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Recent Developments of Special Self-Compacting Concretes

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Synopsis:

During the last decades new cementitious materials were available. These represent a technical revolution with respect to the traditional concretes. The most important innovative "High Tech" materials are Self-Compacting Concretes (SCCs).

In the present paper the compositions, the performances and some practical applications of high-performance SCCs are shown. In particular, some performance improvements carried out in our laboratories are shown for these specific uses:

a) SCC for a Building Engineering application (S. Peter Apostle Church in Pescara, Italy) with white concrete characterized by a marble-like skin;
b) SCC in the form of high-strength concrete with compressive strength over 90 MPa devoted to a work in the field of Civil Engineering (World Trade Center in San Marino);
c) SCC in the form of mass concrete structure with a reduced risk of cracking induced by thermal difference between the nucleus and the skin of the elements;
d) SCC in the form of lightweight precast concrete with a density of 1750 kg/m^3, 28-day compressive strength of 35 MPa, and 28-day flexural strength of 5 MPa;
e) SCC in the form of a shrinkage-compensating concrete for reinforced concrete walls 8 m high and 55 m long.

Keywords: expansive agent; high performance concrete; lightweight concrete; mass concrete; self-compacting concrete; shrinkage reducing admixture; silica fume; superplasticizer; viscosity modifying agent

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INTRODUCTION

With respect to the traditional concretes, the new cementitious materials, thanks to the availability of new raw materials, allow the concretes to reach much higher performances in terms of execution on job sites, useful service life, and mechanical strength. These new raw materials include:

- New synthetic polymers (poly-acrylates) which, in comparison with naphthalene- or melamine-sulphonated polymers, are able to reduce even more effectively the amount of mixing water and the water-cement ratio with all the consequent benefits [1,2].
- Viscosity Modifying Agents (VMA) to produce thixotropic mixes and then to obtain cohesive fresh concretes even when they are very fluid [3].
- Mineral additions characterized by amorphous silica such as silica fume (waste from silicium-iron alloys) in the form of very fine particles (size of some μm/m) or UFACS (Ultra-Fine Amorphous Colloidad Silica) synthetically produced in the form of very small particles with size of some nm [4].
- Shrinkage Reducing Admixture to improve the dimensional stability of concrete structures with geometric characteristics, in terms of size and form, which may have cracks related to drying shrinkage.

EXPERIMENTALS AND DISCUSSION OF RESULTS

The term Self-Compacting Concrete (SCC) refers to a special type of concrete mixture, characterized by high resistance to segregation, that can be cast without compaction or vibration. With the advent of superplasticizers, flowing concretes with slump levels up to 250 mm were manufactured with no or negligible bleeding, provided that an adequate cement factor was used, that is at least 350 kg/m^3 [2]. The most important basic principle for flowing and unsegregable concretes including SCCs is the use of the superplasticizer combined with a relatively high content of powder materials in terms of portland cement, mineral additions, ground filler and/or very fine sand. A partial replacement of portland cement by fly ash was soon realized to be the best compromise in terms of rheological properties, resistance to segregation, strength level, and crack-freedom, particularly in mass concrete structures exposed to restrained thermal stresses produced by cement heat of hydration. Some other mineral additions, alternative to fly ash, have been considered for the five works presented in this paper: they are silica fume, ground limestone, and an expansive agent.

In this paper five specific concretes are shown all belonging to the SCC type: for an architectural concrete of the church of S. Peter Apostle in Pescara, Italy; for a HSC of the World Trade Center of San Marino; for a mass concrete placed in a slab foundation near Venice, Italy; for precast lightweight concrete structures, in Milan, Italy; and for shrinkage-compensating concrete devoted to a Museum Center in Rome, Italy.

Pure portland cement (CEM I according to European Norm EN 197/1) was used only for the HSC, whereas blended cements were used in all the other works.

For the mix-design of the three concretes, laboratory and field tests have been carried out. In the following sections the results for each of the five concretes are shown and discussed.

Architectural SCC: The properties required by the structural engineers of the S. Peter Apostle church erected on the sea beach of Pescara (Italy), may be summarized by the following data:

1) high fluidity in terms of **slump flow**: ≥ 600 mm after 1 hr at 30°C (ready-mixed concrete placed in summer time);
2) **cube compressive characteristic strength**: ≥ 35 MPa;
3) **impermeability** in terms of water penetration according to the ISO DIS 7031 test: ≤ 20 mm (this requirement was adopted to guarantee durable concrete exposed to sea water);
4) **marble-like effect** of the skin of the concrete placed in the absence of vibration due to the very congested reinforcement.

In order to reach all these requirements, the composition adopted for the concrete mixture was that shown in Table 1.

The performances really obtained are shown in Table 2 and they are all capable of meeting the above first three performances required by the structural designers.

As far as the marble-like effect of the skin is concerned – which was very important for the work from an architectural point of view – it was visually assessed by comparison of two white concretes, both placed without any vibration: the former at a superfluid consistency S5 (slump = 225 mm), and the later in form of SCC. Figure 1 shows, for instance, the marble-like effect of the skin obtained only in the case of the SCC. Then, thanks to the special rheological properties of the SCC in the fresh state, even the fourth requirement needed by the architect was met. Figure 2 shows the splendid appearance of SCC at a white wall of the church placed without vibration.

High-Strength SCC: For the World Trade Center in San Marino (designed by Norman Foster and Partners, London, U.K.), a special concrete was required with the typical properties of SCC as shown in the previous section and, additionally, with a high compressive strength. These are the requirements needed for the work [5]:

1) high fluidity in terms of **slump flow**: ≥ 600 mm after 1 hr;
2) **cube compressive strength** ≥ 40 MPa at 1 day and ≥ 80 MPa at 28 days;
3) **dynamic elastic modulus**: ≥ 40 GPa;
4) **drying shrinkage**:≤ 500 μm/m at two months;
5) **uniformity** in terms of specific mass, elastic modulus, and compressive strength measured on cored specimens through field tests.

Table 3 shows both the adopted composition and the performances of the concrete. These agree with the first four requirements.

One cylinder specimen was cored from the un-vibrated concrete placement 1500 mm thick, and then the following measurements were carried out: density (D) and dynamic elastic modulus (E_d) shown in Fig. 3, and compressive strength shown in Fig. 4.

The data obtained on different parts of the cored material indicated that the results obtained for the concrete of the structure are reproducible and agree very well with those obtained for the specimens cast in laboratory. Then, even the fifth requirement (about uniformity) is met.

SCC for mass concrete structures: In order to manufacture such a special SCC (slump flow of 700-800 mm) near Venice [4, 5] the following ingredients were used: blast-furnace slag cement (CEM III/A 32.5 R with portland cement content of only 40 %), fly ash, ultra-fine amorphous colloidal silica (UFACS) to reduce segregation and bleeding, and polyacrilic superplasticizer with retarding effect in order to reduce the early hydration rate (Table 4). The thermal difference between the nucleus (in a quasi-adiabatic condition) and the skin (considered to be in perfect thermal equilibrium with the environment) was lower than 20°C (recommended value to avoid craking risk) as shown in Fig. 5. The properties of these special SCC's in the fresh state are shown in Table 5.

Figure 6 shows the strength development: the compressive strength was 40 MPa at 28 days with some post-hardening up to 50 MPa at 60 days. Drying shrinkage at RH of 55% was lower than 300 μm/m at 60 days (Fig. 7).

Moreover, laboratory test on SCC's specimens, exposed to chloride aqueous solution (Fig. 8), carbon dioxide (Fig. 9), and water under pressure (5 atm) indicated that this concrete is durable and watertight (water penetration less than 10 mm) although the portland cement content was as low as 120 kg/m^3 (Table 4).

SCC for precast lightweight structures: Self-compacting lightweight concrete was used in the form of precast insulating panels (Fig. 10). The main problem was to avoid segregation of expanded clay (Fig. 11): to do this, a relatively high content of the viscosity modifying agent was used as shown in Table 6 which gives a summary of the performance of this special SCC in terms of slump flow, strength, elastic modulus, drying shrinkage at R.H.of 50%, creep, and durability in terms of CO_2 and Cl^- penetration.

Shrinkage-compensating SCC: For the very prestigious Museum of Modern Arts, in Rome, designed by Zaha Hocchid Architects, London, U.K., a very special shrinkage-compensating SCC was studied in order to avoid the risk of cracks in some special walls (8 m high and 55 m long) without constructions joints. A CaO-based expansive agent in combination with a shrinkage reducing admixture (SRA) was used.

The composition of this special SCC and that of the corresponding SCC mixture without an expansive agent and SRA are shown in Table 7. Figure 12 shows the strength development of the two SCC, with and without an expansive agent and SRA.

Figure 13 shows the length change of the reinforced speciments (manufactured with mix A or B of Table 7) cured by a protective plastic film up to 16 hours and then exposed to unsaturated air (R.H.=60%) at 20°C.

Due to the presence of SRA [6], the early curing of the reinforced specimens manufactured with the shrinkage-compensating SCC was not carried out under water as required by ACI Committee 233, but only with a plastic film to simulate the protection of the concrete surface from drying by the formwork. Even under this un-favorable but realistic conditions of curing, the expansion at 16 hours was relatively high (520 μm/m) and still good at 2 months (280 μm/m) with R.H. of 60%. In the "ordinary" SCC (mix B), without expansive agent and SRA, the shrinkage at 2 months was about 400 μm/m Due to this special behavior, the first results obtained by field tests on concrete structures are very encouraging for the crack-free ability of this SCC.

CONCLUSIONS

The results obtained in the present paper show the extra-ordinary properties which can be obtained by using the innovative concretes recently developed in the field of SCC.

SCC appears to be very succesful because it is easy to place in a safe way independent of the quality and reliability of the workmanship available today on the jobsites.

The architectural SCC presented in this paper is a very special concrete even for the excellent surface (white and with marble-like aspect) required for architectural reasons.

The high-strength SCC studied in this paper can be considered as market nich in the field of Civil Engineering.

The combined use of CEM III/A 32.5R (300 kg/m^3), *AP*-based superplasticizer (0.8-1.5%), fly ash (130-150 kg/m^3), ultra-fine amorphous colloidal silica (1-2%), and aggregate with a maximum size of 20 mm allow the manufacture of self-compacting concretes characterized by low heat development which are particularly suitable for mass concrete structures.

Lightweight SCC can be produced without any segregation of the expanded clay aggregates provided that an adequate dosage of the viscosity modifying agent is used.

Finally, a shrinkage-compensating SCC can be also manufactured with a CaO-based expansive agent and a shrinkage reducing agent as additional ingredients in addition to those usually adopted for SCC (superplasticizer, filler and VMA).

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Table 1 – Composition of Architectural SCC

INGREDIENT	kg/m^3
WHITE Cement CEM/II B-L 32.5R*	400
COARSE CRUSHED MARBLE (2-16 mm)	875
FINE CRUSHED MARBLE (0-4 mm)	440
VERY FINE CRUSHED MARBLE (0-2 mm)	430
GROUND LIMESTONE	100
WATER	180
ACRYLIC SUPERPLASTICIZER	9.6
VISCOSITY MODIFYING AGENT	0.12
WATER-CEMENT RATIO	0.45

* portland cement = 70%

Table 2 – Performances of Architectural SCC

Specific Mass (fresh mix) (kg/m^3)		2417
Concrete Aspect		Cohesive
Slump Flow (mm) at 30°C after:	0 min.	700
	30 min.	680
	60 min.	650
Compressive Strength (MPa) at 20°C as a function of time (days)	1	17.2
	7	35.3
	14	39.4
	28	43.0
Water penetration (ISO-DIS 7031)		6 mm

Table 3 – Composition and properties of High-Strength SCC

Portland Cement (CEM I 42.5 R)	465 kg/m^3
SILICA FUME	65 kg/m^3
WATER	175 kg/m^3
GRAVEL (15-22 mm)	195 kg/m^3
GRAVEL (6-15 mm)	720 kg/m^3
SAND (0-6 mm)	710 kg/m^3
ACRYLIC SUPERPLASTICIZER	4.6 kg/m^3
water/(cement+silica fume)	0.33
Slump flow at 5 and 60 min. (mm) AT 20°C	730-600
Compressive Strength (MPa) at: 1 day	50
28 days	95
Drying shrinkage at 60 days (μm\m)	380
Dynamic elasatic modulus (GPa) at 28 days	45

Table 4 – Composition of SCC mixtures for mass concrete structures.

Mix	Slag Cement * (kg/m^3)	Fly Ash (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	Acrylic superplasticizer (% by powder)**	UFACS (by % powder) **
FA/0	307	128	965	824	178	0.96	0
FA/1	300	125	944	806	174	1.14	1
FA/2	304	127	964	822	176	1.31	2

* portland cement ≈ 120 kg/m^3
** powder= slag cement + fly ash

Table 5 Properties of SCC's for mass concrete structures

Mix	UFACS (%)	SLUMP FLOW				Bleeding capacity (% by vol. of concrete)	Aspect** (Visual Rating)
		After mixing		After 30 min			
		mm	sec*	mm	sec*		
FA/0	0	790	30	750	35	0.11	Slight segregation
FA/1	1	790	29	660	40	0.09	Fair
FA/2	2	800	30	740	36	0.07	Good

*time needed to research the final slump flow
**fair=cohesive, good=very cohesive

Table 6 – Composition and performance of a lightweight SCC with a density of 1750 kg/m^3 and a slump flow of 650 mm, and without segregation at all (B in Fig. 12)

Ingredients	CEM II/A-L 42.5R *	Fly Ash	Sand (0-4 mm)	Expanded Clay (0-15 mm)	Water	Acrylic Superplasticizer	VMA
Composition kg/m^3	400	100	480	570	192	6	0.25
Mechanical performances at 28 day - f_c=35MPa; - f_f=5 MPa; - E=19000 MPa							
- Drying shrinkage at 90 days (R.H. 50%): 675 μm/m - Creep at 90 days (with a load of 12 MPa at 28 days): 1000 μm/m - CO_2 penetration (30% by vol. of the air) at 90 days: 5.5 mm - Cl- (3.5% NaCl aqueous solution) penetration at 90 days: 8 mm							

* portland cement = 85%

Table 7 – Composition of shrinkage-compensating SCC (A) and "ordinary" SCC (B)

Mix	A	B
Cement CEM II A/L 42.5R (kg/m^3)*	350	347
Limestone filler (< 100 μm) (kg/m^3)	150	183
Gravel 4-16 mm (kg/m^3)	877	871
Sand 04-10 mm (kg/m^3)	908	903
Water (kg/m^3)	167	166
Acrilic Superplasticizer (kg/m^3)	6.3	6.3
Expansive Agent (kg/m^3)	35	-
SRA (kg/m^3)	4	-

* portland cement = 85%

Figure 1 – Skin effect marble-like of SCC with respect to a traditional concrete S5 at a superfluid consistency (slump = 225 mm), both placed without compaction.