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Abstract: In recent years, the use of self-compacting concrete (SCC) has been increasing. Although methods for designing the mixture proportions usually derive from experience with conventional concretes, some specific procedures still are not universally accepted. The design and characterization of SCC influences not only the mix components (paste volume and nature, binder amount and type, granular skeleton, etc.) but also the testing methods used to validate the self-compactability (usually in terms of fluidity, viscosity and resistance to segregation). This paper studies the influence on SCC mechanical properties based on the consideration of two types of granular skeleton, discontinuous and continuous, for different strength levels (35 and 60 MPa). For the both strength levels studied, the mix with continuous granular skeleton exhibited slightly higher segregation resistance and mechanical properties than did mixes with discontinuous granular skeleton.

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Experimental study about the effects of granular skeleton distribution on the mechanical properties of self-compacting concrete (SCC)

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In recent years, the use of self-compacting concrete (SCC) has been increasing. Although methods for designing the mixture proportions usually derive from experience with conventional concretes, some specific procedures still are not universally accepted. The design and characterization of SCC influences not only the mix components (paste volume and nature, binder amount and type, granular skeleton, etc.) but also the testing methods used to validate the self-compactability (usually in terms of fluidity, viscosity and resistance to segregation). This paper studies the influence on SCC mechanical properties based on the consideration of two types of granular skeleton, discontinuous and continuous, for different strength levels (35 and 60 MPa). For the both strength levels studied, the mix with continuous granular skeleton exhibited slightly higher segregation resistance and mechanical properties than did mixes with discontinuous granular skeleton.

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1. Introduction

Materials used in self-compacting concrete (SCC) are the same as those used in ordinary concrete. In this type of concrete, both regularity and control have special significance because the properties of SCC are more sensitive to small variations compared with conventional concrete [1].

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4 Some differences come from the procedures used for proportioning SCC, which initially
5 were based on techniques derived from pumpable concretes and concretes with high
6 workability, but more recently SCC has acquired specific features [2–5]. This topic was
7 covered scientifically in several PhD Dissertations around the world in the past decade
8 including [6–12].
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11 Apart from other factors related to constituents of SCC (high fine particles content, source
12 of aggregates, among others), the structure of granular skeleton of concrete is a main
13 parameter assuring an adequate flow of fresh concrete without compaction.
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16 Even though there are several works that address SCC proportioning, few of them link mix
17 proportioning and the casting system; this approach is associated with shotcrete mixture
18 design [13], for example. However, in this case, there is a lack of a general methodology
19 for mix proportioning; therefore, it is normal to design concrete by means of granulometric
20 curves [14].
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23 A reference of interest in this area is the work of [15], which discusses the casting of
24 panels (5 m high, 1 m long and 0.20-m thickness) with the same mix proportion as SCC
25 based on the Japanese Method [2], and using different casting systems (poured by bucket
26 and by pumping). The authors demonstrate the existence of a greater segregation for
27 concrete by pouring compared with pumping by bucket. Consequently, a more pronounced
28 loss of strength between different heights of panel executed by pumping was also evident.
29 This is justified mainly due to the energy supplied to the concrete mass during pumping.
30

31
32 In the mix proportioning of conventional concrete, criteria usually used for the design of
33 granular skeleton is for maximum compactness, with some independence regarding
34 casting system; this is justified by the fact that compaction will rearrange concrete granular
35 skeleton structure to maximum compactness. This does not happen in the case of SCC,
36 where there is not a forced reorganization of granular skeleton [16].
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39 Different approaches lead to two types of granular skeleton. First, there are those with a
40 continuous distribution (Figure 1a), a high content of fine particles, a medium contribution
41 of intermediate aggregate and lower proportion of coarse aggregate. Second, there are
42 those with a discontinuous distribution (Figure 1b), a high content of fine aggregates, a
43 small contribution of intermediate aggregate and medium proportion of coarse aggregate.
44 Actually, the transportation and casting method of SCC influences the proportions of
45 aggregates; if done by pumping, it is necessary to increase the amount of sand to facilitate
46 transportation, reducing for this reason the percentage of coarse aggregate (discontinuous
47 distribution).
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53 *Figure 1. Representation of the two types of granular skeleton.*
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4 However, it can be assumed that self-compactability is obtained by means of a slip of the
5 coarse aggregate over intermediate aggregates and then again over the finest aggregates,
6 and finally on cement; the admixture and the water produce the lubrication of these
7 interfaces. This leads to a continuous concrete proportioning such that the percentage of
8 aggregate decreases as its particle size increases, as shown in Figure 1 [17].
9

10
11 Such approaches become more relevant for granular skeleton consisting of three fractions
12 (sand, fine gravel, gravel), compared to being only configured for two fractions (sand, fine
13 gravel). Regarding the fine material, the binders (cement, microsilica and fly ash), filler and
14 the proportion supplied by the sand, which passes through a 0.063 mm sieve are
15 considered. Fine particles have an important role in the workability of the mixture, and the
16 proposed range by [18] is very broad. In general, if concrete contains large quantities of
17 fine particles, its fluidity decreases and, on the other hand, if concrete contains a small
18 amount of fine particles, there is enough mortar to properly cover the aggregate.
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22 Thus, the quantity of fine particles affects fluidity, cohesion and water retention, which may
23 lead to segregation and bleeding of concrete. For this reason, it is very important to
24 determine properly the amount of fines to be used for manufacturing HAC. An initial value,
25 which is a result of various studies, can be approximately $550 \text{ kg/m}^3 \pm 5\%$ [17], depending
26 on the type of fine aggregates and the required mechanical strength. Large quantities of
27 fine particles enhance self-compactability properties to a threshold quantity, which
28 depends on the properties of fine aggregates used. Furthermore, self-compactability
29 decreases, producing bleeding, segregation, and other results outside established ranges.
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33 The main property of fine particles that affects the behavior of SCC is the specific surface
34 [19]. These authors have correlated the amount of fine particles with specific surface in
35 optimum concretes, obtaining values of the order of 550 kg/m^3 , depending on the specific
36 surface (a value of approximately $2000 \text{ cm}^2/\text{g}$); to reduce this amount, it is necessary to
37 use a material with a higher modulus of fineness.
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41 From analysis of the state of the art, we conclude that, despite the large amount of SCC
42 research performed in recent years, there are areas with numerous gaps and inaccuracies
43 in which progress is possible. For example, many existing mix design methods do not
44 consider casting system. Likewise, we have observed an imbalance between studies of
45 the constituent materials of SCC and its structural performance.
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49 The main objective of this paper is to analyze the influence of casting method on the
50 properties of self-compacting concrete in both fresh and hardened states. This is done in
51 an indirect way, based on consideration of two types of granular skeleton structure
52 (continuous and discontinuous), which are primarily associated with two typical casting
53 systems (direct pouring and pumping). To this end, we have developed an experimental
54 series analyzing SCC with different granular structures and with two types of concretes
55 (high and medium mechanical strength) because SCC has usually been associated with
56 high strength values [20].
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2. Material and methods

In this experimental series, different mechanical properties of SCC were characterized in terms of age (3, 7, 28, 90 and 365 days). This section describes and analyzes the results differentiating the values obtained for each type of granular skeleton studied.

2.1. SCC mix proportions and materials used

To perform a comparative study between the two types of granular skeleton, it was decided to minimize the number of variables to examine a fixed amount of cement, varying only the granular skeleton. As mentioned above, continuous distribution mixtures (C) are associated with casting through direct discharge (bucket), while discontinuous distribution mixtures (D) are associated with pumpable concrete. For each of the two types of granular skeleton (C and D), two levels of strength (35 MPa and 60 MPa) were studied. This allows covering a broad spectrum of possible applications, for example in situ or prefabricated concrete elements. The aggregates used are of limestone origin, obtained by a crushing process. The proportions of the concrete mixture designs are given in Table 1.

Table 1 – Concrete mixture design proportions.

The mixing process was as follows. 1) Pour the aggregates and cement, and dry mix for a few seconds, 2) Pour the water (leaving 2 L out for reserve), 3) Mix for 1 min, 4) Pour the viscosity-modifying admixture with a little water, 5) Mix for 1 min, 6) Pour the superplasticizer with the remaining water and 7) Mix for 4 min.

For each mixture design, 20 concrete batches of 150 L each were fabricated; for each batch, the slump flow test was carried out according to [21] for control purposes. Five batches of each mixture were made consecutively by the same operators to reduce any type of variation.

2.2. Characterization of SCC in a fresh state

To characterize SCC in a fresh state, the following tests were performed according to UNE Standards: slump flow [21], J-ring [22], L-box [23], density [24] and occluded air [25].

2.3. Characterization of SCC in a hardened state

To characterize of SCC in a hardened state, the following tests were performed, according to UNE Standards: compressive strength, modulus of elasticity, tensile strength and bond strength (see Table 2). An IBERTEST MHE series and an INSTRON 8500 (Servo-hydraulic testing system with a stiff frame and under closed-loop control) were used to perform the bond strength test.

Table 2 – Characterizations test for SCC in hardened state.

The Barcelona Test [26–28] consists of applying a concentrated load to both faces of a cylindrical sample (150 mm diameter and 150 mm height) through two punches of 37.5 mm in diameter. The load application is controlled through the piston displacement at a constant rate of 0.5 mm/min; for concretes without fibers, the test ends when the concrete fails or presents fracture.

The indirect tensile strength ' f_t ' is obtained from the maximum breaking load ' P ', the mid-height of the sample ' h ' (75 mm) and the radius ' a ' of the loading plate (18.75 mm), by means of the struts and ties model (equation 1).

$$f_t = \frac{P}{9\pi \cdot h \cdot a} \quad (1)$$

For the characterization of the bond strength between the reinforcing bars and SCC through the beam test [29], a corrugated steel reinforcing bar of 10 mm in diameter was used. To register the displacement of the bar on its ends LVDT sensors of ± 5 mm were used.

3. Results and discussion

3.1. Results of SCC in a fresh state

3.1.1. Slump flow test

Slump flow tests were performed for all mixtures, and its value was used as a self-compactability reference parameter. Table 3 shows the results of the slump flow test; the values marked were discarded because of the Dixon test.

Table 3 – Slump flow test results.

Note that the continuous distribution skeleton (C) show higher diameters in the slump flow test, reflecting greater easiness of flow, which may be because the continuous granular skeleton has a greater amount of paste (cement and sand) coating the coarse particles, allowing them to flow more easily. On the other hand, the discontinuous distribution skeleton (D) show a lower amount of paste and a greater amount of coarse aggregate. This causes an interlock effect among the particles and, ultimately, causes them to have a smaller diameter in the slump flow test.

In the C35 and C60 series, it was necessary to reduce the water content to adjust the slump flow values; therefore, the water content presented in Table 1 is different from the theoretical value of 182 l/m³. In the C35 series, the slump flow diameter resulted in 785 mm with 180 l/m³ of water, which is a much larger value in relation to the established range of 600 to 700 mm; therefore, it was decided to reduce the water content for the next concrete batches.

3.1.2. J-ring slump flow test

Table 4 shows the results of slump flow with J-ring (Japanese ring). This test was performed only in some of the batches, usually in the first one. In general, the SCC flowed homogeneously between the ring bars without any blocking effect, as shown in Figures 2 and 3.

Figure 2 – Slump flow with J-ring, 30 MPa SCC: a) C-30 and b) D-30.

Figure 3 – Slump flow with J-ring, 60 MPa SCC: a) C-60 and b) D-60.

Table 4 – Slump flow with J-ring test results.

For the low strength SCC series (35 MPa), the continuous distribution design (C-35) showed a better passing ability than did the discontinuous distribution design (D-35). For the high strength SCC series (60 MPa), SCC passing ability performance was the same for both concretes (C and D), although the continuous distribution design (C-60) had a smaller diameter of slump flow.

On the other hand, for the continuous distribution skeletons (C-30 and C-60), some stripes were observed in the concrete behind each bar, indicating the way the concrete “closes” itself (see Figures 2a and 3a). This suggests that in this type of mix design, aggregates do not return to fill the space behind the bar of the ring, where there is an accumulation of paste. This behavior is not observed in the discontinuous distribution skeleton concretes (D). Based on the foregoing, we may conclude that the continuous granular skeleton need a greater distance after an obstacle (bar of the ring) than does the discontinuous one (50 mm approximately) to reseal homogeneously.

3.1.3. L-box test

The objective of the L-box test is to assess the passing ability of SCC among the bars. This test was performed for only one batch, usually the first one. The results are presented in Table 5 both for the three measures considered (H1, H2 and H3) and for the time elapsed for the concrete to empty the column. According to [23], the H3/H1 ratio must be computed, but because there is not any interval of acceptable values in this standard, we used the criteria given in [18] consisting of considering an H3/H1 ratio equal or greater to 0.75.

Table 5 – L-box test results.

Note that the continuous distribution skeletons (C30 and C60) have a higher flow (less than H1 and H2 or higher than H3) than discontinuous distribution concretes (D30 and D60) and take less time to pass; this may be the result of the higher content of paste, which was reported previously.

On the other hand, any of the series fulfills the requirement $H3/H1 \geq 0.75$. This fact may indicate that this value is very high for the L-box test and could dispute the validity of same and eventually modify it because the tested SCC presented very good performance regarding self-compactability without segregation and flowed well among the bars.

Importantly, note that discontinuous distribution design concretes (D) have a higher content of 12-20 gravel; this makes it more difficult for SCC to pass among the bars, mainly in the most critical areas with closer spacing.

3.1.4. Density and occluded air

The density and occluded air were assessed in fresh concrete in the first batches for the C-60, D-35 and D-60 and in the second batch for the C-35 design because the slump flow for this mixture was very high and was discharged. The results are presented in Table 6.

Table 6 – Density and occluded air results.

Note that the density is homogeneous for all of the series. The values on the order of 2.3 g/cm³ for these concretes are because they have a greater amount of paste than a conventional concrete, whose density is on the order of 2.4 g/cm³. Regarding entrapped air, the results are low values in all of the cases, showing the relationship that the greater the fluidity of concrete, the greater the slump flow extension and the less the entrapped air content.

3.2. Results of SCC in a hardened state

3.2.1. Compressive strength

Table 7 shows the results of concrete compressive strength tests, both mean values and coefficients of variation (in brackets); the values correspond to a set of six samples for each series and age.

Table 7 – SCC compressive strength.

Continuous distribution design concretes show higher compressive strengths compared to discontinuous distribution designs, this being most significant at early ages (3 and 7 days, where differences can be up to 10%). Nevertheless, this difference decreases over time, with both types having very similar values of compressive strength at 365 days. This behavior was the same for both SCC (35 and 60 MPa).

3.2.2. Modulus of elasticity

Table 8 presents values of modulus of elasticity of concrete for different ages, both mean values and coefficients of variation (in brackets); the values correspond to a set of three samples for each series and age.

Table 8 – Modulus of elasticity of SCC.

Note that continuous distribution design concretes show values of modulus of elasticity slightly higher than the discontinuous ones for all of the ages and strengths. Discontinuous granular skeleton has 45 kg/m³ more coarse aggregate than the continuous one. Due to the effect of coarse aggregate on the stiffness of concrete, one would anticipate a greater modulus of elasticity in concretes with discontinuous granular skeleton. This could be because the packing of the continuous granular skeleton provides a stiffer structure with higher modulus of elasticity. On the other hand, a comparative analysis was performed between the experimental values and the ones obtained through the analytical equations given in some construction codes [30–34]. Table 9 shows equations in which the coefficients were manipulated as a function of the system of units.

Table 9 – Analytical equations for modulus of elasticity (MPa).

Based on the analytical equations, the modulus of elasticity was calculated for each age and for each series and plotted together with those obtained experimentally; these graphs are shown in Figures 4a, 4b, 4c and 4d.

Figure 4 – Modulus of elasticity, experimental and analytical.

Note that EHE-08 and EC-2 equations are those that best fit the experimental data. On the other hand, NBR-6118 as well as ACI-318 relate the modulus of elasticity to the square root of compressive strength, leading to an increment of the modulus with age higher than obtained experimentally. Regarding the influence of granular skeleton on the stiffness of SCC, this factor has no significant effect on the evolution of modulus of elasticity with time.

3.2.3. Tensile strength

The indirect tensile strength of SCC was characterized with three experimental tests: flexure tensile [35], the Brazilian test [36] and the Barcelona test [26]. The results are presented in Table 10, including the mean values and the coefficient of variation (in brackets) for each age, taking five samples for the Barcelona test and two samples for both the Brazilian and the flexure tensile tests.

Table 10 – Indirect tensile strength F_t of SCC.

In the previous table, granular skeleton has no significant effect on the tensile strength of SCC, although in all cases the continuous distribution skeleton has shown slightly higher strength values. In addition, the Barcelona test results show an important increment of strength at ages beyond 28 days in all of the series.

In this regard, a greater amount of paste, which is associated with a higher amount of material with greater finesse, leads to slower hydration of the cement and thus, a greater gain in strength over time.

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4 Additionally, the trend of indirect tensile strength is different between the Barcelona test
5 and the Brazilian test because in the Barcelona test, an increase in tensile strength is
6 observed with age. In contrast, the highest gain of tensile strength in the Brazilian test
7 occurs up to 28 days and shows no important increase in strength after that age.
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10 The above discussion may be related to the fact that in the Barcelona test, cement paste
11 has a greater contribution and eventually a propitious gain resistance. However, in the
12 Brazilian test, the granular skeleton has greater significance and, therefore, tensile
13 strength does not increase over time.
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16 Note also that the difference in tensile strength between the 35 MPa and 60 MPa series is
17 not very significant, being of the same order of magnitude as the influence of the granular
18 skeleton. Therefore, if we consider the two variables at the same time, the values of tensile
19 strength of the C-30 and D-60 series are very similar, especially in the Brazilian test.
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22 Furthermore, in the case of characterization by means of the flexural-tensile test, it is
23 observed that the continuous granular skeleton mixture C-35 has a slightly higher tensile
24 strength than the discontinuous skeleton D-35, as has been shown in other tests.
25 Furthermore, we also note that the D-30, D-60 and C-35 series all show a similar behavior
26 with an increase in strength by 25% between 7 and 28 days.
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28

29 Finally, the result obtained for the C-60 series is lower than for the C-35 series. This is not
30 expected “a priori” because both series have the same granular skeleton distribution, and
31 cement paste should resist a higher flexural-tensile strength for a greater compressive
32 strength.
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35 The samples intended for the flexural-tensile strength test of the C-60 series belonged to
36 the fourth batch, which showed a reduced value in the slump flow test. This reduction
37 probably occurred due to an error in the dosage amounts of aggregates, confirming that
38 the slump flow test is a good control parameter for the acceptance of SCC.
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41 3.2.4. Bond strength

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43 In the adherence test performed according to standard [29], two parameters are obtained:
44 the adherence stress ($\sigma_{\text{adherence}}$) and the bond strength (σ_{bond}). Adherence stress is
45 calculated by averaging stress values resulting from vertical displacements of 0.01, 0.1
46 and 1 mm. Bond strength is maximum stress sustained by the beam for a vertical
47 displacement of 3 mm. Table 11 contains the results of adherence stress and bond
48 strength, as well as the maximum load applied in the beam (P_{breaking}) and the coefficient of
49 variation (in brackets).
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53 *Table 11 – Adherence test results: $\sigma_{\text{adherence}}$, σ_{bond} (MPa) and P_{breaking} (kN).*
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The results show that granular skeleton has no influence on the results of adherence because the same strength series presented similar values. Moreover, in the series of low strength (30 MPa), the discontinuous skeleton (D) has achieved a slightly higher adherence stress, while in the high-resistance series, the results alternate. In either case, the differences are representative.

These differences may be related to adherence mechanisms present in each case. In low-strength concretes (35 MPa), the difference between the two granular skeletons (C and D) may be associated with mechanical bonding. Therefore, the discontinuous granular skeleton, presenting a higher coarse aggregate content, have a higher mechanical bonding.

However, the series of higher strength (60 MPa) can be associated with a greater contribution of bond mechanism acting by means of adherence. In this case, the continuous granular skeleton has a greater proportion of adherence by bond mechanism due to its greater amount of paste (more fines due to the higher content of sand). Likewise, regardless of mechanical strength, it exhibits rapid changes in adherence, reaching at 7 days 95% of the bond strength at 28 days.

Note that in performing these tests, we observed a brittle fracture adherence mechanism because the beam passed quickly from a condition of stability without deformation to an excessive deformation with bond rupture, as shown in Figure 5.

Figure 5 – Adherence test at 3 days (C-35 series).

4. Conclusions

- Regarding the ability to flow, continuous distribution mixtures (C) lead to higher slump flow values because the continuous granular skeleton has a greater amount of paste (cement and sand) covering coarse aggregate particles, allowing these to flow more easily. Discontinuous distribution mixtures (D) have a smaller amount of paste and a greater amount of coarse aggregate; this leads to an increased interlock effect of granular skeleton and, consequently, to a smaller diameter in the slump flow test.
- The risk of segregation is less in continuous granular skeleton because smaller aggregates form a barrier that prevents the descent of larger particles. In the case of discontinuous granular skeleton, lack of intermediate sizes of aggregate increases the probability of segregation.

- Regarding mechanical properties, the continuous granular skeleton has slightly higher values for the same category of concrete (35 MPa and 60 MPa) for compressive strength, indirect tensile strength and modulus of elasticity, between 2 and 15%; this may reflect a more rigid and more interlocked aggregates structure.
- Both types of granular skeletons allow achieving the specified strength. This indicates that there is no unique way to design SCC and that the casting method can be taken as a criterion, in line with the hypothesis proposed initially. Often, technicians in the ready-mix concrete sector prefer a discontinuous granular skeleton because of the lower influence of aggregates moisture.
- SCC studied showed a significant increase in strength over 28 days, achieving a further 30% after one year; this can be explained by the slow hydration of cement including a larger amount of material with higher fineness. This growth is lower in the case of the evolution of the modulus of elasticity with time, yielding an increase of 5% over the first year from the measured value at 28 days.
- Concerning bond strength results, granular skeleton apparently has no significant influence on this property because the series of similar strength have similar values. This may be due to opposing factors caused by different bonding mechanisms; on the one hand, the discontinuous skeleton may have increased mechanical bonding due to the higher content of coarse aggregate. On the other hand, the continuous skeleton may have increased adhesion due to the greater amount of paste (more fines due to the higher content of sand). The SCC studied showed a rapid evolution of adherence, achieving at 7 days 95% of bond strength at 28 days.

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Highlights

- Continuous distribution mixtures (C) are associated with casting through direct discharge (bucket), while discontinuous distribution mixtures (D) are associated with pumpable concrete.
- Continuous distribution mixtures (C) lead to higher slump flow values because the continuous granular skeleton has a greater amount of paste.
- Discontinuous distribution mixtures (D) lead to an increased interlock effect of granular skeleton and to a smaller diameter in the slump flow test.
- The risk of segregation is less in continuous granular skeleton (C) because smaller aggregates form a barrier that prevents the descent of larger particles.
- The continuous granular skeleton (C) has slightly higher values for compressive strength, indirect tensile strength and modulus of elasticity.

Table1
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Materials (kg/m ³)	C-35 MPa	D-35 MPa	C-60 MPa	D-60 MPa
Sand 0-2 mm	115	115	—	—
Sand 0-4 mm	876	876	976	926
Fine gravel 5/12 mm	505	168	505	168
Gravel 12/20 mm	292	674	292	674
Water	175	182	176.3	182
Admixture Melcret® PF-75	2.7	2.88	2.7	2.7
Admixture Glenium® C303 SCC	8.73	7.41	8.73	8.73
Cement CEM II A-L 32.5 B-C	380	380	—	—
Cement CEM II A-L 42.5 R	—	—	450	450
Water/Cement ratio	0.479	0.479	0.404	0.404

Table2
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Characterization test		Standard	Samples			
			Type (in cm)		Each mixture	Total
Compressive strength	3, 7, 28, 90 and 365 days	UNE 12390–3	Cylindrical	15 x 30	25	100
Modulus of elasticity	3, 7, 28, 90 and 365 days	UNE 83316	Cylindrical	15 x 30	15	60
Tensile strength (Flexure tensile)	7 and 28 days	UNE 12390–5	Prismatic	15 x 15 x 60	6	24
Tensile strength (Brazilian test)	3, 7, 28, 90 and 365 days	UNE 12390–6	Cylindrical	15 x 30	10	40
Tensile strength (Barcelona test)	3, 7, 28, 90 and 365 days	UNE 83515	Cylindrical	15 x 15	25	100
Bond strength (Beam test)	3, 7 and 28 days	UNE 36740	Reinforced beam	10 x 18 x 60	6	24
Total					87	348

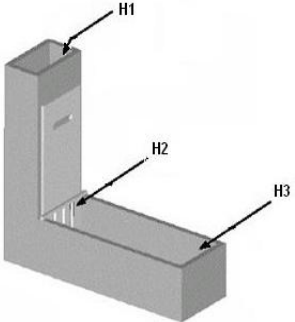
Table3
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Mixture design	Diameter (mm)					Mean value	CV
	1	2	3	4	5		
C-35	785*	680	700	680	685	686	1.2%
D-35	600	595	625	665	660	630	4.6%
C-60	690	700	695	500*	615*	695	0.6%
D-60	620	715	630	705	685	670	5.8%

Table4

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Slump flow (mm)	C-35	D-35	C-60	D-60
Without J-ring	686	630	695	670
With J-ring (measure 1)	680	560	600	590
With J-ring (measure 2)	680	565	610	600
Mean value (J-ring)	680	562.5	605	595

	Parameter/Mixture	C-30	C-60	D-30	D-60
	Time (s)	46	36	55	114
	H1 (mm)	120	120	145	175
	H2 (mm)	80	70	95	95
	H3 (mm)	69	–	55	38
	H2/H1	0.67	0.58	0.66	0.54
	H3/H1	0.58	--	0.38	0.22

Property	C-35	D-35	C-60	D-60
Density (g/cm³)	2.27	2.27	2.30	2.29
Occluded air (%)	2.6	2.6	2.4	2.9
Slump flow (mm)	680	600	690	620

SCC	Concrete compressive strength in MPa (C.V.)				
	3 days	7 days	28 days	90 days	365 days
C-35	28.4 (10.0%)	33.6 (6.4%)	42.7 (4.2%)	51.3 (4.2%)	53.7 (2.4%)
D-35	27.9 (4.5%)	33.9 (2.1%)	40.9 (5.9%)	46.8 (1.7%)	53.3 (1.9%)
C-60	46.2 (1.7%)	48.8 (9.1%)	63.5 (3.8%)	69.3 (4.3%)	80.0 (2.4%)
D-60	41.0 (8.4%)	44.9 (9.6%)	54.9 (3.4%)	65.3 (3.9%)	78.9 (1.6%)

SCC	Modulus of elasticity of concrete in GPa (C.V.)				
	3 days	7 days	28 days	90 days	365 days
C-35	30.5 (2.2%)	32.5 (1.6%)	36.0 (0.9%)	37.0 (2.2%)	37.0 (1.8%)
D-35	29.5 (2.6%)	31.5 (2.2%)	34.5 (2.0%)	35.5 (1.3%)	36.5 (2.6%)
C-60	35.5 (1.4%)	37.0 (0.02%)	39.5 (0.4%)	41.5 (5.6%)	41.5 (1.5%)
D-60	34.0 (2.6%)	36.5 (3.1%)	38.0 (1.7%)	40.5 (3.5%)	41.0 (1.9%)

Table9
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Code	Equation	Comments
CEB-FIP 2010	$E_{ci} = 21500 \cdot \alpha_E \cdot \sqrt[3]{0,1 \cdot f_{cm}}$	f_{cm} : compressive strength of concrete (MPa) obtained from cylindrical samples 150 mm diameter and 300 mm height. α_E : factor dependent on the type of aggregate
ACI 318-05	$E_{cm} = 4700 \cdot \sqrt[2]{f_c'}$	f_c' : compressive strength of concrete (MPa) obtained from cylindrical samples 150 mm diameter and 300 mm height.
EC 2: 1992-1-1	$E_{cm} = 9500 \cdot \sqrt[3]{f_{ck} + 8}$	f_{ck} : characteristic strength of concrete (MPa) obtained from cylindrical samples.
NBR 6118 2007	$E_{cm} = 5600 \cdot \sqrt[2]{f_{ck}}$	
EHE 2008	$E_{cm} = 8500 \cdot \alpha \cdot \sqrt[3]{f_{cm}}$	" α ": factor dependent on the type of aggregate. f_{cm} : compressive strength of concrete (MPa) obtained from cylindrical samples.

Table10
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Ft (MPa) (CV)	Series	Age (days)				
		3	7	28	90	365
Barcelona test UNE 83515	C-35	2.4 (9.1%)	2.7 (7.6%)	3.3 (7.2%)	4.1 (3.1%)	4.4 (3.5%)
	D-35	2.5 (5.9%)	2.8 (4.6%)	3.2 (2.9%)	3.8 (0.8%)	4.3 (5.5%)
	C-60	3.4 (3.1%)	3.9 (4.3%)	3.7 (7.9%)	5.0 (6.3%)	5.4 (3.8%)
	D-60	3.4 (8.6%)	3.7 (4.5%)	4.2 (8.9%)	4.6 (6.4%)	5.0 (7.4%)
Brazilian test UNE 12390–6	C-35	2.95 (8.6%)	3.85 (6.3%)	3.91 (2.6%)	4.65 (9.3%)	4.58 (8.9%)
	D-35	3.12 (1.2%)	3.48 (8.3%)	3.42 (0.3%)	3.85 (0%)	4.07 (1.6%)
	C-60	3.67 (7.3%)	3.69 (4.3%)	5.18 (6.2%)	5.19 (7.4%)	5.19 (9.7%)
	D-60	3.39 (2.3%)	3.53 (5.5%)	4.62 (3.0%)	4.68 (6.9%)	4.70 (9.3%)
Flexure tensile test UNE 12390–5	C-35		4.66 (3.9%)	5.69 (0.2%)		
	D-35		3.98 (0.5%)	4.29 (3.1%)		
	C-60		3.90 (1.9%)	4.95 (2.7%)		
	D-60		4.85 (1.7%)	6.29 (0.9%)		

Series	3 days			7 days			28 days		
	$\sigma_{adherence}$ (CV)	σ_{bond} (CV)	$P_{breaking}$ (CV)	$\sigma_{adherence}$ (CV)	σ_{bond} (CV)	$P_{breaking}$ (CV)	$\sigma_{adherence}$ (CV)	σ_{bond} (CV)	$P_{breaking}$ (CV)
C-35	6.2 (13.7%)	11.6 (23.9%)	41.9 (23.9%)	8.1 (8.2%)	13.0 (4.2%)	47.0 (4.2%)	7.3 (5.2%)	13.2 (15.3%)	47.6 (15.3%)
D-35	6.9 (7.8%)	13.0 (13.9%)	47.1 (13.9%)	8.2 (11.9%)	13.7 (14.6%)	49.5 (14.6%)	8.9 (9.6%)	14.3 (1.3%)	51.8 (1.3%)
C-60	9.3 (4.3%)	14.3 (2.3%)	51.7 (2.3%)	10.7 (0.0%)	16.0 (0.0%)	58.0 (0.0%)	9.8 (10.8%)	16.8 (3.0%)	60.9 (3.0%)
D-60	6.1 (7.2%)	12.3 (3.3%)	44.7 (3.3%)	10.8 (11.2%)	15.9 (17.1%)	57.4 (17.1%)	9.7 (0.0%)	16.1 (0.0%)	58.2 (0.0%)

Figure1

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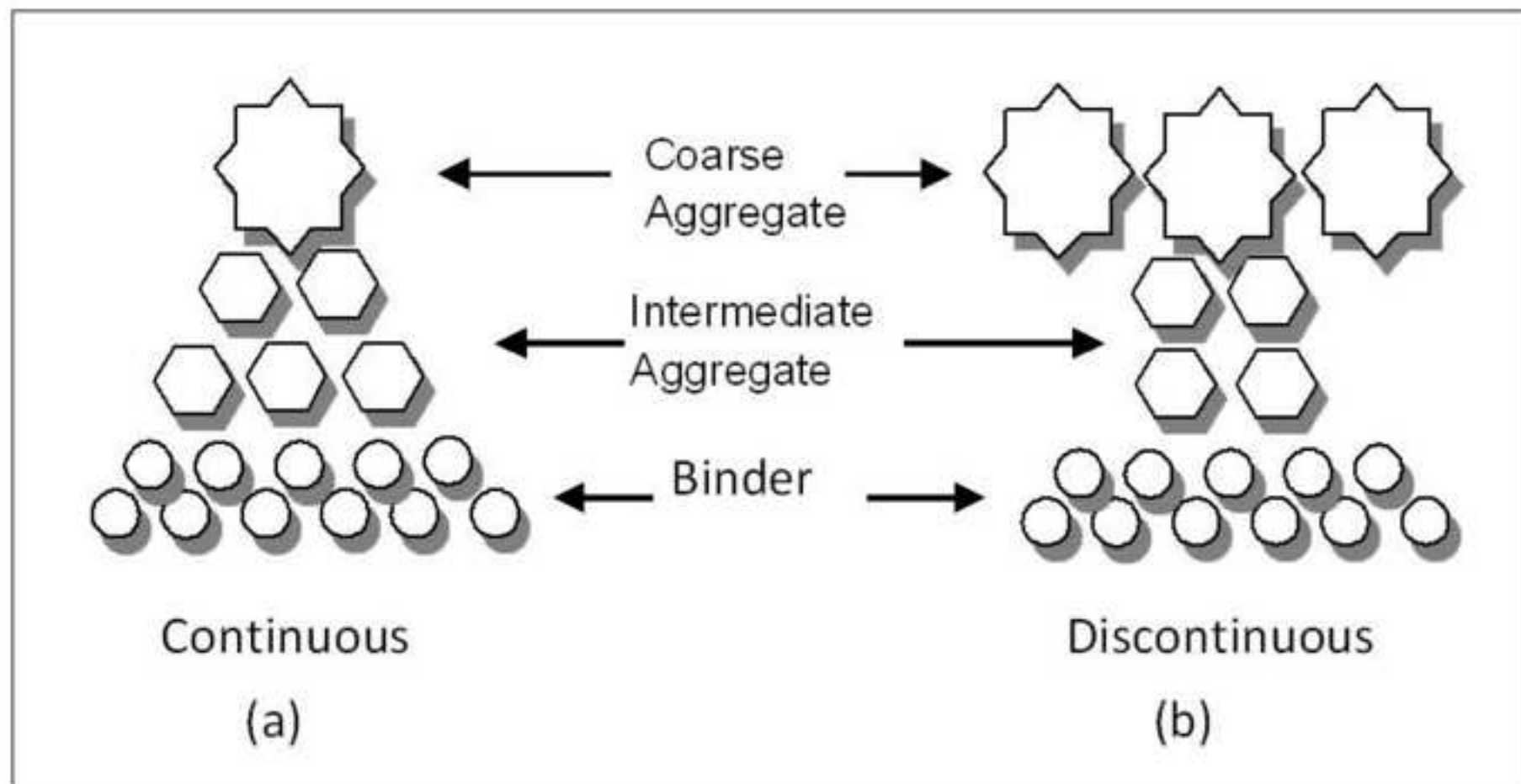


Figure2

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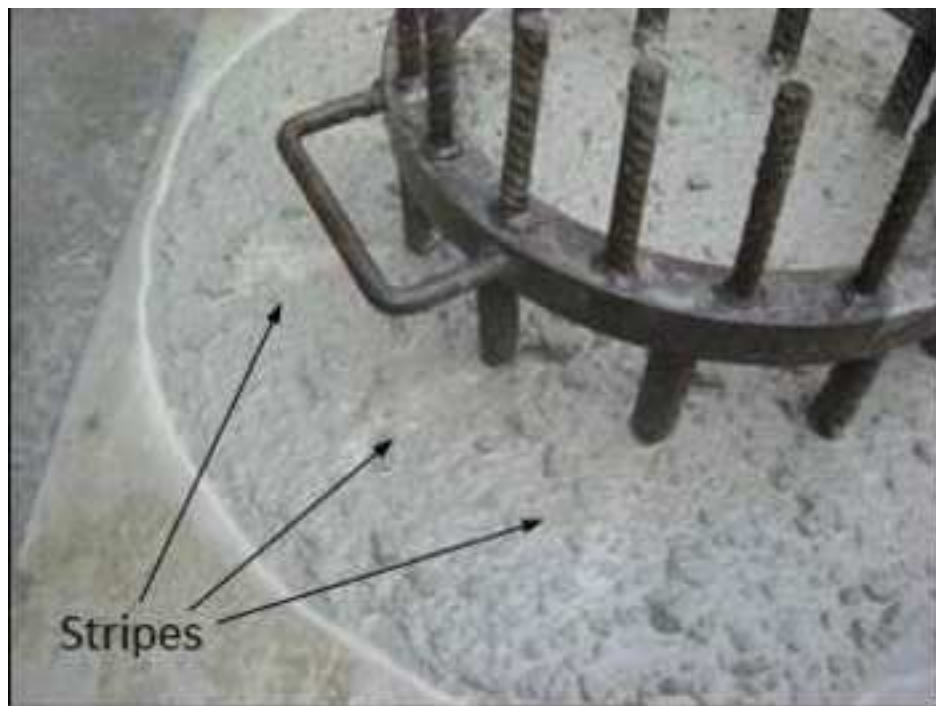


Figure3

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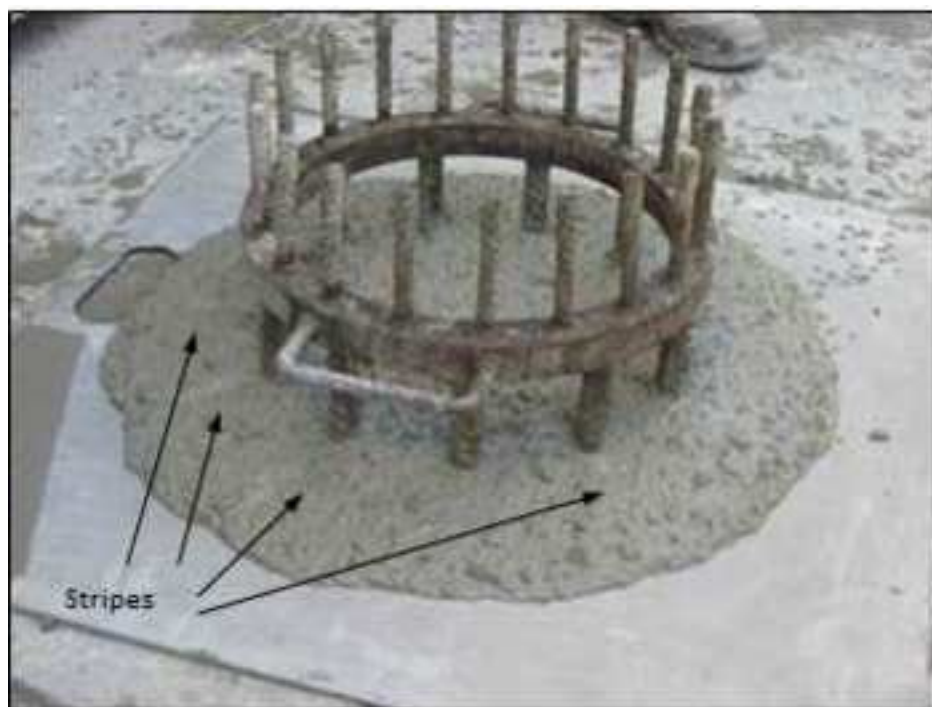


Figure4
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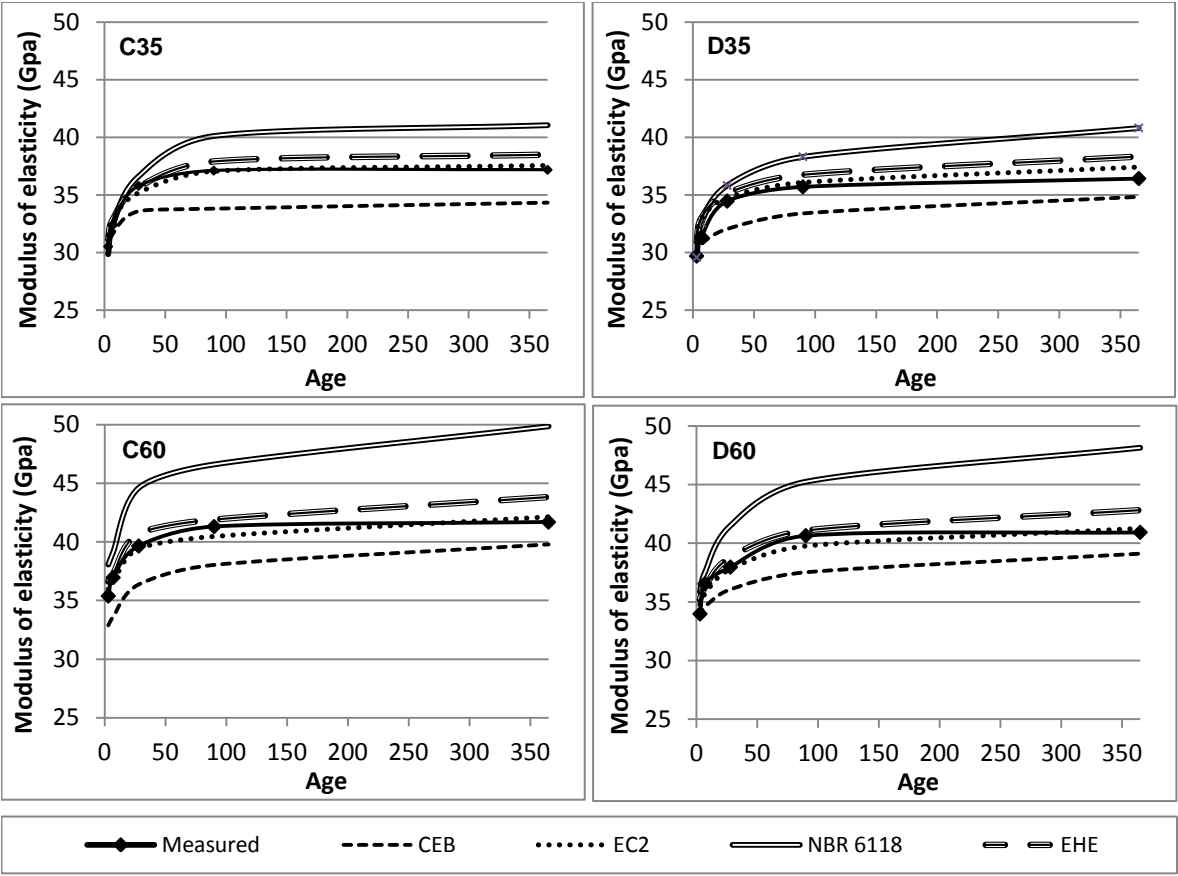


Figure5

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