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A review of the hardened mechanical properties of self-compacting concrete

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Abstract

Data from more than 70 recent studies on the hardened mechanical properties of self-compacting concrete (SCC) have been analysed and correlated to produce comparisons with the properties of equivalent strength normally vibrated concrete (NVC).

The significant scatter obtained in much of the data is a consequence of the wide range of materials and mixes used for SCC, but clear relationships have been obtained between cylinder and cube compressive strength, tensile and compressive strengths, and elastic modulus and compressive strength. It is also clear that limestone powder, a common addition to SCC mixes, makes a substantial contribution to strength gain.

Bond strength of SCC to reinforcing and prestressing steel is similar to or higher than that of normally vibrated concrete. Variation of in situ properties in structural elements cast with SCC is similar to that with NVC, and the performance of the structural elements is largely as predicted by the measured material properties.

The analysis has shown that sufficient data have been obtained to give confidence in the general behaviour of SCC, and future studies need only be focused on specific or confirmatory data for particular applications.

Keywords: Self-compacting concrete; Compressive strength; Tensile strength; Modulus of elasticity; Limestone powder; Bond to steel; In situ properties; Structural properties

1. Introduction

Since self-compacting concrete (SCC) was introduced to the construction industry in the early 1990s, much of the extensive research and development work has of necessity been concerned with the achievement and assessment of fresh properties. It is, however, the hardened properties that are of paramount interest to structural designers and users, and much data have also been obtained on all aspects of these. Compressive and other strength data have routinely been obtained during mix development studies; other properties, such as elastic modulus, creep, shrinkage, bond to steel and durability have often been the subject of more specific investigations of varying size and scope.

Many of these numerous investigations have been limited to a relatively small number of mixes with a limited range of properties. Although the data obtained are useful, there is considerable advantage to be gained by comparing, correlating and critically reviewing them. So far, such reviews have mainly taken the form of summary sections in general specification and guidance documents produced by national and international committees and working parties e.g. [1–4]. These documents are aimed at specifiers and users, and cover all aspects of SCC; the sections on hardened properties are, of necessity, relatively brief. Klug et al. [5] have created a database from an unspecified number of sources on strength and elastic and time dependent deformation of SCC and analysed these in relation to values and limits in the European CEB-FIB model code [6].

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The amount of published material on SCC is burgeoning rapidly. As well as numerous papers in journals and conferences concerned with all aspects of concrete technology and practice, there have been six major international conferences[1] devoted specifically to SCC in the past seven years. A more comprehensive and critical review than hitherto of the substantial amount of information on hardened properties that is now available is therefore timely; this will be of interest to potential users of SCC, structural designers and those formulating experimental research and testing programmes. This paper presents the results of the first part of this review which has collated, analysed and compared test data on the mechanical properties of strength (compressive and tensile), fracture processes, elastic modulus, bond to steel and in situ and structural properties.

SCC includes a wide range of mix types with a wide range of both fresh and hardened properties, with practice often varying significantly within and between countries. Some caution is therefore required when making comparisons. The approach that is normally adopted within individual studies is to make comparisons of properties of SCC with those of equivalent strength conventional or normally-vibrated concrete (NVC)[2], although in many cases the number of SCC mixes tested is considerably larger than those of NVC. This approach is useful to designers in that it enables rules in codes of practice based on strength to be followed or modified as appropriate. Such comparisons have been included in this paper together with a more rigorous examination of the trends obtained. For the analysis of strength and elastic properties only data from specimens that have been cured in water at normal temperatures have been used.

2. Compressive strength

Some studies concentrated specifically on strength, but many others whose principal aim was the investigation of other properties (shrinkage, creep, durability, etc.) included compressive strength measurements; considerable quantities of data suitable for analysis were therefore available.

To achieve satisfactory combinations of high fluidity and stability (or, in rheological terms, low yield stress and moderate plastic viscosity) SCC requires high powder volumes at relatively low water/powder ratios with significant quantities of superplasticizers (sometimes supplemented by viscosity modifying agents). The powder generally consists of a combination of Portland cement with one more additions such as limestone powder, pulverized fuel ash (fly ash, pfa), ground granulated blast furnace slag (ggbs) and/or condensed silica fume (microsilica, csf), therefore strength tends to be governed as much by the type and proportion of powder addition than by the water/powder ratio.

The effect of an addition on strength can be analysed by determining its cement efficiency factor (k). This is the factor by which the quantity of addition is multiplied to give an equivalent amount of cement, which is then added to the actual amount of cement for calculation of an equivalent water/cement ratio. This approach is particularly useful for strength estimation during mix design e.g. [7]. In many of the studies which involved comparison of the properties of SCC and NVC, the NVC mixes consisted of CEM I (or similar) Portland cement with no additions. Estimates of the k-factors could then be made by

- assuming a typical variation of strength with water/cement ratio for the CEM I cement;
- determining the equivalent water/cement ratio for the concrete with the addition;
- obtaining the k-factor by simple calculation.

The values of k-factors obtained in the analysis are discussed below, after first considering the resulting strength vs. water/cement ratio relationships.

The test method – cubes or cylinders – and the aggregate type – crushed rock or uncrushed gravel – are likely to influence the strength vs. equivalent water/cement relationship, and the data were examined for the effect of both of these. Fig. 1 shows the data and relationships between cube strengths and equivalent water/cement ratio for SCC mixes with the two aggregate types and Fig. 2 the same relationship for cylinder strengths. The two sets of data show considerable overlap, which is to be expected considering the number of sources involved. With the cube strengths (Fig. 1) the crushed aggregate mixes have a higher strength, which is similar to the behaviour of NVC, but the average 4 MPa difference between the two best-fit curves is less than typical values of 8 MPa assumed in mix design procedures for NVC e.g. [7]. Fig. 2 seems to indicate the opposite behaviour for cylinder strengths, but there are fewer data with some scatter and only partial overlap of w/c values for SCC and NVC mixes.

Grouping the data for each aggregate type, the best fit lines for cube and cylinder strengths give the relationship between the cylinder/cube strength ratio and cube strength shown in Fig. 3. The ratio increases from 0.8 to near 1 with increasing strength, which is wider than the previously reported range of 0.9–1.00 [5]. It is also distinctly different to the near constant ratio of 0.8–0.83 for all concrete strengths used for the specification of strength classes in BS EN 206-1 [38]. In fact a similar increasing trend with strength, but with lower ratios, has been reported by Smeplass for high-strength NVC [39].

A possible explanation for this difference between the behaviour of SCC and NVC may come from the studies of Schiessl and Zilch [40] on the contribution of aggregate

[1] RILEM symposia 1–4: Stockholm (1999), Tokyo (2001), Reykjavik (2003), Chicago (Oct/Nov 2005); North American symposium 1 (2002), China symposium (2005). Papers from all of these conferences have been used in the analysis in this paper.

[2] In this paper the term 'normally vibrated concrete' (NVC) will be used for mixes which have to be compacted by vibration. This is thought preferable to such terms as 'normal' or 'traditional' concrete.

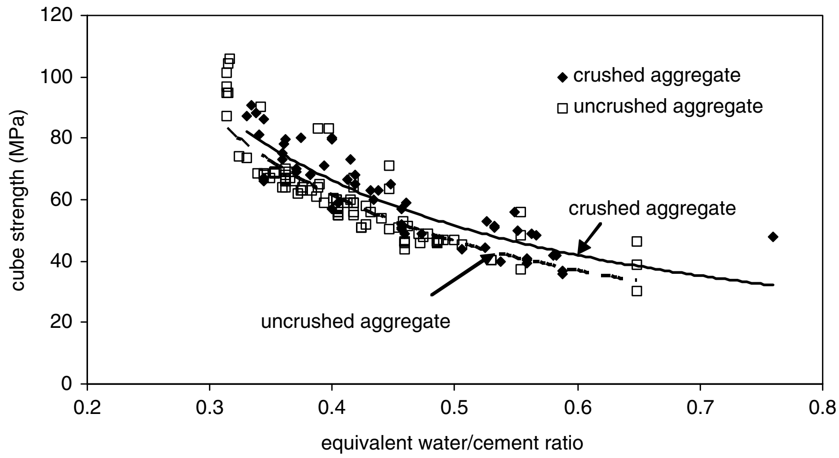

Fig. 1. Cube compressive strength vs. equivalent water/cement ratio (data from Refs. [8–29]).

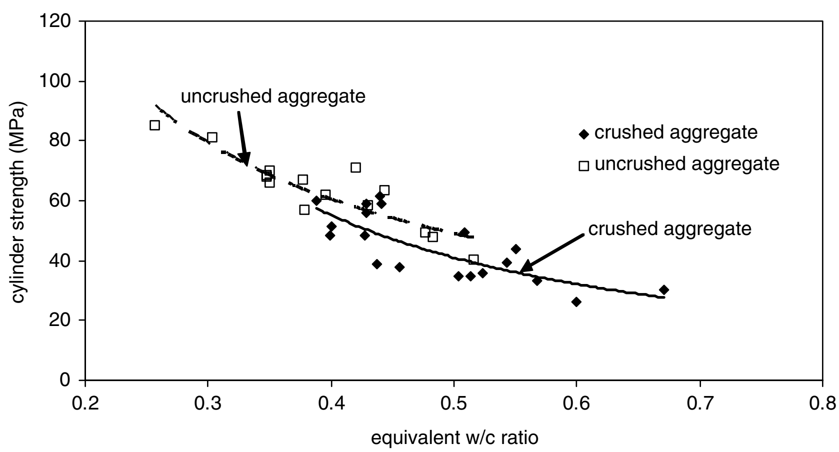

Fig. 2. Cylinder compressive strength vs. equivalent water/cement ratio (data from Refs. [30–37]).

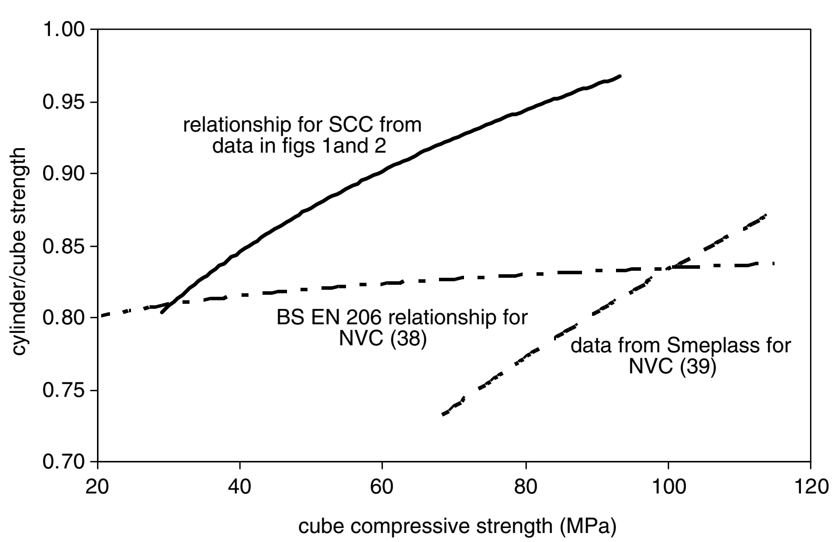

Fig. 3. Cube and cylinder compressive strength relationships.

interlock to the shear strength of cracked sections. They determined the shear strength of the interface between pre-fractured surfaces under varying levels of normal stress, and found that for similar strength concrete, the shear strength for any given normal stress was about 10% lower with SCC. They attributed this to the smoother crack surfaces in the SCC as a result of the lower coarse aggregate content. In compression tests, cracking and breakdown in cubes occurs under a more complex system of biaxial stress than in the centre section of cylinders, and hence shear movement between cracked surfaces will have a more significant effect on the ultimate average stress of cubes than of cylinders. In SCC, if the shear movement can occur at lower stress levels, then the cube strengths will be reduced and the cube and cylinder strengths will be closer.

3. Cementing efficiency factors

As mentioned above, only results from binary mixes with CEM I Portland cement were used in the cement efficiency (k) factor – strength analysis. Considerable variations obtained in the factor values were due to both the scatter of individual strength results and the variations between materials in the different test programmes. However, sufficient results were available for the determination of reliable average factors for limestone powder at 1, 7 and 28 days and for some other additions at 28 days; these are shown in Table 1.

The values for limestone powder are particularly interesting. The average value was significant at one day (0.22), and showed some increase at 7 and 28 days (0.36 and 0.29). There was no discernable trend of variation with increasing powder contents, which varied from 15% to 55% of the total powder. The contribution to strength was therefore substantial for all mixes at all the ages.

Table 1
Cementing efficiency factors from strength data analysis (from data in Refs. [8–37])

Addition	Range of addition rates (% total powder)	Average efficiency (k) factors		
		1 day	7 days	28 days
Limestone powder	15–55	0.22 (14)	0.36 (12)	0.29 (123)
pfa	20–60	–	–	0.56 (21)
ggbs	37–44	–	–	0.86 (5)
Chalk powder	25–55	–	–	0.23 (6)

Number of results in brackets.

There have been several studies on the effect of limestone powder on Portland cement hydration [41–44] which have shown that there are two distinct actions:

a. the fine limestone particles act as nucleation sites for calcium silicate hydrates, thereby accelerating the strength development at early ages;
b. carboaluminate compounds are produced by reaction with the aluminate phases (particularly the C_3A), and these have some cementitious properties. The magnitude of this effect depends on the C_3A content of the cement. There is also some reaction with the C_3S and C_2S phases producing carbosilicate hydrates.

The k-factor values obtained at 1, 7 and 28 days in the analysis are consistent with these two phenomena, but the values are somewhat higher than previously reported [43]. A model for this effect in SCC, including the effect powder particle size, has been suggested [44], but this is based on limited tests; more extensive testing to fully quantify the potential benefits of limestone powder would therefore seem to be appropriate.

The average k-values for the other additions were obtained from fewer data points. Those for pulverized fuel ash and ground granulated blast furnace slag are to be expected from knowledge of the pozzolanic nature of these materials. Interestingly, a few results with chalk powder as the addition indicate similar performance at 28 days to limestone powder; no results were reported at earlier ages [20].

4. Compressive vs. tensile strength

Indirect tensile strength tests have been included in many of the studies. Figs. 4 and 5 show the relationships

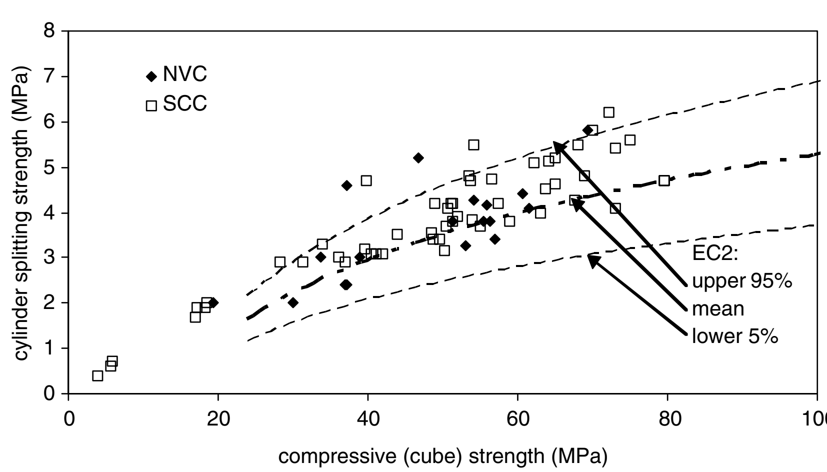

Fig. 4. Cylinder splitting vs. compressive strength (data from Refs. [11,15,20,32,33,10,45–50]).

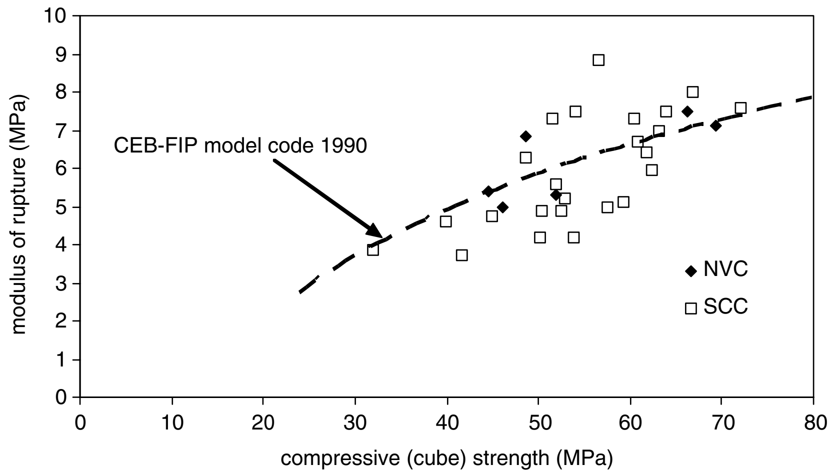

Fig. 5. Modulus of rupture vs. compressive strength (data from Refs. [27,45,47,51,52]).

between the cylinder splitting strengths and the modulus of rupture values respectively with compressive cube strength for both SCC and NVC mixes. Where compressive cylinder strengths have been reported these have been converted to cube strengths using the relationship shown in Fig. 3 before being plotted.

For both types of strength, there is significant scatter but no apparent difference between the behaviour of NVC and SCC. Fig. 4 shows that nearly all cylinder splitting results fall in the 5–95% centile ranges given in Eurocode 2 [53], with the majority being the upper half of this, and a few above the upper limit. The modulus of rupture results (Fig. 5) show higher scatter, with the mean being close to the relationship given in the CEB-FIP model code 1990 [6].

5. Modulus of elasticity

The relationships between cube compressive strength and static elastic modulus values for NVC and SCC mixes are shown in Fig. 6. Again, where compressive cylinder strengths have been reported these have been converted to cube strengths using the relationship shown in Fig. 3 before plotting.

The data in both sets show considerable scatter, which is to be expected since there was variation of both aggregate type and proportions within each set. The best fit line for the NVC data is very close to that of the approximate relationship given in EC2, but the stiffness of the SCC mixes is on average, about 40% lower than those of the NVC mixes at low strength levels, with the difference reducing to less than 5% at high strengths. This behaviour is consistent with the lower coarse aggregate quantities in SCC.

6. Fracture processes and mechanics

Fracture processes are important when considering the ultimate load characteristics and behaviour of concrete, and hence are relevant to ultimate limit state analysis. It might be expected that SCC would exhibit more brittle behaviour than NVC, as a crack can, on average, propagate further through the paste or mortar phase before being stopped or diverted by a coarse aggregate particle.

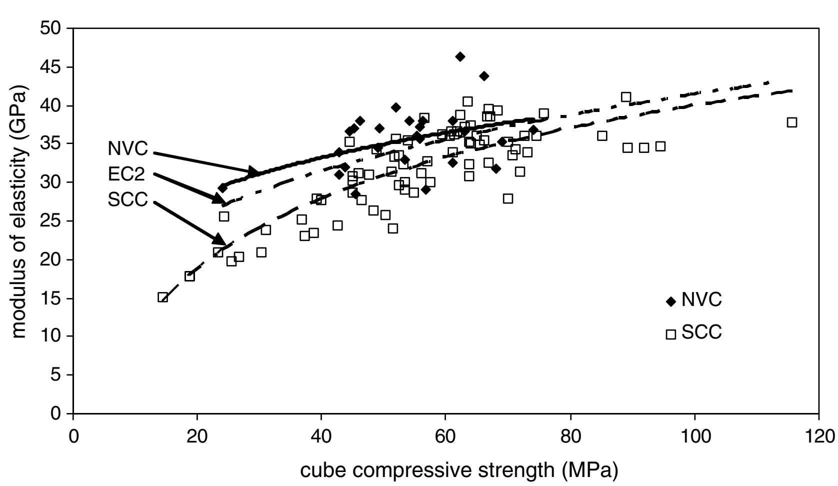

Fig. 6. Elastic modulus vs. compressive strength (data from Refs. [14,23,26,27,30,32,34,36,47,52,54,37,55,56]).

Results from two studies are, however, conflicting. Fava et al. [47] have compared the fracture processes in similar strength (50 MPa) notched specimens tested in three point bending. The specimens were 400 × 100 × 75 mm, with a 50 mm deep notch at midspan; midspan deflection and crack mouth opening displacement were measured during testing. They found similar facture behaviour in terms of fracture energy and characteristic length values in the SCC and NVC specimens.

Zhao et al. [57] measured the toughness and fracture toughness of four SCC mixes with compressive strengths of 40–150 MPa with wedge splitting tests on notched specimens. They obtained similar toughness values between 51 and 67 N m/m^2, which are lower than the typical values for NVC of 90–135 N m/m^2 given in the CEB-FIP model code 1990 [6]. The characteristic length of the mixes reduced with increasing strength, indicating more brittle behaviour, but the fracture toughness increased from 1 to 1.75 MPa m$^{0.5}$ over the compressive strength range, from which it was concluded that it is not an appropriate indicator of brittleness.

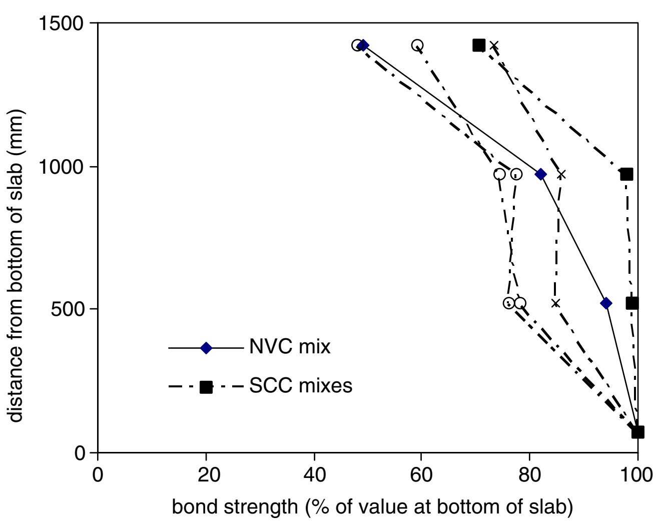

Fig. 7. Variation of bond strength to 20 mm dia. deformed reinforcing bars with height in a wall slab element (data from Ref. [59]).

7. Bond to steel

The bond between steel and concrete is important when considering anchorage lengths required for reinforcement and transmission and anchorage lengths in prestressing wires in pretensioned elements. Bond defects may also render the steel vulnerable to corrosion.

Studies of the bond of SCC to reinforcing steel have taken two forms:

- pull-out tests on bars embedded at varying heights in mock-up structural elements, to assess the so-called 'top bar' effect;
- tests on single bars in smaller prismatic specimens using the CEB/RILEM test method or similar [58].

The top-bar effect arises from the reduction of bond efficiency by the formation of voids under horizontal bars which are perpendicular to the casting direction of the concrete. Rising bleed water can be trapped under the bars, and any settling of the concrete can leave air voids under the bars which will compound the effect. The amount of bleeding increases with concrete depth below the bar, resulting in lower bond strength in the upper parts of a deep section. For example, EC2 [53] requires the ultimate bond stress where there is more than 250 mm of concrete below the bar to be reduced to 70% of its value in shallower sections.

Properly designed SCC, although having high fluidity, is sufficiently stable to have minimal bleed and hence it might be expected that the top-bar effect could be reduced. Figs. 7 and 8 summarise the results of two programmes that have investigated this.

Fig. 7 shows the results of tests on a set of five wall elements, each 1.5 m high, with deformed bars at four levels. Four of the elements were cast with SCC of differing compositions and one with an NVC mix. The in situ

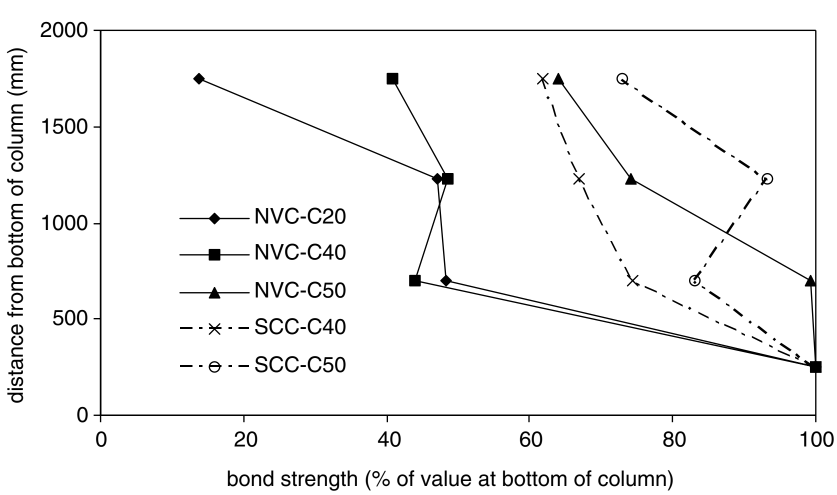

Fig. 8. Variation of bond strength to 10 mm dia. plain reinforcing bars with height in a columns element (data from Soylev and Francis [33]).

strength for the NVC was approximately 50 MPa, and the in situ SCC strengths varied from 35 to 43 MPa. All mixes showed a reduction in bond strength with increasing height in the wall, i.e. with a greater depth of concrete below the bars. Three of the SCC mixes behaved similarly to the NVC mix and one somewhat better at all heights. The NVC and two of the SCC mixes also showed a reduction greater than the EC2 top-bar factor at the top of the section.

More extreme behaviour was obtained from tests on round bars in 2 m high columns (Fig. 8 [33]). Each data point is the average from bars at three closely spaced levels. Columns with three NVC and two SCC mixes with varying strength levels were tested, and considerable reductions in bond strength (of up to 80%) were obtained with the two lower strength NVC mixes. The two SCC mixes and the highest strength NVC mix showed broadly similar behaviour, with reductions in bond strength similar to that recommended in EC2 [53].

Clearly a range of behaviour can be obtained with both and SCC and NVC; Petrov et al. [60], with similar test procedures to those used to produce the results in Fig. 7, have shown the importance of the stability of SCC in maintaining bond strength.

Results relating bond strength and concrete compressive strength are shown in Fig. 9. This includes data from the programmes which produced the results in Figs. 7 and 8 (in which the in situ concrete strengths were measured at locations close to the bars). Bond strengths vary with bar size, bar type (plain or deformed) and concrete strength, and also show significant scatter within each programme, but nevertheless it is apparent that there is little difference between the bond to SCC and that to NVC when all other variables are constant.

In programmes in which a more limited number of results have been obtained, de Almeida Filho et al. [26] obtained similar bond strengths with SCC and NVC, Chan et al. [62] and Daoud et al. [63] obtained 5% higher strengths with SCC, and Collepardi et al. [25] and Zhu et al. [64] strengths of up 25% higher with SCC, but lower bond stresses with increasing bar size. Zhu et al. also investigated the steel–concrete interfacial transition zone (ITZ) with a nano-indentation technique, and found that their increased bond strength with the SCC mixes could be attributed to a greater uniformity in the ITZ around bars. Finite element analysis of the bond mechanism has successfully modelled this effect [65].

These results show that the bond strength of steel to SCC is certainly no lower that to the equivalent NVC and it some cases may be usefully higher. However, the inherent scatter in data and the range of properties that can be expected from SCC mean that a number of tests with any particular mix and bar geometry must be carried to substantiate any increased bond capacity.

Bond of prestressing strand has become increasingly important with the spread of SCC to precast concrete production. A key parameter is the transmission length of strand required for full development of the prestress in the concrete at transfer.

Results from two programmes using similar 7-wire 12 mm dia. strand are shown in Fig. 10 [66,15]. Different transmission lengths were obtained in the two programmes at higher concrete compressive strengths, but within each programme the strands in SCC and NVC performed similarly. Conversely, Burgeno and Haq [67] found transmission lengths with SCC up to 50% longer than those with an NVC, with significant differences between the three SCC mix tested (but no concrete strength values were reported).

Larson et al. [68] found a significant top-strand effect in 600 mm deep beams cast with SCC, with the top strand 50 mm below the upper face of the beams. Khayat et al. [36] have carried out pull-out tests on prestressing strand form a 1.5 m high wall element, and assessed the variation of bond strength with height in a similar way to that used to produce the results shown in Fig. 7. The same general effects were obtained, with SCC producing similar bond strengths to NVC.

Although it is therefore likely that, as with bond to reinforcing steel, prestressing strands behave similarly in SCC

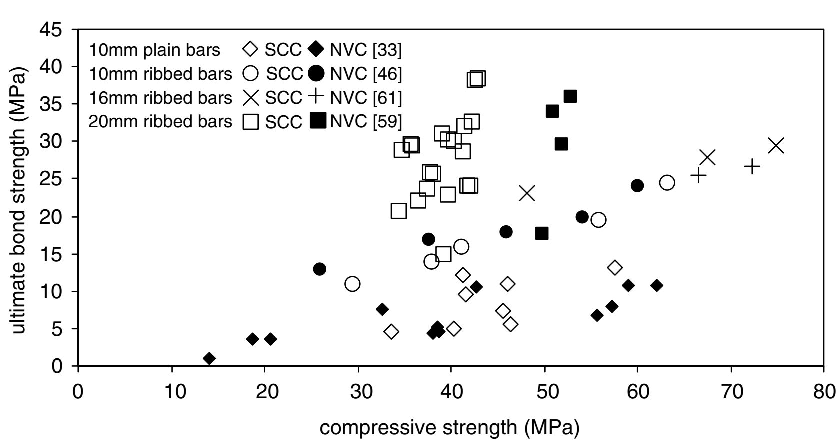

Fig. 9. Bond strength of reinforcing bars vs. concrete compressive strength (data from Refs. [59,33,46,61]).

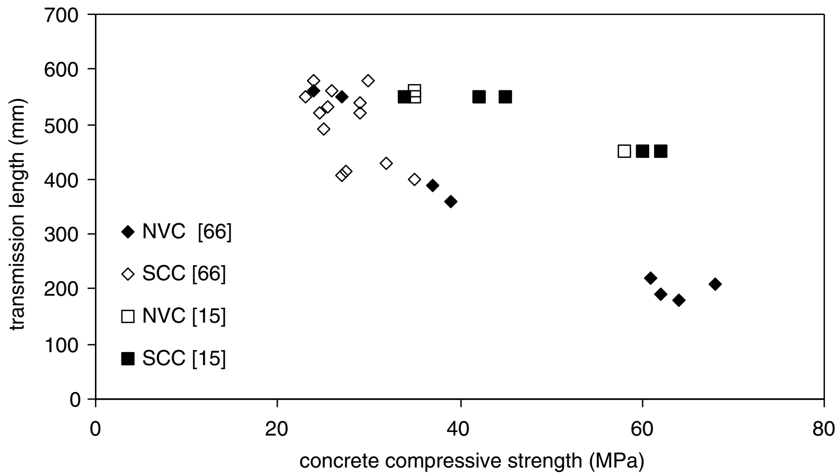

Fig. 10. Transmission length of prestressing strand vs. concrete compressive strength at transfer (data from Refs. [66 and 15]).

and NVC, confirmation with more extensive tests would be helpful.

8. In situ properties

Knowledge of the variation of in situ properties within structural elements and the relationship between the in situ properties to those of standard specimens made from samples of the concrete taken at casting are important for both design and performance. Table 2 summarises the results from five studies with varying types and sizes of elements, each testing a combination of SCC and NVC control mixes.

All the studies included tests on wall or column elements of significant height. A reduction in in situ strength with height would be expected, and the top/bottom strength ratios show largely similar behaviour of SCC and NVC mixes, albeit with some variations within and between studies. The uniformity of strength within the test elements, expressed as coefficients of variation of core strengths, has a tendency to be a little higher for SCC and than for NVC, but again there is no consistent pattern. A similar comment

Table 2
Variation of SCC properties in structural test elements

Reference	Elements	Concrete type and strength	Top/bottom strength ratios	Strength variation in elements (cov)	In situ/sample strength
Khayat et al. [59]	1.5 × 0.95 × 0.2 m walls unreinforced	8 SCC mixes, 1 NVC mix 40–70 MPa	SCC 10 mm agg. 97–104% SCC 20 mm agg. 92–100% NVC 94%	SCC 10 mm agg. 2.9–3.3% SCC 20 mm agg. 1.8–5.5% NVC 6.5%	SCC 10 mm agg. 90% SCC 20 mm agg. 75–85% NVC 85–90%
Khayat et al. [30]	1.4 × 0.24 × 0.24 m columns unreinforced	1 NVC and 1 SCC mix, 50 MPa	SCC 101% NVC 87%	SCC 2.8% NVC 6.8%	SCC; 87% NVC: 91%
Zhu et al. [69]	3 m columns reinforced 3.8 m beams reinforced	C35 and C60 SCC and NVC reinforcement in elements with C60 concrete	SCC 89, 97% NVC 88, 97% –	SCC 6.6, 6.3% NVC 5.6, 9.0% SCC 8.8% NVC 5.7, 6.6%	SCC 91, 94% NVC 90, 91% SCC 83% NVC 79, 96%
Hoffmann et al. [13]	Parts of in situ tunnel walls, 5 m × 2 m Lab cast complex element 1.13 × 1.95 × 0.2 m reinforced Lab cast walls 2.7 × 0.75 × 0.2 m reinforced	3 sections with SCC 1 section with NVC strength 45–70 MPa 2 SCC + 1 NVC mix strength 50 MPa 3 SCC and 1 NVC mix strength 55 MPa		SCC: 8.5, 10.6, 12.9% NVC 13.6% SCC: 7.5, 10.3% NVC 8.4% Coefficients of variation: SCC: 4.7, 6.9, 7.8% NVC 6.7%	
Khayat et al. [36]	Lab cast walls 1.54 × 1.1 × 0.2 m unreinforced	1 NVC mix (flowing) 2 SCC mixes strength 56–59 MPa	All mixes 95%		NVC: 85% SCC: 88–104%

Table 3
Stuctural tests on concrete elements

References	Test details	Concrete type and strength	Results: SCC vs. NVC
Reinforced concrete			
Khayat et al. [30]	2.35 m columns, axial load	40–50 MPa SCC and NVC (2 columns with each)	Similar stiffness and load response ultimate strains 50% higher in SCC columns
Sonebi et al. [11]	3.8 m beams in 4-point bending	C60 NVC and SCC (1 beam with each)	Similar cracking and ultimate loads narrower cracks with SCC 5% greater deflection in SCC beam
Das et al. [70]	1.2 m beams in 4-point bending tensile steel only shear failure	SCC 46 MPa at 28 days NVC 59 MPa at 28 days (8 beams with each)	Similar load deflection behaviour Narrower cracks with SCC Shear strength 9–12% higher in SCC beams
Peter et al. [45]	3 m beams in 4-point bending:	72 MPa SCC, 69 MPa NVC	12% higher peak loads in SCC beams
	(a) Singly under-reinforced		10–15% higher deflection at first cracking in SCC beams
	(b) As (a) with shear stirrups		10% higher curvature in SCC beams similar crack width and spacing
Angotti et al. [71]	2 m slender columns, eccentric loading	4 NVC mixes: 48–120 MPa 3 SCC mixes: 46–93 MPa (60 columns tested)	Generally similar behaviour, but with lower strength and greater ductility in SCC columns
Huang [72]	3 m × 1.65 m frame under cyclic loading	SCC and NVC	Viscous damping higher in SCC frame less energy absorbed in plastic hinge in SCC frame
Prestressed concrete			
Naito et al. [48]	10 m pretensioned T-beams	59 MPa SCC, 51 MPa NVC	Marginal greater deflection in SCC beams similar strength levels

applies to the relationship between in situ and cast sample strengths.

These tests therefore show that SCC has no greater problems than NVC with regard to in situ properties, which was the aim of some of the studies. All of the test elements were prepared with full attention to good practice, e.g. full vibration of the NVC, and the studies have not attempted to assess the ability of SCC overcome the problem of lack of site skills and supervision, one of original driving forces for its development SCC in Japan. Also, the good behaviour of SCC depends on the mix being properly designed and produced to have properties suitable for the specific application. Clearly, mixes must have adequate filling and passing ability for the specific application, and as noted by Hoffmann and Leeman [13], any tendency to segregation can have significant detrimental effects.

9. Structural performance

There is sufficient knowledge of structural behaviour for structural performance to be predicted with reasonable confidence from property data such as those described in this paper. The relatively limited number of test programmes on structural elements which have been reported area have generally confirmed this.

The scope and results from several such test programmes on structural elements cast with SCC and NVC of similar strength are summarised in Table 3. Despite some conflicting results, reinforced SCC beams have

- similar load capacity;
- some tendency to greater defections and ultimate strains (consistent with the lower elastic modulus values shown in Fig. 6);
- greater shear strength, for beams with no shear reinforcement (apparently inconsistent with lower shear strength reported by Schiessl and Zilch [40] discussed earlier).

A greater ultimate strain capacity, and hence ductility, of SCC elements has also been obtained in the test programmes on columns. At first glance this would seem be in contradiction to the possibly lower toughness of SCC discussed earlier. However, it is likely that the apparent ductility of structural elements results from the lower elastic modulus of the SCC in the uncracked region of the element, and any susceptibility of the SCC to earlier tensile cracking is of lesser importance. The tests on the behaviour of frames under cyclic loading indicate a potential advantage of SCC in seismic design, which is perhaps an area for useful further research.

One set of tests on three prestressed members have shown essentially similar behaviour for SCC and NVC.

10. Conclusions

Analysis and comparison of data from more than 70 studies of the hardened mechanical properties of self-compacting concrete has shown significant scatter both with and between different studies, which is understandable in view of the range of materials, mix designs and test procedures used. However, a number of clear conclusions have been obtained about the behaviour of SCC in relation to NVC.

1. Compressive strength results show that
   - the difference of strength between mixes with crushed and uncrushed coarse aggregate is lower for SCC than for NVC;
   - the ratio of cylinder to cube strength for SCC varies from about 0.8 at strengths of 30 MPa to near 1 at strengths of 90 MPa, which at all but the lowest strength is greater than values used for NVC;
   - limestone powder, a commonly used addition in SCC, contributes significantly to strength at ages up to at least 28 days: a cementing efficiency factor between 0.2 and 0.3 is appropriate.
2. The ratio of tensile to compressive strength for SCC is similar to that for NVC, with the great majority of cylinder splitting results for both types of concrete falling in the upper half of the range suggested in EC2.
3. The elastic modulus of SCC can be up 40% lower than of NVC at low (c. 20 MPa) compressive strength, but the difference reduces to less than 5% at high strengths (90–100 MPa).
4. There are conflicting results on toughness and ductility of SCC. Fracture toughness tests on plain concrete show that SCC may have similar or lower toughness to NVC, but structural performance tests on reinforced concrete elements indicate greater ductility, particularly with columns. However, only a limited number of test programmes have been carried out in this area.
5. The bond of SCC to embedded reinforcing and prestressing steel, either in the relation to concrete strength or in the top-bar effect in deep sections, is essentially similar to the equivalent NVC.
6. The variation of in situ properties in structural elements with SCC is likely to be similar to that for NVC, but with SCC the mix design is the most important factor giving good performance whereas with NVC site practice is more critical.
7. The behaviour of reinforced or prestressed structural elements cast with SCC is as expected from the material properties i.e. similar load capacities at slightly higher deflections than with the equivalent NVC.

Overall, the analysis of the substantial amount of data from the extensive test programmes carried out in the past few years has lead to confidence in the hardened properties of SCC, and that applicability of the design rules and practice for NVC developed over many decades can be used for structures cast with SCC. In most areas analysed in this paper, only confirmatory tests on the properties of particular SCC mixes for specific applications are now required. The exception is in the structural performance of SCC in demanding applications, for example in earthquake resistant structures.

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