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Characterization of self-compacting concretes prepared with different fibers and mineral additions

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ABSTRACT

In this work, several self-compacting concretes were prepared by using three different types of fibers made of steel, poly-vinyl-alcohol (PVA) and high toughness poly-propylene (PPHT) and two different types of mineral addition (limestone powder and powder from recycled concrete). The water to cement ratio was held constant at 0.40. Fresh concrete behavior was evaluated by means of slump flow, V-funnel and L-box tests while the hardened concrete behavior was evaluated by means of flexure and compression tests, as well as free drying and restrained plastic shrinkage tests. Excellent performances were generally obtained, particularly for the self-compacting concretes prepared with steel fibers and powder from recycled concrete.

1. Introduction

Self-compacting concrete can be placed and compacted under its own weight without any vibration effort, assuring complete filling of formwork even when access is hindered by narrow gaps between reinforcement bars. Concrete placement without vibration is a challenge to the building industry. In order to achieve such behavior, the fresh concrete must show both high fluidity and good cohesiveness at the same time.

In this work, several self-compacting concretes were designed for thin pre-cast elements, which only require steel reinforcement for dead and minor loads. For this reason, fibers were added to the mixture to counteract early-age cracking of concrete (due to plastic and autogenous shrinkage, as well as thermal stress), and delayed cracking due to restrained drying shrinkage. Several authors have shown the effectiveness of fiber addition on counteracting plastic shrinkage cracking of concrete [1–6] and, in general, their positive effect for reducing concrete cracking due to restrained drying shrinkage [6–9]. However, from a functional point of view, a compressive strength class of at least 45 MPa was necessary on the basis of structural design, taking into account early flexural strength for lifting and moving, as well as fatigue and creep effects.

2. Materials and procedures

2.1. Materials

A commercial portland-limestone blended cement type CEM II/A-L 42.5 R according to the European Standards EN-197/1 was used. The Blaine fineness of cement was 0.42 m^2/g and its relative specific gravity was 3.05. The chemical composition of cement is reported in Table 1.

A commercial limestone powder, originating from marble was used as a mineral addition. The effectiveness of this kind of mineral addition for producing SCC was already checked by the authors in a previous work [10]. It was chosen bearing in mind the suggestion on fineness (that should be lower than 0.80 m^2/g) reported in [11]: in fact, its Blaine fineness resulted 0.61 m^2/g. Moreover, its specific gravity was 2.65 and its chemical composition is reported in Table 1.

Alternatively, a powder obtained from the recycling process of old concrete was employed. This process mainly consists of crushing concrete waste from building demolition and collecting the material passing through a suitable sieve (in this case the sieve ASTM No. 100 corresponding to 0.150 mm). This recycled-concrete powder had Blaine fineness of 0.73 m^2/g and specific gravity of 2150 kg/m^3. Its chemical composition is reported in Table 1. The positive effect on SCC cohesiveness of high values of mineral addition fineness was already studied by the authors [12] by means of rheological tests on cement pastes.

Gravel (15 mm maximum size) and quartz sand (6 mm maximum size) were used. The gradation of both gravel and sand are

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Table 1
Chemical composition and fineness of materials passing the sieve ASTM No.100.

		Cement	Recycled-concrete powder	Limestone powder
Blaine fineness (m^2/g)		0.42	0.73	0.61
Oxides (%)	SiO_2	29.67	84.99	38.70
	Al_2O_3	3.74	4.47	8.02
	Fe_2O_3	1.80	3.91	3.34
	TiO_2	0.09	0.11	0.12
	CaO	59.25	2.94	40.61
	MgO	1.15	1.10	2.93
	SO_3	3.25	1.30	1.20
	K_2O	0.79	0.77	1.37
	Na_2O	0.26	0.41	1.00
Loss on ignition at 1000 °C		11.62	26.57	34.23

shown in Fig. 1 and their physical properties are reported in Table 2. As water reducing admixture, a 30% aqueous solution of carboxylic acrylic ester polymer was added to the mixtures.

In some mixtures, steel fibers were employed at a dosage of 0.6% by volume. This dosage was decided on the basis of information reported in the literature [11,13,14], which showed that an increase in fiber content from 0.5% to 1% resulted in lower concrete performances. Alternatively, either poly-vinyl-alcohol (PVA) fibers or high toughness poly-propylene (PPHT) fibers were added at a dosage of roughly 0.8 and 0.6% by volume, respectively. Fiber length, diameter, aspect ratio (AR), Young modulus and tensile strength are reported in Table 3. Moreover, their morphology is shown in Fig. 2.

2.2. Concrete mixtures proportions

The mixtures proportions are reported in Table 4. All concretes were prepared with the same water to cement ratio of 0.40.

In order to optimize the grain size distribution of the solid particles in the concrete, the fine and the coarse aggregate fractions

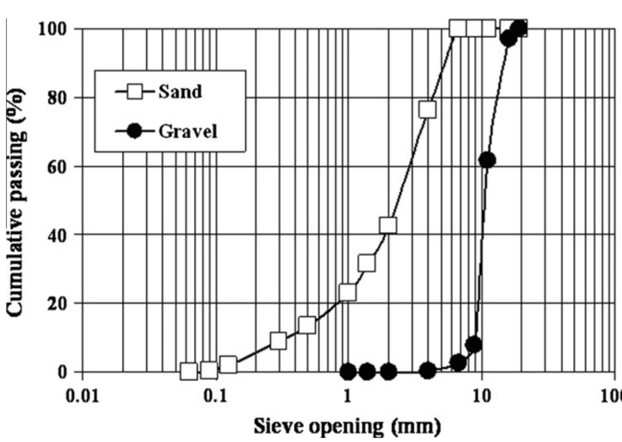

Fig. 1. Grain size distribution curves of the aggregate fractions.

Table 2
Some physical properties of the aggregate fractions.

Aggregate fractions	Specific gravity[a] (kg/m^3)	Water absorption (%)	Passing the 75 μm sieve (%)
Quartz sand	2610	3.1	0.9
Gravel	2660	2.6	0.1

[a] Evaluated in SSD (saturated surface dry) condition.

Table 3
Main characteristics of the fibers used.

Type of fiber	Length (mm)	Diameter (mm)	Aspect ratio (AR)	Young's modulus (GPa)	Tensile strength (MPa)
Steel	30	0.70	43	170	450
PVA	12	0.20	62	30	1000
PPHT	35	0.62–0.69	51–57	3.8	600–750

were suitably combined, taking into account also the suggestions reported in the literature concerning the mixture proportion of self-compacting concrete, particularly in terms of maximum dosage of coarse aggregate, that is 340 l/m^3 [15,16].

In order to achieve a volume of very fine particles of about 190 l/m^3, it was necessary to alternatively employ the mineral additions besides to cement, at a dosage of 58 kg (recycled-concrete powder) or 70 kg (limestone powder), depending on their volumetric mass. In this way, a water to very fine material ratio in the range 0.35–0.36 was obtained. Superplasticizing admixture was dosed at 1.4% by weight of cement in order to fit the slump flow range of 650–700 mm (see Table 5).

The cement dosage was quite high, equal to 500 kg/m^3. For this reason, the eventual early-age concrete cracking due to autogenous shrinkage and/or thermal stress (induced by high cement hydration rate) was investigated. A reference SCC mixture was also prepared without fibers by using limestone powder as filler.

3. Experimental methods

3.1. Slump flow test

As a first step, properties of the fresh concrete other than slump were evaluated according to Italian Standards UNI 11041, since in this case the slump value is not relevant due to very fluid concrete. Therefore, the attention was focused on the measurement of the slump flow, which is the mean diameter (Φ_{fin}) of the slumped concrete. Then, also the elapsed time to gain the mean diameter of 500 mm (t_{500}) and the elapsed time to gain the final configuration (t_{fin}) were detected.

3.2. V-funnel test

Time elapsed for the SCCs passing through V-funnel was detected, according to Italian Standards UNI 11042 [17].

3.3. L-box test

In order to evaluate the filling capacity of highly congested structural members further tests were carried out by means of L-box with vertical steel bars, according to Italian Standards UNI 11043 [18]. The difference in the concrete level between the beginning and the end of the box (ΔH_{fin}, expressed in mm) and the elapsed time to establish the final configuration (t_{stop}, expressed in s) were measured.

3.4. Compression test

Nine cubic specimens, 100 mm in size, were cast for each concrete mixture for compression tests, according to Italian Standards UNI EN 12390-1. These specimens were cast in polystyrene forms and wet cured at 20 °C (UNI EN 12390-2).

Compressive strength was evaluated according to Italian Standards UNI EN 12390-3 on cubic specimens, which were tested at right angles to the position of casting. Therefore the bearing faces

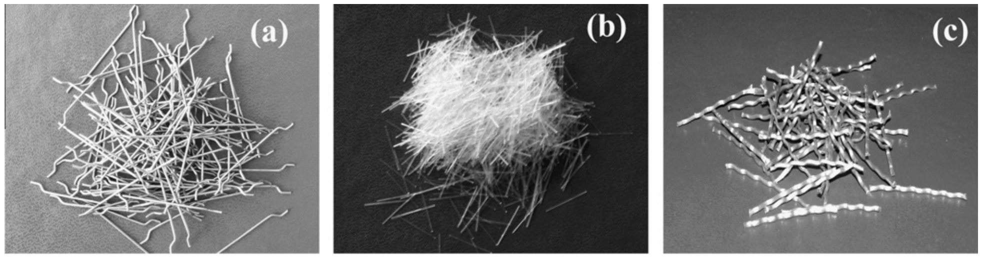

Fig. 2. Fibers used: (a) steel fibers, (b) PVA fibers and (c) PPHT fibers.

Table 4
Concrete mixture proportions.

Mixture	REF	S-RP	S-LP	PPHT-RP	PPHT-LP	PVA-RP	PVA-LP
Water/cement	0.40						
Water (kg)	200						
Cement (kg)	500						
Sand (kg)	1080						
Gravel (kg)	420						
Limestone powder (LP) (kg)	70	–	70	–	70	–	70
Recycled-concrete powder (RP) (kg)	–	58	–	58	–	58	–
Steel fibers (S) (kg)	–	50	50	–	–	–	–
High toughness poly-propylene fibers (PPHT) (kg)	–	–	–	5	5	–	–
Poly-vinyl-alcohol fibers (PVA) (kg)	–	–	–	–	–	10	10
Superplasticizer (kg)	7	7	7	7	7	7	7

Table 5
Rheological test results.

Mixture		REF	S-RP	S-LP	PPHT-RP	PPHT-LP	PVA-RP	PVA-LP
Slump flow test	Φ_{fin} (mm)	670	700	700	680	680	680	680
	t_{500} (s)	2	3	3	3	3	2	2
	t_{fin} (s)	10	13	13	13	13	12	12
V-funnel test	t (s)	8	5	5	8	7	8	8
L-box test	ΔH_{fin} (mm)	70	65	65	40	60	30	50
	t_{stop} (s)	15	12	12	19	15	21	18

were sufficiently planar and smooth as to require no capping or grinding. The specimens were loaded at a constant strain rate until failure.

3.5. Flexure test

Nine prismatic specimens, 100 by 100 by 450 mm in size, were cast for each concrete mixture for 3-point bending tests, according to Italian Standards UNI EN 12390-1. These specimens were cast in steel forms and wet cured at 20 °C (UNI EN 12390-2).

Flexural strength was evaluated according to Italian Standards UNI EN 12390-5 on prismatic specimens by calculating the maximum tensile stress reached at the bottom of the middle cross-section of the tested specimen. The Modulus of Rupture (MOR) was obtained as follows:

$$MOR = \frac{3}{2} \cdot \frac{L \cdot d}{e^3} \qquad (1)$$

where L is the maximum load applied (N), d is the distance between the supports (400 mm) and e is the edge dimension of the square cross-section (100 mm).

3.6. Static modulus of elasticity and toughness evaluation

Three cylindrical specimens, 300 mm high with a diameter of 100 mm, for each concrete mixture were manufactured for evaluating static modulus of elasticity in compression according to Italian Standards UNI 6556. In addition toughness was evaluated by calculating the area under the stress–strain curve obtained in compression tests, which were performed under displacement controlled conditions [19]. Two values of toughness were determined: one was calculated up to the strain related to the maximum strength of concrete and it was called *A*-peak; the other (called *A*-0.45%), was calculated up to a strain equal to 0.45% (generally higher than the previous strain).

3.7. Drying shrinkage test

Three prismatic specimens (100 by 100 by 500 mm) were prepared for each concrete mixture according to Italian Standard UNI 6555 'Hydraulic Shrinkage Determination'. After one day of wet curing, the specimens were stored at constant temperature (20 ± 2 °C) and constant relative humidity (50 ± 2 %), while measuring drying shrinkage at different curing times.

3.8. German angle test

This method for evaluating restrained shrinkage of concrete was developed by the Technical Academy Aachen in Germany and adopted as the Technical Test Regulations (TP BE-PCC) by Highway Construction Department of the Federal Ministry of Transport [20]. In this case, the German angle test was carried out under a severe exposure condition (under halogen lamp irradiation) in order to simulate the effect of wind and/or sun warming on the plastic shrinkage of early-age concretes.

Prismatic specimens were cast (one for each concrete mixture) in a steel angle of 75 mm × 75 mm, 8 mm thick and 1030 mm long (see Fig. 3) for the German angle test. Since their manufacturing, these specimens were kept in open air and exposed to halogen lamp irradiation (150 W) in order to simulate the sun warming. The lamp was placed at 100 mm from the upper surface of the angle specimens. In this way, the concrete surface temperature after 4 h was constant at 77 ± 1 °C.

4. Results and discussion

4.1. Slump flow test

As shown in Table 5, all concretes had enough deformability under their own weight (strictly related to the value of the mean diameter), and quite a high viscosity (related to the value of the elapsed time to stop), which is necessary to avoid segregation of coarse aggregate particles. In fact, neither the presence of a halo of cement paste around the slumped concrete nor the so-called 'sombrero effect' were observed.

4.2. V-funnel test

As shown in Table 5, the time elapsed for the SCCs passing through the V-funnel was found to be in the range 5–8 s in all cases, widely within the acceptance limits [17].

4.3. L-box test

The results obtained are reported in Table 5. All concrete showed good, in some cases excellent, results in terms of mobility through narrow sections, particularly in the presence of the recycled-concrete powder (RP mixtures), probably due to the better rheological properties conferred to the cement paste [12]. Moreover, concerning with the flow-segregation, separation between the coarse aggregate particles and the surrounding cement paste was never observed.

4.4. Compression test

Behavior of concrete in compression was studied at curing times of 1, 7 and 28 days and the results obtained are reported in Fig. 4. The target class strength of 45 MPa was reached in every case. In particular, except for the reference mixture and those prepared with PVA fibers, the mean compressive strength after 28 days of curing was around 60 MPa.

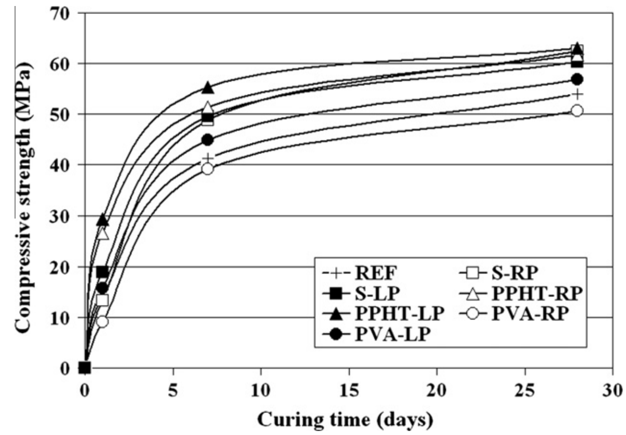

Fig. 4. Compressive strengths vs. curing time.

4.5. Flexure test

Flexural behavior of concrete was studied at curing times of 1, 7 and 28 days and the results obtained are reported in Fig. 5. Results obtained showed the effectiveness of steel fibers in improving the flexural behavior of concrete (enhanced in this case by the particular shape of the fibers, see Fig. 2). On the other hand, the SCC mixture prepared with polymeric fibers (PVA or PPHT) showed reduced performance in flexure with respect to the reference mixture without fibers.

4.6. Static modulus of elasticity and toughness evaluation

Results obtained after 28 days of curing are reported in Fig. 6. Values of elastic static moduli were in the range predictable for ordinary concrete on the basis of the concrete strength class [21,22]. In particular, the different value of fiber Young modulus (see Table 3) seems not to affect the values of static elastic modulus of concretes, due to the low content of fiber here used. Toughness of fiber-reinforced SCC was always quite high, independently of the strain considered, and particularly for those mixtures prepared with steel or PPHT fibers. The *A*-0.45% toughness values seem to track the Young's modulus values very closely, so the lower values detected for the mixtures prepared by using PVA fibers could simply reflect the lower concrete quality.

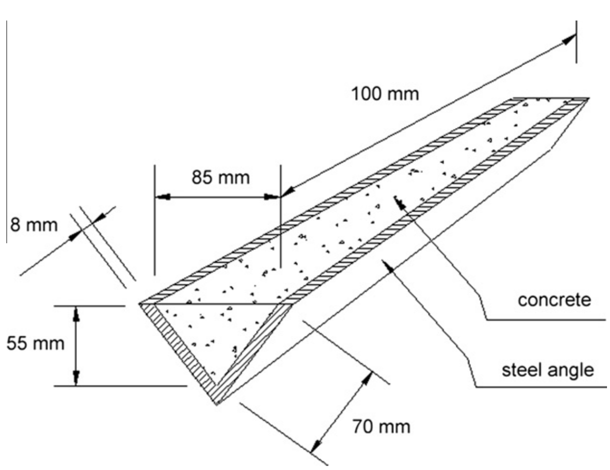

Fig. 3. Scheme of the steel angle used for German angle test.

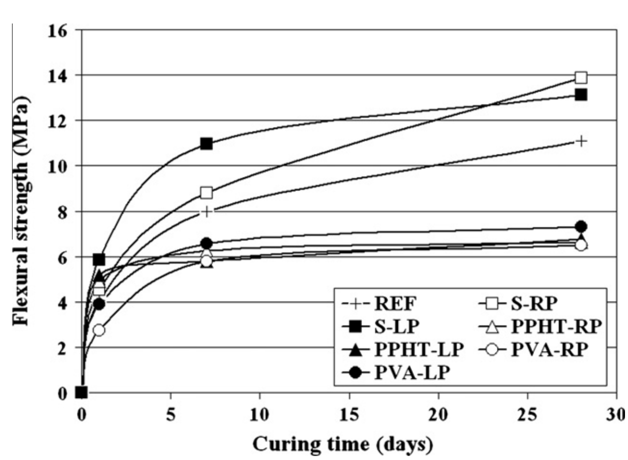

Fig. 5. Flexural strengths vs. curing time.

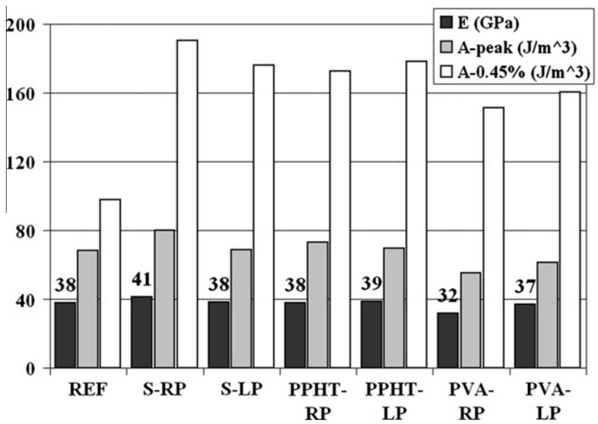

Fig. 6. Elastic modulus (E) and toughness values (*A*-peak, *A*-0.45%) calculated from experimental data obtained by means of compression tests.

In particular, the ratio between *A*-0.45% and *A*-peak, representing an indication of the post-cracking behavior is in the range 2.35–2.75 for all the mixtures, except for the reference mixture without fibers showing worse post-cracking behavior.

4.7. Drying shrinkage test

Fig. 7 shows the results obtained up to 180 days. A drying shrinkage between 550 and 400 μm/m can be predictable after 1 year of exposure to a relative humidity of about 50% for all the SCC mixtures. The effectiveness of fibers addition (whichever the type) in counteracting drying shrinkage of concrete is quite evident. In fact, for the reference concrete prepared by using limestone powder (LP) without fibers, drying shrinkage higher than 500 μm/m after six months was measured, while values around 400 μm/m were detected for those fiber-reinforced SCC mixtures containing limestone powder as well. Concerning the use of mineral additions, higher tendency to shrink was detected when recycled-concrete powder was used together with low modulus (polymeric) fibers, the reason probably lies in its higher fineness with respect to limestone powder which caused slightly higher water absorption.

4.8. German angle test

Only the reference mixture without fibers showed evident cracking under German angle testing. On the other hand, the two concrete mixtures prepared with steel fibers only showed very light microcracking, while the other four mixtures did not show any appearance of cracks. However, the age of cracking was less than one day in both cases, thus indicating that plastic shrinkage instead of drying shrinkage was the main cause of concrete cracking.

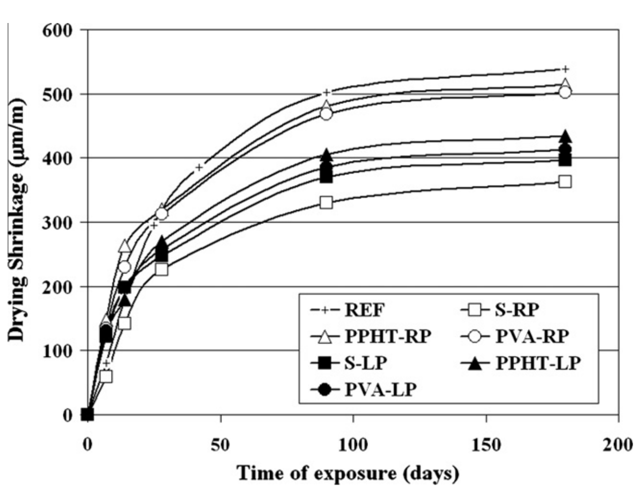

Fig. 7. Drying shrinkage measurements up to 180 days of exposure to 50% relative humidity.

5. Conclusions

All concretes, which were prepared for manufacturing thin precast elements, met both the self-compaction requirements, while fresh, and the mechanical requirement of 45 MPa, when hardened. The fiber additions proved to be very effective in counteracting both early age cracking (particularly PVA and PPHT fibers) and delayed drying shrinkage (particularly steel fibers) of self-compacting concrete, which are usually a great problem for this material, rich in powders (particularly cement) and poor in the coarse aggregate fraction.

The use of recycled-concrete powder instead of limestone powder for producing SCC seems to be promising, particularly in terms of fresh concrete flowability, even if higher tendency to shrink was detected when recycled-concrete powder was used with polymeric fibers.

Concerning further durability aspects such as carbonation and chloride penetration depth as well as frost resistance, encouraging data are reported in a previous work concerning a very similar FRSCC mixture with steel fibers [23].

In conclusion, the best concrete mixture in terms of hardened concrete behavior was the one prepared with steel fibers and recycled-concrete powder. In terms of fresh concrete behavior the differences among the various mixtures are quite small, with the best results provided by the mixture containing PVA fibers and recycled-concrete powder. However, this mixture was the worst in terms of mechanical performance.

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