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A comparison between mechanical properties of self-compacting concrete and the corresponding properties of normal concrete

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Abstract

An experimental and numerical study on mechanical properties, such as strength, elastic modulus, creep and shrinkage, of self-compacting concrete (SCC) and the corresponding properties of normal compacting concrete (NC) is outlined in this article. The study included eight mix proportions of sealed or air-cured specimens with water–binder ratio (w/b) varying between 0.24 and 0.80. Half of the mixes studied were based on NC. The age at loading of the concretes in the creep studies varied between 2 and 90 days. Four different stress to strength levels were studied. Parallel studies were performed on strength (f_c) and relative humidity (RH). The results show that elastic modulus, creep and shrinkage of SCC did not differ significantly from the corresponding properties of NC. The ongoing study was started in 1997. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Compressive strength; Creep; Elastic moduli; Particle size distribution; Shrinkage; Workability

1. Background and objective

In Japan, self-compacting concrete (SCC) has been used for large office buildings and also for advanced types of extruded tunnels in combination with steel fibers [1,2]. Use of SCC lowered the noise level on the construction site and diminished the effect on the environment. In Sweden, SCC has been used for 19 highway bridges so far and for slabs in a dwelling house where a 60% increase in productivity was observed [3]. Use of SCC thus improved both the conditions for the labor on the work site and for the surroundings. Beside problems with building moisture, a more modern technique for production is an issue to be solved for concrete that is cast on site. Problems with building moisture have been solved by use of high-performance concrete (HPC; w/b < 0.38) [4–6]. Like normal compacting concrete (NC), SCC contains small quantities of superplasticizer. Furthermore, in order to avoid separation of large particles in SCC, additives to increase the viscosity or fillers are used [7–9]. An additive to increase the viscosity is often used when casting concrete under water and for SCC in tunnels [10]. To increase the viscosity in SCC the following fillers may be used:

- fly ash,
- glass filler,
- limestone powder,
- silica fume (or silica fume slurry),
- quartzite filler (fine sand).

Table 1 shows the mix proportions of SCC used in Okayama and in Malmö [11,12]. Intense development work on SCC is currently going on in Sweden [13–16]. The objective of this study was to compare the mechanical properties of SCC, such as strength, elastic modulus, creep and shrinkage, with the corresponding properties of NC.

2. Experimental

2.1. Material and preparation of specimens

The aggregate had the properties given in Table 2 [17]. Table 3 presents the chemical composition and the main characteristics of the cements [18]. Table 4 gives the mix composition, main characteristics and workability of the

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Table 1
Mix proportions of SCCs in Japan and Sweden (slab only) (kg/m^3 dry weight) [11,12]

Material/application	Beams	Piles	Slab in Sweden	Slabs	T-beams	Tunnel
Aggregate content (% by vol.)	0.72	0.80	0.70	0.80	0.73	0.75
Cement, c	520	310	520	310	500	400
Fly ash, glass filler			100 (glass)			100
Superplasticizer (% of c)	1	1	0.4	0.7	0.7	0.7
Viscosity agent (% of w)	0.5	0.15	–	0.15	–	0.52
Water, w	160	170	200	170	160	190
w/b	0.31	0.55	0.38	0.55	0.32	0.48
Slump flow (cm × cm)	50 × 65	55 × 70	56 × 63	55 × 75	55 × 70	62 × 66
Air content (%)	3–5	3–6	1	3–6	3–6	1

studied concretes [20]. In order to obtain high workability three of the reference mixes contained air-entrainment, the air content of which lowered the strength in comparison with mixes without air-entrainment, when w/b was constant. A total of 88 cylinders, 10 cm in diameter and 50 cm in length, were studied, of which 64 cylinders were studied for creep. Double layers of adhesive aluminum foil sealed half the number of the cylinders. The cover was carried out in a chamber with RH = 95% in order to avoid moisture loss. No moisture loss was observed from the sealed specimens during the study. The drying specimens were placed in an ambient climate of 20°C and RH = 60% after 1 day of curing in a steel mold. The maximum temperature was 25°C at demolding. The temperature movements were compensated for by a thermal coefficient, $\alpha = 1.0 \times 10^{-5}$ [18].

2.2. Methods

Both air-cured and sealed concretes were studied. The internal temperature varied between 18°C and 25°C. Dew point meters performed the RH tests after calibration according to ASTM E 104-85 [19]. At commencement of creep testing the age of the concretes was either 2, 7, 28 or 90 days. The ambient RH was held at 60% RH. The creep specimens were placed in traditional spring-loading devices. The loading was 0.20, 0.40, 0.55 and 0.70 of the current strength, and was applied by about 1 MPa/s. From 2 days' age parallel studies were done on shrinkage. The total strain in the creep studies was reduced by the shrinkage strain in order to obtain the creep strain. During the first week of creep the loading was held constant automatically. Later on, the correct loading was applied in the spring-loading device at all times of measurement. The compressive strength was obtained on 100-mm cubes at 2, 7, 28, 90 and 360 days' age, three cubes of each concrete mix composition. RH was obtained on fragments from the strength tests. The creep and shrinkage measurement device was mechanical and calibrated. The equipment for measurement of strength and RH (dew point meter) was also calibrated.

Table 2
Properties of the aggregate (quartzite sandstone) [17]

Compressive strength (MPa)	Split strength (MPa)	Elastic modulus (GPa)	Ignition losses (%)
333	15	60	0.3

3. Results and discussion

3.1. Results of experiments

Fig. 1 shows the strength of sealed SCC (no air-entrainment) versus the water–binder ratio (w/b) at different ages. From Fig. 1 the strength of sealed SCC, f_{cB}, was well correlated to Eq. (1) (MPa):

$$f_{cB} = 2.07[\ln(t) + 11.7] \times (w/b)^{-0.042[\ln(t)+29]} \qquad R^2 = 0.92 \tag{1}$$

f_{cB} denotes the strength of sealed SCC; ln denotes the natural logarithm; t denotes age ($1 < t < 18$ months); w/b denotes the ratio of amount of water to cement and silica fume; R^2 denotes an accuracy factor.

Fig. 2 shows the elastic modulus versus 100-mm cube strength, f_c. Also in this case little difference between the elastic modulus, E, of NC and SCC was observed when the strength was held constant. An equation for E [Eq. (2)] was calculated based on Fig. 2 (GPa):

$$E = 3.75\sqrt{f_c} \qquad R^2 = 0.78 \tag{2}$$

Fig. 3 shows the $1\frac{1}{2}$ year shrinkage versus the 28-day strength, which was well correlated to Eqs. (3) and (4). The result in Fig. 3 exhibits small differences between shrinkage of SCC and NC at constant strength, which is realistic. Strength reflects the porosity of the concrete, which in turn affects drying shrinkage.

$$\varepsilon_{shr,B} = 6.4 \cdot f_c - 0.034 \cdot f_c^2 - 20 \qquad R^2 = 0.58 \tag{3}$$

$$\varepsilon_{shr,D} = 5.8 \cdot f_c - 0.053 \cdot f_c^2 + 530 \qquad R^2 = 0.67 \tag{4}$$

f_c denotes the 28-day strength ($25 < f_c < 140$ MPa); $\varepsilon_{shr,\ B}$ denotes $1\frac{1}{2}$ year shrinkage with sealed curing (mil-

Table 3
Chemical composition and the characteristics of the cements [18]

Type	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	Specific Surface (Blaine)	Density
Degerhamn	64.9	22.2	3.36	4.78	0.91	0.56	0.04	2.00	302 m^2/g	3220 kg/m^3
Slite Std	62.2	19.6	4.29	2.18	3.53	1.33	0.28	3.73	363	3110

Table 4
Mix composition and characteristics of the concretes (kg/m^3 dry material) [20]

Material/mix	27S	32N	38N	38S	50N	50S	80N	80S
Quartzite 11–16 mm	800	660	560	620	420	525	600	270
Quartzite 8–11 mm	60	135	270	305	330	285	300	395
Sand 0–8 mm, Åstorp	880	694	780	790	860	840	1000	1000
Quartzite fillers, B6, B7	50	106	68	145	33	165		185
Cement, Degerhamn	500							
Cement, Slite		389	360	400	285	340	250	260
Silica fume	50							
Air-entrainment, L14 (g/m^3)		50	45		27	24		
Superplasticizer, Cementa 92 M		3.6	2.6		0.93			
Superplasticizer, Glenium 51	5.0			2.0		1.2		1.0
Water reducer, Cementa LP40		1.7	0.90		1.1			
Water	133	126	137	153	142	170	200	207
Aggregate content (% by vol.)	0.72	0.75	0.77	0.77	0.79	0.78	0.81	0.80
Density	2478	2115	2178	2415	2072	2325	2350	2318
Air content (%)	1.3	12	12	1.4	13	3.5	1.2	1.9
Slump or slump flow (cm)	70 × 72	11	16	53 × 54	22	56 × 60	8	54 × 57

lionths); $\varepsilon_{shr,\ D}$ denotes $1\frac{1}{2}$ year shrinkage with air curing (millionths).

Fig. 4 shows the 28-day RH of the concretes versus age [20,21]. Autogenous shrinkage is caused by self-desiccation, which occurs at high strength (Fig. 4) [22]. Fig. 3 and Eqs. (3) and (4) show that shrinkage of SCC did not differ to any great extent from that of NC when strength was held constant. This is reasonable since shrinkage is mainly affected by the porosity of the concrete provided that the aggregate was more or less held constant, Table 4 (the aggregate content varied between 0.72 and 0.81 but was held constant at each w/b). The workability of the concrete in the fresh state, NC or SCC, did not exhibit any influence on the shrinkage, which, again, is believable.

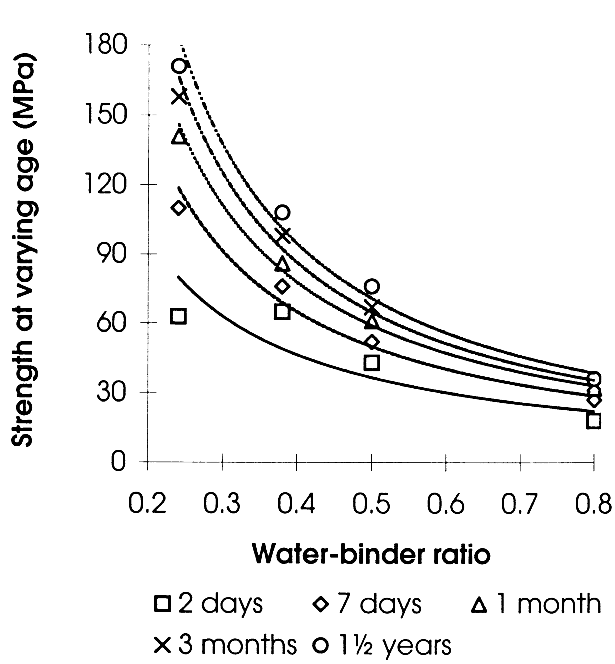

Fig. 1. Strength of SCC versus w/b at different ages.

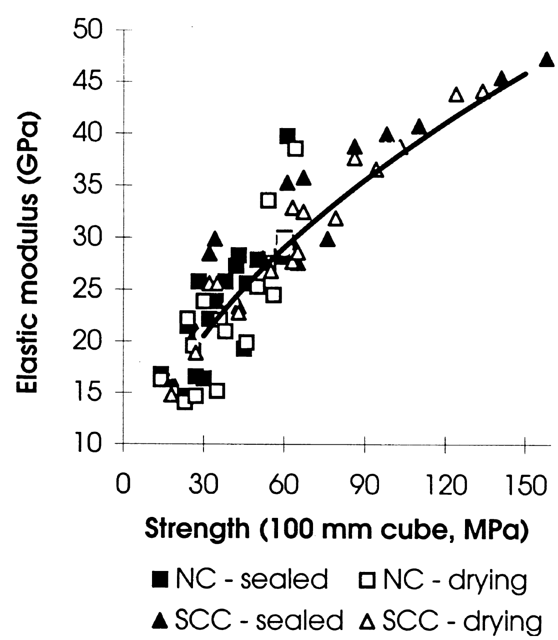

Fig. 2. Elastic modulus (GPa) versus 100-mm cube strength (MPa). Type of curing.

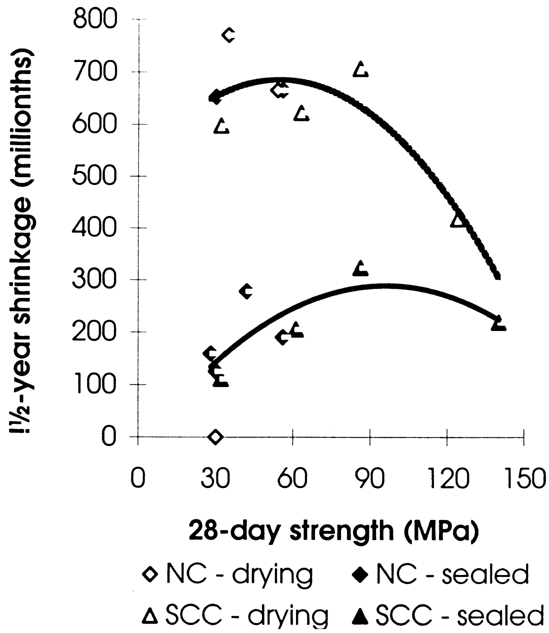

Fig. 3. $1\frac{1}{2}$ year shrinkage versus 28-day strength. NC = normal compacting.

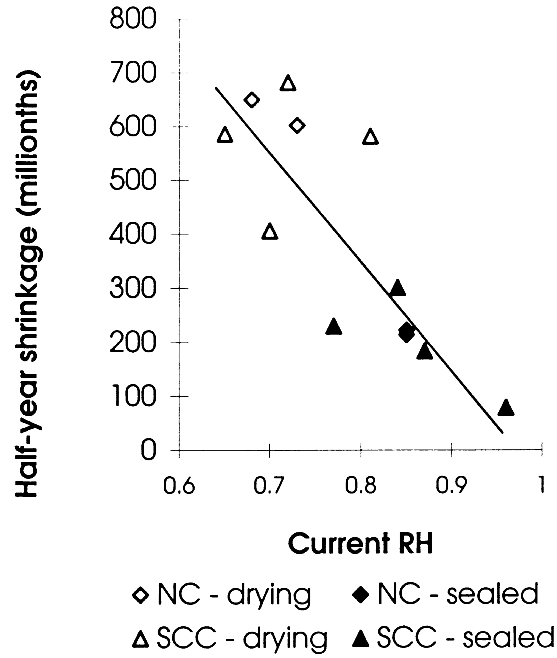

Fig. 5. Half-year shrinkage versus current relative humidity.

Fig. 5 shows that shrinkage, ε_{shr}, did not diverge between NC and SCC when RH was held constant. This observation in turn indicated that self-desiccation performed more or less parallel in NC and SCC, also a foreseen result. Fig. 6 shows the deformation under constant loading, compliance, ε/σ, versus the time of load duration for the SCC with w/b = 0.38. Fig. 7 shows the 1-year creep coefficient of mature concrete (which was 28 days old when loading) versus strength at 28 days' age. The different stress to strength levels, σ/f_c, 0.20, 0.40, 0.55 and 0.70 did not cause any significant difference between the calculated

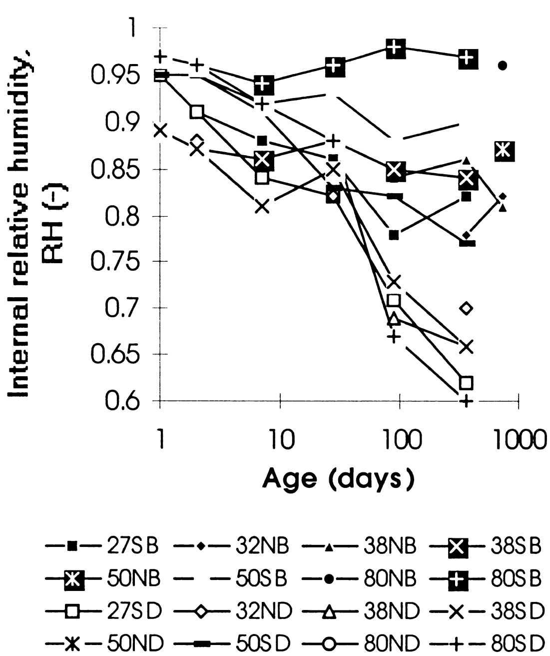

Fig. 4. RH versus age. 38 = w/b (%), B = sealed, D = drying, N = NC, S = SCC.

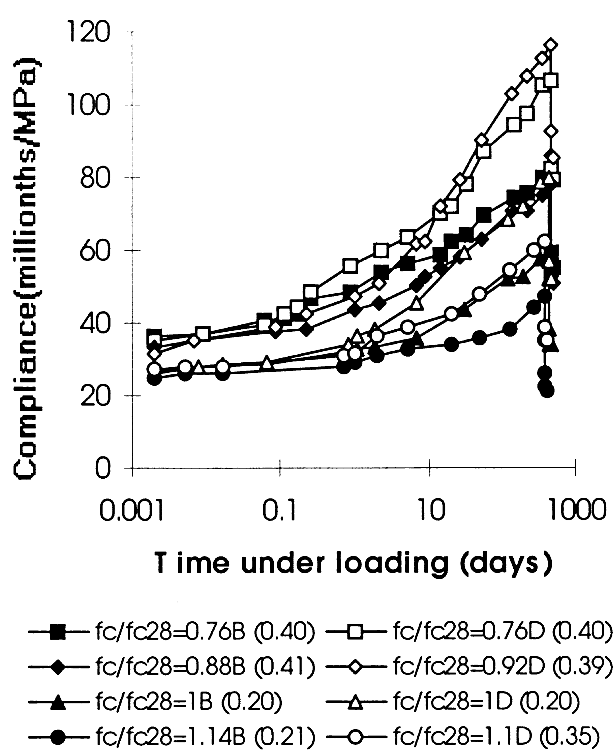

Fig. 6. Compliance versus time under loading. SCC with w/b = 0.38. f_c = strength at loading (MPa), f_c28 = 28-day strength (MPa), B = sealed, D = drying, (. . .) = stress/strength ratio.

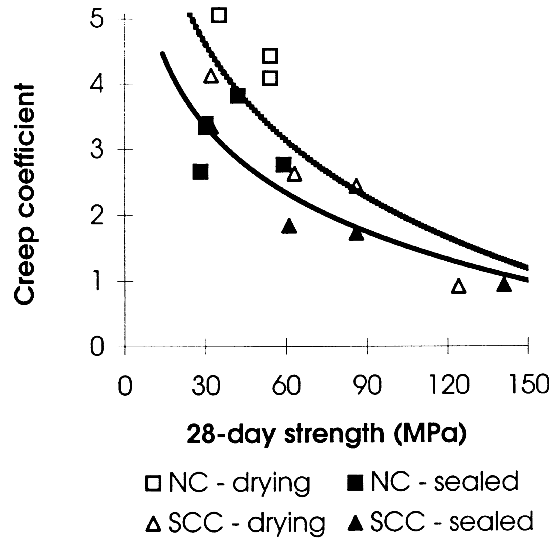

Fig. 7. Half-year creep coefficient of mature concrete (28 days old) versus cube strength.

creep coefficients. The following equations (Eqs. (5) and (6)) were obtained:

$$\varphi_B = 1.46[5.71 - \ln(f_c)] \qquad R^2 = 0.71 \tag{5}$$

$$\varphi_D = 2.13[5.55 - \ln(f_c)] \qquad R^2 = 0.63 \tag{6}$$

$\ln(f_c)$ denotes the natural logarithm of the compressive strength; φ_B denotes the sealed creep coefficient; φ_D denotes the drying creep coefficient.

Finally, Fig. 8 shows the effect of the relative 28-day strength on the creep coefficient. The effect of the relative strength of the concrete when it was loaded corresponded well with the results obtained by Müller and Küttner [23].

3.2. Discussion of reasonableness

A comparison between SCC with quartzite filler and NC without filler showed that SCC obtained about 20 MPa higher strength at w/b = 0.40 and about 5 MPa higher strength at w/b = 0.80 compared with NC (both concrete types without air-entrainment) [24]. Also, a comparison between SCC and NC at constant porosity shows small differences, which indicates the corresponding strength properties of the two types of concretes [20]. Similar results as related to strength were observed for the elastic modulus of SCC and NC (Fig. 2). Regression of the four different alternatives in the experimental study of the elastic modulus, SCC and NC — sealed or air-cured, exhibited more or less corresponding curves (Fig. 2), which was expected since the strength of SCC and NC also corresponded well when the porosity was held constant. What is more notable is a comparison between SCC and NC with self-desiccation (Fig. 4). When w/b was held constant, RH of the two kinds of concrete (with sealed curing) behaved identically, i.e. the filler added to the SCC did not at all affect self-desiccation. This is logical since a quartzite filler does not cause any chemical shrinkage in the structure, the fundamental reason for self-desiccation [21]. Also, with air-curing RH in SCC and NC seemed to proceed in parallel ways, which indicates that the filler content of SCC did not delay desiccation. The capillary pores are small in comparison with the size of the filler particles. Since RH is the driving force of shrinkage and RH proceeds in similar ways in SCC and NC, this also applies to shrinkage (Figs. 3 and 5) (given constant aggregate content at each w/b since the aggregate restrains shrinkage). The creep coefficient shows similar tendencies in SCC and NC since creep also is a phenomenon related to moisture movements in the structure (Fig. 7). The moisture conditions, aggregate content and loading conditions being

Half-year creep coefficient of mature concrete (28 days old) versus cube strength.

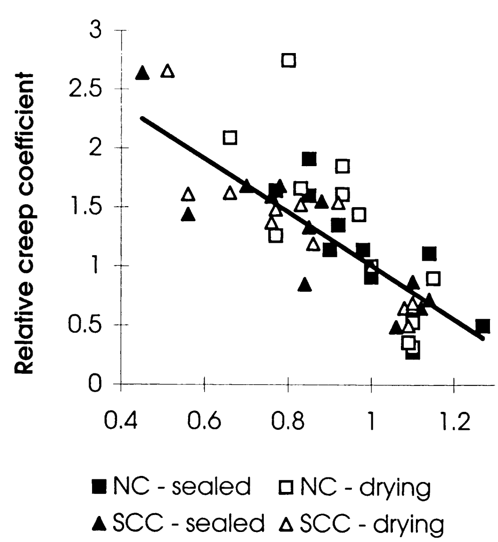

Fig. 8. The effect of the relative 28-day strength on the creep coefficient.

equal when testing SCC and NC, the results of creep also will be alike. Finally, Figs. 6 and 8 confirmed that the results for NC apply to SCC, i.e. when age at loading increased in the testing procedure the creep coefficient diminished.

4. Summary and conclusions

Experimental and numerical studies were performed on $1\frac{1}{2}$ year strength; elastic modulus, creep and shrinkage of SCC, including eight mix compositions of sealed or air-cured specimens with water–binder ratio, w/b, varying between 0.24 and 0.80. Half of the mixes studied were based on NC. The age at loading varied between 2 and 90 days. Four different stress to strength levels, σ/f_c, were studied, 0.20, 0.40, 0.55 and 0.70. Parallel studies were performed on strength, f_c, and relative humidity, RH. The following conclusions are drawn:

- Creep, shrinkage and elastic modulus of SCC coincided well with the corresponding properties of NC when the strength was held constant.
- The creep coefficient of mature SCC coincided well with the corresponding property of NC when the strength at loading was held constant.
- The creep coefficient of young SCC increased substantially when the concrete was loaded at low age, in the same manner for SCC and NC.
- The creep coefficient decreased substantially when the strength of the concrete was high, i.e. in HPC.

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