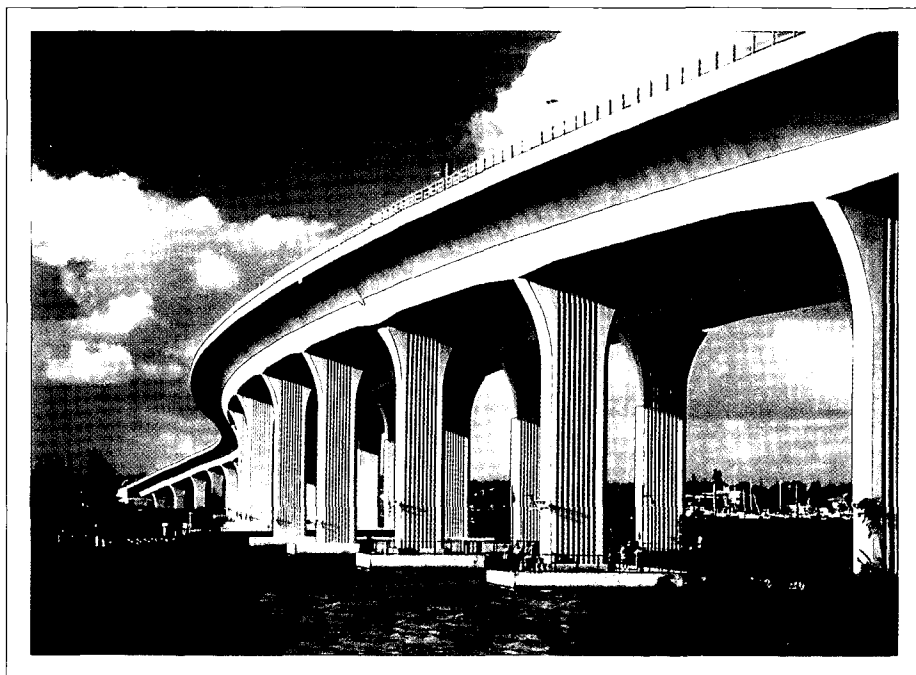

2004

SEVENTH CANMET/ACI SEPTIÈME CANMET/ACI

INTERNATIONAL • CONFERENCE • INTERNATIONALE



**RECENT
ADVANCES IN
CONCRETE
TECHNOLOGY**

**PROGRÈS RÉCENTS
DANS LE DOMAINE
DE LA TECHNOLOGIE
DU BÉTON**

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Seventh CANMET/ACI International Conference on Recent Advances in Concrete Technology

Editor

V. Mohan Malhotra



First printing, May 2004

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PREFACE

The Canada Centre for Mineral and Energy Technology (CANMET) of Natural Resources Canada, Ottawa, has played a significant role in Canada for over 40 years in the broad area of concrete technology. In recent years, CANMET has become increasingly involved in research and development dealing with supplementary cementing materials, high-performance normal-weight and lightweight concretes, and alkali-aggregate reactions. As a part of CANMET's technology transfer program, an international symposium on Advances in Concrete Technology was sponsored jointly with the American Concrete Institute and other organizations, and held in Athens in May 1992. In June 1995, CANMET, in association with the American Concrete Institute and other organizations in Canada and the United States, sponsored the Second CANMET/ACI International Symposium on Advances in Concrete Technology in Las Vegas, U.S.A. For the Athens symposium, CANMET publication "Advances in Concrete Technology" constituted the proceedings of the symposium; for the Las Vegas symposium, the proceedings were published by the American Concrete Institute as ACI SP-154.

In August 1997, CANMET, in association with the American Concrete Institute and other organizations in Canada and New Zealand, sponsored the Third CANMET/ACI International Symposium on Advances in Concrete Technology in Auckland, New Zealand. The symposium brought together representatives from industry, universities, and government agencies to present information on the latest advances and to explore new areas of needed research and development. Thirty-three refereed papers from 15 countries were presented. In addition to the refereed papers, more than 20 other papers were presented and distributed at the symposium. The proceedings were published as ACI SP-171.

In June 1998, CANMET, in association with the American Concrete Institute, Japan Concrete Institute, and several other organizations in Canada and Japan, sponsored the Fourth CANMET/ACI International Conference on Recent Advances in Concrete Technology in Tokushima, Japan. More than 80 papers from 20 countries were received and reviewed in accordance with the publication policies of the American Concrete Institute. Sixty-one refereed papers were accepted for presentation at the conference and for publication as ACI SP-179. In addition to the refereed papers, more than 30 other papers were presented and distributed at the symposium.

In July-August 2001, CANMET, in association with the American Concrete Institute and several organizations in Singapore, sponsored the Fifth CANMET/ACI International Conference on Recent Advances in Concrete Technology in Singapore. More than 100 papers from more than 25 countries were received and reviewed in accordance with the policies of the American Concrete Institute. Forty-six refereed papers were accepted for presentation at the conference and were published as ACI SP-200. In addition to the refereed papers more than 25 other papers were presented and distributed at the conference.

In June 2003, CANMET, in association with the American Concrete Institute and several organizations in Romania, sponsored the Sixth CANMET/ACI International Conference on Recent Advances in Concrete Technology in Bucharest, Romania. More than 40 papers presented at the conference were distributed "as received" and no formal ACI special publication was published.

In May 2004, CANMET, in association with the American Concrete Institute and several other organizations in the United States, sponsored the Seventh CANMET/ACI International Conference on Recent Advances in Concrete Technology in Las Vegas, U.S.A. Seventeen refereed papers from more than 10 countries were presented and distributed at the conference. The proceedings consisting of refereed papers were published as ACI SP-222. In addition to the refereed papers, 20 other papers were presented and distributed at the conference.

Thanks are extended to the members of the CANMET/ACI paper review panel which met in Sorrento, Italy in Nov. 2003 to review the papers. Without their prompt review and constructive comments, it would not have been possible to bring out the ACI special publication for distribution at the conference in Las Vegas. The cooperation of the authors in accepting reviewers' suggestions, and in revising their manuscripts accordingly is greatly appreciated. Particular thanks are extended to H.S. Wilson, Consultant, Ottawa, and G.D. Brearley and M. Venturino, both of CANMET, for their help in the processing of the draft manuscripts.

The help of Messrs. A. Bilodeau (Chair), B. Fournier, and R. Chevrier (Members) of the Audio-Visual Review Panel is greatly appreciated.

R. Hartford, Editor, ACI Special Publications, and her staff deserve very special mention for their assistance in getting this publication ready on time for distribution at the conference.

V. M. Malhotra, P.Eng.

Editor

Chair, CANMET/ACI Seventh International Conference on Recent Advances in Concrete Technology

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Recent Developments of Special Self-Compacting Concretes

by M. Collepardi, A. Borsoi, S. Collepardi, and R. Trolì

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/m³, 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 $\mu\text{m/m}$) 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**: $\geq 600 \text{ mm}$ after 1 hr at 30°C (ready-mixed concrete placed in summer time);
- 2) **cube compressive characteristic strength**: $\geq 35 \text{ MPa}$;
- 3) **impermeability** in terms of water penetration according to the ISO DIS 7031 test: $\leq 20 \text{ mm}$ (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.

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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 $\mu\text{m/m}$ 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 polyacrylic 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 cracking 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 $\mu\text{m}/\text{m}$ 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 Hadid 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 construction 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 specimens (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 unfavorable but realistic conditions of curing, the expansion at 16 hours was relatively high (520 $\mu\text{m}/\text{m}$) and still good at 2

months (280 $\mu\text{m/m}$) with R.H. of 60%. In the “ordinary” SCC (mix B), without expansive agent and SRA, the shrinkage at 2 months was about 400 $\mu\text{m/m}$. 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 successful 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 niche 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 elastic 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 $\approx 120 \text{ kg/m}^3$

** 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							
- $f_c=35 \text{ MPa}$; - $f_r=5 \text{ MPa}$; - $E=19000 \text{ MPa}$							
- Drying shrinkage at 90 days (R.H. 50%): $675 \mu\text{m/m}$ - Creep at 90 days (with a load of 12 MPa at 28 days): $1000 \mu\text{m/m}$ - 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
Acrylic Superplasticizer (kg/m ³)	6.3	6.3
Expansive Agent (kg/m ³)	35	-
SRA (kg/m ³)	4	-

* portland cement = 85%

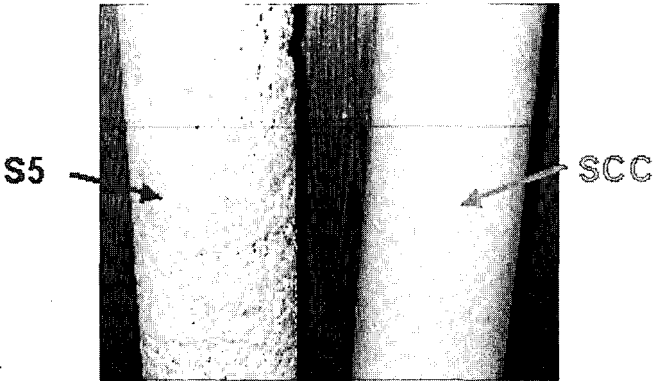


Figure 1 – Skin effect marble-like of SCC with respect to a traditional concrete S5 at a superfluid consistency (slump = 225 mm), both placed without compaction.

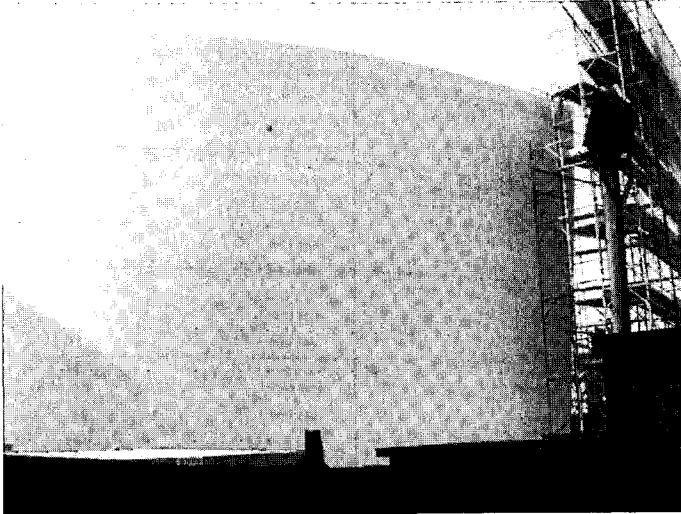
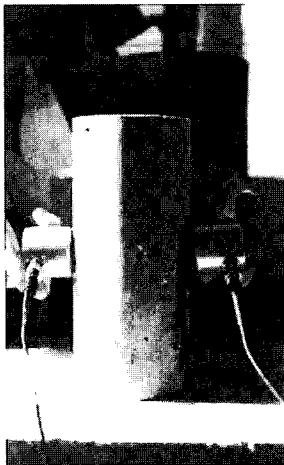


Figure 2 – View of a white wall of the S. Peter Apostle Church in Pescara (Italy).



$D = 2383 \text{ kg/m}^3$
 $E_d = 43619 \text{ MPa}$

$D = 2382 \text{ kg/m}^3$
 $E_d = 43755 \text{ MPa}$

$D = 2385 \text{ kg/m}^3$
 $E_d = 44570 \text{ MPa}$

$D = 2381 \text{ kg/m}^3$
 $E_d = 43887 \text{ MPa}$

Figure 3 – Density (D) and dynamic elastic modulus (E_d) measured on cored concrete of high-strength SCC.

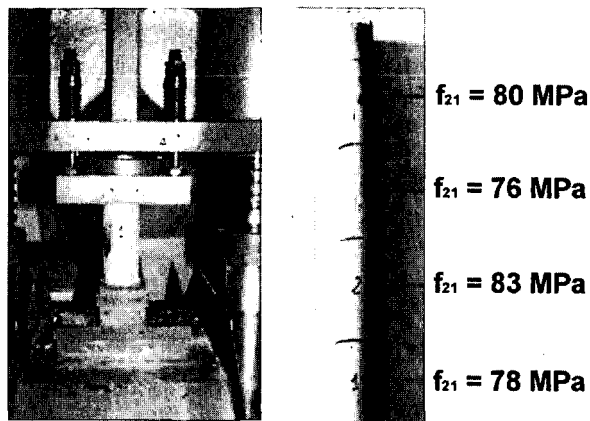


Figure 4 – Cylinder compressive strength measured (f_{21}) at 21 days from cored concrete 1 m long (on the right) of high-strength SCC.

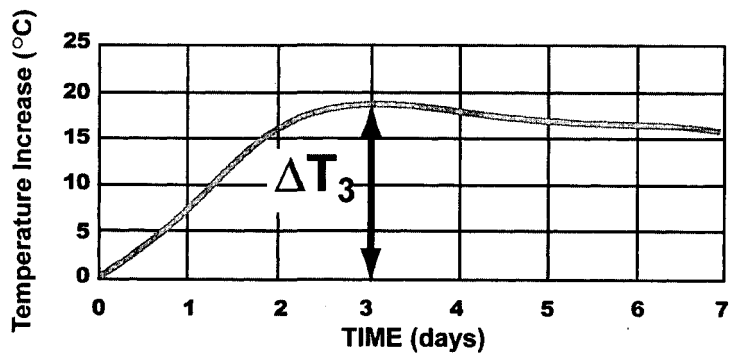


Figure 5 – Temperature increase in the nucleus of SCC with FA/2 (Table 4) in a quasi-adiabatic condition [5].

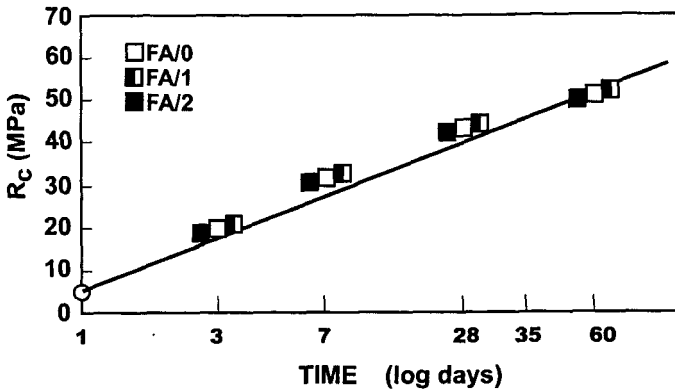


Figure 6 – cube compressive strength (R_c) as a function of time of SCC with fly ash and UFACS (Table 4).

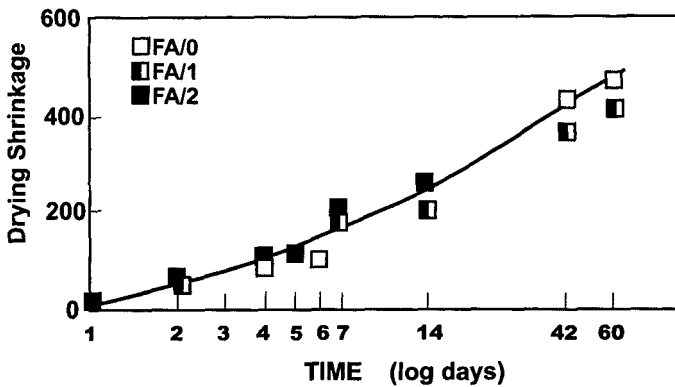


Figure 7 – Drying shrinkage of concrete mixture as a function of time for the SCCs with fly ash and UFACS (Table 4).

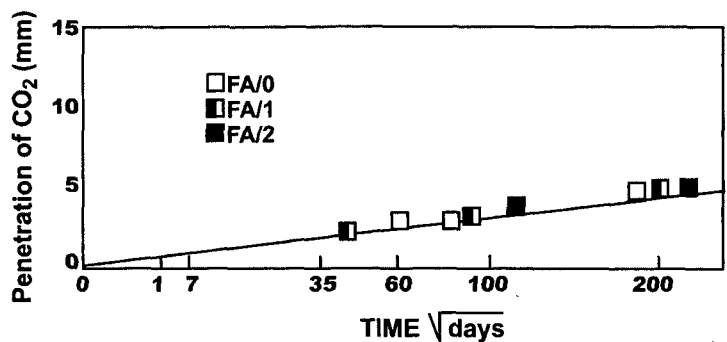


Figure 8 – Penetration of CO₂ as a function of time ($\sqrt{t}$) in SCCs with fly ash and UFACS (Table 4).

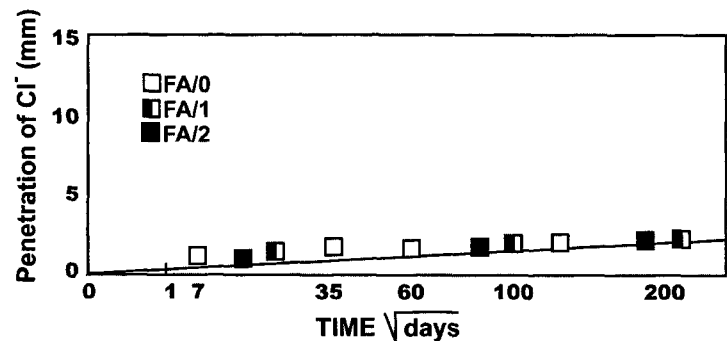
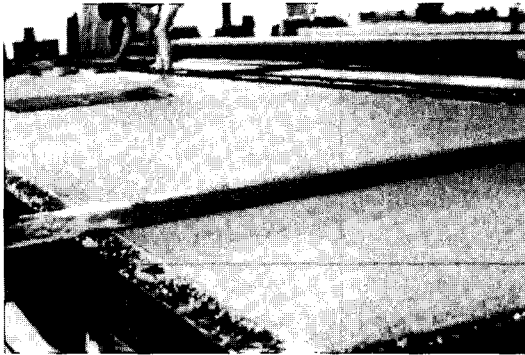


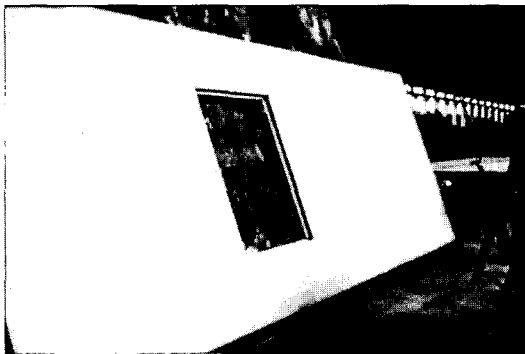
Figure 9 – Penetration of Cl⁻ ions as a function of time ($\sqrt{t}$) in SCCs with fly ash and UFACS (Table 4).



(A)



(B)



(C)

**Figure 10 – Precast lightweight concrete: casting of SCC (A);
Screeding without vibration (B); demolding of the hardened
lightweight panel (C).**

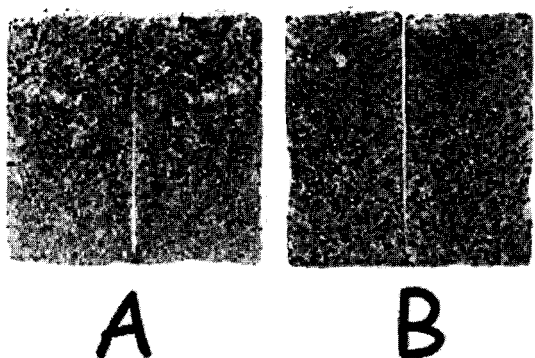


Figure 11 – Flowing concrete with segregation of the lightweight coarse aggregate on the top (A) in comparison with the corresponding lightweight SCC without segregation.

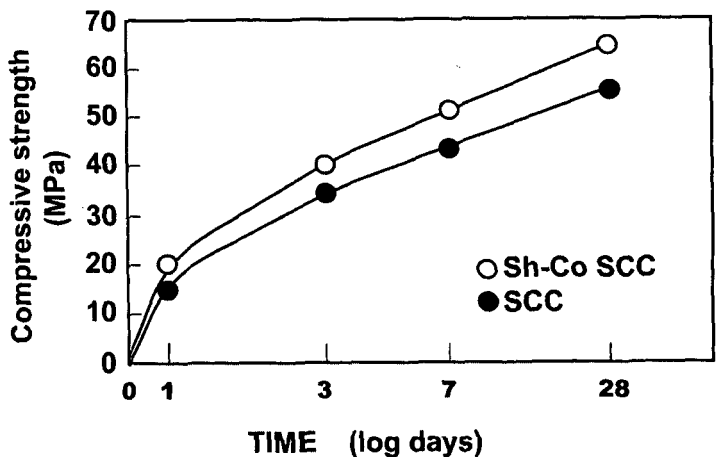


Figure 12 –Strength development of shrinkage-compensating self-compacting concrete (Sh-Co SCC) and “ordinary” self-compacting concrete (SCC).

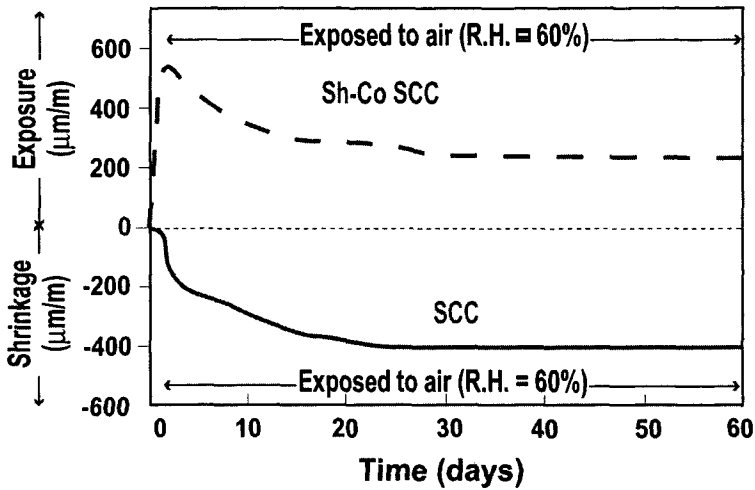


Figure 13 – Length change of shrinkage-compensating (Sh-Co) SCC and ordinary SCC (mix A and B, respectively in Table 7) after an early curing (16 hr) by protection of a plastic film.

Influence of Internal Friction and Cohesion on the Variations of Formwork Pressure of Self-Consolidating Concrete

by J. Assaad and K. H. Khayat

Synopsis:

A comprehensive research program was undertaken to determine the influence of coarse aggregate concentration, binder type and content, and the use of set-modifying admixtures on lateral pressure exerted by self-consolidating concrete (SCC). Experimental columns measuring 200 mm in diameter and either 2100 or 2800 mm in height were used to determine the distribution of lateral pressure during the plastic stage of cement hydration. The effect of thixotropy of the concrete on pressure variations was investigated.

Test results show that lateral pressure exerted by SCC is significantly affected by the development of shear strength properties of the plastic concrete, namely internal friction and cohesion. Mixtures incorporating greater coarse aggregate volumes and/or lower binder contents were found to exhibit higher degree of internal friction. This can reduce the mobility of the concrete and result in lower initial pressure. However, given that internal friction is an inherent property of the material which remains constant with time, the rate of drop in pressure was shown to depend mainly on the increase in cohesion. Therefore, mixtures containing higher binder contents and/or a set-accelerating admixture can exhibit sharper rate of pressure drop with time.

Concrete with higher degree of thixotropy was found to develop lower initial lateral pressure and higher rate of pressure drop with time. This is attributed to the stiffening effect which enables the material to re-gain its shear strength when left at rest without any shearing action.

Keywords: aggregate; binder; cohesion; formwork lateral pressure; internal friction; self-consolidating concrete; set-modifying admixture; thixotropy

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INTRODUCTION

Self-consolidating concrete (SCC) is a new class of high-performance concrete that flows readily under its own weight and achieves good consolidation without any mechanical vibration. Given its high consistency, formwork systems prepared to receive SCC are often designed prudently by considering that the concrete exerts full hydrostatic pressure until the setting. This increases the construction costs and reduces the allowable rate of rise of the concrete in the formwork.

Numerous laboratory and field tests were carried out to evaluate formwork pressure of concrete with normal consistency. For example, Rodin (1) reported that formwork pressure depends mainly on the rate of casting, method of consolidation (hand consolidation or mechanical vibration), concrete temperature, setting time, mixture proportioning, consistency, as well as size and shape of the formwork. When external vibrators are used, the author concluded that the formwork should be designed for full hydrostatic pressure of a fluid having the same unit weight as the concrete. For design purposes, ACI Committee 347 proposed that lateral pressure should be hydrostatic from the upper free surface down to some limiting value beyond which it remains constant until the bottom of the formwork (2).

To evaluate the effect of cement content, Roby (3) investigated a series of rich, normal, and lean concrete mixtures made with different cement:sand:coarse aggregate ratios of 1:1.25:2.25, 1:2:3.5, and 1:2.5:5, respectively. An ordinary portland cement was used and the slump values of the mixtures varied between 50 and 150 mm. The author reported that the cement content has a significant effect on lateral pressure. The rich mixtures developed 40% greater pressure than the normal mixtures, which in their turn, developed 15% greater pressure than the lean ones. This was indirectly related to the lower volume of coarse aggregate in the lean mixtures (3). A greater volume of aggregate particles can lead to higher degree of internal friction which reduces the mobility of the concrete, and thereby the transformation of vertical load in lateral pressure.

Limited information exists regarding the effect of portland cement replacement by supplementary cementitious materials (SCM) on the

development of lateral pressure. Gardner (4) investigated the influence of cement replacement by fly ash for mixtures with slump values ranging between 65 and 115 mm. The fly ash replacement varied between 0 and 50%. Concrete mixtures containing fly ash were found to develop higher lateral pressure than similar concrete prepared with only Type 10 cement. According to Gardner (4), the incorporation of fly ash increases the mobility of fresh concrete and reduces the rate of strength gain, thus resulting in higher lateral pressure.

Ore and Straughan (5) reported that cement hydration tends to limit the formwork pressure after the initial vibration used for concrete placement, but does not prevent an increase in pressure due to revibration after an elapsed time from casting. The effect of incorporating a set-retarding agent on cement hydration was found to have limited influence on initial formwork pressure.

Limited information exists on the factors affecting the initial maximum formwork pressure of SCC and its rate of drop with time. More recently, the CEBTP (6) carried out a large-scale field experiment on diaphragm wall elements measuring 12 m in height to determine the lateral pressure developed by SCC. The mixture was made with a water-to-cementitious materials ratio (W/CM) of 0.46 and a slump flow of 700 mm. The results showed that the pressure envelope is not linear. At the base of the formwork, the deviation from the hydrostatic distribution was found to be 30% and 35% in the case of SCC pumped from the bottom of the formwork and that cast using a bucket from the top, respectively.

This paper presents an overview on the effect of coarse aggregate volume, binder type and content, and the use of set-modifying admixtures on both initial pressure and rate of pressure drop developed by SCC with 650 ± 15 mm slump flow consistencies. The influence of thixotropy on pressure development is also investigated.

EXPERIMENTAL PROGRAM

Concrete Proportions

The effect of coarse aggregate concentration on lateral pressure variations was investigated by evaluating various SCC mixtures with different sand-to-total aggregate ratios (R), by volume (7). A commercially available ternary cement containing 6% silica fume and 22% Class F fly ash replacements was used at a fixed dosage of 450 kg/m^3 . The W/CM was held constant at 0.40, and the maximum aggregate size was set at 10 mm. Some typical mixtures are presented in Table 1.

A Type 10 Canadian cement along with three blended cements were used to determine the effect of binder type on pressure development (8). The blended cements included a binary cement with 8% silica fume replacement, a ternary

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cement such as the one specified earlier, and finally a quaternary cement with 6% silica fume, 26% Class F fly ash, and 18% blast furnace slag replacements, by mass of total binder. Further, a Type 30 Canadian cement was employed. The binder content ranged between 400 and 550 kg/m³ (Table 1). The W/CM and R values remained constant at 0.40 and 0.46, respectively, throughout this study (8).

A non-chloride-based set-accelerating admixture and a lignosulfonate-based set-retarding admixture were used to determine the effect of set-modifying admixture on pressure variations (9). These mixtures were prepared with 450 kg/m³ of ternary or binary cement. The W/CM was set at 0.42, and the R values varied from 0.44 to 0.50 (Table 1).

All of the investigated mixtures had initial slump flow consistencies of 650 ± 15 mm, concrete temperatures of 20 ± 2 °C, initial air contents of $6 \pm 2\%$, and unit concrete weights of 2200 ± 200 kg/m³.

Instrumented Formworks for Measuring Lateral Pressure

Instrumented PVC columns measuring 200 mm in diameter and either 2100 or 2800 mm in height were used to determine lateral pressure distributions. The tubes had a smooth inner face to minimize any friction. The lateral pressure was determined using five pressure sensors of 100 kPa capacity mounted at 50, 250, 450, 850, and 1550 mm from the bottom. The face of each sensor was set flush with the inside of the formwork. The sensors were properly calibrated using a free head of water prior to use.

Testing Program

The L-box flow characteristics and surface settlement of SCC mixtures were evaluated. The L-box test is an L-shaped apparatus with a gate separating the vertical and horizontal compartments (10). The vertical part of the box is filled with concrete and left at rest for one minute before opening the gate separating the two compartments. The ratio of the height of concrete remaining in the leading edge (h_2) to that remaining in the vertical section (h_1) was determined. In general, values greater than 0.80 were obtained, indicating good self-levelling characteristics.

The surface settlement was assessed by casting concrete in a PVC column measuring 200 mm in diameter and 800 mm in height (11). The settlement was monitored using a linear dial gauge fixed on top of a thin plate positioned and anchored at the concrete surface. Values lower than 0.5% were obtained, indicating that the mixtures are stable with minimum degree of bleeding or segregation.

The protocols adopted for evaluating the thixotropy of SCC are presented elsewhere (12). Four structural breakdown curves determined at rotational

speeds of 0.3, 0.5, 0.7, or 0.9 rps were determined for each mixture. Immediately after the vane drive mechanism is started, readings of the torque were noted as a function of time without any delay. The first reading is considered as the initial maximum torque value, and the mean of the five smallest measurements over the 25 sec duration at each rotational speed is taken as the equilibrium torque value. The time required to perform each of the structural breakdown tests at a given rotational speed was 7.5 min (in some cases 12.5 min), of which 5 min (or 10 min) when the concrete was at rest in the rheometer bowl and 2.5 min required for the testing and rehomologizing the concrete before subsequent measurements. In total, 30 min (or 60 min) were necessary to determine the four structural breakdown curves during the first time interval (T_1). In order to determine the variations of thixotropy with time and its influence on changes in lateral pressure, two additional series of measurements, referred to as T_2 and T_3 , were performed at time intervals of 60-90 (or 60-120) and 120-150 (or 120-180) min, respectively.

The general procedure of filling the experimental columns consisted of discharging continuously the SCC at a rate of rise of 10 m/hr without any vibration. Given that the PVC column had to be emptied prior to stiffening, the monitoring of lateral pressure distributions was stopped once the concrete had an approximate slump of 125 mm.

TEST RESULTS AND DISCUSSION

Variations in Lateral Pressure with Respect to Height and Elapsed Time

A typical example showing the drop in lateral pressure with time after placement is given in Fig. 1 for a mixture made with 550 kg/m³ of ternary cement and 0.40 W/C/M. The loss in slump flow consistency with time is also indicated. Right after casting, the lateral pressure exerted by the SCC corresponded to 94% of hydrostatic pressure. Three hours latter, the pressure envelope decreased to approximately 52% of the hydrostatic.

Effect of Shear Strength Properties on Lateral Pressure Development

The lateral pressure exerted by plastic concrete is highly affected by the development of shear strength properties which include (i) the frictional resistance and interlocking among solid particles and (ii) the bond among the particles due to cement hydration (13). The former component of shear strength is termed internal friction and requires strain to be mobilized, while the latter component is referred to as cohesion. Cohesion results from cement hydration, and therefore depends on the elapsed time after the initial contact of water with cement (13). The influence of each component is further discussed below.

Effect of Internal Friction--An example showing the variations of the ratio of maximum pressure measured using the 2800-mm high experimental column to

the hydrostatic pressure ($P(\text{maximum})/P(\text{hydrostatic})$) is plotted in Fig. 2 for mixtures made with various R values. The slump consistency measured at the end of lateral pressure monitoring is noted. Mixtures prepared with low concentrations of coarse aggregate (higher R values) are shown to develop higher initial relative pressure and lower rate of pressure drop with time. For example, the reduction in the R value from 1.0 to 0.50 and 0.30 resulted in lower initial relative pressures corresponding to 99%, 92%, and 77%, respectively. Given that the SCC mixtures are prepared with the same binder content of 450 kg/m^3 and W/CM of 0.40, such variations can predominantly be attributed to the various degrees of internal friction resulting from coarse aggregate (7). After placement, aggregate particles surrounded by the cement-mortar matrix tend to consolidate and settle down, hence achieving greater granular packing. When the mixture has relatively high R value corresponding to low aggregate concentration, aggregate particles can have greater freedom to translate and rotate within the matrix. In consequence, given that fresh concrete behaves in a dilatant fashion and expands when subjected to a given vertical load (14), it can be expected that the reduced degree of internal friction resulting from lower coarse aggregate concentration can increase the mobility of the fresh concrete. This can therefore increase the expanding response and result in higher lateral pressure.

Increased degree of internal friction within the freshly cast concrete can be achieved by the incorporation of higher volume of coarse aggregate as well as by substituting the Type 10 cement by SCM. The effect of binder type on the variations of $P(\text{maximum})/P(\text{hydrostatic})$ values for mixtures made with 450 kg/m^3 of binder is illustrated in Fig. 3. It is important to note that the coarse aggregate concentration was held constant at 0.46 throughout this study (8). The SCC made with only Type 10 cement developed the highest initial pressure of 98% of the hydrostatic value and the lowest rate of pressure drop with time. Mixtures made with quaternary, binary, or ternary cement yielded respectively lower initial pressures. The substitution of part of the Type 10 portland cement by an equal mass of silica fume, fly ash, or granulated blast furnace slag results in an increase in the solid volume of the powder materials. It is to be noted that the specific gravities of the Type 10 cement, silica fume, fly ash, and blast furnace slag are 3.14, 2.22, 2.53, and 2.88, respectively. Their surface areas are 325, 20250 (B.E.T.), 410, and 445 m^2/kg , respectively. This can increase the degree of flocculation and inter-particle links leading to higher level of particle interlock (8). In consequence, the use of blended cements can increase the degree of internal friction within the cement paste, thus resulting in lower development in lateral pressure.

Even though the replacement of portland cement by SCM can reduce the initial lateral pressure and increase the rate of pressure drop, such beneficial effect can decrease beyond certain limits of Type 10 cement replacements. This is the case of the mixture proportioned with 50% SCM compared to SCC made with binary or ternary cement containing 8% and 28% SCM, respectively. Higher contents of SCM was shown to increase the demand of high-range water-

reducing admixture (HRWRA), thus resulting in relatively lower loss in consistency with time (8). As can be seen in Fig. 3, after approximately 250 min from casting, slump values of 150 and 140 mm were measured for mixtures made with binary and ternary cement, respectively. This increased to 240 mm for the SCC prepared with quaternary cement. The material can then behave like a fluid for a longer period of time and result in higher lateral pressures.

The SCC prepared with Type 30 cement exhibited the lowest initial relative pressure of 78% and the highest rate of pressure drop (Fig. 3). This can be due to the increased surface area of the Type 30 cement (600 m²/kg) that increases significantly the degree of flocculation and number of inter-particle links (8). The high surface area, as well as the chemical composition of the cement, can lead to faster rate of hydration which increases the loss in slump flow and thereby the rate of pressure drop following casting.

Effect of Cohesion--The $P(\text{maximum})/P(\text{hydrostatic})$ values determined on the 2800-mm high column are plotted in Fig. 4 for four SCCs made with various contents of ternary cement. The R value and W/CM were set at 0.46 and 0.40, respectively. Mixtures prepared with higher binder contents developed greater initial pressure. This can be related to the relatively lower coarse aggregate volume that can reduce the degree of internal friction, thus increasing the mobility of the concrete and yielding greater initial pressure (7). However, unlike the effect of binder content on the initial pressure, the rate of pressure drop is enhanced with the increase in binder content. Alexandridis and Gardner (13) reported that internal friction is an inherent property of fresh concrete that remains constant with time and temperature changes. For longer elapsed periods after casting, it is the increase in cohesion that enables the plastic concrete to develop higher shear strength through the formation of a gel structure capable of carrying an increasing fraction of the vertical load (13). In consequence, mixtures made with higher binder contents can result in increased development of cohesion, thus leading to higher drop in lateral pressure. It is important to note that the HRWRA dosage can also indirectly affect the rate of reduction of lateral pressure. Mixtures prepared with lower binder contents necessitated higher HRWRA dosage that can enhance fluidity retention. This can therefore enable the material to behave like a fluid for longer elapsed times, thus reducing the rate of pressure drop.

The effect of using set-modifying admixture on variations in $P(\text{maximum})/P(\text{hydrostatic})$ values for SCC mixtures made with 450 kg/m³ of ternary cement, 0.42 W/CM, and R of 0.50 is plotted in Fig. 5. The rate of pressure drop is shown to be significantly increased by the incorporation of a set-accelerating admixture (9). As already mentioned, the increase in cohesion as a result of cement hydration allows the plastic concrete to develop higher shear strength at longer elapsed periods after casting. Knowing that the rate of hydration can be controlled by incorporating a set-modifying agent, the use of such admixtures can have direct influence on cohesion and thereafter on the drop in lateral pressure with time.

Relationship Between Thixotropy and Lateral Pressure

The relationship between the values of the breakdown area evaluated during the first time interval (T_1) of rheological measurements and the corresponding residual pressure, $P(\text{maximum})/P(\text{hydrostatic})$, determined right after filling the formwork is illustrated in Fig. 6. This figure also illustrates the relationship between the values of the breakdown area evaluated during the T_2 and T_3 time intervals and the $P(\text{maximum})/P(\text{hydrostatic})$ calculated at 100 and 200 min after casting, respectively. For the three correlations, the $P(\text{maximum})/P(\text{hydrostatic})$ ratio decreases for mixtures exhibiting a higher degree of thixotropy. Such decrease becomes more accentuated with time as indicated by the sharper slope obtained at 100 and 200 min after casting.

As already mentioned, lateral pressure exerted by fresh concrete depends largely on shear strength development. On the other hand, it is well established that thixotropy is a reversible phenomenon that takes place as soon as the material is left standing at rest (12). The onset of the structural build-up phase causes the structure to flocculate and increase its cohesiveness. For mixtures having greater degree of thixotropy, the increased kinetics of the build-up phase can cause a faster increase in the shear strength properties, thus precluding the development of higher lateral pressure.

CONCLUSIONS

Based on the above results, the following conclusions can be drawn:

1. Depending on the type of structure and major requirements of the field, one could recommend lower initial pressure or higher rate of pressure drop with time. The former could be of special interest to reduce the design loads, whereas the later could be important for scheduling issues of concrete placement.
2. The initial lateral pressure developed by SCC is significantly affected by the degree of internal friction. Mixtures prepared with greater coarse aggregate volumes and/or lower binder contents can exhibit higher internal friction and lower initial pressure. For a given content of coarse aggregate, the use of blended cement can also increase the degree of internal friction compared to mixtures made with Type 10 cement without any SCM.
3. The rate of drop in lateral pressure following casting is mainly dependent on the development of cohesion with time. Mixtures containing higher binder contents or a set-accelerating admixture can exhibit greater degree of cohesion, hence sharper rate of pressure drop.
4. The formwork pressure of SCC mixtures can be directly related to the magnitude of thixotropy. The greater the degree of thixotropy, the lower the

initial lateral pressure can be and the faster is the rate of pressure drop with time.

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Table 1 – Typical SCC mixtures used in this study

Effect of coarse aggregate concentration (7)
Ternary cement = 450 kg/m ³ and water = 180 kg/m ³ (W/CM = 0.40)
Coarse aggregate = 970 kg/m ³ and sand = 640 kg/m ³ (R = 0.40)
Ternary cement = 450 kg/m ³ and water = 180 kg/m ³ (W/CM = 0.40)
Coarse aggregate = 810 kg/m ³ and sand = 810 kg/m ³ (R = 0.50)
Effect of binder type and content (8)
Binary cement = 450 kg/m ³ and water = 180 kg/m ³ (W/CM = 0.40)
Coarse aggregate = 890 kg/m ³ and sand = 760 kg/m ³ (R = 0.46)
Ternary cement = 400 kg/m ³ and water = 160 kg/m ³ (W/CM = 0.40)
Coarse aggregate = 940 kg/m ³ and sand = 800 kg/m ³ (R = 0.46)
Ternary cement = 550 kg/m ³ and water = 220 kg/m ³ (W/CM = 0.40)
Coarse aggregate = 780 kg/m ³ and sand = 660 kg/m ³ (R = 0.46)
Effect of set-modifying admixture (9)
Ternary cement = 450 kg/m ³ and water = 189 kg/m ³ (W/CM = 0.42)
Coarse aggregate = 890 kg/m ³ and sand = 710 kg/m ³ (R = 0.44)
Set-retarder = 75 mL/100 kg of CM
Ternary cement = 450 kg/m ³ and water = 189 kg/m ³ (W/CM = 0.42)
Coarse aggregate = 890 kg/m ³ and sand = 710 kg/m ³ (R = 0.44)
Set-accelerator = 1000 mL/100 kg of CM

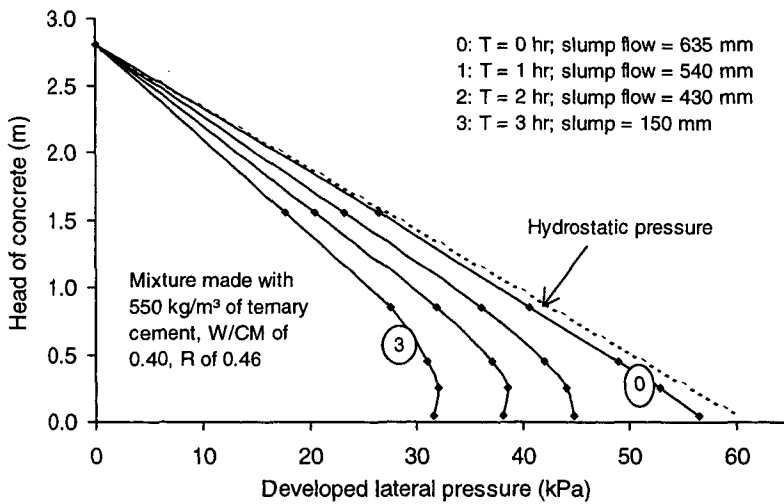


Fig. 1 – Typical example on lateral pressure developed on formwork (8)

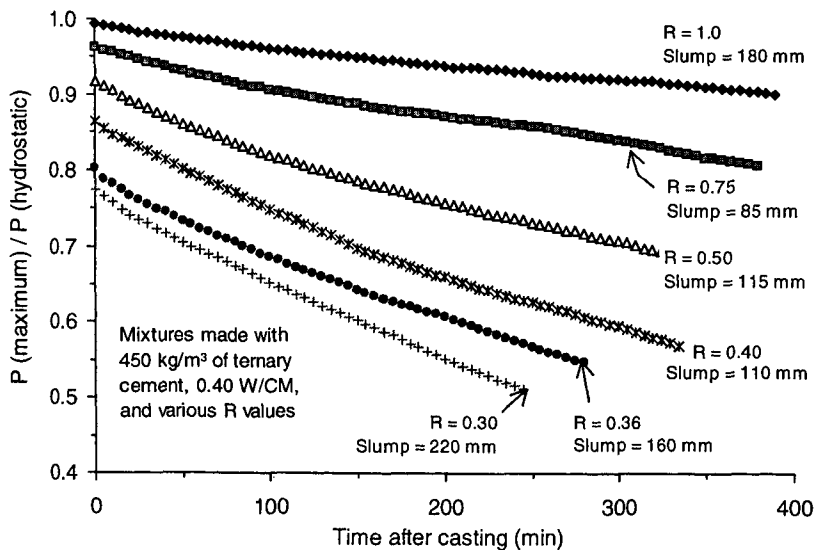


Fig. 2 – Effect of coarse aggregate concentration on lateral pressure variations (7)

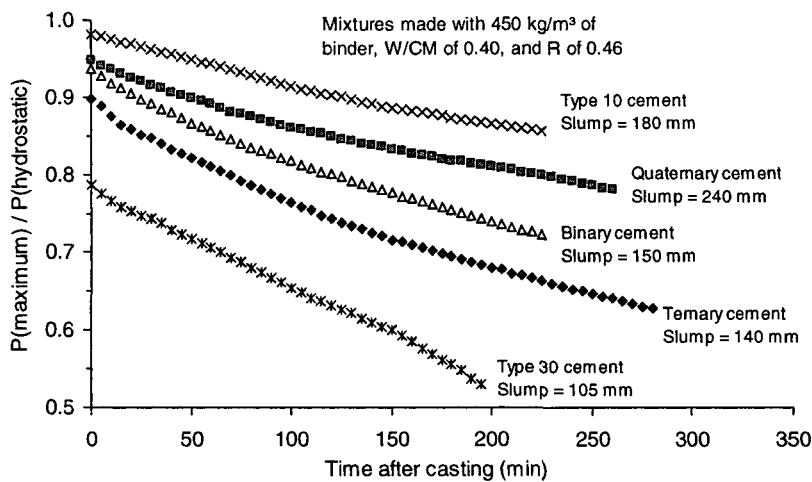


Fig. 3 – Effect of binder type on lateral pressure variations (8)

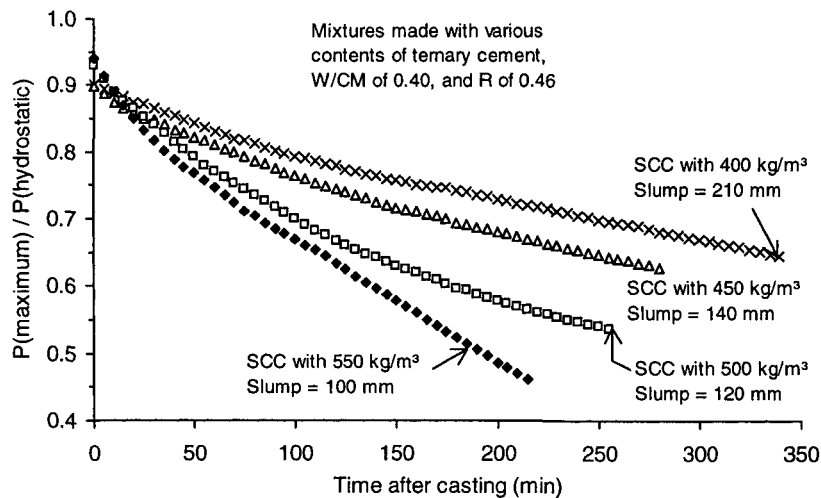


Fig. 4 – Effect of binder content on lateral pressure variations (8)

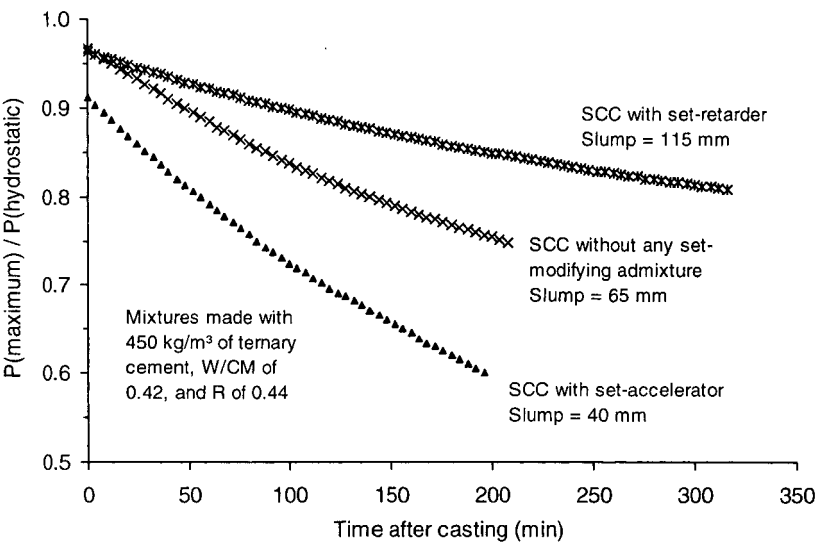


Fig. 5 – Effect of set-modifying admixture on lateral pressure variations (9)

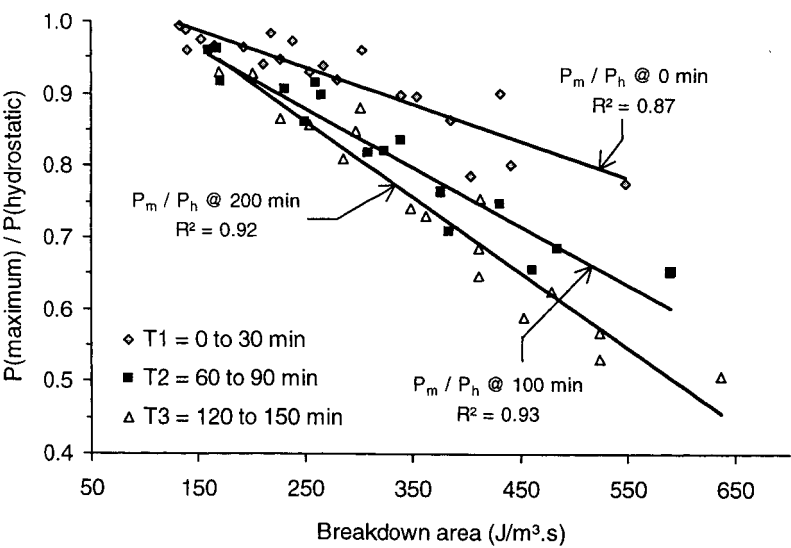


Fig. 6 – Relationship between thixotropy and lateral pressure

Self-Consolidating Concrete at Padgett-Thomas Barracks—The Citadel

by G. Amekuedi, R. Morrow, M. Nigels, and B. Guedel

Synopsis:

The Citadel in Charleston, South Carolina is steeped in tradition down to the buildings at the campus. Currently under construction is a replacement for the Padgett-Thomas Barracks, which was demolished in 2001. The new structure will be identical to the original barracks. It will showcase a classic fortress design that requires intricate forming and careful planning in the proportioning and placement of the concrete mixtures, in order to minimize/eliminate cost over-runs that have been experienced in previous construction projects at the campus.

Through a cooperative effort involving all parties in the construction of the new barracks, self-consolidating concrete (SCC) is now being used in lieu of the originally specified regular slump concrete. The use of SCC in the construction of the narrow 150mm (6 in.) thick walls have significantly increased placement/construction efficiency. It has also resulted in a greatly enhanced surface finish and sharper edges.

This paper chronicles the project from the pre-construction meetings and trial placements to the placement efficiencies that have been realized due to the use of SCC. About 7646 cubic meters (10,000 cubic yards) of SCC are going to be used for this project, which is scheduled for completion in 2004. Data on the properties of the SCC mixture from the field and companion laboratory studies are presented and discussed.

Keywords: compressive strength; flexural strength;
self-consolidating concrete; shrinkage

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INTRODUCTION

Established in 1822, The Citadel – The Military College of South Carolina, is an academy rich in history and tradition. Located on .712 km² (176 acres) on the banks of the Ashley River in Charleston, South Carolina, the picturesque campus has 24 major buildings, where students pursue studies in 19 different degree programs. Originally an all-male institution, women were admitted in 1996. The Citadel has long been respected as a premier educational institution and is consistently ranked among the best colleges in the region.

At The Citadel, “*students*” are called “*cadets*” and the word “*barracks*” is used in place of “*dormitories*”. Four barracks house roughly 1900 cadets who attend the college.

Constructed in 1922, the Padgett-Thomas Barracks was the oldest building and the largest student housing facility on campus. For eighty years, it served as perhaps the best-known symbol of the military college and a model for all other barracks on the campus. An imposing, brilliant white unreinforced masonry structure complete with turrets and a large clock tower overlooking the parade ground to the east, the center of the Padgett-Thomas Barracks was designed as a quadrangle onto which each room opened, and spiral stairways graced each of the four corners.

By 2000, the venerable structure -- with its narrow dorm rooms with high ceilings and hardwood floors -- was declared a safety hazard with collapsed ceilings, fallen concrete, backed-up sewer lines, and structural instability. In the early part of 2000, The Citadel made the decision to demolish and replace the Padgett-Thomas Barracks.

DESIGN

The Structure

Architect Davis & Floyd, Inc. of Charleston, SC, began work on the design of the new Padgett-Thomas Barracks in 2000. The goal – design a new structure, identical in appearance to the landmark building but incorporating modern conveniences and designed to withstand strong hurricanes. In addition, the design had to accommodate the fact that Charleston is on top of an ancient fault line. A devastating 7.3 magnitude earthquake struck the city in 1886 (1) and recent changes to the International Building Codes' seismic requirements meant doing things differently. They delivered a plan for a four-story building that is a work of art and a showcase of excellence. Almost an exact replica of the original, it features a classic fortress design with precast concrete battlements and reconstruction of the magnificent eight-story tower, complete with the original clock, wrought iron gates, and brass seal. The 10,400 m² (112,000 ft²) building was to be constructed entirely of cast-in-place concrete walls and slabs. And not simple walls and slabs – nearly half of the construction would be 150 mm (6 in.) thick, 3.7 m (12 ft) high walls that required intricate forming to achieve nearly 1000 block-outs for doorways, window casings, archways, and utilities. Because of the new seismic code requirements, the 150 mm (6 in.) thick bearing walls would have two mats of steel reinforcement, leaving no room for pump hoses or vibrators. The cadet room walls would be exposed, only receiving paint for their

finished surface, requiring better than normal surface finish with these difficult constraints.

Concrete Mixture

The specifications called for 27.6 MPa (4000 psi), air-entrained concrete with a maximum water-cement ratio (w/c) of 0.40 and a maximum slump of 100 mm (4 in.). With the addition of a high-range water reducer (HRWR), the maximum slump was extended to 180 mm (7 in.). The maximum size coarse aggregate allowed was 25 mm (1 in.) and fly ash was initially not permitted.

Locally available aggregates are conducive to proportioning concrete mixtures with good characteristics with respect to gradation, cleanliness, and water demand. A crushed granite meeting the ASTM C 33 requirements of a #67 material (Table 1) and natural sand having a fineness modulus of 2.57 (Table 1) were initially chosen. The cement to be used was an ASTM C 150 Type I/II portland cement.

It was known that a large portion of the project would be constructed in the typically very hot summer Charleston, S.C. is renowned for. Therefore, limits were placed on initial concrete temperature with a minimum of 10 °C (50 °F) and a maximum of 32 °C (90 °F). In addition, a time limit of 1-½ hours from batch until unloading was specified. The size of the walls required slow placement and careful consideration of these necessary precautions.

PRE-CONSTRUCTION PLANNING

The success of concrete placement on a project is often determined by the timeliness and thoroughness of good pre-construction meetings. In the case of the Padgett-Thomas Barracks, it was crucial. The construction team consisting of the owner's representative, the design engineer, the concrete supplier, the admixture supplier, and facilitated by a forward-thinking contractor's superintendent, was assembled in the Spring of 2002. It was noted that previous attempts to place the designed concrete in 150 mm (6-in.) thick walls with two layers of steel reinforcing mats had proved problematic. The inability to insert internal vibrators had left severe honeycombing and poor surface finish. The amount of rubbing required to achieve a smooth enough texture to accept a heavy paint had been devastating. Rubbing costs alone had approached \$32/m² (\$3/ft²). During the pre-construction meeting, the concept of higher slumps utilizing HRWR admixtures was introduced and this led to the introduction of self-

consolidating concrete (SCC). Data were provided showing SCC's engineering properties as comparable to or better than the properties of conventional concrete.(2) The team agreed that something out of the ordinary would be required to place the walls as designed in a cost effective manner. It was agreed to begin wall construction using a polycarboxylate HRWR at 180 mm (7-in.) slumps to ease placement. At the same time, the ready mix supplier would begin trials with SCC.

SELF-CONSOLIDATING CONCRETE TRIALS

Implementing SCC into this project took on the following seven-step process:

1. Consider Hardened Property Requirements
2. Evaluate Element Characteristics
3. Evaluate Raw Materials
4. Establish Fresh Performance Targets
5. Proportion Mixtures
6. Run Trial Batches
7. Production/Field Trials

Hardened Properties

The hardened properties had been established by the specification – 27.6 MPa (4000 psi), air-entrained concrete at 28 days with a w/c of 0.40 for corrosion protection of the reinforcement from the chloride-laden air. The structural element characteristics were the impetus for the SCC mixtures - narrow walls with tight reinforcement and the need to strip the walls in reasonable time with minimal surface defects.

Raw Materials

Evaluation of raw materials focused on aggregate selection and the amount of cementitious material that would be required to keep the mixture stable. In order to proportion SCC mixtures, it is important to utilize fine and coarse aggregates in such a way as to minimize the potential for segregation. This implies developing a blend of aggregates that best fits together, eliminating the amount of gaps in the gradations and thus the potential for settlement in high-flow mixtures. Practicality dictates the use of readily available aggregates but

evaluation of other options that would not normally be considered may be required. In the case of the Citadel, the concrete producer had available the #67 coarse stone previously submitted and a #789 stone that could fill some gaps (Table 1). The proportions of these aggregates and the fine aggregate, natural ASTM C 33 concrete sand, were plotted against a best-fit curve for both total % passing (Fig. 1) and total % retained (Fig. 2). This best-fit curve was also utilized to arrive at a sand-to-aggregate ratio (s/a) that would minimize the chance for segregation. This curve was developed from the modification of similar equations in an attempt to take into consideration the high fluidity of these mixtures. Early guidelines for SCC often stressed an elevated s/a as high as 0.50. Due to the concerns about durability and increased shrinkage, this ratio had been optimized to keep it as close as possible to that normally associated with normal slump concrete and thus resulted in an s/a value of 0.46.

Because of the slump flows that would be required to successfully place SCC in The Citadel walls, it was determined that a minimum of 445 kg/m^3 (750 lb/yd^3) of cementitious material should be employed to ensure there would be enough fines to avoid segregation. For economic reasons and to aid in lowering the heat of hydration, class F fly ash was utilized at 26% of the total cementitious material. Permission was obtained from the structural engineer for this deviation from the specifications and the concrete producer supplied past compressive strength performance data with similar mixtures for review.

In order to achieve the fluidity required, a new generation polycarboxylate HRWR was utilized in conjunction with an ASTM C 494 Type A water reducer. To provide stability at high slump flows, and to maintain the required properties in the hardened state, a viscosity-modifying admixture (VMA) was utilized.

Fresh Performance Targets

Because of the high fluidity of SCC, additional measurements must be considered to measure properties with respect to fluidity and stability. The slump flow test measures fluidity. It is used in conjunction with the T_{50} test, which measures how much time is required for a mixture to achieve a slump flow of 50 cm (20 in). T_{50} is a simple measurement of viscosity. The U-box measures the ability of a mixture to flow from a 680 mm (26.8 in.) column through reinforcement and into an identical column. The reinforcement varies depending on the type of structure in which the mixture will be placed and is categorized by rank. A rising height of 300 mm (12 in.) is considered passing. The Visual Stability Index (VSI) for the categorization of mixtures with respect to stability was applied on all slump flow tests (3).

Using a chart (Fig. 3), developed by Constantiner and Daczko (4), that evaluates flow properties with respect to element characteristics, a slump flow of at least

660 mm (26 in.) was required to handle the form intricacy, finish importance, form length/depth, and wall thickness. The same matrix also suggested a U-box rank of 1, meaning a high level of passability. The mixtures performing best had T_{50} times less than 2 seconds. This meant that the viscosity was low enough to transport the mixture well and not trap air at the finished surface, but high enough to minimize segregation and help with aggregate transport around the steel reinforcement.

Trial Mixtures

The ready mix supplier and admixture representatives, Daczko et al., began work using the parameters developed by the specifications and above criteria. Trials were conducted with small batches produced in a modern central-mixed concrete plant instead of a trial mixer. Initially, only the #67 coarse aggregate was utilized as it was thought the gradation was adequate. A small 1.5 m^3 (2 yd^3) slab was placed at the plant. Slump flow attained 510 mm (20 in.), and T_{50} time was 2.5 s. The VSI was observed to be 2.5, indicating minor aggregate piling in the center of the spread patty. Additional full loads of 6 to 7.6 m^3 (8 to 10 yd^3) were evaluated in highway barrier forms with increased slump flows. This also allowed for a placement similar to the walls on the project that required transport through a narrow section without segregation and a good surface finish upon stripping. As slump flows were increased to 660 mm (26 in.), it became apparent that the #67 coarse aggregate alone was inadequate – resulting in segregation and poor surface finish with some voids. A #789 stone was added at 35% of the total coarse aggregate amount, a value obtained from the blending program mentioned previously. Also, a VMA was added to aid with stability at the higher slump flows. Additional trials were completed using the barriers and all criteria improved to acceptable levels. The engineering team from the project was invited to observe the mixture being placed at the plant and agreed to allow a test placement on the project.

Field Trials

A critical step, the field trial at the project, was conducted on the first stage of an elevator pit wall. Conditions were quite similar to the walls to be placed using SCC and accessibility was such that all could easily observe the placement both during the pour and after stripping. Although slump flow was below the desired 660 mm (26 in.), the placement was a success and the surface finish was greatly improved over normal slump, vibrated concrete. Next, an actual wall was placed. Again, conservative slump flows of 510 to 560 mm (20 to 22 in.) were used. The concrete was placed by boom pump and because of the steel

reinforcement spacing; the flexible hose end could not be inserted into the form. Concrete was allowed to fall 3.7 m (12 ft), and although segregation was not observed, aggregate trapped between the steel and the form and was able to build up such that after stripping, there were “rock pockets” in several small areas. The remainder of the non-vibrated concrete surface finish was excellent.

A meeting among all parties to review the field trial accomplished several enhancements that greatly contributed to the project’s success. In order to allow insertion of the pump hose, the horizontal extra piece of steel from an incomplete portion of the mat was removed at the end of one of the walls. This allowed the pump to be inserted to the bottom of the wall like a tremmie during placement, allowing the SCC to flow to the other end, turn and go until a bulkhead. This eliminated the “rock pockets”. In addition, results from U-Box testing confirmed the need for highly fluid 610 to 710 mm (24 to 28 in.) slump flow SCC.

PRODUCTION

After modifications were made, the SCC mixture performed well. All parties were so pleased that attention focused on improving the process - not only taking advantage of time and energy savings, but looking for newfound advantages that had not been expected.

Contractor

The contractor began to realize advantages with SCC immediately. Placement times required to place 15 to 23 m³ (20-30 yd³) had been reduced from 2 hours to 1 hour. Crew size was reduced from six men to two men on the wall. No vibration was used; however, a vibrator was kept ready in case of delays or unforeseen problems. Perhaps the greatest advantage was afforded by the extremely smooth finish and clean sharp edges (Figs. 3 and 4) made possible by a mix that was truly self-consolidating. Rubbing costs were reduced by a factor of ten. Because of the relatively high cementitious factor, stripping strengths as well as 28-day strengths were well within the requirements and in most cases greatly exceeded specification (Table 2). Form building required special attention to prevent leakage and blowouts. Steel forms were used and had no problem accommodating the pressure head. At one point, unavoidable leakage into a utility space formed by the intersection of two walls created a need to reduce slump flow. The mix was adjusted to produce a 560 mm (22 in.) slump flow, which solved the problem. U-Box testing confirmed the mixture did not impede the flow required to fill the walls uniformly and without vibration. After the first level of walls this leakage was not a problem and the mix was adjusted

back to a 660-mm (26-in.) slump flow. Pour sizes were increased to as large as 54 m^3 (70 yd^3) as the time required for placement was reduced.

Ready-Mixed Concrete Producer

The concrete producer undoubtedly spent more time and effort developing and insuring quality with the SCC mixture. Attention to aggregate moisture condition becomes critical in producing SCC mixes. Aggregate storage silos and moisture probes in the weigh hoppers that were interfaced with the batch computer aided in this process. Typically, the concrete was batched with all ingredients except approximately 10% of the HRWR. Slump flows of 510 to 610 mm (20 to 24 in.) were produced to allow for larger load size 6 m^3 (8 yd^3) without spillage in transit. At the project site, slump flow and T_{50} times were tested on each truckload and adjusted by quality control personnel to the final desired level – ideally 630 to 710 mm (25 to 28 in.). The U-box was also used on the first few placements to ensure the mix would pass through the reinforcement as designed. Shortened pour times provided greater truck mixer delivery efficiency and less concern about time limit constraints and temperature rise.

Results

As of this writing, over 3440 of approximately 3670 m^3 (4500 of 4800 yd^3) have been placed in walls using SCC. None of the SCC concrete was vibrated. The surface finish, formed edge sharpness, and general appearance of the concrete is reported by all parties to be excellent. Statistical analysis of the compressive strength performance shows the average 28-day strength to be 38.1 MPa (5530 psi) with a standard deviation of 4.65 MPa (674 psi) for 110 tests. These results as reported by the contractor, concrete producer and laboratory, are superior to projects utilizing normal slump 27.6 MPa (4000 psi) concrete. The project is nearing completion ahead of schedule.

LABORATORY ANALYSIS

Because of the great success realized with the SCC mixture on this project, the concrete producer and admixture supplier agreed to perform more in-depth analysis of the properties of the mixture in the admixture supplier's headquarters laboratory. The goal of the project was to record more comprehensive data in both the fresh and hardened states and to identify the properties that made this

mixture perform so well. Development of data to facilitate the use of the product on future projects was also considered.

Procedures

All mixture constituents were transported from the concrete supplier's inventories to the laboratory in sealed steel drums. 0.057 cubic meter (two cubic foot) batches of the mixture utilized at The Citadel were prepared and plastic properties tests performed included slump flow, T_{50} time, U-Box rising height, bleed %, column segregation, and initial and final set. Yield stress and viscosity measurements were recorded by an IBB rheometer. Results are summarized in Table 2.

The hardened tests included compressive and flexural strength at 1, 7, and 28 days, and rapid-chloride permeability at 28 days. An additional laboratory mixture was prepared to measure shrinkage at 4, 7, 14, and 28 days after 7 days moist curing (Table 2).

The original mixture was also modified in the laboratory to observe changes with respect to water-cementitious materials ratio (w/cm) and HRWR dosage.

CONCLUSIONS

It is likely that self-consolidating concrete technology will be adopted for use in concrete structures similar to the Padgett-Thomas barracks as well as many other applications. Based on the success observed on this project, the advantages to be gained by contractors will undoubtedly be utilized in the competitive bid process – thus driving the technology and the impetus to improve it forward.

This example upholds the process of defining and communicating the challenges facing a concrete project before construction begins. It also provides a successful model for the presentation of new technology and the importance of data collection to further that technology. The procedure used to arrive at SCC mixture proportions that are appropriate for the project was successful.

The data presented from the analysis of the Citadel SCC mixture is unique in that laboratory data have been developed on a mixture that is known to be successful on a current project. The new test procedures developed to evaluate SCC mixtures were helpful in the comparison of different mixtures and seem to provide some interesting correlation between slump flow, w/cm and viscosity. Strength analysis seems to indicate that the use of similar SCC mixtures may as a