Available online at www.sciencedirect.com

SCIENCE DIRECT®

Cement & Concrete Composites 28 (2006) 197–208

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Self-compacting concrete: An analysis of 11 years of case studies

P.L. Domone *

Department of Civil and Environmental Engineering, University College London, London, UK

Received 10 May 2005; accepted 11 October 2005
Available online 1 December 2005

Abstract

Sixty eight case studies of applications of self-compacting concrete (SCC) have been analysed. These were published from 1993 to 2003, the period of increasingly widespread use of SCC in many countries.

They were selected for analysis on the basis of including details of concrete formulations and properties. The ranges of properties, component materials and mix proportions show the diverse nature of SCC, and confirm that it should be considered as a family of mixes suitable for a wide range of applications with widely varying requirements.

The outcome of the analysis of the above factors is given in statistical terms—ranges, frequencies, cumulative distributions, medians and deciles. This will be of value to those new to SCC, current users and researchers.

Keywords: Self-compacting concrete; Case studies; Properties; Components; Mix proportions

1. Introduction

A distinctive feature of the short history of self-compacting concrete has been a wide range of applications which have closely followed research and development studies. This short time lag is extremely unusual in the construction industry, given the complexity of its organisation [1].

It is clear from the proliferation of publications both in journals and in major international conferences[1] in the past decade that the volume of research in this exciting new technology has been steadily increasing and has been spreading throughout the world. Publications on research have been complemented by a substantial number of papers describing applications, i.e., case studies. Much of the content of these is concerned with the reasons for using SCC in a particular application, its advantages and disadvantages, the impact on the cost, timescales and efficiency of the construction programme and the benefits to working conditions, the health of construction workers and the local and wider environment. These issues, although important and interesting, are specific to each application and local conditions and do not lend themselves to rigorous quantitative comparisons; some general summaries have been published, e.g., [2,3].

Many of the case studies also include detailed information on the choice of component materials, the mixture proportions and the resulting concrete properties. As Skarendahl [1] has pointed out, direct comparison of the data on individual mixes should only be carried out with caution since their components and proportions will depend on local mix design parameters, the production processes and the application requirements. However there are now a sufficient number of such case studies for a systematic evaluation of the spectrum of mix parameters and properties in statistical terms to be both valid and useful. In particular, this will

- give potential users and formulators an idea of what can be expected with SCC;

* Tel.: +44 20 7679 7299; fax: +44 20 7380 0986.
E-mail address: p.domone@ucl.ac.uk

[1] Kochi 1998; Stockholm 1999; Tokyo 2001; Chicago 2002; Reykavik 2003 (papers from all of these conferences are cited in this paper).

0958-9465/$ - see front matter
doi:10.1016/j.cemconcomp.2005.10.003

- give practitioners a context in which to place and evaluate their own experiences;
- assist researchers who wish to inform their research by production information.

This systematic evaluation is the aim of this paper.

Publication of the case studies depended on the willingness of the authors to make detailed information available. They do not therefore constitute a comprehensive list of all applications, but SCC is sufficiently novel for these to be considered representative of all types of applications in a wide range of countries. The expanding use of SCC means that this claim will be less valid as time passes; this is therefore an opportune time for this analysis.

2. Range and type of case studies

The case studies for analysis were selected on the basis of the concrete having been produced on a production scale of at least a few cubic metres. Sixty eight such studies with sufficient of the detailed information referred to above have been reported in 43 papers [4–46]. Most (75%) were for commercial projects, the remainder were for demonstration or large scale testing purposes. Laboratory produced mixes were not considered.

Table 1 lists the year of publication (normally after completion of the project), the country of use, the type of application, the volume of concrete placed, whether this in in situ or pre-cast, an estimate of the reinforcement congestion, the types of component materials, key mix proportions, key fresh properties and 28 day compressive strength for all the cases. In many of the references more information than this was published, but in nearly all cases all of the above data were given. Gaps in the table indicate where no information was given.

3. Initial observations

The most significant parts of the analysis in this paper are those of the properties, component materials and mix proportions of the concrete. However, some initial observations on the distribution and types of applications are of interest.

The geographical distribution of the case studies in five time intervals is shown in Fig. 1. This will be of no surprise to those who have followed the spread of SCC since its initial development in Japan. Uses in Asia (the majority in Japan) clearly predominate in the early years, with subsequent spread to Europe and more recently to North and South America.

As mentioned above, it is not a function of this paper to discuss the suitability of SCC for the various types of applications, but it is clear from Table 1 that SCC has been used for an enormously wide range of applications and purposes, from high volumes in suspension bridge anchor blocks to small volumes for repairs. Analysis of the principal reasons given for the use of SCC in the in the 51 cast studies relating to commercial applications shows:

- Thirty four (67%) were for technical advantages compared to conventional vibrated concrete, e.g., vibration was difficult or impossible during construction due to congested reinforcement and/or lack of access.
- Seven (14%) were for economic benefit compared to traditional vibrated concrete, e.g., reduced construction time, reduced labour cost.
- Five (10%) involved the use of SCC in a novel form of construction, e.g., steel/concrete composite, thin section pre-cast units.

In the other five cases the principal reason was not stated or was unclear. In many cases the environmental benefits, e.g., low noise and vibration, improved working conditions, were also cited.

Fifty seven of the case studies were for SCC placed in situ, with 11 for pre-cast production. The latter are concentrated in the latter part of the 11 year period, showing the increasing use of SCC in this respect. The overall volumes of pre-cast production were not always given, but in most cases the mixes were used in continuous production over a substantial period.

4. Fresh properties

The slump flow test, which measures the flow capacity, has been universally used, and hence values of slump flow spread are given in all cases. Nearly 50% of the applications used values in the range 650–700 mm, with nearly 90% in the range 600–750 mm (Fig. 2).

Flow rate values, expressed either as T_{500}, V- or O-funnel or Orimet times, were reported in about half of the case studies. They varied considerably; T_{500} times ranged from 1.8 to more than 12 s and V-funnel or O-funnel times from 3 to 15 s; there is thus a wide range in this property.[2]

There was no pattern of higher slump flows being associated with lower flow rate values, indicating the independence of these properties, and the ability to design mixtures with a combination thought suitable for a given application.

Only 17 of the case studies reported values from L-box and U-box tests, or the less widely used J-ring test.[3] L-box blocking ratio values were all in excess of 0.8; U-box values were in excess of 300 mm, with the reinforcement spacing varied in some cases to suit the application.

[2] Descriptions of the tests can be found in [47]. The slump flow and flow rate values together define the filling ability of the concrete. They are related to the Bingham constants of yield stress and plastic viscosity, respectively. SCC requires a low yield stress (high slump flow) for flow under self-weight, and a moderate plastic viscosity (flow rate) for reasonable formwork filling rates whilst still maintaining stability.

[3] These tests involve flow of the concrete between reinforcing bars, and measure the passing ability. Clearly this is not a criterion for the concrete being placed in unreinforced sections.

Table 1
Case study details

Ref. no.	Date	Country	Application	Volume, m^3	Placing	Reinforcing	Coarse aggregate			Powder		w/p, by wt	Paste, vol%	v_f/v_m, vol%	Admixture		sl. flow, mm	T_{500}, s	Other	Strength, MPa @ 28 days
							Max size (mm)	Type	vol%	Composition	kg/m^3				Splast+	VMA				
[4]	1993	Japan	High rise building walls and filled columns	3900	In situ	Medium	20		32.1	pbfc + pfa	500	0.34	34.6	46.0	ae	y	600–700		U-box > 300 mm	60
[5]	1993	Japan	Cable stayed bridge towers	1000	In situ	Dense	20		34.2	pbfc + pfa	500	0.34	34.6	44.3	wr + ae	y	650	10–20		53.7
[5]	1993	Japan	Filled columns in high rise building	885	In situ	Light	20		34.9	pbfc + pfa	500	0.34	34.7	45.5	wr + ae	y	650			44.2
[6]	1993	Japan	LNG storage tank	800	In situ	Heavy	20	Crushed	34.1	pbfc + pfa	488	0.34	33.8	44.9	ae		500		O-funnel 8 s	48
[6]	1993	Japan	Structural walls	80	In situ	Heavy	20	Crushed	30.6	pbfc + pfa	500	0.34	34.6	48.1	ae		650		O-funnel 10 s	
[7]	1994	Japan	Suspension bridge anchor blocks	240,000	In situ	Medium	40	Crushed	36.4	pbfc + pfa + lsp	410	0.35	29.6	50.0	wr + ae		550			
[7]	1994	Japan	Suspension bridge anchor blocks	4000	In situ	Medium	40	Crushed	42.3	pbfc + pfa + lsp	410	0.35	29.6	44.2	ae		550			36
[8]	1993	Japan	rc core of high rise building	1500	In situ	Heavy	20		34.3	pbfc + pfa	500	0.34	34.2	46.0	wr + ae	y	675	4–10	U-box 300 mm	53
[9]	1994	Japan	lw concrete structural panels		Pre-cast	Heavy	15	Ltweight	34.9	pbfc	607	0.26	36.0	40.3		y	650			65
[10]	1996	Japan	Bridge pier caps	1000	In situ	Heavy	20	Crushed	31.2	pbfc	470	0.35	34.0	48.4	ae		620		V-funnel 3 s	50–60
[10]	1996	Japan	Bridge pier caps	1000	In situ	Heavy	20	Crushed	37.5	pbfc + pfa	472	0.35	33.9	43.8	ae		650		V-funnel 7 s	50–60
[11]	1995	Japan	Port structures	760	In situ	Heavy	20	Crushed	30.9	pbfc + pfa	385	0.48	31.2	51.8	ae	y	645	11	V-funnel 15 s	41
[12]	1997	Japan	Jetty reconstruction	1190	In situ	Heavy	20	Crushed	31.0	pc + ggbs+gyp	448	0.40	32.7	48.7		y	600–695	4–6	V-funnel 7–11 s	56
[13]	1996	France	Walls and accropode units (demo)	6	In situ	Medium	20	Crushed	35.2	pc + lsp	484	0.35	33.1	49.8			600–700			50
[14]	1996	France	Viaduct piers (demo)	50	In situ	Medium	20	Crushed	32.9	pc + csf	473	0.38	33.5	50.8	ret		640			94
[15]	1998	Canada	Reaction wall	240	In situ	Medium	10		33.6	pc + pfa + csf	520	0.42	38.3	41.6	ret	y	640			42
[15]	1998	Canada	Basement wall (demo)	4	In situ	None	25		32.5	pc + pfa + csf	466	0.45	37.0	43.5	ret + aea	y	580			45
[15]	1998	Canada	Basement wall (demo)	4	In situ	None	25		31.8	pc + ggbs + csf	537	0.42	40.3	38.1	ret + aea	y	610			58
[15]	1998	Canada	Repair to car park wall	3	In situ	Heavy	14		29.6	pc + pfa + csf	532	0.41	40.4	38.8	ret + aea	y	615		V-funnel 4 s	35
[16]	1999	UK	Beams and columns (demo)—housing	7.5	In situ	Medium	20	Crushed	28.3	pc + lsp	525	0.38	38.3	46.5			650	1	L-box 0.81, Orimet 2.3 s	47
[16]	1999	UK	Beams and columns (demo)—civ eng	7.5	In situ	Medium	10	Crushed	28.3	pc + ggbs	530	0.37	36.9	47.6			690	2	L-box 0.99, Orimet 4 s	80
[17]	1999	Japan	Suspension bridge anchor blocks	13,000	In situ	Medium	20		33.2	pc + lsp	470	0.35	32.6	49.2		y	525			
[18]	1999	Sweden	Bridge walls and decks	460	In situ	Medium	16		29.5	pc + lsp	595	0.28	36.7	44.5	ae		670	3		62.3
[18]	1999	Sweden	Bridge walls and decks	230	In situ	Medium	16		31.0	pc + lsp	526	0.31	33.7	47.9	ae		700	5		69.3
[19]	1998	Sweden	Housing mix (Brite Euram)		In situ		16		30.9	pc + lsp	525	0.34	36.1	46.3			650			44
[19]	1998	Sweden	Civil engineering mix (Brite Euram)		In situ		10		31.1	pc + lsp	480	0.35	32.6	50.0			710			70
[20]	1999	Japan	psc LNG storage tank	12,000	In situ	Medium	20	Crushed	29.8	pc + lsp	585	0.30	36.5	43.7			650		V-funnel 10 s, U-box > 300 mm	60
[21]	1999	Japan	ps thin-walled elements		Pre-cast	Dense	15	Crushed	33.3	pc + lsp	580	0.32	37.4	47.0	ae	y	695	4.1	V-funnel 13.8 s	73
[22]	1999	Switzerland	Tunnel lining	73,000	In situ	None	16	Gravel	29.5	pc + pfa	434	0.48	34.6	51.5			580			
[23]	2000	UK	Filled tubular columns	400	In situ	Heavy	20	Gravel	30.0	pc + pfa	550	0.35	38.4	43.4		y	625			75
[24]	1999	Japan	Dam spillway		In situ	Medium	20	Crushed	32.9	pc	533	0.30	32.9	47.5		y	650			32.5
[24]	1999	Japan	Floor slab	2800	In situ	Heavy	20	Crushed	32.6	pc + lsp	625	0.27	38.8	39.7		y	650			24
[24]	2000	Japan	Caisson shell	4800	In situ	Light	20	Crushed	33.4	pc + lsp	635	0.26	39.0	40.6		y	700			24
[24]	1999	Japan	Steel concrete composite tunnel elements	7200	Pre-cast	Light	20	Crushed	31.0	pc + ggbs	554	0.32	35.7	45.9		y	650			30
[25]	1999	Switz	Tunnel ring elements (demo)	0.9 each	Pre-cast	Medium	16	Gravel	30.1	CEM II	480	0.36	32.5	52.6	ae		640	5		50
[25]	1999	Switz	Tunnel lining (demo)	30	In situ	Light	16	Gravel	31.3	CEM II + lsp	460	0.40	33.3	52.9	ae		670	5		50
[25]	1999	Switz	Tunnel lining (demo)	30	In situ	Light	32	Gravel	38.6	CEM II + lsp	460	0.37	32.2	50.0	ae		650	7		50
[26]	1999	Japan	Pre-cast building elements	10,000	Pre-cast	Medium	20	Crushed	30.3	pc + ggbs	607	0.29	37.4	44.3			650–700			
[26]	1999	Japan	Lweight pre-cast panels	11,000	Pre-cast	Medium		Ltweight	35.4	pc + ggbs	607	0.26	36.0	41.1			650–701			

(continued on next page)

Table 1 (*continued*)

Ref. no.	Date	Country	Application	Volume, m^3	Placing	Reinforcing	Coarse aggregate			Powder		w/p, by wt	Paste, vol%	v_f/v_m, vol%	Admixture		sl. flow, mm	T_{500}, s	Other	Strength, MPa @ 28 days
							Max size (mm)	Type	vol%	Composition	kg/m^3				Splast+	VMA				
[27]	1999	Japan	Water purification plant	200,000	In situ	Medium	20		31.0	pc + lsp	501	0.33	33.4	48.5			605		O-funnel 8.5	39
[28]	1999	Japan	rc building (demo)		In situ	Medium	20	Gravel	30.9	pc + ggbs	529	0.34	35.6	46.9		y	700			
[28]	1999	Japan	Tunnel lining (demo)	170	In situ	Dense	20	Gravel	29.5	pc + pfa	462	0.35	33.2	50.2		y	650		V-funnel >10 s	21–24
[29]	1999	Japan	Tunnel lining	4000	In situ	None	20		28.0	pc + lsp	600	0.28	37.4	48.0		y	725	5–9	U-box 367 mm, rank 1	
[29]	1999	Japan	Tunnel lining	4000	In situ	None	20		28.9	pc + lsp	520	0.30	33.6	52.5		y	670	5–9	U-box 360 mm, rank 2	>24
[30]	2000	Japan	Underwater diaphragm wall	11200	In situ	Heavy	20		31.8	pc + pfa + ggbs	500	0.32	33.8	48.8	ae	y	650	7	U-box 300 mm, rank 1	>24
[31]	2001	Norway	Radioactive waste containment		In situ	None	20	Crushed	29.5	pc + csf	432	0.45	33.5	49.3	ae	y	725	2	L-box 0.95, J-ringstep 35 mm	52
[32]	2001	Korea	Underground diaphragm wall	32800	In situ	Medium	20	Crushed	29.9	pbfc + lsp	438	0.41	32.4	49.0	ae	y	650	5.5	V-funnel 12 s, U-box 350, rank 2	64
[33]	2001	Japan	lng storage tank wall	6600	In situ	Heavy	20	Crushed	30.6	pc + lsp	529	0.30	33.5	49.6	ae		650		O-funnel 12 s, U-box > 300 mm	60
[34]	2001	Germany	Bridge element (demo)	14	Pre-cast	Medium			29.5	CEM II/A-L + pfa	570	0.29	38.0	44.2		y	805	2	V-funnel 14 s J-ring step 0 mm, L-box 1	80
[35]	2001	Sweden	Quay wall	3200	Pre-cast	Medium	16	Crushed	29.8	pc + lsp	538	0.33	36.0	48.8	ae		700			78
[35]	2001	Sweden	Quay wall	1600	Pre-cast	Medium	16	Crushed	29.4	pc + lsp	532	0.32	34.8	50.3	ae		700			78
[36]	2001	Switzerland	Tunnel lining renovation	700	In situ	None	16	Gravel	30.9	CEM II/A-L + pfa	473	0.39	34.8	47.5						
[37]	2001	UK	Dock fender blocks	1300	In situ	Heavy	20	Crushed	37.7	pc	450	0.40	32.3	48.8		y	630			62
[38]	2002	Canada	Wall repair	100	In situ	Heavy	10	Crushed	29.7	pc + csf	480	0.37	33.4	49.2	ae	y	675		V-funnel 12 s	57
[39]	2002	Sweden	Tunnel linings and entrances	19,000	In situ	Heavy	16	Crushed	30.5	srpc + lsp	600	0.28	36.8	45.3	ae		740		V-funnel 3.7 s	70–80
[40]	2002	Argentina	Building panels		In situ	Medium	12.5	Crushed		pc + lsp	610	0.29	38.4				680	1.8	U-box 345 mm, L-box 0.96	50
[40]	2002	Argentina	Bank vault panels		In situ	Heavy	12.5	Crushed		pc + lsp	610	0.29	38.4				660	2	U-box 340 mm, L-box 0.93	49
[40]	2002	Argentina	rc columns in high rise building		In situ	Medium	19	Crushed		pc + ggbs	500	0.34	33.4				700	2.6	U-box 315 mm, L-box 0.90	59
[41]	2002	Canada	rc columns	2100	In situ	Heavy	10	Gravel	34.0	pc + ggbs	450	0.42	33.7	48.5	wr + ret	y	660			28
[42]	2002	USA	Precast structural elements		Pre-cast	Varied			35.8	pc + pfa	474	0.35	32.7	46.3	wr + ret	y	600			
[43]	2002	Italy	Architectural wall		In situ	Light	16	Crushed	31.3	CEM II + lsp	500	0.36	34.5	50.5		y	700			43
[43]	2002	Italy	Structural concrete		In situ	Heavy	22	Gravel	34.5	CEM I + csf	530	0.33	35.2	43.7			730			95
[43]	2002	Italy	Mass concrete		In situ	Light		Gravel	31.1	CEM III + pfa	435	0.41	33.2	52.8		y	790			42
[44]	2003	Norway	Readymixed SCC —low grade	20,000/yr	In situ	Medium	20	Crushed	29.5	CEM III + csf	432	0.47	34.0	48.9	wr + ae	y	725	2		52
[44]	2003	Norway	Readymixed SCC —high grade	13,000/yr	In situ	Medium	16	Crushed	32.1	CEM II + lsp + csf	474	0.38	34.8	48.5		y	650			50
[45]	2003	Italy	Base slab	500	In situ	Heavy	16	Crushed	30.1	CEM II + pfa + lsp	601	0.32	41.5	40.6			>600	<12	V-funnel 4–12 s, L-box > 0.8	
[46]	2003	Japan	Cable stayed bridge piers	15,000	In situ	Heavy	20		31.7		470	0.33	30.4	52.3	ae		630	6.1	V-funnel 11.8 s, U-box > 338 mm	74
[46]	2003	Japan	Precast, ps, bridge beams		Pre-cast	Medium	20		28.1		575	0.30	37.3	46.4			665		V-funnel 12.1 s	71

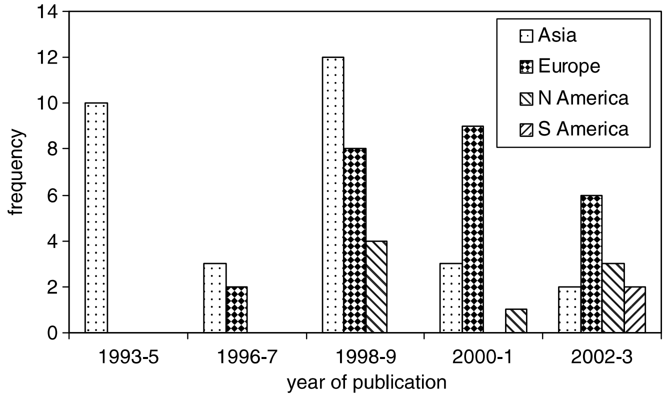

Fig. 1. Geographical distribution of case studies.

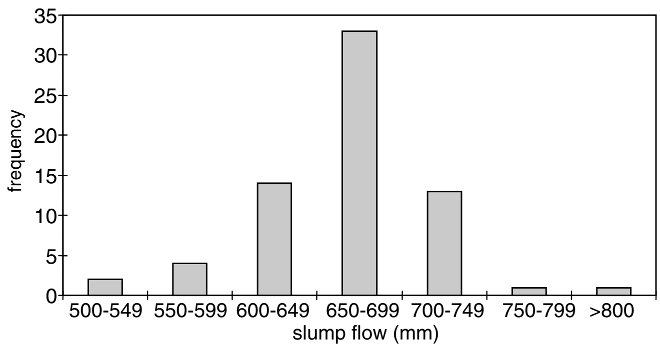

Fig. 2. Slump flow values from all case studies.

No measurements of stability (or segregation resistance) values were reported. This indicates the lack of a generally accepted test, and also that stability was evaluated during the mix development work that pre-ceded most of the applications, and during production was assessed subjectively and/or proven by sampling the hardened concrete.

5. Compressive strength

The 28 day strength values were reported in nearly all cases. Values ranged from 20 to nearly 100 MPa, with about 80% of mixes having strengths in excess of 40 MPa (Fig. 3).

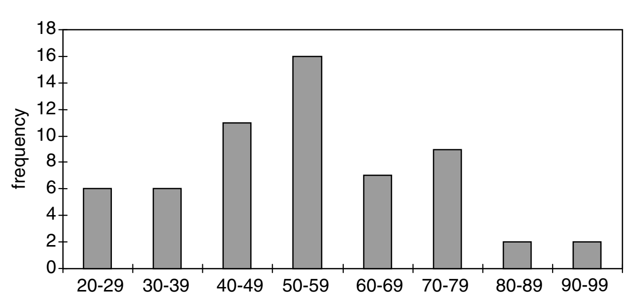

Fig. 3. 28 day strengths from case studies.

This confirms that it is possible to produce SCC with strengths to suit nearly all normal concreting situations. As discussed below, strengths are controlled mainly by the binder composition, and not with water/binder ratio as in conventional workability concrete.

6. Mixture constituents

6.1. Coarse aggregate

The number of the occurrences of coarse aggregate type and maximum size in the case studies are given in Table 2.

Crushed rock was used over three times as often as gravel (uncrushed) aggregates, primarily reflecting local availability. Two cases used lightweight aggregate.

Forty eight cases (about 70% of the total) used a maximum aggregate size in the range 16–20 mm (the value depending on local practice). Six cases used larger—22, 25, 32 or 40 mm—aggregate (40 mm was used in the large volumes of concrete for the anchor blocks of the Akashi-Kaikyo bridge, a spectacular early use of SCC [8]) and 10 cases used 10–15 mm. There was no clear pattern of the use of smaller aggregates with more congested reinforcement. The influence of aggregate type and size on the mixture proportions will be discussed below.

6.2. Powder components

Table 3 gives the components of the powder in the case studies. All but two used a blend of Portland cement with one or more additions, either in the form of blended cement and/or added at mixing. In 19 cases a ternary mixture and in three cases a quaternary mixture was used. Limestone powder was the most often used, in 28 cases.

The most common explanations for the choice of the blend were to reduce the temperature rise during of hydration and/or to reduce the compressive strength, since if the high powder content (see below) comprised all or nearly all Portland cement, both would be excessive. There were few comments on the choice of the specific components, which generally seemed to be governed by local practice and availability. It was often difficult to be precise about the exact composition, thus no attempt has been made to include such data in Table 1. It is clear that in more than half the case studies the powder contained more than 30% additions.

Table 2
Coarse aggregate types and maximum sizes

Type	Number of cases	Max size	Number of cases
Crushed	34	40 mm	2
Gravel	10	32 mm	1
Lightweight	2	22–25 mm	3
No info.	22	16–20 mm	48
		10–15 mm	10
		No info.	4

Table 3
Components of powders

Powder components	Number of cases
Portland cement	2
Portland cement + limestone powder	19
sr portland cement + limestone powder	1
Portland limestone cement + limestone powder	3
Portland cement + ggbs	8
Portland blast furnace cement	2
Portland cement + csf	5
Portland blast furnace cement + pfa	9
Portland blast furnace cement + limestone powder	1
Portland cement + pfa	4
Portland cement + pfa + csf	3
Portland cement + pfa + ggbs	1
Portland limestone cement + pfa	3
Portland limestone cement + limestone powder + pfa	1
Portland cement + ggbs + csf	1
Portland fly ash cement + limestone powder + csf	1
Portland blast furnace cement + pfa + limestone powder	2
No information	2

6.3. Admixtures

All mixes included a superplasticizer by necessity. There was more use of polycarboxylic acid-based materials later in the 11 year period, some of which were described as being developed specifically for use in SCC. Variation of performance even within broad types makes any analysis of dosage of little significance, and hence values of this have not been included in Table 1.

In 30 cases, an air-entraining agent was also used, sometimes as a preblended product with the other admixtures. It was not always clear if this was primarily to provide freeze–thaw resistance or to improve the rheology.

In 34 cases, a viscosity-modifying agent of some form was also used. The reasons given were to provide stability and/or reduce sensitivity of the mix to variations in materials during production, particularly the aggregate moisture content. Again, the influence of this on the mixture proportions will be discussed below.

7. Mixture proportions

The analysis of the mixture proportions takes account of the general principles of achieving the required combination of properties of SCC mixes:

- the coarse aggregate content is sufficiently low for individual aggregate particles to be lubricated by a layer of fine/mortar paste, thereby increasing fluidity and reducing the risk of aggregate bridging and hence concrete blocking when passing through narrow gaps, i.e., increasing the passing ability;
- sufficient fluidity and viscosity of the mortar is obtained by limiting the fine aggregate content and water/powder ratio, adding a superplasticizer and (optionally) a viscosity modifying agent (VMA), thereby combining adequate filling ability with segregation resistance.

These result in mixes that, compared to conventional workability concrete, contain:

- lower coarse aggregate contents,
- increased paste contents,
- high powder (material <0.125 mm) contents,
- low water/powder ratios,
- high superplasticizer doses,
- (sometimes) a viscosity-modifying agent.

The following key proportions for the mixes, listed in Table 1, were therefore selected for analysis:

- coarse aggregate content (by volume),
- paste content (by volume),
- powder content (by weight),
- water/powder ratio (by weight),
- volume of fine aggregate/volume mortar.

The analysis was carried out for mixes with maximum aggregate size in the range 10–20 mm. The six mixes with larger aggregates were excluded.

In most cases, local practice was for the division between coarse and fine aggregate to be at either 4 or 5 mm particle size, and the mix proportions as reported were then used for the analysis. In the few cases where some other division was used, e.g., 2 or 8 mm, the coarse and fine aggregate quantities for a 4 mm division were obtained by calculation from the published data.

The powder contents were taken as the cement plus additions. From information given, no calculation could be made of the contribution to this of the proportion of fine aggregate less than 0.125 mm, but this amount is generally relatively small and will not affect the outcome of the analysis significantly.

Cumulative distributions are an informative method of showing the ranges of the key proportions and their variations for subsets of mixtures. These are shown for the above proportions in Figs. 4–8 and 10, respectively. In each figure, the distribution for the whole set of cases is plotted, supplemented in the first five cases with those for subsets of mixes for which some differences of proportions might be expected.

In addition, Table 4 shows the first and ninth deciles and medians of each proportion for the whole data set (the deciles are preferable to the extremes of ranges as descriptors), and the ratio of the decile range to the median.

7.1. Coarse aggregate content

The coarse aggregate contents (Fig. 4) varied from 28% to 38% by volume of the concrete, with 80% of these within the range 29.1–34.8% (Table 4), equivalent to about

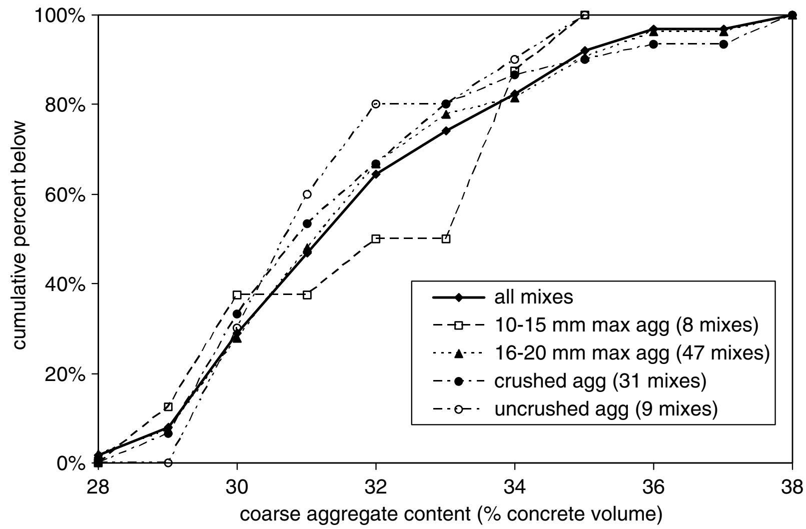

Fig. 4. Distribution of coarse aggregate contents.

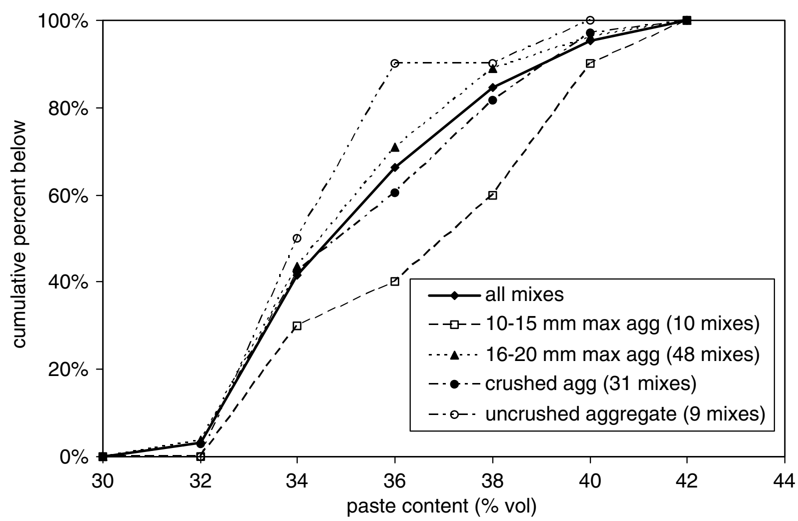

Fig. 5. Distribution of paste contents.

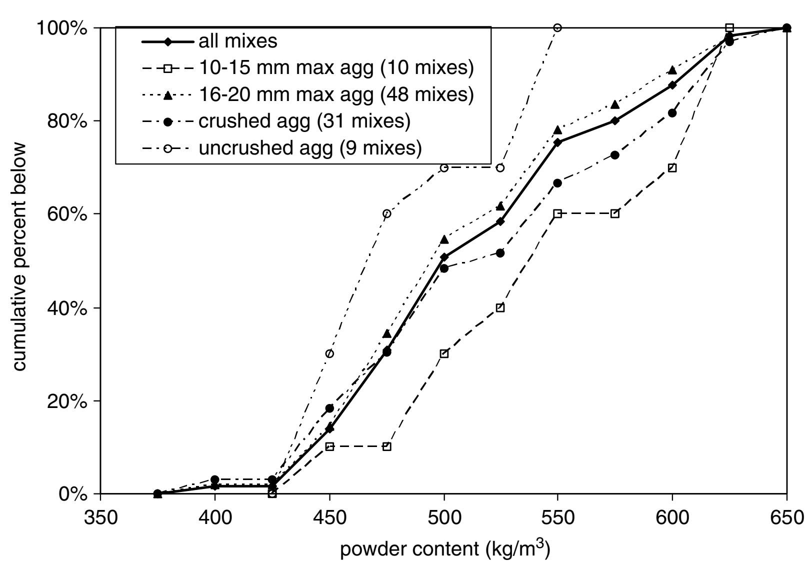

Fig. 6. Distribution of powder contents.

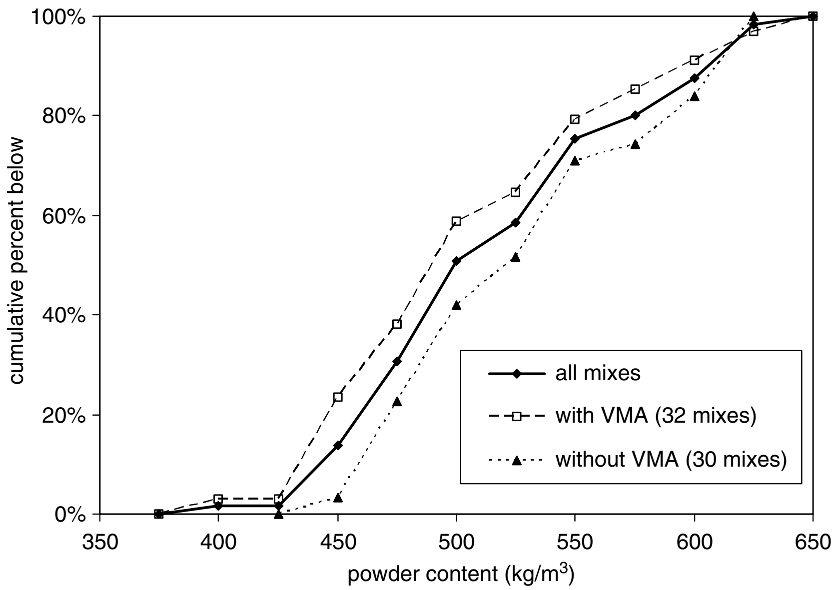

Fig. 7. Distribution of powder contents for mixes with and without a viscosity modifying agent (VMA).

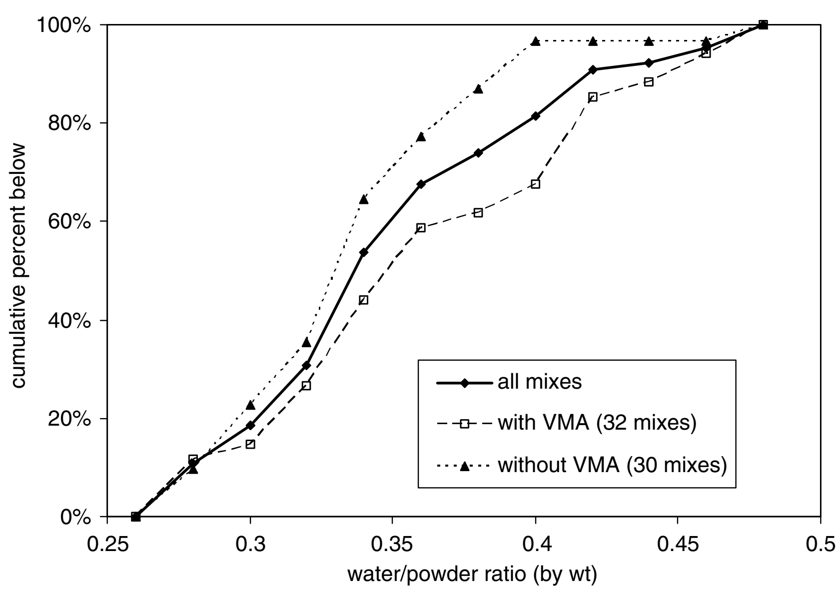

Fig. 8. Distribution of water/powder ratios.

770–925 kg/m^3 for a typical aggregate relative density of 2.65. The median value for mixes using a maximum aggregate size from 10 to 15 mm was higher (by about 1%) than that for whole set of mixes (31.2%), and the median for mixes with uncrushed (gravel) aggregate lower (by about 0.5%). Both trends are the opposite to what might be expected, but the distribution curves depart from that for the whole set over part of the range only, and the number of data points in each subset is small. Also, it is possible that the overall aggregate grading might be a more important factor than size or type.

7.2. Paste content

The paste contents (Fig. 5) varied from 30% to 42% by volume of the concrete, with 80% of these within the range 32.3–39% (Table 4). Again, the variations from the overall behaviour were for mixes with a maximum aggregate size from 10 to 15 mm, which have a higher median value (by about 2.5%) and those with uncrushed aggregate have a lower median value (by about 1%) than that for the whole set of mixes (34.8%). These trends are what might be expected.

Table 4
Deciles, medians and ranges of key mix proportions from all case studies

		First decile	Median	Ninth decile	(Ninth – first decile)/median, %
Coarse aggregate content	% concrete by vol	29.1	31.2	34.8	18
Paste content	% concrete by vol	32.3	34.8	39.0	19
Powder content	kg/m^3	445	500	605	32
Water/powder ratio		0.28	0.34	0.42	42
Fine agg/ mortar	% by vol	41.0	47.5	51.5	22

7.3. Powder content

With the exception of two outliers, the powder contents (Fig. 6) ranged from 425 to 625 kg/m^3, with 80% in the range 445–605 kg/m^3 (Table 4). Fig. 6 shows similar variations from the median for the whole set of mixes (500 kg/m^3) for aggregate size and type to those for paste content. About half the mixes contained a viscosity modifying agent, and Fig. 7 shows that this results in consistently lower powder contents, with a difference of about 30 kg/m^3 at the median value.

7.4. Water/powder ratio

Water/powder ratios (Fig. 8) ranged from 0.26 to 0.48, with 80% falling in the range 0.28–0.42 (Table 4). The water/powder ratio has very significant effects on both the fresh and hardened properties of SCC, with often its effect on the fresh properties restricting the choice of its value. Conversely, the powder composition has a more significant effect on the hydration processes (and hence heat output, strength gain, etc.) and is therefore used to control these properties. Detailed analysis of these effects is, however, not possible from the level of information provided in the case studies.

As with powder content, Fig. 8 shows clear differences for mixes with and without a viscosity-modifying agent (VMA); the median value for the former was about 0.01 higher than that for whole set of mixes (0.34), and about 0.01 lower for the latter.

During the development of SCC, mixes were classified into one of the three broad types depending on the method of providing sufficient plastic viscosity to prevent segregation [46,47]:

- powder-based, with very low water–binder ratios, high powder and high superplasticizer doses;
- VMA based, with higher water–binder ratios and significant doses of the viscosity agent (essentially an extension of underwater concrete);
- combined type, which are intermediate to these two, i.e., moderately-low water binder ratios with some VMA.

It would seem from consideration of the mix proportions and comments in the case studies that most mixtures are either of the powder based or combined type, with little use of VMA based mixes (although the dividing line between the latter and combined types is not well defined). As discussed above, the case studies show some clear differences of powder contents and water/powder ratios between these; it can be expected that continued development of admixtures and more efficient mix design procedures may amplify these differences.

Another widely claimed advantage of the use of VMAs is that they reduce the sensitivity of the mix to variations in material supply, such as the grading or moisture content of the aggregate, i.e., the mixes are more robust.

Information on the effect of water content on slump flow was provided in some of the case studies [7,15,30,32] and other relevant data from laboratory studies have also been reported [48,49]. Fig. 9 has been compiled from this. Mixes without VMAs all have steeper slopes and are indeed therefore more sensitive to variation in water content. There is a range of behaviour within each type, but the average sensitivities for mixes with and without a VMA is roughly equivalent to changes in slump-flow of 70 mm and 150 mm, respectively, for a 1% change in aggregate moisture content (assuming a typical aggregate content). This therefore confirms the claim of increased robustness of mixes containing a VMA.

7.5. Mortar composition

The mortar composition in terms of volume percentage of the fine aggregate (Fig. 10) varies from 38% to 54%, with 80% in the range 41–52%. Mix design procedures early in the development of SCC recommended a value of 40% [50,51] for robust, safe mixes, but clearly subsequent developments have shown this to be conservative.

7.6. General comments on mixture proportions

The last column in Table 4 expresses the range from the first to ninth decile as percentage of the median for each of the key proportions. It is interesting that the coarse aggregate and paste contents of the concrete and the fine aggregate percentage of the mortar all have values on this basis of about 20%, whereas the powder content and water/powder ratio are much higher (32% and 42%, respectively). This indicates that the former three proportions are more critical for successful SCC, with concrete producers having greater flexibility with the latter two.

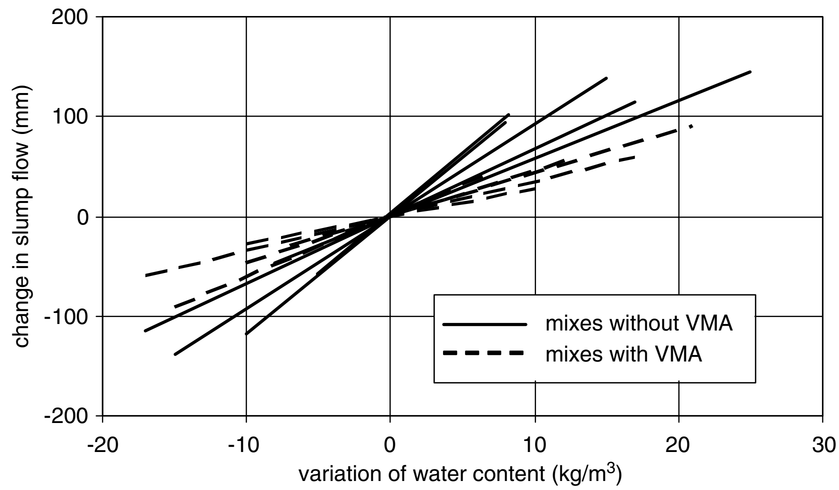

Fig. 9. Effect of variation of water content of slump flow of SCC mixes with and without VMAs (compiled from Refs. [7,15,30,32,48,49]).

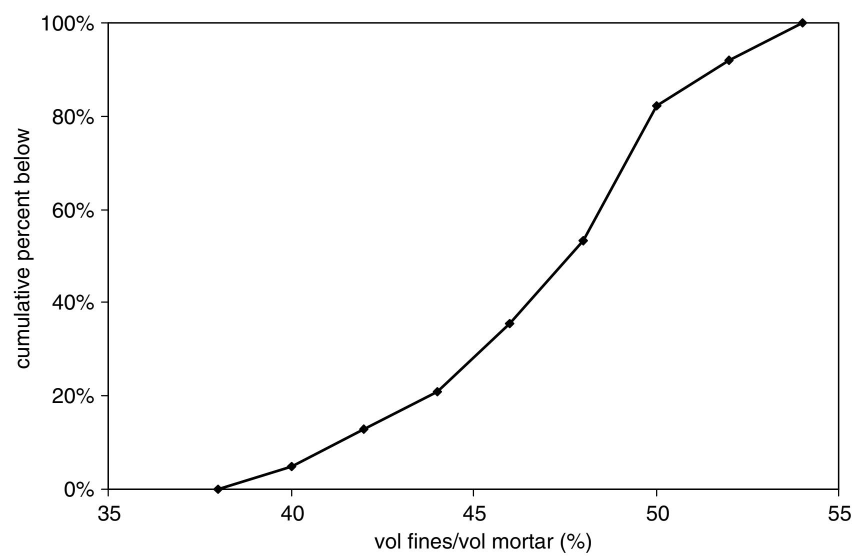

Fig. 10. Distribution of mortar compositions.

All of the reported mixtures have been successfully used for their particular applications, and the wide range of component materials, properties and, most importantly, mix proportions clearly demonstrate that SCC is widely family of mixes, and there is no unique mix for a given set of requirements.

The overall impression is that there is considerable scope for optimisation of mixes for greater efficiency, for example by minimising the powder content, and to develop mixes for an even wider range of applications. Local practice and availability of materials will, however, be an important factor in this.

8. Conclusions

A sufficient number of case studies of SCC applications with details of fresh properties, compressive strength, constituents and mix proportions have been published to enable some useful conclusions for practitioners and researchers to be drawn.

This paper has analysed 68 such case studies published during the first decade of significant SCC use, from 1993 to 2003. These reflect the geographical progression of SCC in this period, and show the applicability of SCC to almost all types of concrete construction.

Properties

- Ninety percent of the cases used SCC with slump flows in the range 600–750 mm, and 80% had compressive strengths in excess of 40 MPa.

Component materials

- A clear majority (70%) of cases used aggregate with a maximum size between 16 and 20 mm. The use of crushed rock or gravel aggregates seemed to depend on local availability.

- Nearly all cases used either a binary or ternary blend of Portland cement with additions of all the types used in conventional concrete. Limestone was the most common addition (41% of the cases).
- Approximately half the cases used a viscosity-modifying agent (VMA) in addition to superplasticizer and could therefore be considered as a combined type of SCC, which are generally more robust than mixes without a VMA.

Mix proportions

- Median values of the key mix proportions were
  - coarse aggregate content: 31.2% by volume,
  - paste content: 34.8% by volume,
  - powder content: 500 kg/m^3,
  - water/powder ratio: 0.34 by weight,
  - fine aggregate/mortar: 47.5% by volume.
- In each case, mixes with considerable variations from the median values have been reported, with the range of powder contents and water/powder ratio being proportionally greater than the other three.

Overall, the case studies have confirmed that SCC is a wide family of mixes, and there is no unique mix for a given application or set of requirements. There remains considerable scope for optimisation of mixes for greater efficiency and economy.

References

[1] Skarendahl A. The present—the future. Proceedings of 3rd RILEM international symposium on self compacting concrete, Reykjavik, Iceland, August. Bagneux, France: RILEM Publications PRO 33; 2003. p. 6–14.

[2] Skarendahl A, Petersson O, editors. Self-compacting concrete—state-of-the-art report of RILEM Technical Committee 174-SCC, RILEM Report 23. Cachan, France: RILEM Publications; 2000. p. 154.

[3] Walraven J. Structural applications of self compacting concrete. In: Wallevik O, Nielsson I, editors. Proceedings of 3rd RILEM international symposium on self compacting concrete, Reykjavik, Iceland, August. Bagneux, France: RILEM Publications PRO 33; 2003. p. 15–22.

[4] Hayakawa M, Matsuoka Y, Shindoh T. Development and application of superworkable concrete. Proc of Int RILEM workshop on special concretes—workability and mixing, Paisley, Scotland, June. London: E&FN Spon; 1993. p. 183–90.

[5] Sakamoto J, Matsuoka Y, Shindoh T, Tangtermsirikul S. Application of super-workable concrete to actual construction. Proc of Int Conf economic and durable construction through excellence, Dundee Scotland, September. London: E&FN Spon; 1993. p. 891–902.

[6] Miura N, Takeda N, Chikamatsu R, Sogo S. Application of super workable concrete to reinforced concrete structures with difficult construction conditions. ACI SP-140 high performance concrete in severe environments. Detriot, USA: American Concrete Institute; 1993. p. 163–86.

[7] Furuya N, Itohiya T, Arima I. Development and application of highly flowing concrete for mass concrete anchorages of Akashi-Kaikyo Bridge. Proc of Int Conf on high performance concrete (supplementary papers), Singapore. Detroit, USA: American Concrete Institute; 1994. p. 371–96.

[8] Kuroiwa S, Matsuoka Y, Hayakawa M, Shindoh T. Application of super workable concrete to construction of a 20-story building. ACI SP-140 high performance concrete in severe environments. Detroit, USA: American Concrete Institute; 1993. p. 147–61.

[9] Umehara H, Uehara T, Enomoto Y, Oka S. Development and usage of lightweight high performance concrete. Proc of Int Conf on high performance concrete (supplementary papers), Singapore. Detroit, USA: American Concrete Institute; 1994. p. 339–53.

[10] Kosaka H, Higuchi M, Takeuchi H, Nanni A. 'Flowable' concrete in bridge pier caps. Concr Int 1996;18(2):56–61.

[11] Fukute T, Moriwake A, Sano K, Hamasaki K. Development of superworkable concrete for multi-functional port structures. In: Proc of 2nd Canmet/ACI Int Symp on advances in concrete technology, Las Vegas, USA, ACI SP 154. 1995. p. 335–56.

[12] Fukute T, Hamada H, Sano K, Sueoka E, Moriwake A, Tkeichi H. Development of superworkable concrete with viscosity agent for reconstruction of jetty structures destroyed by the Hanshin Great Earthquake. In: Proc of 3rd Canmet/ACI Int Symp on advances in concrete technology, Auckland, New Zealand, ACI SP 171. 1997. p. 339–66.

[13] Sedran T, de Larrard F, Hourst F, Contamines C. Mix design of self-compacting concrete (SCC). Proc of RILEM Int Conf on production methods and workability of concrete, Paisley, Scotland, June. London: E&FN Spon; 1996. p. 439–50.

[14] de Larrard F, Gillet G, Canitrot B. Preliminary HPC mix design study for the Grand Viaduc de Millau—an example of LCPCs approach. In: Proc of 4th Int Symp on utilization of high strength/high performance concrete, May, Paris France, 1996. p. 1323–331.

[15] Khayat HK, Aitcin P-C. Use of self-consolidating concrete in Canada—present situation and perspectives. In: Proc of Int Workshop on self-compacting concrete, August, Kochi University of Technology, Japan, 1998. p. 11–22.

[16] Sonebi M, Bartos PJM. Hardened SCC and its bond with concrete. Proc of 1st RILEM Int Symp on self-compacting concrete, Stockholm, Sweden, September. Rilem Publications; 1999. p. 275–89.

[17] Kashima S, Kanazawa K, Okada R, Yoshikawa S. Application of self compacting concrete mad with low heat cement for bridges substructures of Honshu-Shikoku Bridge Authority. In: Proc of Int workshop on self-compacting concrete, August, Kochi University of Technology, Japan, 1998. p. 255–61.

[18] Billberg P, Petersson O, Osterber T. Full scale casting of bridges with self-compacting concrete. Proc of 1st RILEM Int Symp on self-compacting concrete, Stockholm, Sweden, September. Paris: RILEM; 1999. p. 639–50.

[19] Petterson O. Final Report of Task 1: Preliminary Mix Design, SCC—Brite Euram Contract No. BRPR-CT96-0366, February 1998. Available from: www.civeng.ucl.ac.uk/research/concrete/sccBE.asp.

[20] Nishizaki T, Kamada F, Chikamatsu R, Kawashima H. Application of high-strength self-compacting concrete to prestressed concrete outer tank for LNG storage. Proc of 1st RILEM Int Symp on self-compacting concrete, Stockholm, Sweden. Paris: RILEM; 1999. p. 629–38.

[21] Nagai T, Kojima T, Miura N. Application of high-strength/superworkable concrete to thin-walled prestresed concrete products. Mag Concr Res 1999;51(3):53–162.

[22] Botte J, Burdin J, Zermatten M. SCC Tunnel applications: Cleuson Dixence project and Loetschberg Basis Tunnel Switzerland. Proc of 1st RILEM Int Symp on self-compacting concrete, Stockholm, Sweden. Paris: RILEM; 1999. p. 681–93.

[23] Henderson N. Self-compacting concrete at Millenium Point. Concrete 2000;36(4):26–7.

[24] Mizobuchi T, Yania S, Takada K, Sakata N, Nobuta Y. Field applications of self-compacting concrete with advantageous performances. Proc of 1st RILEM Int Symp on self-compacting concrete, Stockholm, Sweden. Paris: RILEM; 1999. p. 605–16.

[25] Wetzig V. SCC for tunnel lining. Proc of 1st RILEM Int Symp on self-compacting concrete, Stockholm, Sweden. Paris: RILEM; 1999. p. 669–80.

[26] Umehara H, Hamada D, Yamamuro H, Oka S. Development and usage of self-compacting concrete in precast field. Proc of 1st RILEM Int Symp on self-compacting concrete, Stockholm, Sweden. Paris: RILEM; 1999. p. 705–17.

[27] Chikamatsu R, Shinkai C, Kushigemachgi H. Application of low-shrinkage type self-compacting concrete to an advanced large water purification plant. Proc of 1st RILEM Int Symp on self-compacting concrete, Stockholm, Sweden. Paris: RILEM; 1999. p. 659–68.

[28] Maeda MK, Yamada K, Uchida A. Evaluation on the practicability of SCC. Proc of 1st RILEM Int Symp on self-compacting concrete, Stockholm, Sweden. Paris: RILEM; 1999. p. 617–28.

[29] Tanaka M, Mori K. Application of self-compacting concrete to steel segments of multi-micro shield tunneling method. In: Proc of 2nd Int Symp on self-compacting concrete, Tokyo, Japan, October 2001, COMS Engineering, Japan. p. 651–60.

[30] Inoue H, Takeichi Y, Ohtomo T. Construction of rigid foundation of underground diaphragm wall with highly congested reinforcing bar arrangement by using self-compacting concrete. In: Proc of 2nd Int Symp on self-compacting concrete, Tokyo, Japan, October 2001, COMS Engineering, Japan. p. 643–50.

[31] Johansen K, Kyltveit B-P. SCC in a rock repository for radioactive waste. In: Proc of 2nd Int Symp on self-compacting concrete, Tokyo, Japan, October 2001, COMS Engineering, Japan. p. 681–86.

[32] Ohtomo T, Asaka S, Kim JY, Park CG, Beak SJ, Jung CS, et al. Self-compacting concrete used for underground diaphragm walls of world's largest 200,000 kl inground tanks at Inchon LNG terminal in Korea. In: Proc of 2nd Int Symp on self-compacting concrete, Tokyo, Japan, October 2001, COMS Engineering, Japan. p. 661–70.

[33] Kubo M, Nakano M, Aoki H, Sugano S, Ouchi M. The quality control method of self-compacting concrete using testing apparatus for self-compactability evaluation. In: Proc of 2nd Int Symp on self-compacting concrete, Tokyo, Japan, October 2001, COMS Engineering, Japan. p. 555–64.

[34] Brameshuber W, Uebachs S. Practical experience with the application of self-compacting concrete in Germany. In: Proc of 2nd Int Symp on self-compacting concrete, Tokyo, Japan, October 2001, COMS Engineering, Japan. p. 687–96.

[35] Centing M, Jonsson U, Nilsson H, Tuutti K, Widenbrant K. Site applications of self-compacting and pigmented concrete. Proc Int. Conf. on innovations and developments in concrete materials and construction, Dundee, September. London: Thomas Telford; 2002. p. 465–72.

[36] Jacobs F, Hunkeler F. SCC for the rehabilitation of a tunnel in Zurich/Switzerland. In: Proc of 2nd Int Symp on self-compacting concrete, Tokyo, Japan, October 2001, COMS Engineering, Japan. p. 707–14.

[37] Fleming D. Smooth sailing at Pembroke Dock New Civil Engineer supplement 'The other side of concrete', November, 2001, p. 18–9.

[38] Khayat KH, Morin R. Performance of self-consolidating concrete used to repair parapet wall in Montreal. In: Proc of the 1st North American Conf on the design and use of self-consolidating concrete, Centre for Advanced Cement Based Materials, North Western University, Chicago, November 2002. p 475–80.

[39] Osterberg T. The use of SCC in the Sodra Lanken project. In: Proc of the 1st North American Conf on the design and use of self-consolidating concrete, Centre for Advanced Cement Based Materials, North Western University, Chicago, November 2002. p. 445–50.

[40] Fornasier G, Giovambattista P, Zitzer L. Self-consolidating concrete in Argentina: development program and applications. In: Proc of the 1st North American Conf on the design and use of self-consolidating concrete, Centre for Advanced Cement Based Materials, North Western University, Chicago, November 2002. p. 439–44.

[41] Lessard M, Talbot C, Baker D. Self-consolidating concrete solves challenging placement problems at the Pearson International Airport in Toronto, Canada. In: Proc of the 1st North American Conf on the design and use of self-consolidating concrete, Centre for Advanced Cement Based Materials, North Western University, Chicago, November 2002. p. 413–16.

[42] Shadle R, Somerville S. The benefits of utilizing flay ash in producing self-consolidation concrete (SCC). In: Proc of the 1st North American Conf on the design and use of self-consolidating concrete, Centre for Advanced Cement Based Materials, North Western University, Chicago, November 2002. p. 235–41.

[43] Collepardi M, Collepardi S, Ogoumah Ologat JJ, Troli R. Laboratory-tests and field-experiences of high performance SCCs. Proc of 3rd RILEM Int Symp on self compacting concrete, Reykjavik, Iceland, August. Bagneux, France: RILEM Publications PRO 33; 2003. p. 904–12.

[44] Fredvik TI, Gundersen NL, Johansen K. Development of SCC in Norway—use of csf. Proc of 3rd RILEM Int Symp on self compacting concrete, Reykjavik, Iceland, August. Bagneux, France: RILEM Publications PRO 33; 2003. p. 975–85.

[45] Paris M, Tavano S, Albeiro E. Self-compacting concrete (SCC): the construction of the base for the mill of the Unimed cement plant of Barletta (Italy). Proc of 3rd RILEM Int Symp on self compacting concrete, Reykjavik, Iceland, August. RILEM Publications PRO 33; 2003.

[46] Ouchi M, Sada-aki N, Osterberg T, Hallberg S-E, Lwin M. Applications of self-compacting concrete in Japan, Europe and the United States US Federal Highway Administration Office of Bridge Technology, 2003, ISHPC. Available from: http://www.fhwa.dot.gov/bridge/scc.pdf.

[47] European Project Group The European Guidelines for self-compacting concrete EFNARC, UK, May 2005. Available from: www.efnarc.org.

[48] Nawa T, Izumi T, Edamatsu Y. State of the art report on materials and design of self-compacting concrete. In: Proc on international workshop on self-compacting concrete, Kochi University of Technology, Japan, August 1998. p. 160–90.

[49] Aarre T, Domone PL. Reference concretes for evaluation of test methods for SCC. In: Wallevik O, Nielsson I, editors. Proceedings of 3rd RILEM international symposium on self compacting concrete, Reykjavik, Iceland, August. Bagneux, France: RILEM Publications PRO 33; 2003. p. 495–505.

[50] Okamura H, Ozawa K. Self-compactable high performance concrete. International workshop on high performance concrete. Detroit: American Concrete Institute; 1994. p. 31–44.

[51] Okamura H, Ozawa K. Mix design for self-compacting concrete. Concr Lib JSCE 1995;25:107–20.