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ScienceDirect

Procedia Structural Integrity 5 (2017) 147–154

Structural Integrity Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Structural Integrity, ICSI 2017, 4-7 September 2017, Funchal, Madeira, Portugal

Developing a Commercial Self-Compacting Concrete Without Limestone Filler and With Volcanic Aggregate Materials

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Abstract

Self-compacting concrete (SCC) is a concrete with enhanced fresh properties that allows pouring without external compaction. Its advantages also are extended to good segregation resistance, higher homogeneity, lower permeability, which among others, lead to a product with higher durability. Although the SCC advantageous, up to the begin of this research program, never a SCC composition was been produced and commercialized in the Madeira Island. This paper describes the experimental program carried out on the development of a commercial SCC composition, using the materials currently available in the local market of Madeira Island. Moreover, it aims to contribute to the establishment of a methodology that leads to optimized compositions to satisfy the performance requirements of the commercial SCC compositions. Several SCC mix compositions were tested, studies being initially carried out on pastes and mortars. As limestone filler is not currently available in the local market, the powder content was increased by incorporating fly ash, being the water-to-cement ratio kept low by using a superplascyzer and a plasticyzer. All the aggregates were from volcanic origin; the fine sand was from the ocean and the coarse sand, fine gravel and coarse gravel were crushed. At the end, an optimized SCC composition was validated in real/commercial conditions: it was produced in a ready-mix concrete plant, transported and applied in a real structure wherein self-compacting properties were required due to high reinforcement content. Since no markedly changes were introduced from production up to casting, results were considered satisfactory. Consequently, the concrete plant decided to commercialize the SCC composition in the Madeira Island market.

Peer-review under responsibility of the Scientific Committee of ICSI 2017

Keywords: Commercial Concrete; Crushed Aggregates; Madeira Island; Self-Compacting Concrete; Volcanic Aggregates.

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2452-3216
Peer-review under responsibility of the Scientific Committee of ICSI 2017
10.1016/j.prostr.2017.07.085

1. Introduction

Self-Compacting Concrete (SCC) has been worldwide developed based on the Okamura et al. (2000) methodology since 1988. Typically, limestone filler is incorporated to increase powder content and high quality granitic or limestone aggregates are used, with the content and maximum size being limited (RILEM TC 174-SCC, The European guidelines, Wallevik et al. (2003), Silva et al. (2009)). Due to its geological origin and its geographical location, there are no granitic or limestone stones in the Madeira Island. Therefore, there is no limestone filler and concrete aggregates (fine and coarse) currently available are crushed and from volcanic origin. The scarcity of the suggested raw-materials to produce SCC conditioned its development in Madeira Island. However, demand for concretes with high durability, as well as, with high surface finish quality has motivated the development of SCC in Madeira Island.

Thus, an extended research project was developed between the University of Madeira and the company Cimentos Madeira to develop SCC compositions using the raw-materials currently available locally, the end goal being its commercialization. From the research work developed there were published three master's dissertations – the scientific contributions of master's theses of Gomes (2012) and Silva (2012) were essentially on the design of SCC compositions in the laboratory. This paper regards to the scientific contributions present in the third dissertation – Neves (2013), i.e. it documents the procedure followed from the SCC composition developed in the laboratory to the composition produced in the concrete plant for its first commercialization using the materials currently available in Madeira Island. Laboratory evaluation and production of various SCC compositions were, firstly, carried out to achieve economical and robust compositions. Then, a SCC composition was validated for commercialization, being the production process, transport and placement occurred under real conditions to check the “new” product.

2. Experimental Program

2.1. Materials and lab equipment

Two cements currently available in the Madeira Island were used: CEM II / AL 42,5R and CEM II / BL 32,5N (specific gravity of 3100 and 3000 kg/m^3, respectively), both produced the Secil-Outão plant. Due to the (expected) need of fine materials (RILEM TC 174-SCC, Wallevik et al. (2003)) to reach self-compactability fly ash (specific gravity of 2360 kg/m^3) was also used as powder material. Note: although limestone filler is widely used in the production of SCC, it is not currently available in the Madeira Island. Water was supplied from the public network. The superplasticizer Glenium Sky 548 and the plasticiser Pozzolith 390N were used.

Two types of aggregates were used in mortar and concrete compositions, all aggregates being from volcanic origin. Two sands: the finer sand (Sand 0/2) was from the ocean and the coarser sand (Sand 0/4) was crushed. Three crushed gravels: Gravel 4/10, Gravel 8/16 and Gravel 11/22. Table 1 summarize the standardized test results for the characterization of all aggregates and its granulometry.

Paste flowability and viscosity was evaluated with the mini cone (19 mm in the upper diameter, 38 mm in lower diameter, 57 mm in height) and the Marsh cone, respectively. Rheology of mortars was studied by measuring its flowability ($G_p=(d_{flow}/d_0)^2-1$) and viscosity capacity. These tests were carried out using the cone and V-funnel for mortars described in The European guidelines for SCC. Self-compacting properties of the concretes were assessed by the D_{flow}, V-funnel, L-box and segregation tests carried out according to the European Standards for SCC: EN 12350 - {8, 9, 10 and 11} of 2010. Equipment used and mixing procedures for pastes and mortars, although slightly adapted for the materials used, were similar to the procedures described in Standard EN 196-2. For the concretes, mixtures in the laboratory were made in current concrete mixer with 150 liters capacity. The concrete for commercialization was produced in the ready-mix concrete plant.

2.2. Composition formulation and tests

SCC compositions were designed based on the trial-error procedure, with results being analysed for each trial, allowing quickly to reach SCC compositions with the fresh and hardened requirements. It is known that conventional concrete design methods are not applicable for SCC, so it was necessary to adapt another methodology.

Table 1. Properties and granulometry of the aggregates used.

	Sand 0/2	Sand 0/4	Gravel 4/10	Gravel 8/16	Gravel 11/22	Standard
Nominal size d/D (mm)	0/2	0/4	4/10	8/16	11/22	EN 933-1
Specific gravity (kg/m³)	2820	2940	2840	2940	2941	EN 1097-6
Water absorption (%)	2.6±1	2.4±1	2.1±1	1.1±1	1.1±1	
Flatness index	-	-	FI_{35}	FI_{35}	FI_{35}	EN 933-3
Bulk density (kg/m³)	1520	1590	1520	1420	1430	EN 1097-3
Chloride content (%)	≤ 0,01	≤ 0,01	≤ 0,01	≤ 0,01	≤ 0,01	EN 1744-1
Alkali-silica reactivity	-	-	Class 1 No reactive	Class 1 No reactive	Class 1 No reactive	ASTM C1260-05[a]
Abrasion: Micro Deval	-	-	M_{DE25}	M_{DE25}	LA_{25}	EN 1097-1
Fragmentation: LosAngeles	-	-	LA_{25}	LA_{25}	LA_{25}	EN 1097-2
Granulometry (mm)						ASTM C 33
31.5	100.0	100.0	100.0	100.0	100.0	
20	100.0	100.0	100.0	100.0	55.6	
16	100.0	100.0	100.0	98.6	13.6	
14	100.0	100.0	100.0	84.0	3.1	
12.5	100.0	100.0	100.0	49.4	2.0	
10	100.0	100.0	92.9	6.1	1.1	
8	100.0	100.0	69.0	1.8	1.0	
6.3	100.0	100.0	44.4	1.3	0.9	
4	99.7	96.6	7.3	1.2	0.9	
2	97.8	62.5	1.5	1.1	0.9	
1	92.3	36.6	0.9	1.1	0.8	
0.5	86.4	23.0	0.9	1.0	0.8	
0.25	78.6	17.5	0.8	0.8	0.7	
% of material < 0,125 mm	15.4	11.2	0.6	0.7	0.6	EN 933-1
Fineness modulus	1.30	3.53	6.2	7.4	8.8	-

Among the different methodologies disclosed, the method chosen added to be easier and feasible. Thus, for the formulation of the compositions studied an adaptation of the Bolomay method used in the formulation of conventional concretes was carried out, through volumetric ratios between the constituent materials that have the most influence in the SCC composition. The dosages of the constituent materials were based on the Okamura method, as well as the proposed tests for pastes, mortars and concretes.

In the formulation of the pastes, the essential constituents, water (w) and fines (p) were initially used. Mixtures were made with 1.5 liters (according to EN 196-3) and tests were carried out at the Marsh cone (t_{flow}) and flow cone D_{flow}, to determine the values of β_p (water retained by fines) and E_p (deformation factor), to help to select the type of addition and the percentage of cement replacement. The main variations in the pastes were the volumetric water-to-powder ratio (V_w/V_p) and the volumetric ratio between fly ash and total volume of fines (V_{fa}/V_p), with V_w/V_p ratios between 1 and 1.7 and V_{fa}/V_p between 0% and 60%. Admixtures such as plasticizers (Pl) and superplasticizer (Sp) were also introduced at the paste level tests. They were introduced by removing the same volume of water (to keep the initial volume of fluids as the admixtures are mostly liquid or low solids products). Its introduction was performed in volumetric ratio with the powder content.

In the mortars formulation, the volume of paste (V_{paste}) and the volume of sand (V_s) were used and the flow tests were performed in the V-funnel (t_{flow}) and flow cone (D_{flow}). All mortar mixes were made with a volume of 1.2 liters (according to standard EN 196-2). The main variations in the mortars were the volumetric ratio between the fine aggregate and the total mortar (V_s / V_m) and the volumetric ratio between the two types of sands and the total volume of fine aggregate (V_{s1}/V_s and V_{s2}/V_s), with V_s/V_m ratios between 40 and 50% and V_{s1}/V_s and V_{s2}/V_s between 40 and 60%. The percentages of the fine aggregates used in each studied composition were obtained by adapting the Bolomay method.

In the concrete formulation two new parameters were introduced, related to the coarse aggregates in the composition (V_g). The percentages used for the coarse aggregates in each studied composition were obtained by adapting the Bolomay method, with volumetric ratios between the volume of each gravel and the total volume of coarse aggregates (V_{b0}/V_g and V_{b1}/V_g). The estimated volume of voids (Vv) was 1.5%.

3. Results and Discussion

3.1. Pastes

At the past level, studies were basically about the characterization of the fresh stage through determination of β_p and t_{flow}. First, different types of cement, with CEM II / BL 32.5N and CEM II / AL 42.5R (Figure 1.a,b) were analysed. As expected, CEM II/B-L 32.5N cement presents higher deformation and flow capacity than CEM II/A-L 42.5R cement. Therefore, it was decided to choose the cement CEM II / B-L 32.5N to evaluate the effect of partial replacement of cement by fly ash on the viscosity and flowability. Being aware that an industrial production it is important that a concrete composition maintains its fresh properties for some time, it was decided to evaluate the fresh properties (t_{flow} and G_p) immediately after complete mixing and after 30 minutes. The results of the flowability (G_p) test are shown in Figure 1.c,d. The results obtained agree with what is frequently reported in the literature: (i) an increase in the deformation capacity was observed with increasing replacement of the cement by fly ash; (ii) after 30 minutes the flowability capacity was markedly lower. The composition having 30% fly ash was selected and the characterization of the fresh stage was followed by evaluation of the effect of the superplasticizer. Figure 1.e,f shows the results of the flowability where, as expected, the increase in the flowability capacity is observed as it increases the superplasticizer content. Results of the Marsh cone (t_{flow}) can be found in Ref. Neves (2013).

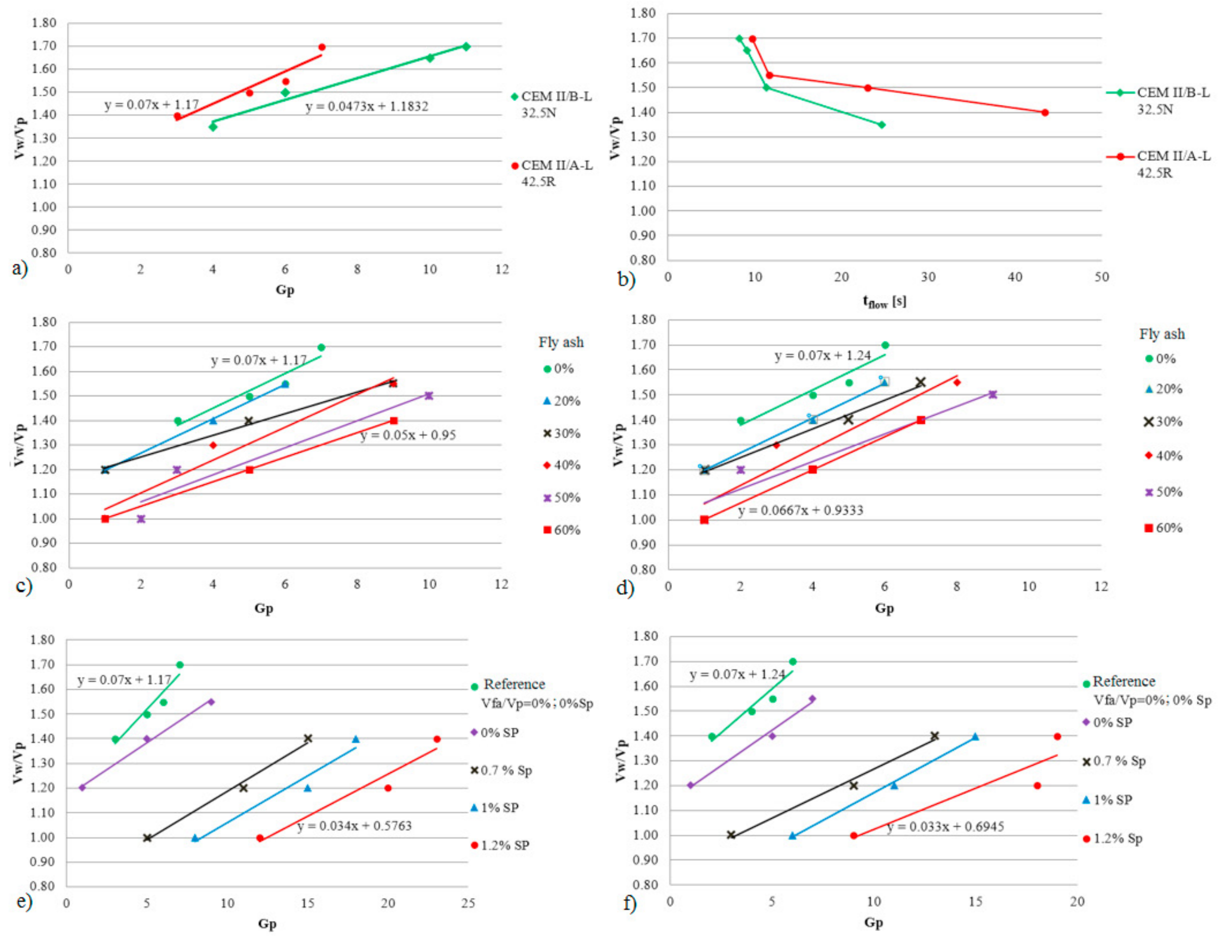

Figure 1. Paste results: a) Flowability of different cements; b) Viscosity of different cements; c) Flowability for different fly ash content immediately after mixing; d) Flowability for different fly ash content 30 minutes after mixing; e) Flowability for different superplasticyzer content immediately after mixing; f) e) Flowability for different superplasticyzer content 30 minutes after mixing.

3.2. Mortars

Thirteen mix proportions were tested, with different ratios of V_w/V_p, V_{fa}/V_p, V_s/V_m, V_{Sp}/V_p and V_{Pl}/V_p. Tests started by a composition with a V_w/V_p, obtained in the paste tests – choosing the one that it presents good rheological behavior. The remaining compositions appeared according to the results obtained by the trial-error procedure. During the study of the mortars it was necessary to introduce the plasticizer together with the superplasticizer, because it was not possible to reach the desired results in the fresh stage only with the superplasticizer (with commercially acceptable dosages). For mortars that present self-compacting properties (mortars number 9 and 13), prisms were molded to evaluate the corresponding the compressive strength. Table 2 presents the compositions produced and Figure 2 the corresponding results.

Table 2. Mortar compositions.

Composition	Vw/Vp	Vfa/Vp [%]	Vs/Vm [%]	Vs_1/Vm [%]	Vs_2/Vm [%]	VSp/Vp + VPl/Vp [%]
1	1.04	40	45.71	47	53	1.55
2	1.07	40	44.93	45	55	1.6
3	1.02	40	45.56	46	54	1.1
4	0.97	35	47.98	48	52	1.2
5	1.04	35	45.20	48	52	1.2
6	1.07	35	44.64	50	50	1.3
7	1.00	40	45.31	47	53	1.3
8	1.03	40	44.84	47	53	1.4
9	**1.04**	**40**	**44.22**	**43**	**57**	**1.3+0.7**
10	1.04	40	44.35	43	57	0.85+1.05
11	1.04	40	44.29	43	57	1.2+0.7
12	1.04	40	44.35	43	57	1.0+0.7
13	**1.04**	**40**	**44.35**	**43**	**57**	**1.1+0.7**

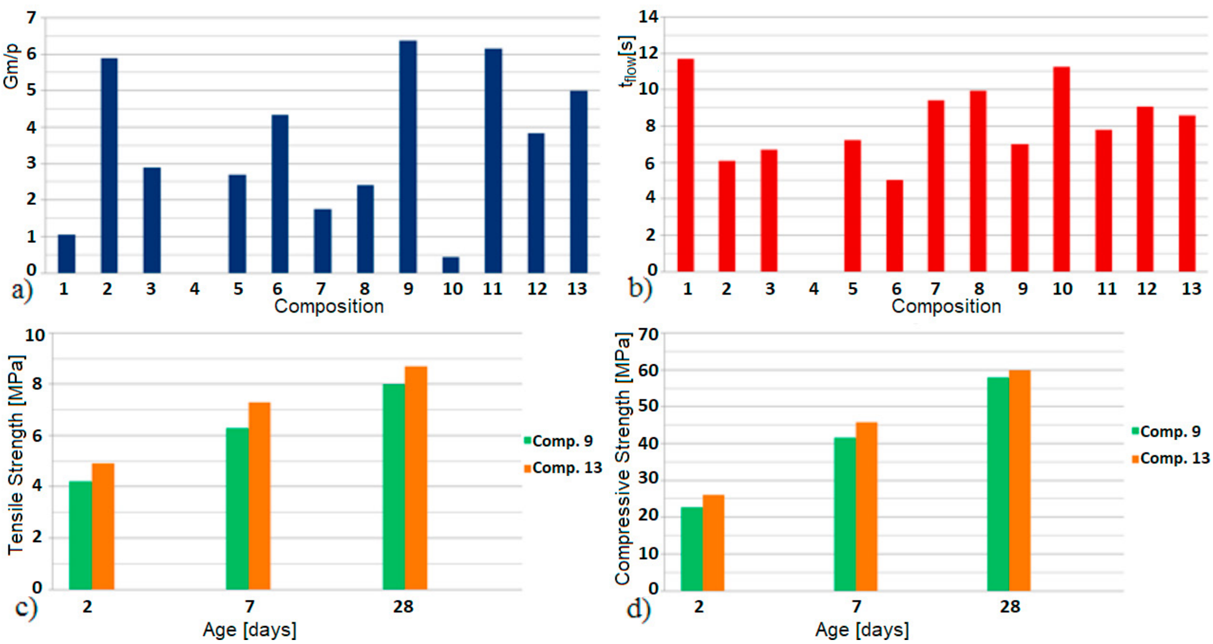

Figure 2. Mortars results: a) Flowability; b) Viscosity; c) Tensile strength; d) Compressive strength.

3.3. Concrete

Through the results obtained in the study of the pastes and mortar, the study of the concrete was started, keeping the same parameters in the optimum composition found in the study of the mortars (Composition 13). Then, 30% of the coarse aggregates (that corresponds to a $V_g/V_{g,lim}$=48.77%) were added to the composition, with the following proportions: 50% of Gravel 4/10, 35% of Gravel 8/16 and 15% of Gravel 11/22. Then, it was verified that this composition was not the most adequate, because it presented too much fluidity and with strong evidence to segregate. Moreover, it was concluded that Gravel 11/22 was a problem because of its maximum dimension. Once again, using the trial-error method, 14 more compositions were produced until reaching the desired composition. Adjustments in compositions were done varying the parameters V_w/V_p between 0.92 and 1.26, V_{fa}/V_p between 20% and 45%, V_{Sp}/V_p between 0.8% to 1.4% and V_{PI}/V_p between 0.6% and 0.9%.

The results obtained for the fresh stage and for the evolution of the compressive strength are shown in Figure 3 (note: in Ref. Neves (2013) is done a description of the compositions studied and the decisions taken during the trial-error). Analysing the results, it is observed that the workability after 30 minutes was markedly lower than initial one. It is also observed that all the compositions presented low viscosity (V-funnel was considerably lower than 7 seconds), difficulty in the capacity of passage in box L (which means less capacity of fill highly reinforced structures) and low segregation (i.e. it might lead to difficulties in filling the molds). With respect to the compressive strength, only composition 15 reached the class C30/37.

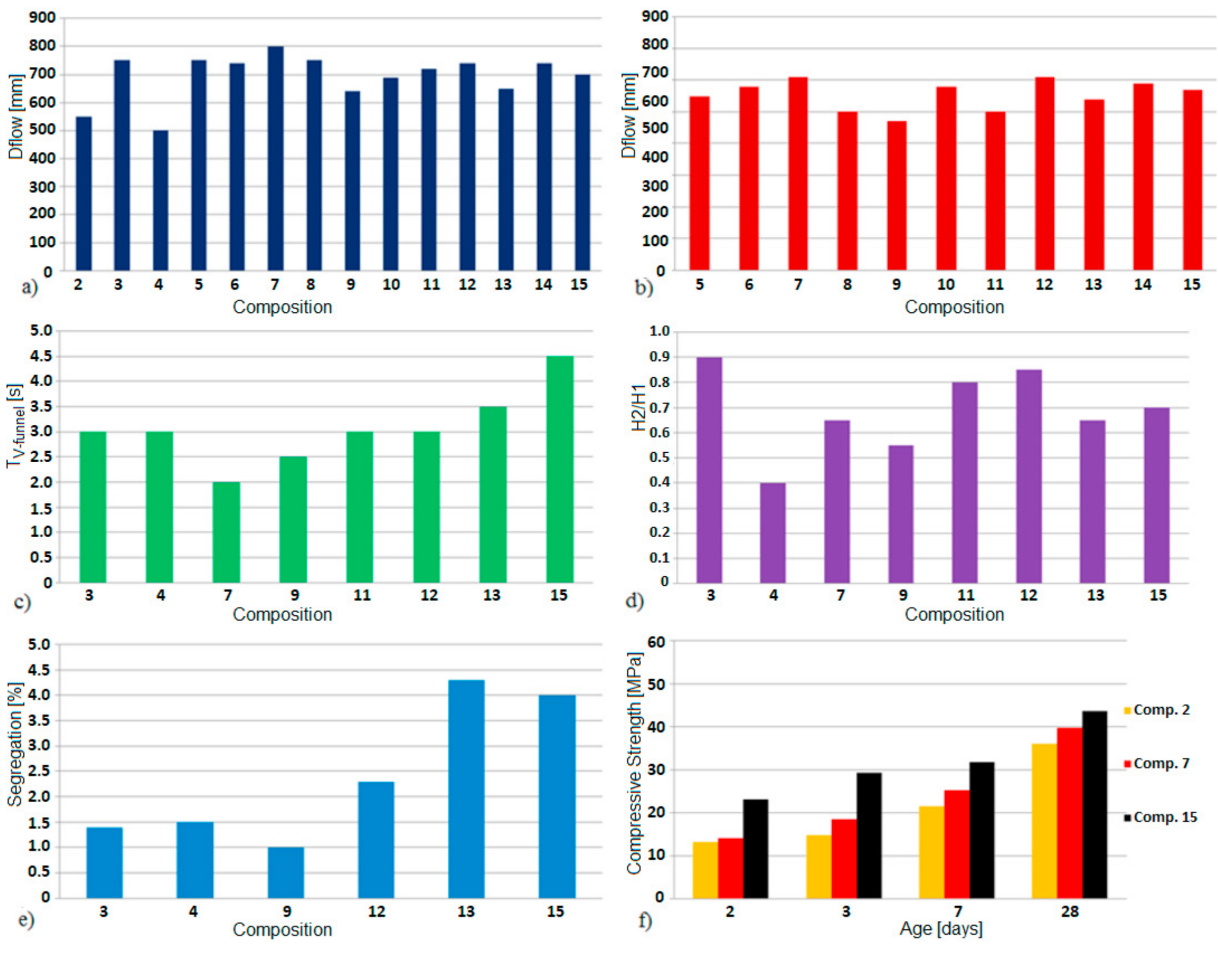

Figure 3. a) D_{flow} immediately after mixing; b) D_{flow} 30 minutes after mixing); c) V-funnel time; d) L-box ratio; e) Segregation %; f) Compressive Strength.

3.4. Production in ready-mix concrete plant and commercialization

The practical application of commercial SCC was carried out in two phases (in different days). The first phase consisted in the pouring of eight beams, with dimensions of 4.30×0.20×0.40 meters. The second phase of the application, another similar eight beams were poured. The formwork used in both applications was a commonly used in conventional concrete structures, i.e. rationalized re-used formwork – maritime plywood panels with dimensions of 1.25×2.5 meters.

SCC mixing was carried out at the ready-mixed concrete plant of the company. To produce SCC in the plant in comparison to conventional concrete, only changes were made in the mixing time – it was increased from 60 seconds to 180 seconds, because the SCC was composed of a higher dosage of admixtures, requiring a longer mixing time. Note: for commercial reasons, the contents of the materials are not revealed.

For each phase, one truck with 4 m^3 were supplied. However, as for in the first phase, the 4 m^3 were produced in four separated batches (1.0+1.0+1.0+1.0 m^3), for the second phase the 4 m^3 were produced in a single batch. As expected, the casting process occurred as usually for SCC – very quick and free of vibration.

During the first phase of application, it was found that the concrete produced at the plant had minor changes to the concrete produced in the laboratory. These changes occurred essentially at the fluidity and segregation level – flowability obtained in the production plant was higher and showing a small segregation than the one obtained in the laboratory. This change was probably due to the production of the concrete in the plant was more efficient than in the laboratory, as a more homogeneous mixing is achieved. Due to the high fluidity and segregation found on the concrete produced in the first phase, it was decided to introduce a viscosity modifier (RheoMATRIX 175) in the second phase of the application to keep the high flowability but without segregation. Table 3 presents the results of the tests carried out in the fresh stage for both application phases. As for the hardened stage, at 28 days the both supplies had a compressive strength in cubes of about 45 MPa.

Table 3. Fresh properties of the commercialized SCC.

Test	1st phase	2nd phase
Slump-flow – D_{flow} [mm]	730 (SF2)	660 (SF2)
V-funnel - T_{flow} [s]	2.3 (VF1)	3.5 (VF1)
L-box – passing ability [-]	0.65	0.70

After removing the molds from the concrete beams it was possible to verify that they were perfectly filled, although in the upper part of the face of the beams some small surface pores were observed. It is believed that the beams were with no interior voids and the reinforcement would have been completely involved. The client was satisfied and since then several other commercial SCC applications have been carried out in Madeira Island.

4. Conclusions

Within this research a commercial composition of self-compacting concrete produced with the materials currently available in the local market was achieved in Madeira Island. The following remarks are pointed:

- Limestone filler is not currently available in the Madeira Island, thus fly ash was used to increase the powder content;
- All aggregates were from volcanic origin and only the finest sand was not a crushed aggregate;
- Cement CEM II/B-L 32.5N presented better rheological characteristics for SCC than CEM II/A-L 42.5R;
- The introduction of fly ash in the pastes led to a substantial increase in workability in the fresh stage, resulting in larger flowability;
- The addition of superplasticizer led to improvements in the rheological properties, with an increase in the flowability capacity. However, as expected excessive dosage of superplasticizer leads to near zero flowability improvements and affects adversely the segregation;
- The Pozzolith 390N plasticizer lead to markedly improvements in rheological behaviour – longer workability;
- The viscosity modeller ReoMATRIX 175 was used to improve concrete viscosity and reduce segregation;

• Although the tests that access self-compactibility are simple to perform in laboratory, in a construction site they are quite difficult to carry out according standards;

• It was possible to produce SCC without significantly changes on the usual concrete production process in a conventional concrete plant;

• Commercial applications were successfully performed with the client being satisfied.

Acknowledgements

Funding provided by the Portuguese Foundation for Science and Project Technology (FCT) and the European Social Fund (ESF), namely for the Research Unit 'CONSTRUCT – Institute of R&D in Structures and Construction', is gratefully acknowledged. Acknowledgements are also addressed to Mr. Miguel Guimarães and to the company Laboratório Cimentos Madeira where the experimental program was carried out.

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