increase and in preventing cracks caused by thermal gradients [1].

The type II (pozzolanic) additions include, among others, ground granulated blast furnace slag, fly ash and silica fume. Of these three industrial by-products, the fly ash is the most frequently used, as it offers improvements in concrete workability due to the spherical shape of the particles [1]. In mixtures with similar flow properties those including silica fume, even where the percentage of cement replaced is lower than 10%, have required large amounts of superplasticizer when compared to any other aforementioned additions, be they type I or type II [2,3].

Other additions originating from industrial waste materials are being tested for use as filler in SCC, such as granite filler or marble dust [4]. Such use of industrial by-products in SCC can provide economic benefits and prevent environmental pollution [4–6]. Moreover, investigations into the effects of binary, ternary, and quaternary blends of fly ash, blast furnace slag, and silica fume on the properties of SCC have concluded that using mineral admixtures in the production of SCCs can improve the durability of concretes [6]. Fibres can also be used as an addition, but they have an influence on viscosity [7–9], which is in itself a property still being studied [10].

The development of self-compacting concrete and the first mix design method, namely that proposed by Okamura, Maekawa and Ozawa, later improved by the contribution of Ouchi et al. [1,11–13], represented an important step for concrete technology. Furthermore, the guidelines proposed by the JSCE [1,11] establish a basis for generalising its use. The method proposed by Okamura was developed for general application and has the advantage of simplicity. However, this method is considered conservative and, in general, it leads to a self-compacting concrete mixture with higher volumes of paste than an optimised mixture [14]. Afterwards, the general tendency was to focus on optimising mixture proportions, aiming to reduce paste volume. The research done by Petersson et al. [15,16], Tangtermsirikul and Bui [17], Bui and
Montgomery [18], Sedran and Larrard [14] should be recognized. Sonebi [19] has also investigated the effects of the content of cement, additions and superplasticizer on the fresh and hardened properties of SCC and proposed a statistical model to simplify the test protocol required to optimise a given mix. Many of the models described are based on a given set of materials and correlations and cannot be generalised to other materials unless new correlations are generated.

As a result of this analysis, the possibility of outlining a different simple approach to the methodology of SCC mix design was considered. At the first stage, the new proposal was supported by tests on the mortar phase as proposed by the Okamura research group [1,11–13]. Our investigation evaluated the mix design parameters of mortars in order to achieve adequate fresh properties and compressive strength when binary and ternary blends of powder materials were used; mixes of two cements and four mineral additions.

The mortars produced had compressive strength values between 25 MPa and 95 MPa and had similar flow properties, proving adequate for the production of self-compacting concretes (Is this what you wanted to say Yes).

An experimental and iterative process was used to obtain adequate flow properties and a parameter was introduced in order to account for the ratios between the absolute volumes of powder materials and fine aggregates (Vp/Vs). The values assumed for the parameter Vp/Vs should vary in such a way that the corresponding volumes of fine aggregates vary below and above those proposed by Okamura et al. [1,11–13]. However, varying the volumes of fine aggregates makes it necessary to evaluate the properties of fresh mortars that produce self-compacting concrete. The flow properties were defined with an interval of variation to include several proposals besides the one presented by Okamura et al. [1,11–13].

Binary and ternary mixes of powder materials were used. These were mixtures of two cements (CEM I 42.5R and CEM II/B-L 32.5N) and four additions: limestone powder, fly ash, microsilica and granite filler. The granite originated from industrial waste and underwent no additional processing. It was used here on a trial basis. The analysis was focused on mortars for SCC in which adequate viscosity was achieved by including large amounts of powder materials, and only the physical and mechanical properties of their behaviour were evaluated.

2. Experimental programme

2.1. Materials

Two types of Portland cement (CEM I 42.5R and CEM II/B-L32.5N) and four mineral additions (limestone powder, granite filler, fly ash and microsilica) were used. The specific gravity and the fineness of cements and additions are indicated in Table 1. The particle distribution analysis of the mineral additions tested in the Coulter LS200 laser particle analyzer is shown in Fig. 1. A modified polycarboxylate based superplasticizer was used. It was supplied in liquid form and had a density of 1.05.

A mixture of two natural sands was used and kept constant for all the mortars produced, with the proportion in absolute volume being 40% for Sand 01 and 60% for Sand 05. Sand 01 is a fine sand, with a specific gravity of 2.59 and a fineness modulus of 1.49. Sand 05 is a coarser river sand, with a specific gravity of 2.61 and a fineness modulus of 2.71. The ratio between the two sands was determined experimentally in order to obtain maximum bulk density and be used as a reference curve. The bulk density of this reference curve was 1598 kg/m$^3$ and the fineness modulus was 2.22. The grading curves of the two fine aggregates and the resulting reference curve are shown in Fig. 2.

2.2. Binary and ternary blends of powder materials

The binary blends of powdered materials are illustrated in Table 2, whereas the ternary blends are illustrated in Table 3. Each mixture is identified by a code that indicates the amounts of the fine materials that constitute that mixture. Thus, for example, in Table 2, the code (80C2 + 20FC) stands for a blend of powder whose total absolute volume is formed of 80% CEM II/B-L32.5N type cement and 20% limestone powder. The remaining codes, therefore, have the following meanings: C1 – CEM I 42.5R Portland cement; FC – granite filler; CV – fly ash; MS – microsilica.

2.3. Production of the mortars

The mix design of the mortars was supported by the following parameters: unit volume percentage of each powder material in the total volume of the blend of powder materials (Vp), unit volume percentage of each fine aggregate in the total volume of fine aggregates (Vs), Vp/Vs (ratio in absolute volume between powder materials and fine aggregates), Vw/Vp (ratio in absolute volume between water and powder materials) and Sp/p% (ratio in percentage between the amounts in mass of superplasticizer and powder materials). The volume of voids when calculating mortars and the contribution towards volume of powder materials originating from fine aggregates were both overlooked.

Each of the blends of powdered materials defined in Tables 2 and 3 was combined with different Vp/Vs. The Vp/Vs varied from 0.60 to 0.80 at 0.05 intervals for binary blends of powders and only the Vp/Vs of 0.80 was used for ternary blends of powders. For each one of such combinations, an experimental and iterative process was used to find the adequate values of Vw/Vp and Sp/p% that provided the required mortar flow properties. The adequate values are those that fulfilled the flow requirements measured experimentally in slump-flow and v-funnel tests, expressed as the relative spread area (Gm) and relative flow velocity (Rm). The interval admissible for Gm and Rm was defined by Gm values between 5.3 and 5.9 and Rm values between 1.14 and 1.30 s$^{-1}$, corresponding, respectively, to Dm values between 251 and

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**Table 1**

<table>
<thead>
<tr>
<th>Powder materials</th>
<th>Specific gravity</th>
<th>Fineness (cm$^2$/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 42.5R (C1)</td>
<td>3.14</td>
<td>3848$^a$</td>
</tr>
<tr>
<td>CEM II/B-L32.5N (C2)</td>
<td>3.04</td>
<td>4617$^a$</td>
</tr>
<tr>
<td>Fly ash (CV)</td>
<td>2.38</td>
<td>4029$^b$</td>
</tr>
<tr>
<td>Limestone powder</td>
<td>2.72</td>
<td>5088$^b$</td>
</tr>
<tr>
<td>Granite filler (FG)</td>
<td>2.65</td>
<td>3349$^b$</td>
</tr>
<tr>
<td>Microsilica (MS)</td>
<td>2.17</td>
<td>1295$^b$</td>
</tr>
</tbody>
</table>

$^a$ Blaine.

$^b$ Laser particle analyser Coulter LS200.
2.4. Fresh properties of mortars

Without stopping the mixer. The brief stop introduced to clean the mixer-blades occurs at normal speed. The superplasticizer is added to the mixture 1 min into the process by a 2 min stop. Then, once again, the mixing procedure is resumed for 1 min and the total amount of water being used are introduced in the mixer, and then except for a brief stop introduced to clean the mixer-blades. All the dry elements are subjected to compressive strength testing.

2.5. Hardened properties of mortars

The spread cone and the v-funnel measure as indicated in Fig. 4. One can observe that for constant Sp/p% the increase in Vw/Vp produces a linear translation of (Gm, Rm) values. For each iterative process, the Vw/Vp and the Sp/p% are defined and the mortar is calculated and tested experimentally to measure de Gm and Rm values. This procedure continues until the pair of Gm and Rm values meets the target assumed in this research. A total number of 237 mortars were produced to obtain the 74 mortars for binary blends of powders with the required flow properties and a total number of 27 mortars were produced to obtain the 7 mortars for ternary blends of powders with the required flow properties. In the iterative process, a mean of three mortars were produced to obtain the required flow properties for each combination between the blend of powders and the Vp/Vs.

The mixing procedure was similar to the one proposed by Domone and Jin [2], except for a brief stop introduced to clean the mixer-blades. All the dry elements and the total amount of water being used are introduced in the mixer, and then the mixing procedure is started at normal speed and continues for 6 min, followed by a 2 min stop. Then, once again, the mixing procedure is resumed for 1 min at normal speed. The superplastizier is added to the mixture 1 min into the process without stopping the mixer. The brief stop introduced to clean the mixer-blades occurs half way through the first stage of the mixing procedure.

263 mm and t values between 7.69 and 8.77 s (is not used this way in English and I am confused by which values correspond to which. It should be written in the form: A corresponds to X and B corresponds to Y). The flow properties of the mortar phase are designed to be suitable for producing SCC, meaning a slump flow diameter between 600 and 700 mm and a v-funnel flow time between 10 and 20 s.

The iterative procedure is shown schematically in Fig. 3. One can observe that constant Sp/p% the increase in Vw/Vp produces a linear translation of (Gm, Rm) values and when the Vw/Vp remains constant and Sp/p% increases it describes a curve displacement of the (Gm, Rm) values. For each iterative process, the Vw/Vp and the Sp/p% are defined and the mortar is calculated and tested experimentally to measure the Gm and Rm values. This procedure continues until the pair of Gm and Rm values meets the target assumed in this research. A total number of 237 mortars were produced to obtain the 74 mortars for binary blends of mortars with the required flow properties and a total number of 27 mortars were produced to obtain the 7 mortars for ternary blends of mortars with the required flow properties. In the iterative process, a mean of three mortars were produced to obtain the required flow properties for each combination between the blend of mortars and the Vp/Vs.

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2.4. Fresh properties of mortars

The spread cone and the v-funnel measure as indicated in Fig. 4. The value for (Gm) is obtained by Eq. (1), whereas (Rm) is obtained by Eq. (2); (Dm) stands for the average spread diameter, in mm; (D0) stands for the initial diameter at the base of the cone, in mm; (t) stands for the time of flow, in seconds.

\[
Gm = \left( \frac{Dm}{D0} \right)^2 - 1 \quad (1)
\]

\[
Rm = \frac{10}{T} \quad (2)
\]

2.5. Hardened properties of mortars

For each of the mortars that fulfilled the flow requirements, four cubic test specimens of 50 mm per side were produced. These were allowed to age for 28 days and then subjected to compressive strength testing.

3. Results and discussion

3.1. Correlations between mix design parameters

3.1.1. Binary blends of powders

\[
\text{Fig. 3. Schematically presentation of the iterative procedure.}
\]

\[
\text{Table 2}
\]

Binary blends of powders.

<table>
<thead>
<tr>
<th>Mixtures</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. 1</td>
<td>100C2</td>
</tr>
<tr>
<td>Binary blends 2</td>
<td>80C2 + 20FC</td>
</tr>
<tr>
<td>3</td>
<td>80C2 + 20FG</td>
</tr>
<tr>
<td>4</td>
<td>80C2 + 20CV</td>
</tr>
<tr>
<td>14</td>
<td>60C2 + 40FC</td>
</tr>
<tr>
<td>15</td>
<td>50C2 + 50FC</td>
</tr>
</tbody>
</table>

\[
\text{Table 3}
\]

Ternary blends of powders.

<table>
<thead>
<tr>
<th>Mixtures</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. 5</td>
<td>100C1</td>
</tr>
<tr>
<td>Binary blends 6</td>
<td>70C1 + 30FC</td>
</tr>
<tr>
<td>7</td>
<td>70C1 + 30FG</td>
</tr>
<tr>
<td>8</td>
<td>70C1 + 30CV</td>
</tr>
<tr>
<td>9</td>
<td>60C1 + 40FC</td>
</tr>
<tr>
<td>10</td>
<td>60C1 + 40FG</td>
</tr>
<tr>
<td>11</td>
<td>60C1 + 40CV</td>
</tr>
<tr>
<td>12</td>
<td>50C1 + 50FC</td>
</tr>
<tr>
<td>13</td>
<td>40C1 + 60FC</td>
</tr>
</tbody>
</table>

3.1.2. Ternary blends of powders

It should be emphasized that microsilica was used to take advantage of the pozzolanic effect and fine powder packing.
mechanism in order to improve mechanical and durability properties. For example, it is known that microsilica, in normal concrete provides marked early strength but significantly decreases the workability of fresh concrete [21]. It is therefore important to verify whether the beneficial effects of one mineral admixture compensate the shortcomings of another within ternary blends.

Taking into account that self-compacting concretes need a large amount of powder materials, it was understood that using microsilica as the only addition in binary blends would make no sense, since it is usually much more expensive than the other additions. Therefore, the option was taken of testing ternary blends in which 5% of cement mass (equivalent to 7% of its volume) would be replaced by microsilica, whereas 30–40% of cement volume would be replaced by one of the three other additions selected for use.

Fig. 7 presents the Sp/p% ratio achieved for each one of the mortars with ternary blends of powders. Very high percentages of superplasticizer were used, especially in the reference mix. The lowest Sp/p% ratio resulted from the A.V.0.80 mix (3.4%), which presented a compressive strength of approximately 70 MPa. Such a value of compressive strength may be considered too low to justify the use of two additions in the mix, as this value had been easily achieved by means of the binary mixes. Therefore and in the light of the proposed goals, the use of these ternary mixes does not seem to be justified.

In studies carried out by Domone and Jin [2] it was observed that, in the binary mix in which Portland cement was replaced by 15% of its volume of microsilica, the recorded consumption of polycarboxylate based superplasticizer was 2.33 times higher than that obtained in the cement-only standard mix and 3.89 times higher than that obtained in the binary mix in which cement was replaced by 40% of its volume of limestone powder. In ternary mixes that combine, in absolute volume, 50% of Portland cement, 40% of limestone powder and 10% of microsilica, the consumption of polycarboxylate based superplasticizer was around 49% of that obtained in the binary mix, composed of 85% of cement and 15% of microsilica, and about 1.13 times higher than that obtained in the cement-only mix. In relative terms, the work carried out by Domone and Jin [2] showed that the introduction of microsilica led to a rate of change of approximately the same order of magnitude as that recorded in the current study for similar amounts of polycarboxylate based superplasticizer.

The use of foundry silica-dust (similar to silica fume) was also reported by Kraus et al. [22] but related to different types of SCC, which incorporate simultaneously a viscosity-modifying
admixture and a polycarboxylate based superplasticizer. Type I Portland cement, fly ash and foundry silica-dust were used as powder materials. SCC mixtures were made using foundry silica-dust as a fly ash replacement material. It was observed that at 30% replacement of fly ash with foundry silica-dust, the amount of superplasticizer required increased considerably, reaching twice that of the reference mixture without foundry silica-dust [22]. For replacement of 10% and 20% of fly ash with foundry silica-dust, the variation in superplasticizer dosage in comparison with the reference mixture was of no significance [22]. The discussion shows that for lower replacement percentages of fly ash with foundry silica-dust the results reported by Kraus et al. [22] differ from those obtained in the present research, probably as a consequence of the use of the viscosity-modifying admixture.

The superplasticizer overdose observed in this study and others discussed here is probably caused by the fact that microsilica surfaces are negatively charged in alkaline solution. The surface charge of microsilica turns from negative to positive due to surface adsorption of Ca$^{2+}$ [23]. Thus microsilica can compete with cement for superplasticizer. This explains why microsilica requires higher dosages of superplasticizer. The solution could be the use of another kind of polycarboxylate molecules that could disperse more effectively in microsilica/cement blends.

3.2. Parameters correlated with compressive strength

3.2.1. Binary blends of powder materials

Fig. 8 shows the relationship between the compressive strength of mortar and Vp/Vs for each binary blend of powders. The compressive strength of mortar varied from 25 MPa to 95 MPa. It may be observed that the average interval of variation in compressive strength in each binary blend of powders was around 10 MPa as Vp/Vs varied from 0.60 to 0.80. This confirms that the compressive strength depends on the Vp/Vs for each binary blend of powder. However, there is no general correlation between the compressive strength of mortar and the Vp/Vs parameter.

Correlations between the compressive strength of mortar and W/C, in mass, are illustrated in Fig. 9. A general correlation regarding each of the cements being used can be observed, independent of the type and amount of the additions. The W/C of the SCC mix is

![Fig. 6. Relationship between Vw/Vp and Sp/p% for the mortars with binary blends.](image)

![Fig. 7. Percentages of superplasticizer for mortars with ternary blends of powders.](image)
the same as its mortar phase. However, it is clear that for the same W/C, a mortar’s compressive strength may be different from the SCC’s compressive strength. The mortar phase is designed with the aim of obtaining an SCC with a specified compressive strength. For this reason, it is important to know in advance the relationship between the SCC’s compressive strength and the mortar’s compressive strength.

Fig. 10 presents such a general correlation obtained from a total of 60 SCCs produced by the authors from mortar phases with different binary blends of powders and different Vp/Vs values designed according to the methodology discussed in this paper. All the concretes have a maximum dimension of coarse aggregates of 19.1 mm and had a slump flow diameter between 600 and 700 mm and a v-funnel flow time between 10 and 20 s. The compressive strength of each SCC was measured from 150 mm cubes while the compressive strength of the mortars was measured from cubes of 50 mm per side. All the specimens were cured and tested in standard conditions after 28 days aging.

One of the initially assumed parameters for controlling the compressive strength was the combination of powder materials. This study has shown that it is possible to establish a relationship...
Fig. 11. Relationship between the unit percentages of cement replacement $f_{Ad}$ and the W/C ratio (in mass) when using CEM I 42.5R and limestone powder.

Fig. 12. Relationship between the unit percentages of cement replacement $f_{Ad}$ and the W/C ratio (in mass) when using CEM I 42.5R and granite filler.

Fig. 13. Relationship between the unit percentages of cement replacement $f_{Ad}$ and the W/C ratio (in mass) when using CEM I 42.5R and fly ash.
between the W/C and the percentage of cement replacement by the addition. However, the study has also clearly shown that such a relationship depends markedly on the Vp/Vs parameter defined for the mortar, as illustrated in Figs. 11–16.

3.3. Methodology for mix design of the mortar phase

The methodology used to achieve both adequate flow properties and the required compressive strength of mortar started with the selection of the fine aggregates (1, 2 or more sands) and the determination of their unit volume percentages with reference to the total volume of Vs, in order to obtain a size distribution close to the reference curve. Secondly, the compressive strength of mortar that leads to a specified compressive strength of SCC can be predicted from Fig. 10. After that, the W/C ratio is defined according to the type of cement and the desired compressive strength of mortar using Fig. 9.

In order to obtain the desired W/C ratio, both Vp/Vs and the type of addition to be used should be decided before calculating the percentage of substitution of cement by the addition. This research work has revealed that the percentage of substitution depends on the Vp/Vs of the mortar. It should be noted that mortars having higher Vp/Vs values, which means a larger volume of powders, will lead to self-compacting concrete with a higher volume of coarse aggregates and a lower volume of mortar for the same workability. On the other hand, lower values of Vp/Vs will result in a self-compacting concrete with a lower volume of coarse aggregates and a higher volume of mortar. This suggests that a Vp/Vs value around 0.80 should be adopted if the objective is to maximize the volume of coarse aggregates in SCC. After selecting the type of addition to be used and the Vp/Vs parameter, the percentage of substitution of cement by the addition can be estimated from the graphs shown in Figs. 11–16. Different additions will lead to different percentages of substitution in order to obtain the same W/C ratio.

The previous steps have defined the unit volume percentage of each powder material in the total volume of the blend of powder materials (Vp), the unit volume percentage of each fine aggregate in the total volume of the fine aggregates (Vs) and the Vp/Vs leading to the appropriate W/C and, therefore, the desired compressive strength of mortar or SCC. To complete the mortar mix design Vw/Vp and Sp/p% still need to be defined. According to the

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![Fig. 14. Relationship between the unit percentages of cement replacement fAd. and the W/C ratio (in mass) when using CEM II/B-L32.5N and limestone powder.](image1)

![Fig. 15. Relationship between the unit percentages of cement replacement fAd. and the W/C ratio (in mass) when using CEM II/B-L32.5N and granite filler.](image2)
proposed methodology, these values must be obtained experimentally by testing a mortar’s v-funnel performance to obtain $R_m$ and its slump-flow performance to obtain $G_m$. As a starting point the $V_s/V_p$ and $S_p/p\%$ parameters shown in Figs. 5 and 6 can be adopted. Experience has shown that the $V_s/V_p$ parameter obtained from the graph in Fig. 5 does not undergo significant variation, even for additions of similar nature from different suppliers, while the $S_p/p\%$ parameter exhibits lower values as the superplasticizers based on modified polycarboxylate are improved. Nevertheless, the changes in $S_p/p\%$ did not significantly affect the compressive strength, since it is used in relatively small percentages.

Using this methodology, mortar parameters such as the unit volume percentage of each powder material in the total volume of the blend of powder materials ($V_p$), the unit volume percentage of each fine aggregate in the total volume of the fine aggregates ($V_s$), $V_p/V_s$, $V_s/V_p$, $S_p/p\%$ and $W/C$ are the same adopted in SCC. Indeed, to complete the mix design of SCC concrete, it is enough to define the volume of void and the parameter $V_m/V_g$ (ratio between the absolute volume of mortar and the absolute volume of coarse aggregates), together with the maximum size and size distribution of coarse aggregates.

### 4. Conclusions

This paper reports the results obtained in tests on mortars appropriate to produce self-compacting concrete (SCC), when binary and ternary blends of powder materials were used, combining two cements and four additions: limestone powder, fly ash, granite filler and microsilica. In the first stage, the influence of mortar constituents and the correlations between the mix design parameters and the flow properties were discussed. After that, the correlations between the mix design parameters of the mortar phase and the compressive strength was evaluated. As a result of this evaluation, a simple methodology was proposed for the mix design of the mortar phase in binary blends of powder to obtain both adequate flow properties and the required compressive strength. The obtained results permit the following conclusions to be established.

Under identical flow properties, the granite filler shows identical demand for superplasticizer compared to the results obtained using fly ash and limestone powder, whereas microsilica requires far more superplasticizer, either in absolute terms or when compared to the remaining additions. On the other hand, the fact seems to stand out that the consumption of mixing water with additions of granite filler is always equal to the consumption of mixing water in mixtures with cement-only, independent of the percentage of cement replaced by the addition. The use of microsilica was included in order to improve mechanical properties and durability. However, considering the very large quantity of superplasticizer required when using microsilica in ternary blends, it was decided to exclude the ternary blends from the proposed methodology analysis. If another kind of polycarboxylate molecules could be made to disperse more effectively in microsilica/cement blends, the presented methodology could be adapted to include ternary blends of powders.

The compressive strength of the mortar phase (50 mm cubes) that leads to a specified compressive strength of SCC (150 mm cubes) can be estimated from the general correlation presented in this paper, and is independent of the constituents materials in use. In binary mixes, the correlation between the $W/C$ and the percentage of substitution of cement by the addition may be improved if $V_p/V_s$ remains constant. It may also be concluded that once the powder materials to be used (cement and addition) are selected and the $V_p/V_s$ is decided, it will be feasible to estimate the percentage of cement to be replaced by the addition that leads to a specified $W/C$.

Finally, a simple methodology was proposed for the mix design of the mortar phase in binary blends of powder to obtain both the adequate flow properties and the required compressive strength. As with other discussed methodologies, the correlations presented in this paper are based on a given set of materials. However, the proposed methodology itself can be generalised, since new correlations can be easily generated using other materials.

### References


