Chapter 2
Mechanical Properties

Pieter Desnerck, Veerle Boel, Bart Craeye and Petra Van Itterbeeck

2.1 Introduction

For more than 20 years, self-compacting concrete (SCC) has been applied in the construction industry. In this period, a lot of research has been performed with regards to the applicability, mix design, pump-ability, durability, rheology, etc. of SCC. In the nineties, little attention was devoted to the mechanical properties of the material and to its structural performance. Recently, an increasing amount of research has been dedicated to these mechanical properties of SCC [1].

Research projects often include data on compressive strength, tensile strength, and Young's modulus, although the main focus remained on other aspects of the concrete as mentioned above. In the past, some authors, e.g. Domone [2] and Holschmacher [3], have presented surveys on the mechanical properties of SCC based on available literature. Due to a scarce amount of available test results, these studies were based on a limited set of data. In this way they did not include, neglect or generalise the influence of some major parameters for the mechanical behaviour, such as type of aggregate. Therefore, it was decided, in the scope of this chapter to develop an extensive database with results on fresh and hardened properties of SCC reported between 1990 and 2011, originating from numerous journal and conference papers.

P. Desnerck (✉)
Center for Infrastructure Engineering Studies, Missouri University of Science and Technology, Rolla, MO 65409-0710, USA

P. Desnerck · V. Boel
Ghent University, Ghent, Belgium

B. Craeye
Artesis University College of Antwerp, Antwerp, Belgium

P. Van Itterbeeck
BBRI, Brussels, Belgium

K. H. Khayat and G. De Schutter (eds.), *Mechanical Properties of Self-Compacting Concrete*, RILEM State-of-the-Art Reports 14,
DOI: 10.1007/978-3-319-03245-0_2,

Table 2.1 Ranges of reported fresh properties for SCC

Property		# measurements	Min.	10 % centile	Mean	90 % centile	Max.
Slump-flow	[mm]	1,545	320	600	690	780	933
V-funnel	[s]	741	1.0	3.5	9.3	16.0	57.2
L-box	[-]	563	0.20	0.73	0.86	0.97	1.12
Sieve stability	[%]	141	0.20	2.24	8.35	15.51	29.30
Air content	[%]	488	0.4	1.3	3.2	6.1	12.8

To allow for a full assessment of the mechanical performance of SCC this database also includes information on the mixture proportion and design, the fresh concrete properties and testing conditions (e.g. type and geometry of specimens). Mixture composition information included in the database are water content, cement content and type (Portland, binary types, etc.), addition content and type (limestone, fly ash, ground granulated blast-furnace slag, silica fume), viscosity modifying agent (VMA) content, superplasticiser content and type (polycarboxylic, etc.), air entrainment content, aggregate type, aggregate content and maximum aggregate size, etc.

To be able to quantify the self-compacting properties of the reviewed mixtures that are reported in the literature, results of fresh concrete property tests such as slump-flow (SF), V-funnel, L-Box, U-Box, sieve segregation, etc. were collected as well. With respect to the mechanical properties, information on the test age, test standards, specimens sizes and types (cylinders, cubes, prisms), compressive strength, direct tensile strength, splitting tensile strength, flexural tensile strength, and Young's modulus were gathered.

With more than 1,500 mixtures reviewed in the database that cover a wide range of SCC types (e.g. powder-type SCC, VMA-type SCC, Combination-type SCC) [4]—taken from more than 200 papers [5–238] (35 different countries)—an extensive dataset is available for thorough investigation of the influences of different parameters on the mechanical properties of SCC's. Based on the data entered in the database, the influence of some parameters, which could be of major interest to users, designers, etc. are derived (see following sections), including W/C, W/B, W/P, S/A, addition content, and ratio of cylinder to cube compressive strength.

In most studies, the fresh properties of the mixtures are characterized by means of the V-funnel, L-box, etc. The most commonly reported fresh property is the slump-flow. The ranges of fresh properties of the so claimed SCCs are listed in Table 2.1. For the V-funnel measurements, different dimensions of the outlet can be used. However, in papers the authors do not often include the applied type. Therefore, all V-funnel measurements are combined regardless of the dimensions.

As can be seen from Table 2.1, the slump-flow values range from 320 to 933 mm. The majority of the test results (95.1 %) are within the range of 550–850 mm defined by EN 206-9 [239] for SCC (Fig. 2.1).

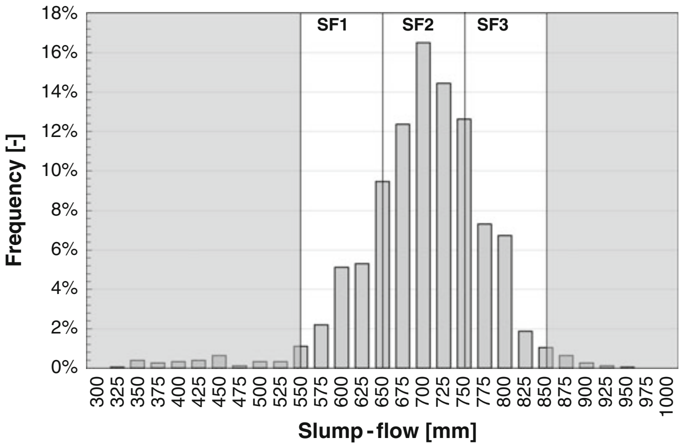


Fig. 2.1 Histogram of reported SF-values for SCC mixtures (based on 1,551 mixtures)

The committee believes that concrete mixtures with slump-flow values of 320 mm cannot be classified as self-compacting. Therefore, for the analysis of the hardened properties, only concrete mixtures with slump-flow values within the limits defined by EN206 (550–850 mm) were considered in this chapter.

As the database contains results from over 250 papers, it can provide insights on the ranges of SCC properties. These total ranges are of importance to determine classes of 'low', 'mean' and 'high' values of the different parameters which on their turn can be used in the analysis, as it will become clear in the following sections. SCC can be developed according to the powder-type SCC, VMA-type SCC or combination type SCC approach [4]. This is noted in the database as well. Based on the amount of mixtures in which a VMA is used, the powder-type approach was chosen in 83 % of the cases, whereas the VMA- or combination-type SCC mixtures were utilised in 17 % of the reported research projects.

Table 2.2 presents an overview of some of the major mixture properties of the different SCC mixtures that are considered in the database. Besides the maximum and minimum values, the mean values and standard deviations (SD) are provided as well as 10 % and 90 % centile values. Values of the water-to-cement ratio (W/C) are mentioned as well as the corrected water-to-cement ratio $(W/C)_{corr}$. The $(W/C)_{corr}$ considers the water content that is included in the superplasticiser as in some mixtures it can be as high as 14 l/m^3, which could lead to a significant contribution to the overall water content.

The cement, sand, and coarse aggregate contents generally vary in over a wide range, covering almost the entire range found for VC. With respect to the W/C, values between 0.19 and 2.73 are found with a mean value of 0.54. The highest reported W/C is relatively high, but it has to be emphasized that, in general, also other types of binders are used. All types of cement are applied in SCC mixtures: CEM I, CEM II, CEM III (according to European standards [240]), ASTM Type I,

Table 2.2 Applied ranges of mixture properties for SCC (1,474 mixtures out of 214 reported studies)

Property		Min.	10 % centile	Mean	90 % centile	Max.
Cement content	[kg/m^3]	83	250	360	490	700
Binder content	[kg/m^3]	150	300	420	550	750
Powder content[a]	[kg/m^3]	275	410	535	625	1272
Sand content	[kg/m^3]	135	600	800	940	1190
Coarse aggregate content	[kg/m^3]	283	650	820	1035	1740
Water content	[kg/m^3]	77	160	185	220	434
Paste volume	[l/m^3]	151	320	370	425	709
W/C	–	0.19	0.38	0.54	0.80	2.73
$(W/C)_{corr}$	–	0.20	0.39	0.55	0.81	2.81
W/B	–	0.15	0.33	0.46	0.63	1.33
W/P	–	0.14	0.27	0.36	0.45	0.65
C/P[b]	–	0.15	0.50	0.69	0.95	1.00
S/A[c]	–	0.10	0.37	0.50	0.60	0.81
Max. grain size	mm	5	10	16	20	25

[a] Powder = cement + SCMs + fillers
[b] C/P = cement to powder ratio by mass
[c] S/A = sand to aggregate ratio by mass

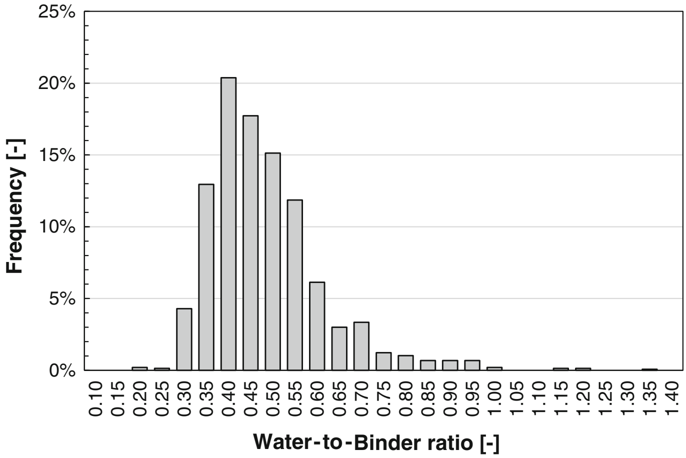


Fig. 2.2 Histogram of the applied W/B in SCC mixtures (based on 1,474 mixtures)

Type II, CEM Type GU (according to ASTM Standards [241]), etc. The W/B for the investigated SCC ranges from 0.15 to 1.33 with a mean value of 0.46. The majority of the mixtures were composed with a W/B between 0.33 and 0.63 (Fig. 2.2).

The higher powder content needed for SCC is obtained by increasing the cement content or more often by increasing the amount of additions (powder-type SCC). The addition can be composed of one or more types. As addition material,

Table 2.3 Origin of main addition materials (based on 1,352 mixtures)

Addition class	Amount (%)	Addition class	Amount (%)
Basalt	0.2	Natural pozzolan	0.2
Fly ash	35.1	Quartz	1.8
Granite	0.3	Rubble powder	0.2
Kiln dust	0.1	Silica	9.2
Limestone	40.7	Slag	9.0
Metakaolin	0.7	Vegetal ash	2.4

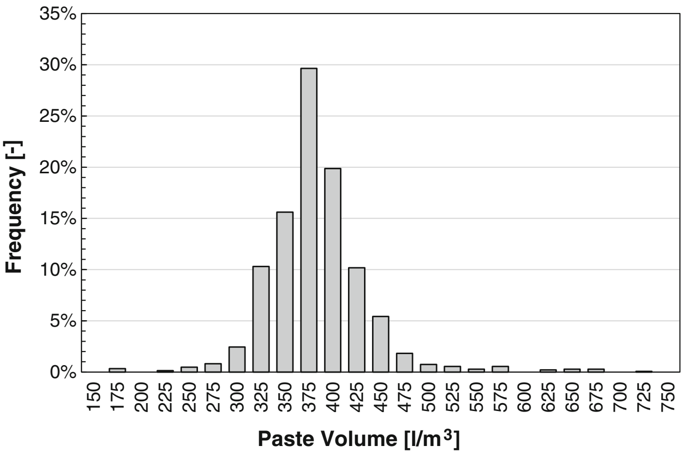


Fig. 2.3 Histogram of applied paste volumes in SCC mixtures (based on 1,474 mixtures)

inert as well as pozzolanic materials are widely used. The most used materials are limestone filler, fly ash, ground granulated blast-furnace slag, and silica fume. Less common fillers but nonetheless used in some cases, we note marble powder, glass powder, rice husk ash, metakaolin, volcanic ash, and granite powder.

In Table 2.3 the main addition type is mentioned together with the frequency of occurrence, as listed in the database. As SCC often is composed of larger amounts of fines compared to vibrated concrete, the powder content is higher as well. According to the database common powder contents for SCC mixtures are situated in the range of 410–625 kg/m^3.

Another important property influencing the mechanical properties of SCC is the paste volume. The total paste volume of a SCC mixture is, in most cases, higher than that of a VC mixture, which could have its repercussions on mechanical properties. The applied paste volumes (excluding air) in SCC mixtures can be seen in Fig. 2.3. Values of 150 l/m^3 up to 710 l/m^3 were found in the database with a mean value around 370 l/m^3, whereas for VC the mean value is situated around 290 l/m^3 [4].

The following paragraphs summarize the findings concerning SCC on the compressive strength, stress-strain relationship, modulus of elasticity, mechanical behaviour at elevated temperatures, and in situ properties. When applicable, the codes Eurocode 2 [257], ACI 318-08 [253], and CEB/FIP Model Code 2010 (MC2010) [268] are taken into consideration. In addition, more information regarding the application of other provisions can be found in NCHRP Report 628 [243].

2.2 Compressive Strength

2.2.1 Introduction

Design rules for concrete structures are often based on the compressive strength of the concrete. In Eurocode 2 concrete is classified solely on the basis of its compressive strength, in accordance with EN 206-1 [242] where cylinders 150/300 mm and cubes 150 mm are used as a reference. In other standards such as AASHTO and ASTM different types and sizes of specimens are also used. Many of the other mechanical properties (e.g. tensile strength, modulus of elasticity, and compressive strain) and physical properties (e.g. related to durability) of concrete are moreover expressed as a function of this parameter.

Many parameters are known to affect the compressive strength of concrete, most of them being interdependent. Some of the important parameters that may affect the compressive strength of concrete are the W/C, cement compressive strength, properties of the aggregates (shape, grading, surface texture mineralogy, strength, stiffness, and maximum grain size), air-entrainment, curing conditions, testing parameters, specimen parameters, loading conditions, and test age [244, 245]. Based on the discussion of the Sect. 2.1, the influence of the paste volume (air content excluded) will also be investigated. In the following section, curing and testing of the specimens are in accordance to international standards and are as such not within the scope of this chapter.

2.2.2 Compressive Strength at 28 days

As mentioned previously, only the SCC-mixtures are taken into account for which the slump-flow values are between 550 and 850 mm, thus meeting the requirements of the slump-flow classes defined in [246]. This results in 1,476 mixtures with 28-day compressive strength results out of 3,739 SCC mixtures. The limits of some parameters in the following analysis are based on the mean values and 10/90 percentiles listed in Table 2.2.

Table 2.4 Strength ratios $f_{ccub,x}/f_{ccub,150}$ [249–253]

Side x [mm]	$f_{ccub,x}/f_{ccub,150}$ [-]				
	Neville	NBN	UNESCO	AASHTO	ACI
100	1.02	1.06	1.00	–	–
120	1.01	1.04	1.00	–	–

Table 2.5 Strength ratios $f_{ccyl,d}/f_{ccyl,150}$ (h/d = 2) [249–253]

Diameter d [mm]	Height h [mm]	$f_{ccyl,d}/f_{ccyl,150}$ [-]				
		Neville	NBN	UNESCO	AASHTO	ASTM
100	200	1.03	1.03	1.03	1.00	1.00
110	220	1.02	1.03	1.02	1.00	–

Table 2.6 Strength ratios $f_{ccyl,150}/f_{ccub,150}$ [249–253]

Neville	NBN	UNESCO	AASHTO	ACI
0.81	0.79	0.80	–	–

2.2.2.1 Strength Ratio

In practice different standards can be followed for the compressive testing of concrete, e.g. EN 12390-3 [247], ASTM C39 [248], and AASHTO T 22 [249]. These standards allow the testing of a wide variety of specimens with different shapes and sizes.

In the case of VC the influence of specimen size and shape on the measured compressive strength is well documented in various papers and books [244, 245], this is however not yet the case for SCC. Tables 2.4, 2.5 and 2.6 list some strength conversion factors utilised in practice originating from different sources [249–253]. The values $f_{ccub,x}$ and $f_{ccyl,d}$, respectively represent the compressive strength determined on cubes side x and cylinders with diameter d. In MC 2010, it is mentioned that in case test specimens other than cylinders 150/300 mm are used to specify the concrete compressive strength, the conversion factors should either be determined experimentally or, when given in national codes used accordingly for a given category of testing equipment [MC 2010] [268].

Because of the differences in mixture composition, changes in the conversion formulas might be expected when comparing Z and VC.

According to Domone [2], the ratio f_{ccyl}/f_{ccub} increases from 0.8 to near 1.0 with increasing strength, which is a wider range than the 0.9–1.0 range reported by Klug and Holschemacher in [254].

In [255] results originating from own research (based on characteristic strength values) and from literature (based on mean strength values) are compared with the EC2 conversion factors. A tendency for the development of higher conversion factors in the case of SCC was noticed. The first CEB International

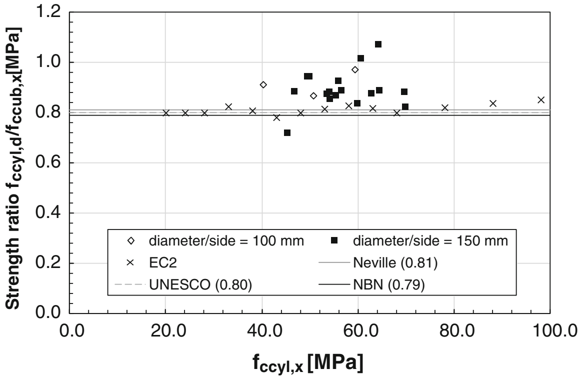


Fig. 2.4 Strength ratio $f_{ccyl,100}/f_{ccub,100}$ and $f_{ccyl,150}/f_{ccub,150}$ versus cylinder compressive strength $f_{ccyl,x}$ (20 results from 9 papers)

Recommendations from 1964 state that experimental conversion factors of f_{ccyl}/f_{ccub} for VC are generally situated within the region of 0.70–0.90. Even taking into account the band of variation found for VC, still ±50 % of the experimental results for SCC was found beyond the upper limit of 0.90.

In Fig. 2.4 experimental strength conversion factors $f_{ccyl,d}/f_{ccub,x}$ for SCC from the database are plotted in function of the cube compressive strength and compared to conversion factors of Tables 2.4, 2.5 and 2.6 and Eurocode 2 [257]. The analysis is based on cubes of 100 and 150 mm and the corresponding cylinders 100/200 and 150/300 mm. Figure 2.4 gathers results from in total nine papers [26, 60, 61, 122–124, 154, 206, 224]. It needs to be mentioned that these conversion factors were calculated through the mean cylinder and cube compressive strength values since in the original publications no information could be found with regard to the scatter present on the SCC experimental results. The EC2 (and EN 206), however, refers to the characteristic compressive strength values. The mean value of the strength ratio $f_{ccyl,d}/f_{ccub,x}$ found with these results is 0.90 with a standard deviation of 0.07. Even though the information is based on only a limited amount of results and further research on this matter is still needed to further confirm this conclusion, it can nonetheless be stated that a first observation seems to indicate that the conversion factor may be higher for SCC than reported for VC [249–253]. This is in accordance with the results of [2, 255]. Taking into account the limited amount of data, no dependency on the compressive strength was noticed, however, which was the case in [2].

Recently, strength results of 25 powder-type SCC mixtures and 2 VC mixtures have been investigated in three different laboratories [256]. The study was performed in order to analyse the effect on the strength ratio of several parameters, including the type of cement (CEMI 52.5 N, CEM III/A 42.5 N LA, CEM I 52.5 R HES), filler (limestone fillers with different fineness, quartz filler, and fly ash), aggregate (gravel, calcareous rubble, and porphyry rubble), and superplasticiser type (two types of polycarboxylate ether with different solid concentrations (PCE1 35 % vs. PCE2 30 %), NFS: naphthalene formaldehyde sulphonate, and MFS: melamine formaldehyde sulphonate).

The influence of the W/C, the C/P, and the powder content (P) is investigated as well. The strength results from literature and those found experimentally by the authors tend towards the same conclusion regarding the ratio $f_{ccyl,150}/f_{ccub,150}$, i.e. a value of 0.90 (±0.06) can be retained to make the conversion between cubes side 150 mm and cylinders diameter 150 mm (h/d = 2). Regarding the ratio $f_{ccub,100}/f_{ccub,150}$ a value, 1.04 (±0.05), is found in agreement with those proposed for VC (Fig. 2.4). Besides, the influence of the W/C, the C/P, the powder content, the type of cement, filler, superplasticiser, and aggregate on the compressive strength seemed to be insignificant or too scattered to be considered.

Among the influencing factors of the strength ratio mentioned in [244], three factors might be responsible for the difference between VC and SCC. The denser microstructure of SCC and enhanced bonding to the aggregates [31, 258] may lead to a more uniform stress distribution during compression. Lower stress concentrations could also decrease the chance of premature failure. This might influence the effect of the specimen size on the strength ratio. In the case of VC lateral stresses are known to affect the stress state over a depth of 0.866 d of a cone- or pyramid shaped region from each end of the specimen. Due to the considerable difference in mixture composition between SCC and VC there might be a different effect of the multi-axial stresses in the cylinders and cubes. SCC contains less coarse aggregates compared to VC. Thus, the wall effect might become less important in the case of SCC. For VC it is known that changing the aggregate grading affects cube strength more than cylinder strength. This effect might be enhanced in the case of SCC.

In [2] the results of the studies of Schiessl and Zilch [259] are mentioned explaining the difference between SCC and VC based on the contribution of aggregate interlock to the shear strength of cracked sections. They found that SCC exhibited 10 % lower shear strength for any given normal stress compared to VC. This is believed to be caused by the smoother crack surfaces in the SCC due to a lower coarse aggregate content. During the compression test in cubes shear movement has a more significant effect on the ultimate average stress. This can explain lower cube strengths and higher f_{ccyl}/f_{ccub} ratios.

As a result of the different standards mentioned earlier the compressive strength results contained in the database used for the analysis of the mechanical properties of SCC consists of a wide scope of compressive strength specimens. In order to be able to incorporate as many collected results as possible in the parametric studies in this chapter, it is important that as many results as possible can be converted to a reference compressive strength (either cylinder or cube compressive strength). In the database, 109 strength results are available from cylinders 150/300 mm, whereas 659 results are available from cubes 150 mm. As the compressive strength $f_{ccyl,150}$ is more common used the conversion is performed to cylinders 150/300 mm, i.e. the equivalent cylinder compressive strength $f_{ccyl,150,eq}$.

Based on the database and Tables 2.4, 2.5 and 2.6 the following conversion factors were derived for SCC. In this way, considering the equivalent cylinder compressive strength, 1,374 results can be analysed.

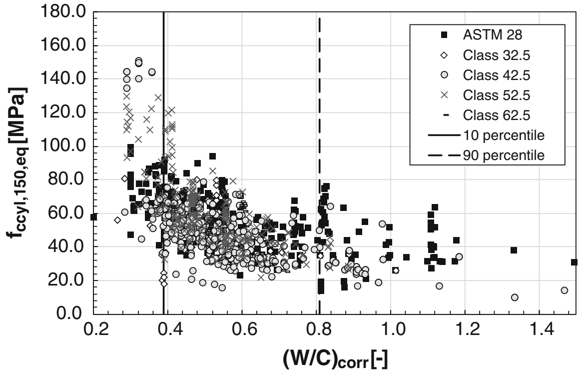


Fig. 2.5 Equivalent cylinder compressive strength $f_{ccyl,150,eq}$ versus W/C_{corr} (1,163 results from 165 papers)

$$f_{ccub,100} \approx f_{ccub,120} \approx f_{ccub,150} \tag{2.1}$$

$$f_{ccyl,100} \approx f_{ccyl,110} \approx f_{ccyl,150}(h/d = 2) \tag{2.2}$$

$$f_{ccyl,150,eq} \approx 0.9 \text{ x } f_{ccub,150} \tag{2.3}$$

The equivalent cylinder compressive strengths $f_{ccyl,150,eq}$ from the database range from 10 to 150 MPa.

2.2.2.2 Cement Strength Class

According to [260] and Feret's law [261] the 28-day cement compressive strength is a decisive key parameter with regards to the concrete strength. All results were divided into five groups of strength classes based on the actual measured 28-day cement compressive strength f_{cem28}, according to [240, 262] or on the cement class if experimental data was not available.

ASTM 28: $f_{cem28} \geq 28$ MPa
Class 32.5: 32.5 MPa $\leq f_{cem28} <$ 42.5 MPa (f_{cem28} known) or CEM 32.5
Class 42.5: 42.5 MPa $\leq f_{cem28} <$ 52.5 MPa (f_{cem28} known) or CEM 42.5
Class 52.5: 52.5 MPa $\leq f_{cem28} <$ 62.5 MPa (f_{cem28} known) or CEM 52.5
Class 62.5: 62.5 MPa $\leq f_{cem28} <$ 72.5 MPa (f_{cem28} known)

In Fig. 2.5 the equivalent cylinder compressive strength $f_{ccyl,150,eq}$ is plotted against the W/C_{corr}, in which the contribution of water content in the admixtures is taken into consideration. Regarding the results for which the actual measured cement compressive strength is unknown, there is a large uncertainty with respect to the group in which they are classified. Therefore, in Fig. 2.6 only the results for which f_{cem28} are known are presented. The 10/90 percentiles from Table 2.2 are indicated in both figures.

Cylinder compressive strengths higher than 90 MPa are reported in six publications (43 results) from which in only one paper (26 results) the f_{cem28} is known,

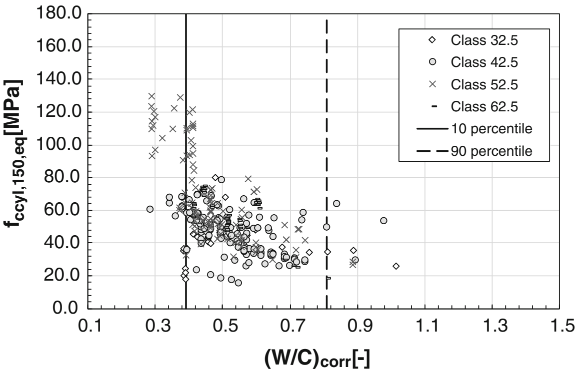


Fig. 2.6 Equivalent cylinder compressive strength $f_{ccyl,150,eq}$ versus corrected W/C, known f_{cem28} (320 results from 41 papers)

i.e. 53.9 MPa [8, 77, 140, 141, 182, 186]. The W/C_{corr} is lower than 0.52 and the W/P lower than 0.46. Silica, vegetal ash, fly ash, and quartz were used as additions.

Beneath the value of 90 MPa, there is a large scatter among the different cement groups, but still the dependency on the W/C can be observed. Also some upward shift can be observed for cement groups with f_{cem28} higher than 42.5 MPa. Within the 10/90 percentiles the results obtained from ASTM cements lie within the same strength region of the European cements, which is not the case above the 90 percentile. No more explicit notable shift of the cement groups was observed when considering the W/P instead of W/C_{corr}. The large scatter is due to the many different parameters varying in the mixtures (e.g. aggregate type, D_{max}, filler type, etc.).

2.2.2.3 Addition Type

As mentioned in the introduction, the most common used addition types are limestone, fly ash, ground granulated blast-furnace slag, and silica. The following analysis is based on the main addition types, secondary addition types are not taken into account. In Fig. 2.7 the equivalent cylinder compressive strength $f_{ccyl,150,eq}$ is plotted against the corrected W/C. The strengths obtained with limestone and fly ash lie within the same region. When slag is used an upward shift can be mentioned compared to the use of limestone and fly ash. Strengths of 90 MPa and higher were only achieved when silica (39 of 41 results) or fly ash (2 of 41 results) was used, and were reported in six publications [8, 77, 140, 141, 182, 186].

In [193] nine mixtures were developed with equal constituents, except from the addition type. With each addition type three concrete strengths were obtained ($f_{ccyl,150,eq}$ of 28, 45, and 64 MPa). The cement content was kept constant for each strength. In the case of fly ash and natural pozzolana a higher water content was needed to obtain the same strength as in the case of limestone was used. As such one could say larger strengths (at 28 days) will be obtained with fly ash and natural pozzolana compared to limestone with equal cement content and a constant C/P. Larger differences in strength will be noticed at higher $(W/C)_{corr}$.

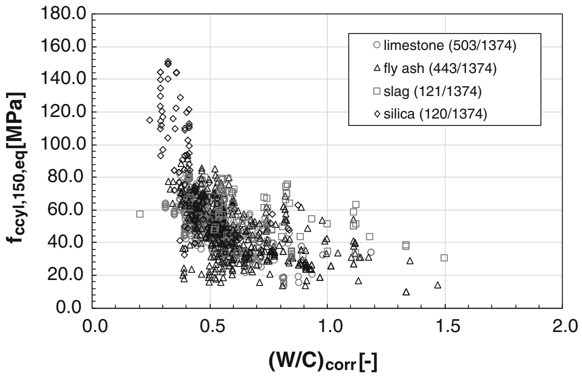


Fig. 2.7 Influence of addition type (1,187 results from 178 papers)

In [220] two identical mixtures were made with the only difference being the addition type, i.e. limestone and marble. The marble powder particles were finer than those of the limestone filler. However, the strength was almost the same.

In the study of [218], the potential of limestone, basalt and marble powder as partial replacement of Portland cement is investigated. The specific surface area of the fines is 4,000 cm^2/g for cement, 8,900 cm^2/g for marble powder, 2,500 cm^2/g for limestone powder, and 6,300 cm^2/g for basalt powder. The powder content was kept constant at 550 kg/m^3, the W/P at 0.33. The C/P was varied from 1.0 to 0.7. When compared to the control mixture where only cement was used increasing amounts of mineral admixtures generally decrease the strength, except when the cement was partially replaced by marble powder. No important difference was found between limestone powder and basalt powder. The strength increase in case of replacement of marble powder was only noticed with a C/P of 0.8 or higher.

Uysal and Yilmaz [218] reported that only limestone and basalt powders act like inert mineral admixtures reducing the compressive strength in case of partial replacement of cement. The good performance with the marble powder is believed to be due to the physical nature of better packing since it is the finest powder used. A denser matrix is achieved. Furthermore, the surface of the marble powder is believed to act as nucleation site for the early reaction products of CH and CSH. The effect of nucleation on the strength is dependent on the mineral admixture's affinity to cement hydrates, and it increases with fineness and specific surface area of the mineral admixture [218].

According to [2], limestone powder which is a common addition to SCC mixtures makes a contribution to strength gain, mainly in the beginning of the hardening phase. In [31], by means of mercury porosimetry on hardened cement pastes, it was illustrated that limestone filler, apart from any chemical influence, also helps realizing a more dense structure by the filling effect, with positive influence on the compressive strength at 28 days. Furthermore this effect is found to influence the development of the pore structure of the hardened cement paste with limestone following Power's model [237].

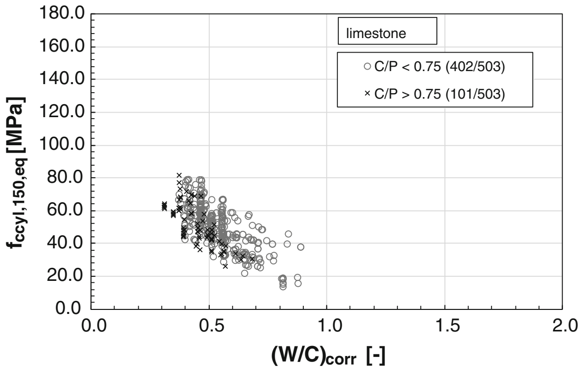


Fig. 2.8 Influence of C/P in case of limestone as addition type (503 results from 100 papers)

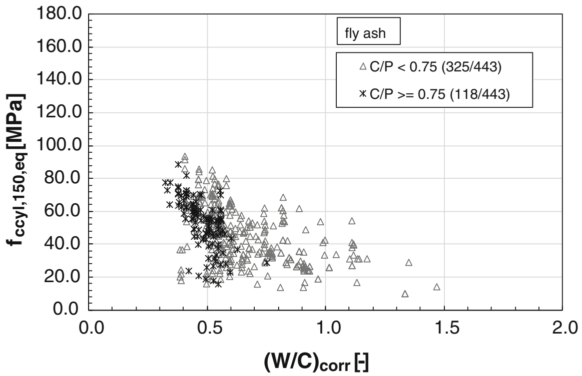


Fig. 2.9 Influence of C/P in case of fly ash as addition type (443 results from 81 papers)

It has to be emphasized that the Blaine finesses of the filler can have a significant effect on the compressive strength. In Some cases, high Blaine finesses of the limestone filler plays a major role in the obtained mechanical properties [273].

2.2.2.4 C/P and Cement Content

The influence of the C/P is investigated for various addition types: limestone, fly ash, ground granulated blast-furnace slag, and silica. In Figs. 2.8 and 2.9 the strength results obtained with limestone and fly ash are presented.

Values of C/P higher than or equal to 0.75 are positioned in the lower left part of the point cloud. At a constant W/C a higher C/P leads to lower strengths. This was also found varying the C/P in [238]. This is probably due to the fact that increasing the cement content also requires the increase in water content to maintain the W/C, thus leading to a higher W/P. More water in the mixture leads to a higher capillary porosity and lower compressive strength. Also less addition will be present to contribute to the strength (e.g. fly ash). No further conclusions could be made by considering the different groups of cement strength. In the case of

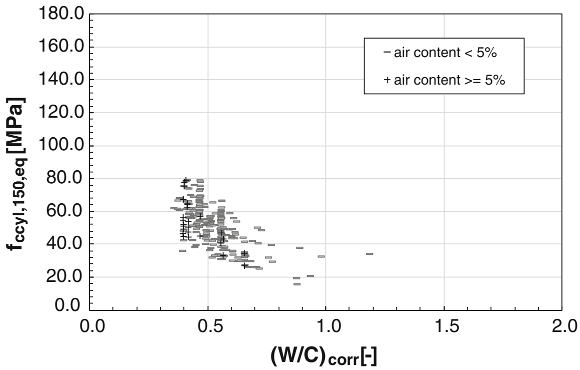


Fig. 2.10 Influence of air content in case of limestone as addition type (261 results from 51 papers)

ground granulated blast-furnace slag and silica no differences could be observed due to the variation of the C/P, probably due to the limited amount of results for this purpose.

2.2.2.5 Air Content

In [186] it was observed that the increased air content decreased the compressive strength of SCC. The reduction in compressive strength was about 4 MPa per 1 % increase in air content.

Considering the database, the influence of the air content was investigated, but no clear trends could be observed since many parameters intervene at the same time. When variation of some of those parameters (C/P, addition type, and aggregate surface/origin) is excluded, there is a small trend of a decrease in compressive strength with the increase in air content. In Fig. 2.10 the influence of the air content is illustrated for mixtures with limestone as addition type.

2.2.2.6 Coarse Aggregate Type/Origin and Maximum Aggregate Size (D_{max})

Coarse aggregates can have an influence on the compressive strength due to their shape, nominal maximum size, surface texture, and origin. According to [263], crushed rock was used over three times greater than gravel (uncrushed) aggregates, primarily reflecting local availability. In [2], crushed aggregate mixtures have higher cube strengths. This is similar to the behaviour of VC, but the average difference between the two best-fit curves was found to be small (4 MPa). The opposite behaviour was mentioned regarding the cylinder strengths, but fewer data were available, and there was only a partial overlap of the W/C's of SCC and VC.

The effect of the surface texture and the origin of coarse aggregates on the compressive strength are presented in Figs. 2.11 and 2.12. In Fig. 2.11, the results related to crushed (63 %) and uncrushed (37 %) coarse aggregates are shown. In

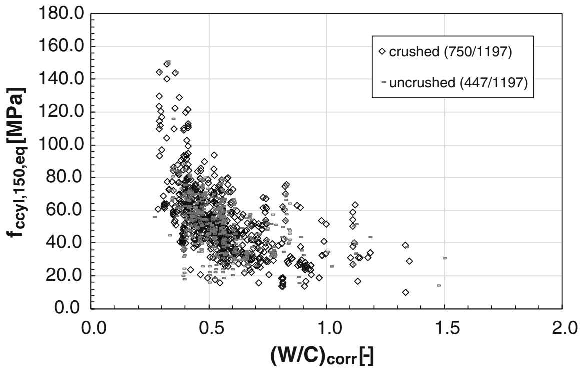


Fig. 2.11 Influence of coarse aggregate—crushed versus uncrushed (1,197 results from 171 papers)

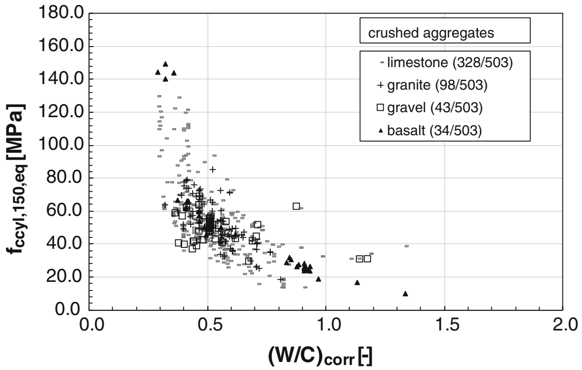


Fig. 2.12 Influence of coarse aggregate—crushed—type of origin (503 results from 71 papers)

the range of 30–90 MPa no obvious difference can be noticed between SCC made with crushed or uncrushed aggregates. The crushed aggregates, however, cover a larger strength range compared to the uncrushed aggregates. Results above 90 MPa are found in six papers. Silica or fly ash was used. A rougher surface could contribute to a compressive strength higher than 90 MPa, but the appropriate addition types have to be applied. In general, rougher surfaces will enhance the bond between the aggregate and the cement matrix which benefits the compressive strength. In [29] two mixtures have been compared with the only difference being the type of coarse aggregate. The mixture with gravel (2/8 and 8/16) had an equivalent cube compressive strength of 50.8 MPa whereas the mixture with crushed limestone (4/14) reached a strength of 67.2 MPa.

In Fig. 2.12 the actual origin of the crushed aggregates is depicted. Besides the fact that quite a lot aggregate origins are not specified in the papers it can be observed that crushed aggregates often consist firstly of limestone and secondly of granite and, uncrushed aggregates of gravel (371 of 447). The origin of the coarse aggregates depends on the local availability. No clear trend could be observed regarding the origin of the aggregates. The higher the compressive strength the more important becomes the aggregate compressive strength and as such the origin. At normal strength the compressive strength is mainly governed by the strength of the cement matrix. Consequently, as most strength results are lower than 90 MPa no effect of the aggregate origin is noticed on the compressive strength. In [215, 217] a comparison was made between two types of crushed aggregate. In [215] no clear conclusion could be drawn when the strength results of mixtures with crushed limestone or crushed basalt were studied. A 5.4 MPa higher compressive strength was found for the mixture with limestone aggregates in cases limestone filler and fly ash were used as additions. When only limestone filler was used as addition, the mixture with limestone aggregates showed a 3.6 MPa lower strength compared to the mixture with basalt aggregates. In [217] the application of crushed limestone and pumice was investigated on eight different mixtures. For all four comparisons the mixtures with pumice showed much lower strengths (only 40 % of the strength of the mixtures with limestone).

De Larrard [264] emphasizes of the need to reduce the maximum aggregate size to attain high strength. In [263] 70 % of the investigated SCC mixtures used had a maximum aggregate size in the range of 16–20 mm (value depending on local practice). According to the database, only 47.5 % of the aggregate sizes lie between 16 and 20 mm. A mean value for the maximum aggregate size was found to be 16 mm. There is a tendency to use smaller coarse aggregate sizes, probably linked to the desire of reaching higher compressive strength. However, it was observed that small coarse aggregate sizes were also found in combination with low compressive strength. The effect of the maximum aggregate size, D_{max}, on the compressive strength was investigated, but as such no clear influence was observed.

A lower D_{max} also contributes to a better segregation resistance and passing ability.

2.2.2.7 Strength Model

Over the years, several strength models have been proposed for VC. In a first step, some of those models are applied on the available database. Subsequently, an adapted model for SCC, as proposed by Poppe [265], is applied.

Lambotte combined the research results of Waltz with the strength model proposed by Bolomey into a new formula (Eq. 2.4) [266]. In this internationally known model the cement compressive strength f_{cem28} and the W/C are the only parameters.

$$f_{ccub,150} = 0.483\ f_{cem28}/(W/C)\ [MPa] \tag{2.4}$$

In Fig. 2.13 all the results with known f_{cem28} are used to calculate the cube compressive strength as proposed by Lambotte ($f_{ccub,150,cal}$). The corrected W/C was used for the calculation. The calculated values are plotted in function of the equivalent cube compressive strength ($f_{ccub,150,eq}$/0.9). A 95 % confidence interval has been plotted. Several calculated results are close to $f_{ccub,150,eq}$. Although some

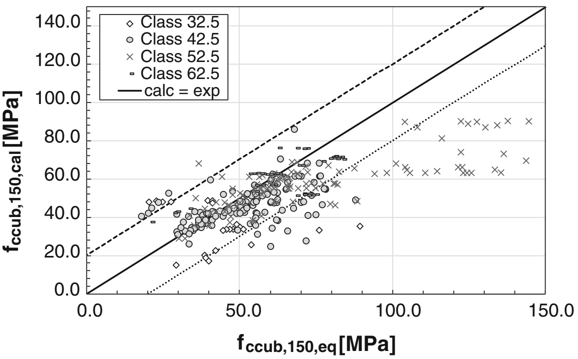


Fig. 2.13 Calculated cube compressive strength according to Lambotte versus equivalent cube compressive strength (320 results from 41 papers)

calculated values overestimate the actual strength, most of the calculated values underestimate the strength. This is probably due to the use of higher powder contents by incorporating additions and the use of superplasticisers. More dispersed cement leads to higher hydration, and the additions realize a more dense structure by the filling effect or, even in some cases influencing the formation of hydration products [31, 265]. Also, this model does not incorporate the effect of the W/P or C/P. The effect becomes even more important for higher compressive strengths. The model of Lambotte is valid for fully VC, i.e. with an air content of 1 %. The air content mentioned in this analysis varies from 0.6 % till 9.0 %. Although there should be (based on the limited amount of results for which the air content of the fresh concrete is known), no clear effect of the air content on the Lambotte model could be found. This is probably due to the contribution of other parameters.

After evaluating the different influencing parameters on compressive strength, it is believed that an improvement of Lambotte's model can be obtained by adding parameters related to the C/P, addition type, and the use of superplasticiser, as proposed by Poppe [265]. In this latter reference, it is suggested to use Eq. 2.5 to calculate the cube compressive strength on cubes 150 mm.

$$f_{ccub,150} = \frac{0.483.\mathrm{f}_{\mathrm{cem28}}\left(\mathrm{a}_1.\frac{\mathrm{sp}}{\mathrm{C}}+1\right)}{\left(\frac{\mathrm{W}}{\mathrm{C}}+\mathrm{a}_2.\left(\frac{\mathrm{C}}{\mathrm{P}}-1\right)\right)} \tag{2.5}$$

with sp/C the dosage of superplasticiser, by mass of cement, a_1 a coefficient depending on the superplasticiser type and a_2 a coefficient depending on the addition type. Also in this case, the corrected W/C_{corr} will be used for the analysis. As a-values are depending on the addition and the superplasticiser type, a further analysis is performed on the data results with limestone, silica fume, or fly ash as first or main addition type, and polycarboxylate ether as superplasticiser. However, when investigating the effect of the superplasticiser no clearly defined regions could be observed of the mixtures with the same superplasticiser type. The results were plotted according to Poppe, with different a-values for different addition types. A better fitting was the result, but due to the fact that besides the main addition type other addition types are often used, there is still an important distribution on the results. Also the derived a-values have no scientific meaning. For this reason, the graphs are not included. However, when mixtures from individual experimental programs were used, it was found that it was possible to find valid models.

In [198], based on experimental data, genetic programming (GP) was used to model and formulate the fresh and hardened properties of SCC containing pulverised fuel ash (PFA). Twenty-six mixtures were made with W/P of 0.38–0.72, 183–317 kg/m^3 of cement, 29–261 kg/m^3 of fly ash, and 0–1 % total liquid mass of polycarboxylate ether superplasticiser by mass of powder. Graded crushed basalt aggregate with a D_{max} of 20 mm was used, together with well-graded quartzite sand with a fineness modulus of 2.74. The mass of coarse aggregate was fixed for all mixtures at 837 kg/m^3 to enhance the filling ability, passing ability, and the resistance to segregation. The formula for the compressive strength at 28 days is given by Eq. 2.6.

$$\begin{aligned}\text{Compressive strength} &= \left[\left(\frac{C + CA/sand - 70}{W/P} - C - SP\right)\right.\\ &\quad \left.\times\left(\frac{3\times 28 - PFA + W/P + C\times W/P + C + 26.1}{4}\right)\right]^{1/5}\\ &\quad \times\left(\frac{\sqrt{[5]28}}{(CA/sand)^4} + \ln(28)\right)\end{aligned} \tag{2.6}$$

With cement (C) content (kg/m^3), pulverised fuel ash (PFA) content (kg/m^3), water-to-powder ratio (W/P), superplasticiser (SP) content, and ratio of coarse aggregate to sand (CA/sand), respectively.

Results showed that the derived GP model is capable of accurately predicting the compressive strength at 28 days used in the training process. The model can also effectively predict compressive strength at 28 days for new mixtures designed within the practical range with variation of the mix ingredients. The performance of the GP-model is illustrated in Fig. 2.14.

Also this model cannot be generalized for the database, since many parameters are involved (filler type, superplasticiser type, aggregate type, etc.). However, it is believed that, when mixtures from individual experimental programs will be used, valid models will be found based on Eq. 2.5. Probably the model could also be optimised incorporating the actual measured 28-day cement compressive strength f_{cem28}, in case different cement types are used.

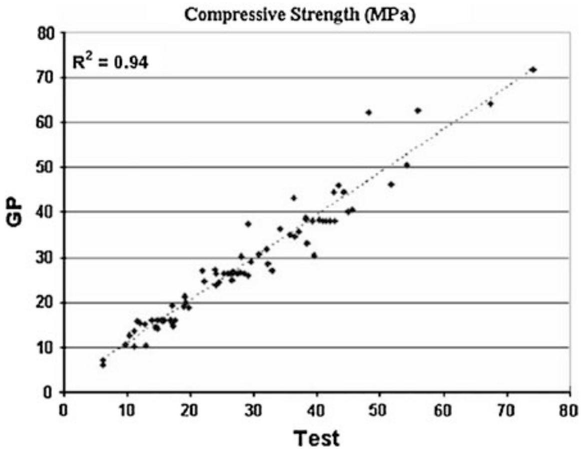


Fig. 2.14 Performance of GP model versus test results for compressive strength [198]

2.3 Stress-Strain Relationship

Until now, very little is known about the differences between the stress-strain behaviour of SCC and that of VC. Most research programs include tests to determine the compressive strength and some include Young's modulus as well, but the stress-strain relationship is almost never recorded.

Above that, accurate measurements of the stress-strain relationship require a high level of care and an appropriate steering signal when executing the tests [267]. Therefore, different conclusions can be found in the literature just because research programs were performed with different test set-ups and more or less attention to side-effects.

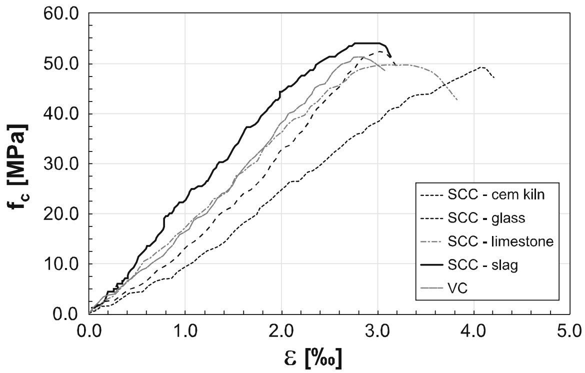
2.3.1 Ascending Part of the Stress-Strain Relationship

Georgiadis [79] performed tests on cubes (sides 100 mm) made of SCC of two strength classes and with several filler types. The modulus of elasticity for all SCC's was smaller compared to VC but the compressive strengths were slightly improved which they attribute to the improved ITZ quality.

When SCC was produced with limestone filler, cement kiln dust or ground granulated blast-furnace slag, the toughness was higher than the one recorded for VC. However, when glass filler was used, the peak strain increased (Fig. 2.15). No additional details are given about the properties of the filler materials (grading curves, chemical composition, etc.) or test set-up and the recorded strains seem to be on the high side as one should expect values of the peak strain ε_{c1} in the range of 1.8 till 2.7 ‰ [254].

Anagnostopoulos et al. [14] looked into the influence of fire on the stress-strain relationship of SCC. They ran tests after heating to 300 and 600 °C, but also on

Fig. 2.15 Stress-strain relationships of VC and SCC with different fillers (based on [79])



reference specimens stored at 20 °C. All SCCs contained limestone filler and had a total powder content of 475 kg/m^3. To obtain different compressive strengths the ratio between cement and filler in the total powder content was varied. No noticeable difference between SCC and VC was recorded with respect to the shape of the stress-strain curves. Comparing the curves between the two applied strength classes, it can be mentioned that the higher the strength class, the steeper the slope of the ascending branch of the stress-strain curve and the more linear the descending one. The peak strain decreased at increasing compressive strength.

The stress-strain behaviour of SCC was measured on cylindrical specimens with slenderness ratios (ratio of height to diameter) of 3.0 or 3.6 by Desnerck [60]. During the experiments the specimens were subjected to a continuously increasing deformation rate of 0.003 mm/s. The axial deformations in the central part of the specimen, the circumferential deformation and the stress applied to the specimen were recorded. In total, four SCC mixtures containing limestone filler and three VC mixtures were tested. The 28-day cylinder compressive strength of the SCC mixtures varied between 45 and 60 MPa.

From the obtained results it can be seen that the peak strain at different ages (3 days up to 3 months) and concrete strengths for SCC (range of 20–70 MPa) is higher than for VC (Fig. 2.16).

Besides the influence of limestone filler, the use of blast furnace slag, fly ash, and silica fume has been investigated. For almost all tested compositions, the peak strain ε_1 of SCC was higher than those of VC. The largest normalised peak strains were measured for SCC containing limestone filler. The values for the concrete compositions with fly ash, silica fume, or blends of these SCMs were slightly lower. The lowest values were found when blast furnace slag was used as addition (Fig. 2.17).

In their study, the Belgian Building Research Institute (BBRI) [26] used cylindrical specimens (diam. 100 mm and height 200 mm). The tests were displacement-controlled at a speed of 60 μm/min. A friction reducing sheet was applied.

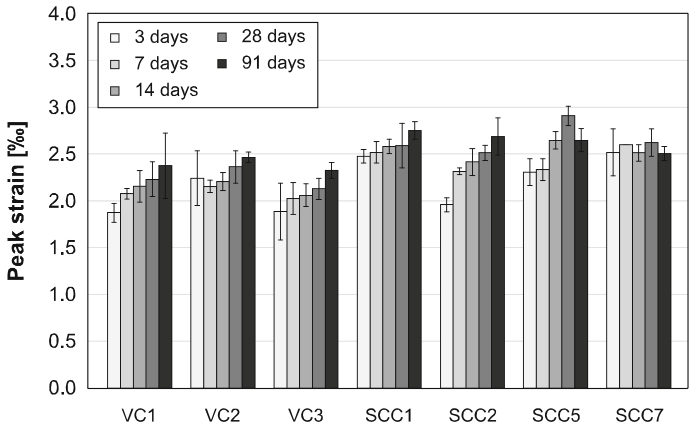
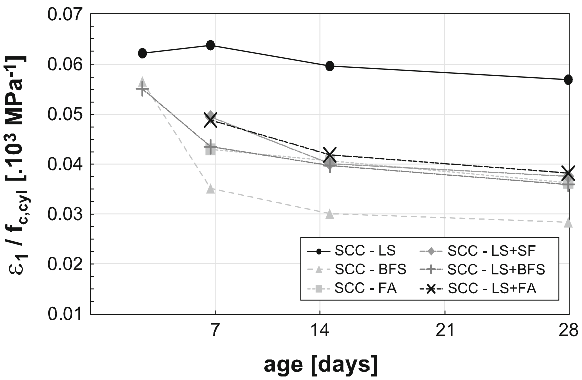


Fig. 2.16 Measured peak strain values for limestone SCCs and VCs at different concrete ages [60]

Fig. 2.17 Normalised peak strain values for SCCs with different additions and different concrete ages [60] (*LS* Limestone, *BFS* Blast furnace slag, *FA* Fly ash, *SF* silica fume)



In total eight SCCs and one VC were tested. It was found that the scatter on the obtained stress-strain relationships was rather small (see Fig. 2.18). Concretes with lower compressive strengths (40–50 MPa) showed a more ductile behaviour than higher strengths SCCs (50–60 MPa). When high amounts of fly ash were combined with blast furnace slag, the behaviour was most brittle. As reported by Desnerck [60] as well, the peak strain is increasing at increasing compressive strength.

2.3.2 *Strain-Softening Behaviour*

Desnerck [60] investigated the stress-strain behavior of SCC paying special attention (by applying the proper steering signal) to the descending branch of the stress-strain diagram to evaluate the so called 'strain-softening' behaviour of the

Fig. 2.18 Comparison of measured stress-strain curves for SCC and VC mixture [26]

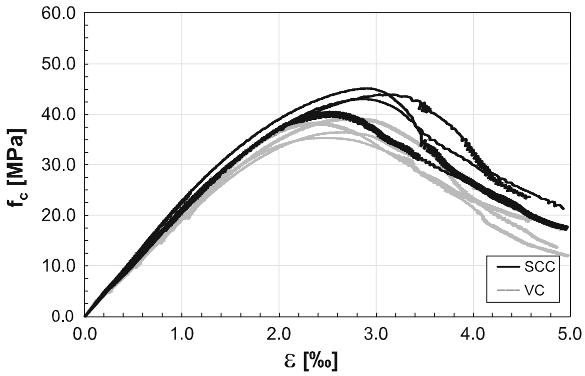
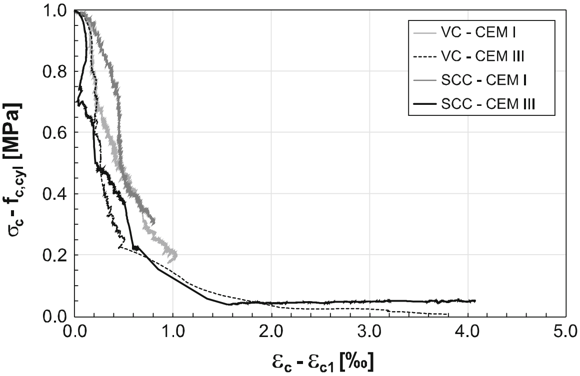


Fig. 2.19 Comparison of normalised strain-softening behaviour of limestone SCC mixtures at 28 days [60]



material. He concluded that the strain-softening behaviour of SCC and VC are comparable for the same compressive strength level (Fig. 2.19). Based on the total stress-strain relationship measured during the experiments, the toughness was determined (area underneath the entire stress-strain diagram). The toughness of the tested limestone-containing SCC was slightly higher than that for VC. The largest difference was found for the ascending branch, whereas the area underneath the descending branch was comparable. However, BBRI [26] found that the normalised toughness's did not differ significantly when comparing SCC specimens to VC specimens or the Eurocode2 [254] provisions.

2.4 Tensile Strength

For the evaluation of the tensile strength of SCC, and concrete in general, three well-known methods are being used: (i) the direct tensile test, (ii) the splitting tensile test and (iii) the bending tensile test (3-point or 4-point). Due to the difficult

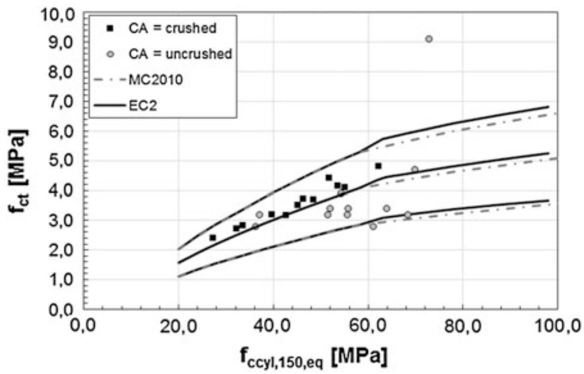


Fig. 2.20 Direct tensile strength versus equivalent cylinder compressive strength of SCC mixtures and the effect of the coarse aggregates (CA) shape (25 results from 6 studies)

test setup direct tensile strength tests are rather scarce. Therefore, the tensile strength is quite often derived from test results originating from splitting tensile or bending (e.g. flexural) tensile strength tests. By means of models offered by e.g. Eurocode 2 (EC2) [257] or Model Code 2010 (MC2010) [268], it is possible to convert these test results. However, it is not quite clear whether these conversion factors can still be used for SCC. Note that the upper and lower limit curves provided in the figures are the 5 % and 95 percentile provided by EC2 and MC2010.

2.4.1 Direct Tensile Strength

For the evaluation of the direct tensile strength of SCC, a limited amount of test results can be found in the literature (25 data results originating from 6 studies). This is mainly due to the complexity of the test equipment and execution of the experiments. The test results are obtained at different ages of the samples (14–90 days). The most common shape of the test specimens was cylindrical. In one study [177], the dog-bone shape was used for preferential rupture.

In Fig. 2.20, the correlation between the direct tensile strength and the equivalent cylinder compressive strength is expressed. All compressive test results were converted into $f_{ccyl,150,eq}$ by using Eq. 2.3 obtained by means of the database.

An increasing trend of direct tensile strength is noticed for increasing cylinder compressive strength (Fig. 2.20). For this limited amount of data, the results tend to follow the mean relationship proposed by the EC2 and MC2010, especially if crushed coarse aggregates (limestone or calcareous) are being used. On the other hand, the test results originating from mixtures based on uncrushed coarse aggregates (gravel) lie between the 5 percentile range and the mean value proposed by EC2 and MC2010.

Based on limited data, it can be stated that no significant effect of paste volume or filler type on the correlation between direct tensile strength and compressive

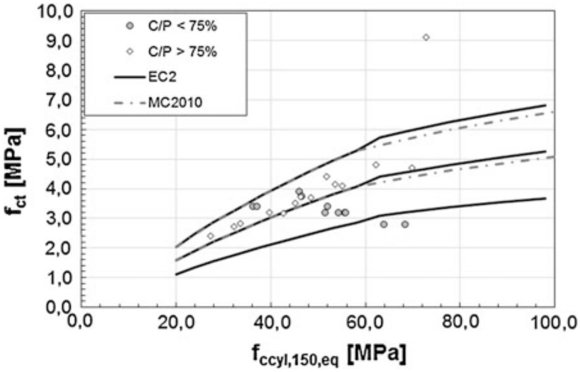


Fig. 2.21 Direct tensile strength versus equivalent cylinder compressive strength of SCC mixtures and the effect of C/P (25 results from 6 studies)

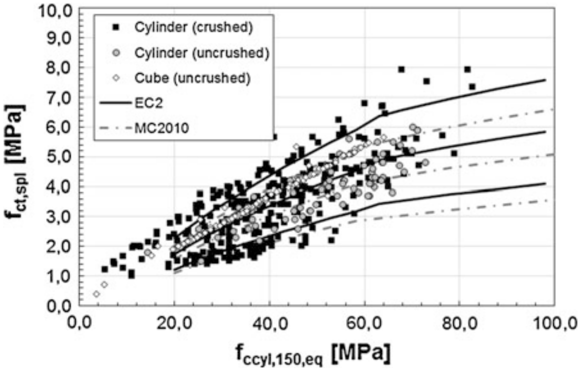


Fig. 2.22 Splitting tensile strength (sample shape: cylinder or cube) versus equivalent cylinder compressive strength of SCC mixtures and the effect of coarse aggregates shape (crushed vs. uncrushed) (536 results from 49 studies)

strength can be found from the database. However, the effect of the C/P is noticeable, as depicted in Fig. 2.21. SCC mixtures with a C/P less than 0.75 tend to lie beneath the mean values proposed by the EC2 and MC2010.

Overall, more experimental results are necessary to obtain reliable conclusions regarding the direct tensile strength of SCC.

2.4.2 Splitting Tensile Strength

For the evaluation of the splitting tensile strength of SCC, a considerable number of test results can be found in literature (608 data results originating from 60 studies) with test ages varying from 1 to 365 days. Mostly, the shape of the test specimens is cylindrical (399 from 43 studies) or cubic (137 results from 6 studies). The correlation between splitting tensile strength (of cubes and cylinders) and cylinder compressive strength is given in Fig. 2.22.

Note that all compressive test results have been converted into $f_{ccyl,150,eq}$ by using the conversion factors proposed in Sect. 2.2 (Eq. 2.3). In EC2 and MC2010

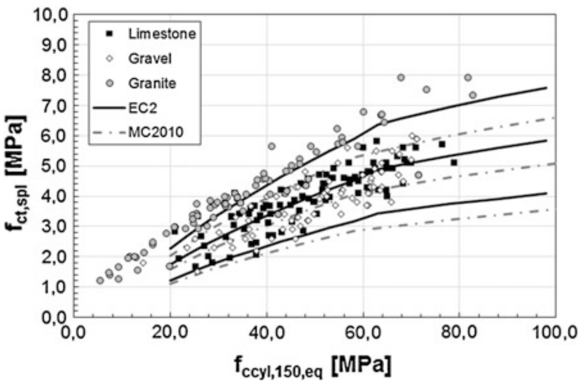


Fig. 2.23 Cylinder splitting tensile strength versus equivalent cylinder compressive strength of SCC mixtures and the effect of coarse aggregates type (granite vs. limestone vs. gravel) (256 results from 27 studies)

it is mentioned that the relationship between splitting tensile strength and compressive strength is based on the cylinder compressive strength.

According to [2] cylinder splitting results fall in the 5–95 percentile ranges given in EC2, with the majority being the upper half of this, and a few above the upper limit. An explanation can be found in a possible underestimation of the used conversion factor between cylinder and cube compressive strength, as mentioned in [26]. No significant difference between SCC and VC is found.

An increasing trend of splitting tensile strength is noticed for increasing cylinder compressive strength (Fig. 2.22). The behaviour of cubes under splitting tensile stress tends to follow the mean relationship proposed by EC2 (for f_{ccub} lower than 40 MPa), and the maximum range proposed by MC2010. A linear trend is identified between $f_{ct,spl}$ of cubes and $f_{ccyl,150,eq}$ (originating from one study) which is likely to be confirmed by Topçu and Uygunoglu [210].

Although higher splitting tensile strength results can be expected when cubic samples are used (10 % higher values compared to cylinders, according to EN 12390-6), this cannot be confirmed by the data of Fig. 2.22. A rather high percentage of the widely scattered splitting tensile strength results of cylinders lie between the 5 and 95 percentile or maximum ranges (or even above) of EC2, and mostly in the upper half of the MC2010 range. An explanation was found in the improved bond between the paste and the aggregates in the SCC mixtures.

Splitting tensile strength results of SCC using granite coarse aggregates lie in the upper half or above the ranges proposed by EC2 and MC2010 (Fig. 2.23). When limestone or gravel aggregates are used, this is not the case: the data tend to follow the mean relation proposed by EC2. The cylinder splitting tensile strength as a function of the cube compressive strength was also investigated on SCC and VC mixtures produced with limestone and siliceous aggregates by [14]. The splitting tensile strength of SCC mixtures was slightly lower (decreased by 6–8 %) than that of the VC mixtures produced with the same W/C and cement content when the mixtures were produced with quartz aggregate. When crushed limestone aggregate was used, SCC mixtures had similar splitting tensile strength as the reference VC mixtures. The ratio between the splitting tensile strength measured for SCC and the splitting tensile strength measured for VC of equal W/C is influenced by the aggregate type [14].

Further analysis of the database shows that there is not a significant effect of coarse aggregate size or paste volume on the correlation between splitting tensile strength and compressive strength. However, according to [11] larger maximum aggregate size and higher coarse aggregates volume (thus, smaller paste volume) leads to higher splitting tensile strength. The influence of C/P or filler type is not significant according to the database.

It can be concluded that using models proposed by the EC2 and MC2010 for estimating the tensile strength of SCC can result in safe values for the prediction of splitting tensile strength.

A limited amount of test results can be found in literature dealing with the evolution of splitting tensile strength in time. These results can be valuable for the evaluation of the early-age (thermal) cracking behaviour of massive concrete structures, as internal stress build up due to the thermal gradient and can exceed the tensile strength of the concrete at young age. According to a study performed by [255], a rather good prediction (small underestimation) of the splitting tensile strength evolution can be obtained for the SCC mixtures made with Ordinary Portland Cement (OPC) using the model proposed by EC2 (using β_{cc} factor). In case fly ash is added to the OPC, a slower strength evolution is noticed; however, the EC2 does not account for the use of fly ash.

Data originating from one study [255] (6 SCC mixtures with limestone filler or fly ash, W/C = 0.45–0.61 and C/P = 0.50–0.67) indicates that the conversion factor A_{sp} to correlate the splitting tensile strength and the direct tensile strength, is slightly lower (0.84 ± 0.04) than the values proposed by EC2 and MC90 ($A_{sp} = 0.9$) or by MC2010 ($A_{sp} = 1.0$). Thus, when determining f_{ct} by means of spitting tensile strength results and based on the previously mentioned codes, an overestimation of the tensile strength is obtained. The conversion factor for bending A_{sfl} (0.59 ± 0.10) was significantly lower than the 0.69 prescribed in EC2 and MC2010.

2.4.3 Flexural Tensile Strength

For the evaluation of the flexural tensile strength of SCC, a limited amount of test results can be found in literature (4-point loading: 27 data results originating from 4 studies, 3-point loading: 78 data results from 7 studies, all data have a ratio specimen depth/span length between 3 and 4). The correlation between bending tensile strength and cube compressive strength is given in Fig. 2.24. Note that all compressive test results have been converted into $f_{ccyl,150,eq}$ by using the conversion factors proposed in Sect. 2.2 (Eq. 2.3).

An increase in flexural tensile strength is noticed when cylinder compressive strength is increased (Fig. 2.24). As could be expected, higher values of $f_{ct,fl}$ are

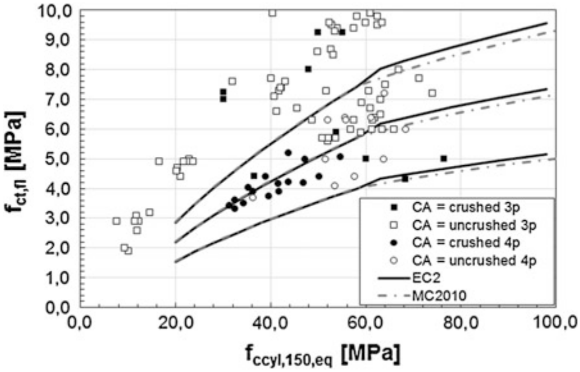


Fig. 2.24 Flexural tensile strength (3-point or 4-point bending tests) versus equivalent cube compressive strength of SCC and the effect of coarse aggregate shape (crushed vs. uncrushed) (105 results from 11 studies)

found when the 3-point bending test is used: most of the results lie above the mean value and even above the upper range proposed by the EC2 and MC2010.

In case of the 4-point bending test, the data tend to follow the mean value proposed by the EC2 and MC2010. All of the data are located between the upper and lower ranges proposed by the codes.

The determination of $f_{ct,fl}$ by means of 3-point testing method results in an overestimation of the flexural tensile strength. Therefore, it is advised to use the 4-point bending test to obtain realistic values for the flexural tensile strength.

The influence of the shape of the coarse aggregate is not noticeable. Also no significant tendencies were found with regards to aggregate type, paste volume, C/P, or filler type, mainly due to a limited amount of available flexural data.

2.5 Modulus of Elasticity

Due to the considerable contribution of aggregates to the overall stiffness of concrete, it is often assumed that SCC—with its higher paste content—is characterised by a lower modulus of elasticity (E_c). Some studies [1–3] have reported that the modulus of elasticity of tested SCC mixtures was lower than that of companion VC mixtures, with a similar compressive strength. Pineaud et al. [167] studied the effect of the paste volume and W/C. By varying the paste volume between 359 and 452 l/m^3 a decrease in E_c was found for an increasing paste volume. The influence of the W/CM on the modulus of elasticity was found to be comparable to that observed on the compressive strength. A survey by Domone [2] seems to indicate that the difference between SCC and VC in the modulus of elasticity is greater for lower compressive strengths. According to Klug and Holschemacher [254] the scatter present on the SCC results is smaller, causing all results to remain within an acceptable band for design using CEB-fib Model Code 1990 [269], validating as such still the use of the common relationship between the modulus of elasticity and the characteristic compressive strength. The survey by

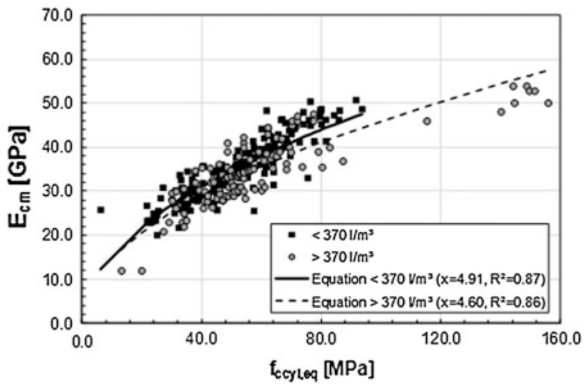


Fig. 2.25 Influence of paste volume on E-modulus (314 results)

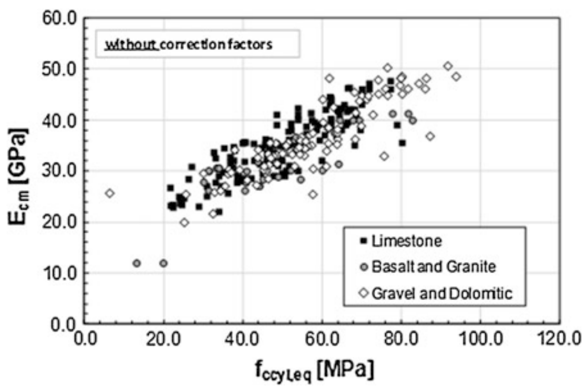


Fig. 2.26 Influence of aggregate type on E-modulus without taking into account the correction factor according to EC2 (276 results)

Van Itterbeeck et al. [255] also found that the E-modulus results for SCC conformed well to the Eurocode 2 predictions and remained well within the band of the CEB-fib Model Code [270]. A similar overall scatter was also observed within this study for SCC and VC.

Since the RILEM database includes a large variety of SCC mixtures with a wide range of paste volumes (results in Fig. 2.25, paste volume range from 280 to 560 l/m^3) the results were first analysed as a function of the paste volume. All results were expressed in function of an equivalent cylinder (diameter 150 mm length 300 mm) compressive strength. Only the secant E-modulus results were included in this analysis. Figure 2.25 could perhaps indicate a 'slight' influence of paste volume. However, the scatter on the results is more important and thus cannot be solely related to paste volume.

When analysing the results in function of the coarse aggregate origin (see Fig. 2.26) a clear influence on the E-modulus cannot be observed. Data scatter appears to increase when the EC2 correction factors are applied, taking into account the effect of aggregate type (Fig. 2.27). Therefore, no conversion factors will be used in this paragraph.

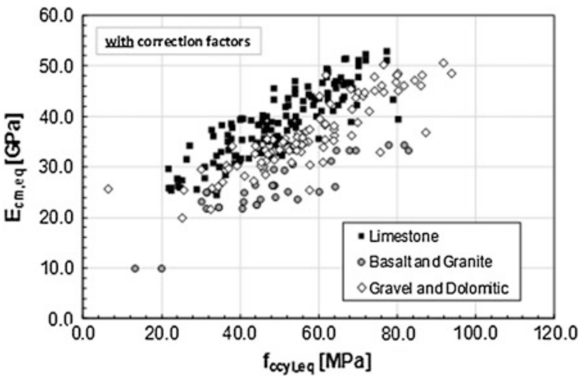


Fig. 2.27 Influence of aggregate type on E-modulus with taking into account the correction factor according to EC2 (276 results)

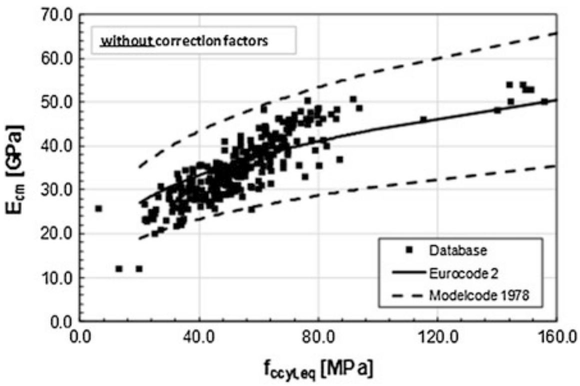


Fig. 2.28 Comparison of E-modulus results from RILEM database with Eurocode 2 provisions (314 results)

In Figs. 2.28 and 2.29 the E-modulus results from the database are compared with the Eurocode 2 [254] and ACI318-11 [253] predictions. The results were not compared with the ModelCode 2010 since, in contrast with the Eurocode 2 and ACI 318-08, it provides information with regard to the tangent E-modulus instead of the secant E-modulus. All results seem to conform to the Eurocode 2 [254] and fit well into the band acceptable for design using the CEB-fib Model Code [270]. A general observation which could thus be made with regard to the modulus of elasticity of SCC after viewing the graph presented in Fig. 2.28 is that it seems to be similar to that for VC, with an important but similar scatter present on the results for both types of concrete. Figure 2.29 indicates that the ACI318-08 captures the relationship between compressive strength and E-modulus better, but seems to provide an underestimation of the modulus of elasticity.

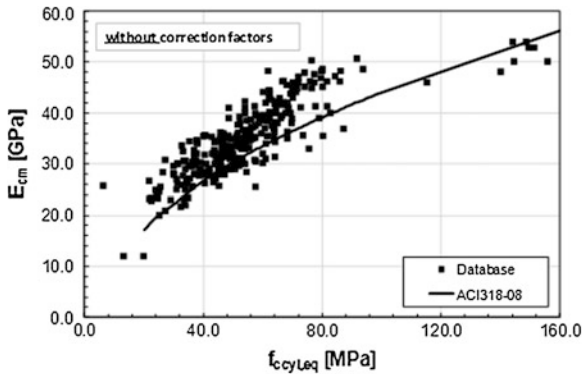


Fig. 2.29 Comparison of E-modulus results from RILEM database with ACI318-08 provisions (314 results)

2.6 Mechanical Behaviour of SCC at Elevated Temperatures

For the evaluation of the fire resistance of a structural system, knowledge on the properties of SCC at high temperatures is essential: thermal, mechanical, deformation properties, and material specific phenomena, such as fire induced spalling. In this section, the behaviour of the mechanical properties of plain SCC (without fibers) is discussed and (where possible) compared to the behaviour of VC. Similar properties of FRSCC are discussed in Chap. 6.

Many physical and chemical changes occur in concrete when subjected to high temperature. When the cement paste is exposed to increasing temperature, the following temperature regions can be identified by means of thermo-gravimetric investigations [271–273]:

- At a temperature of 100 °C: the cement paste loses weight due to the evaporation of free water present in the capillary pores. This process is accompanied by a slight expansion of the cement paste.
- At temperatures between 100 and 200 °C: a continued evaporation of the free water is identified. At 180 °C the dehydration of the calcium silicate hydrates (C–S–H) begins and leads to the breakdown of the chemically bound water which results in a non-linear weight reduction. This process is accompanied by a significant shrinkage of the cement paste. At a temperature of 200 °C, the weight loss of SCC is about 12 % (comparable to HPC).
- At temperatures between 200 and 400 °C: the weight loss continues at a decreased rate mainly due to the loss of water from the gel pores and the further dehydration of the C–S–H. At 400 °C, the weight loss of SCC is about 15 % (17 % for HPC) [271].
- At temperatures between 400 and 600 °C: the weight loss increases non-linearly and is caused by the decomposition of portlandite (especially at 450–500 °C). The total weight loss at 500 °C is 18 % for SCC (20 % for HPC), whereas at 600 °C this is 19 % for SCC (compared to 21 % for HPC). At 500 °C, approximately 70 % of the CSH gel is decomposed.

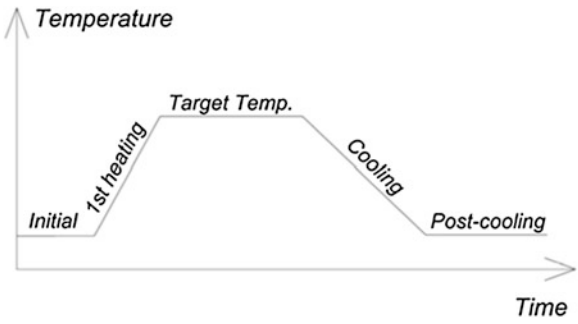


Fig. 2.30 Different temperature stages of fire influencing the remaining strength [271]

- At temperatures between 600 and 800 °C: the decarbonation of the calcite starts: $CaCO_3 \rightarrow CaO + CO_2$. In SCC the calcite is part of the unhydrated cement grains or limestone filler of the cement paste. According to [272], the weight loss between 730–770 °C is defined as the loss due to decarbonation. At 800 °C, the total weight loss reaches 30 % for SCC, compared to 23 % for HPC. According to [31] this peak in mass loss is not identified for VC were for SCC a steep mass reduction was determined at 750 °C. The lack of limestone filler (calcite) in the VC explains the absence of the decarbonation process and the mass loss peak.
- At temperatures exceeding 800 °C: the chemical conversion of the CSH is completed at 850 °C, leading towards a marginal reduction of the weight. However, at about 800 °C ceramic binding may form in the cement paste, which increases only the residual strength, not the hot strength. OPC paste starts to melt around 1,100 and 1,350 °C.

A number of studies can be found in literature dealing with the behaviour of SCC exposed to elevated (up to 100 °C) or high temperatures (up to 800 °C), or on the mechanical behaviour of SCC exposed to fire. In order to evaluate the residual strength of SCC members exposed to fire, it is necessary to determine the residual or hot strength properties. Four strength stages can be identified according to [274]: initial strength (before fire), hot strength (during fire), residual strength (<1 day after fire) and post-cooling strength (>1 day after fire) (Fig. 2.30).

To obtain those strength characteristics, a different experimental set-up is needed. For the evaluation of the hot strength and the residual (or post-cooling) strength two types of tests can be used: residual and hot tests. The difference lies in the different scenarios to which concrete can be subjected mechanically. While data of hot methods are obtained by testing the samples at maintained elevated temperatures (which simulates the behaviour of concrete in a structure under fire), residual and post-cooling test results are obtained by testing the samples after cooling (which simulates the scenario of a concrete element cooled after fire).

Table 2.7 Overview of research on mechanical properties of heated SCC with temperatures up to 700°

Study	[14]	[271]	[276]	[70]	[195]
T-range	20–600 °C	20–600 °C	20–105 °C	20–600 °C	20–700 °C
Mechanical property	$f_{ccub150}$ $f_{ct,spl}$	$f_{ccub,150}$	$f_{ccub150}$ $f_{ct,spl}$	f_{ccyl} $f_{ct,fl}$ E_c	$f_{ccub100}$ $f_{ct,spl}$
Residual or hot	Residual	Residual	Residual	Residual	Residual
Cement type	CEM II/A	CEM I	CEM I	CEM I CEM II/B	CEM II/A
Filler type	Limestone BFS Glass filler	Limestone	Limestone	Limestone	Silica fume
Aggregate type	Granite Limestone	Siliceous	Limestone	Siliceous	Granite
W/B	0.40–0.55	0.48	0.50	0.57–0.61	0.45–0.57
$f_{ccub150,eq\ init}$ [MPa]	37.1–54.0	65.0	57.5	41.1–60.0	33.7–73.2

2.6.1 *Mechanical Properties of SCC at Elevated Temperatures*

2.6.1.1 Introduction

Due to its higher paste volume and due to the presence of a higher content of additions compared to VC, the mechanical behaviour of SCC under or after thermal load is expected to be different. The dense microstructure of SCC seems to be a disadvantage when exposed to fire. The few studies on SCC subjected to high temperatures show that differences exist between the properties of SCC and VC after being subjected to high temperature (Tables 2.7 and 2.8). The obtained test results indicate a decrease in mechanical properties (compressive strength, tensile strength and modulus of elasticity), comparable or higher than VC. According to [275] plain SCC and VC show similar behaviour with regard to either the relative decay of mechanical properties with respect to room temperature conditions and the higher sensitivity to temperature exposure with increasing strength.

2.6.1.2 Residual or Hot Compressive Strength of Heated SCC

Indications of comparable residual compressive strength losses of SCC and VC (up to 16 %) due to elevated temperatures up to 105 °C were found by [276]. SCC and VC had comparable W/C (0.5) and the same raw materials were used (Table 2.7). The samples were tested immediately after the removal from the heated environment. Explanations are found in an increase in capillary porosity, measured by means of fluorescence microscopy, in a microscopical crack width

Table 2.8 Overview of research on mechanical properties of heated SCC with temperatures above 700°

Study	[275]	[162]	[207]	[273, 278]
T-range	20–800 °C	20–800 °C	20–800 °C	20–800 °C
Mechanical property	f_{ccyl} $f_{ct,spl}$ E_c	$f_{ccyl100/200}$ E_c	f_{ccyl}	$f_{ccub100}$
Residual or hot	Hot	Hot residual	Hot	Residual
Cement type	CEM I ASTM C-150	CEM I CEM II	CEM I	CEM I
Filler type	FA BFS	Limestone	Limestone	FA BFS Limestone Marble Basalt
Aggregate type	Limestone	Gneiss Granite	Limestone	Limestone
W/B	0.28	0.40–0.70	0.64	0.33–0.47
$f_{ccub150,eq\ init}$ [MPa]	67.8	44.4–97.8	24.6	60.0–75.0

enlargement through the aggregates and in higher weight losses compared to the reference samples (20 °C).

A study performed by [70] showed that for SCC heated from 20 to 150 °C, a small loss of strength can be observed, associated to an evaporation of free water as well as to an increase in porosity of the tested concrete, which is confirmed by [279]. This porosity increase is an expansion of the pores diameter and therefore leads to an increase in permeability. Between 150 and 300 °C, an increase in compressive strength is observed for SCC (Fig. 2.31). This increase could be attributed to a modification of the bonding properties of the cement paste hydrates (rehydration of the paste due to the migration of water in the pores). Beyond 300 °C, the residual compressive strength of the tested concretes decreased quickly, which is linked to the appearance of micro-cracking and consequently an increase in porosity and permeability of the tested concretes.

Heated SCC of different strength classes was studied in [14]: at 300 °C there is a residual compressive strength reduction for the SCC C25/30 between 12 and 15 %, while for the SCC C30/37 the strength loss percentage reaches 18 %. The corresponding strength loss percentages for the equivalent VC are 18 % for both strength classes. At 600 °C the reduction in compressive strength ranges from 52 to 57 % for all mixtures (SCC and VC).

Residual mechanical properties were determined in [195]: the residual compressive strength of SCC mixtures linearly decreased at increasing temperature, and the strength reduction is parallel to that observed on VC mixtures of the same strength category. Only the VC C25/30 mixture showed a steeper strength reduction than the SCC C25/30 mixture when heated at temperatures above 300 °C. At all tested temperatures, the residual compressive strength of the SCC

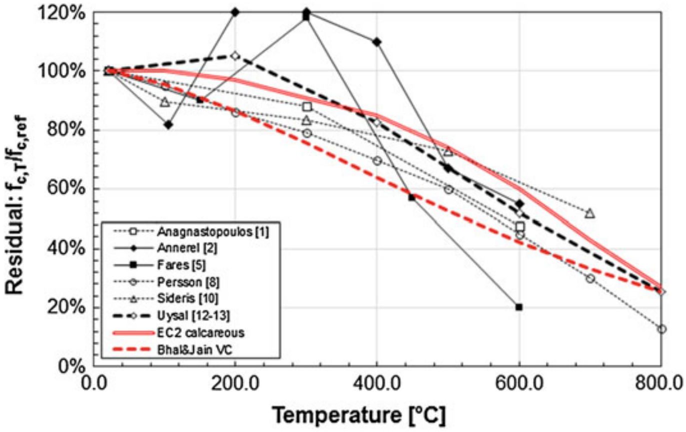


Fig. 2.31 Variation in residual compressive strength of heated SCC as function of temperature (strength determined at room temperature)

mixtures was higher than the one measured on the VC of the same class. This is in accordance with the findings of [279], who reported that concrete specimens produced with SCC had a greater stability below 700 °C compared to VC specimens prepared with the same W/C.

Strength grade has an effect on the hot strength loss of concrete, especially in the temperature range below 400 °C [207].

In Figs. 2.31 and 2.32 an overview of available experimental data on the ratio of (residual and hot) compressive strength at a certain temperature to that at reference temperature (20 °C) as a function of temperature for heated SCC is given.

Strength decreases of SCC can be expected due to thermal load. Comparable degradation behaviour of the residual compressive strength of SCC can be found, which is lower compared to the curves for residual VC given by [280]. In comparison with the curves given by NBN EN 1992-1-2 (Eurocode 2, for hot calcareous VC), the degradation of residual compressive strength of SCC is higher, except for the results by [271, 273, 275, 278] for temperatures between 100 and 400 °C.

The reduction in residual and hot compressive strengths with temperature observed by Persson [162] is gradual without any peaks or outliers. The strength of SCC at fire temperature (hot strength) and the residual or post-cooling strength more or less follow the strength decrease by Eurocode 2 and by [280]. The decrease of the strength of SCC is less than those of HPC with temperature increase.

The effects of elevated temperature on the properties of SCC produced with blast furnace slag (BFS), fly ash (FA) and other mineral additions (limestone powder LP, marble powder MP and basalt powder BP) is examined by [273, 278] (Fig. 2.33). By gradually replacing the cement (CEM I) by BFS or FA, the residual

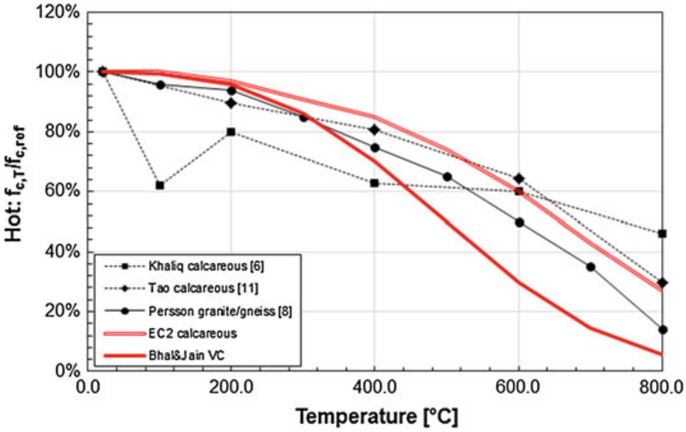


Fig. 2.32 Variation in hot compressive strength of heated SCC as function of temperature (strength determined at room temperature)

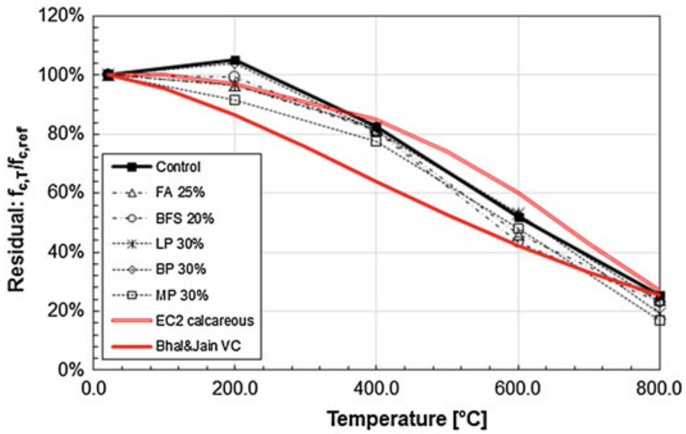


Fig. 2.33 Influence of mineral additions on the residual strength of heated SCC as function of temperature (strength determined at room temperature)

or hot compressive strength loss increases especially when temperatures exceed 400 °C. The increases in the BFS or FA replacement ratios do not significantly affect registered weight losses, however, higher weight losses were observed in the FA series compared to the BFS series. On the other hand, the BFS series showed a higher reduction in the pulse velocity (procedure described in EN 12504-2) compared with the FA series. BP series showed a better performance than other series for all heating cycles. At higher replacement levels of LP, MP and BP further weight losses are observed. Higher weight losses were observed in LP series compared to BP and MP series. Compared to Eurocode 2 and [280] the residual compressive strengths tend to follow the proposed curves of VC.

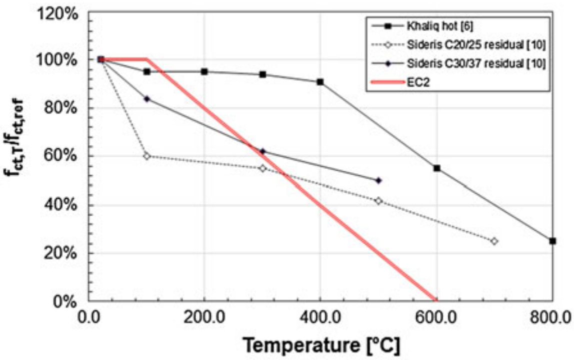


Fig. 2.34 Variation in hot and residual tensile strength of heated SCC as function of temperature

According to [14], SCC produced with limestone filler generally performs better compared to mixtures prepared with ladle furnace slag and glass filler [14] and maintains a greater residual strength after exposure to high temperature.

2.6.1.3 Residual or Hot Tensile Strength of Heated SCC

Also the tensile behaviour of SCC under thermal load or fire exposure is discussed in the literature, as the spalling of concrete is linked to the tensile strength. The tensile strength is dependent on the same factors that affect compressive strength.

In Fig. 2.34 an overview of the effect of elevated temperatures on the tensile strength behaviour of SCC is given. Variations in tensile strength results under thermal load of SCC are observed, also when compared to VC (Eurocode 2). Due to the limited amount of data available, conclusions are difficult to draw. It can be stated that the loss in tensile strength is higher in comparison to the more gradual loss that is obtained for compressive strength with the increase in temperature, as reported by [195]. This is mainly due to the development of micro-cracks as a result of thermal incompatibility between the hydration products and the inert aggregate skeleton of concrete, which is also confirmed by [281, 282].

A similar behaviour was observed for both SCC and VC mixtures of the lower strength categories C20/25 and C25/30: the relative splitting tensile strength is lower after reaching 300 °C. With regard to higher strength categories (C30/37 and C50/60), SCC can have a smaller degree of reduction of relative tensile strength than VC of the same strength class. However, using the Eurocode 2 to predict the residual tensile strength of SCC, heated up to temperatures inferior to 300 °C, can lead to an overestimation.

The effect of temperature on the tensile strength of SCC becomes more pronounced at higher temperatures since the increase in pore pressure due to further temperature increase causes rapid loss of tensile strength.

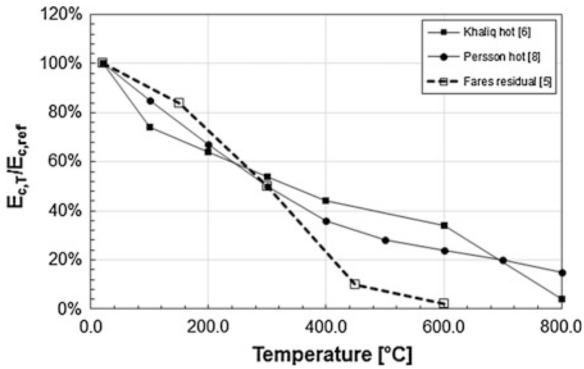


Fig. 2.35 Variation in hot and residual modulus of elasticity of heated SCC as function of temperature

Even at temperatures up to 105 °C, higher residual splitting tensile strength losses were found for SCC (up to 10 %), whereas for VC no significant strength loss was observed [276].

According to [277], the loss in splitting tensile strength of SCC measured at elevated temperatures is gradual and varies almost in a linear fashion up to 400 °C, followed by a sharp reduction in tensile strength between 400 and 800 °C. This sharp reduction in splitting tensile strength beyond 400 °C can be attributed to the development of excessive micro- and macro-cracks resulting from thermal stresses and thermal incompatibility within the concrete. These results were not compared to VC samples, but they were compared to the Eurocode 2. The test curve is significantly higher than the curve of predicted from the code provision (Fig. 2.34).

Up to 800°, a continuously decrease of the flexural strength of SCC is found by Fares et al. [70]. This is associated with the evaporation of bound water and corresponding large mass loss.

2.6.1.4 Residual or Hot Modulus of Elasticity of Heated SCC

The fire response of concrete structures influences the modulus of elasticity of concrete. As shown in Fig. 2.35, a sharp decrease of the modulus of elasticity of SCC of temperature can be obtained with temperature increase. This is mainly due to the disintegration of the hydration products. This behaviour depends on the thermal transient creep, the aggregate type, and the weight loss [277]. At temperatures higher than 300 °C, the hot residual modulus of elasticity seems to be higher than the residual one.

Lower elastic moduli at temperatures encountered during fire were observed in SCC than in VC [162]. The residual modulus of elasticity decreases continuously up to 800 °C due to the evaporation of bound water, corresponding to a large mass loss [70].

2.6.2 Material Specific Phenomena of Heated SCC: Fire-Induced Spalling

Concrete elements exposed to a rapid temperature increase (e.g. fire) may suffer severely from spalling of the outer concrete layers of the elements. According to [271], spalling is the violent or non-violent breaking off of layers or pieces of concrete from the surface of a structural element when it is heated rapidly. Four types of spalling can be identified: aggregate spalling, explosive spalling, surface spalling, and corner/sloughing-off spalling. Many factors have been identified from experiments as influencing spalling of concrete in fire: the heating rate (especially above 3 °C/min), the permeability of the material (a denser concrete is more sensitive for pore pressure build up, for example HPC and SCC compared to VC), pore saturation level (especially above 2–3 % moisture content by weight of concrete), aggregate size/type, the presence of reinforcement (fibers), the shape/size of the samples and the level of externally applied load [271, 272].

The origin of spalling can be explained as a combination of the stresses formed by the thermal expansion and the vapour pressure within the concrete and stresses due to phase changes of some aggregates [283, 284]. The main reason for concrete spalling at elevated temperatures is considered to be the internal pore pressure that builds up due to the vaporization of the free and chemically bound water [195].

In concrete mixtures with finer pore structure, such as HPC or SCC, this internal pressure is not released sufficiently, thus it can lead to severe spalling of the surface layers.

The probability of spalling of SCC is much higher compared to VC, which can be explained by the slower drying rate of SCC due to its lower permeability [285]. However, according to [195], SCC has an explosive spalling tendency similar to the one of VC of the same strength class. Spalling is only dependent on the cement and water content of the mixture and not on the way of its compaction: the self-compacting samples and the samples with VC of the lower strength classes tested (C20/25 and C25/30) did not spall at any temperature up to 700 °C. SCC and VC of the strength class C30/37 suffered from explosive spalling at temperatures between 500 and 580 °C, whereas for the highest strength category mixtures (C50/60) spalling already occurred in the temperature range of 380–458 °C.

A study performed by [14] found that explosive spalling occurs in SCC and VC at 600 °C. The use of ladle furnace slag as filler material instead of limestone filler leads toward higher initial compressive strength but also towards a higher explosive spalling risk. Overall, SCC is expected to spall more than VC due to the lower permeability and higher moisture content.

Explosive spalling was also observed in columns made with SCC but not in those made with VC, even though the VC columns were cured in exactly the same way as the SCC columns [162]. Spalling occurred at a heating rate of 480 °C/h, at a rate of 240 °C/h no spalling occurred. The explosive fire spalling is mainly dependent on the stress in the concrete, the C/P, and water-cementitious materials ratio. An option to limit the amount of explosive fire spalling in columns with SCC to the same level as in columns with VC is to introduce polypropylene fibers into the concrete mix proportions. Another way is to keep the combination of C/P and W/C sufficiently high.

Steel fibers, polypropylene fibers (PP), and others can be used to improve the residual or hot properties of concrete being exposed to elevated temperatures. The incorporation of PP fibers can reduce the damage as the melted fiber form a connected channel system through which heat and water vapour could escape without causing extensive damage to the concrete [279]. Further discussion of the behaviour of steel fibre reinforced concrete (fibers added to overcome the adverse effects of fire induced spalling) is presented in Chap. 6.

Due to the complex physics behind the spalling behaviour of concrete, no valuable prediction models are available to date.

2.7 In-situ Properties

In literature, several papers dealing with in situ properties of SCC can be found. Domone [286] summarized 68 examples of applications of SCC in practice, in the period from 1993 to 2003, including details and ranges of properties, used materials and mix proportions, details of fresh properties, and mechanical properties. This enables concrete practitioners and researches to draw their own conclusions on the suitability and the wide range of concrete applications. This study is a good starting point in the process of identifying the differences and similarities of (i) in situ properties of SCC and properties of SCC tested in laboratory conditions, and (ii) in situ properties of SCC and VC. Ninety percent of the considered cases used SCC with slump flows of 600 and 750 mm, and compressive strength higher than 40 MPa. The maximum aggregate size lies between 16 and 20 mm. The local availability of the aggregates quite often determines the use of crushed rock versus natural gravel. Limestone filler as additional powder is used in 41 % of the cases. In half of the cases VMA was being used to make the mixtures more robust. The median values of the mixture proportions are determined:

- 31.2 vol % coarse aggregates
- 34.8 vol % paste content
- Powder content 500 kg/m^3
- W/P: 0.34.

As expected, there is no unique composition for SCC for a given application. Different types of applications worldwide are mentioned in the literature: columns in high rise buildings, tunnel linings, wall elements for tunnelling, panels, bridge piers, beams for bridges, slabs, architectural purposes, etc.

Some interesting case studies dealing with in situ mechanical properties of SCC are highlighted in the following section.

2.7.1 Case Studies

A demonstration conducted by Sonebi et al. [287] deals with in situ compressive strength of walls (height: 2 m, width 1.95 m, thickness: 0.25 m) using free falling SCC (2 m high). The composition consists of Portland cement Class 42.5, limestone filler, crushed granite aggregates (maximum aggregate size of 20 mm) and polycarboxylate ether as superplasticiser: precise compositions are mentioned in [287]. Compared to the 28 day cube strength of 72.7 MPa, the in situ strength determined by means of 100 mm drilled cores is between 54.5 and 58.6 MPa, thus on average 22 % lower. Although the shape of the specimens is different, the main reason for the difference in results was associated with the core samples being perpendicular to the casting direction, which is not the case for the control cubes (tested in the direction of casting). Nevertheless, a high degree of strength uniformity of the cores was found along the different heights of the wall.

Khayat et al. [116] also reported on the in situ strength of walls (1.5 m in height) cast with SCC (compressive strength up to 40–50 MPa). Compared to laboratory produced cylinders of the same diameter, cylindrical cores (h/d = 2) had slightly lower compressive strength. Core samples extracted from SCC and VC wall elements exhibited an approximate reduction of compressive strength of 10(maximum aggregate size of 10 mm). Again, this was mainly associated with the fact that the core samples were perpendicular to the casting direction. A strength-reduction of 8 % was obtained between cores drilled from the top and bottom sections.

Khayat et al. [288] carried out investigations on the structural behaviour of congested columns cast with SCC of 40-50-60 MPa compressive strength as well as control columns cast with VC of similar strength. The results indicate that the columns with SCC could develop similar in situ compressive strength and greater ductility than columns cast with VC. The estimated compressive strength of SCC elements tested in compression was reported to be 10 % lower than that determined on control 100 $\times$ 200 mm cylinders.

Nunes et al. [154] present the results of a study dealing with the use of SCC and VC in a precast factory. The main goal was to evaluate the feasibility of replacing VC (strength class C45/55) by SCC of the same strength class while maintaining the constituent materials. A large number of specimens (cylinder, cube and prism) were cast along with full-size precast elements. The composition of the SCC consisted of Portland cement class 52.5R, limestone filler, siliceous natural fine and coarse sand, crushed calcareous aggregates (maximum aggregate size of 12.5 mm), and polycarboxylate ether superplasticiser: precise compositions mentioned in [154]. In-situ properties of SCC and VC are obtained by means of compressive strength of drilled cores out of a U-shaped element (two vertical walls and one horizontal slab) at the age of 60 days. The results were compared to cube specimens (150 mm side) and cylinders (300/150 mm) tested at 28 days. Overall, the SCC exhibited an improved mechanical behaviour, mainly due to the lower W/C. More important is the finding that a more uniform strength along the full-size elements (slab vs. wall elements) was obtained for SCC, due to a combination of proper mix-design in combination with controlled mixing and placing. It is concluded that in general SCC exhibits a more compact and homogenous matrix and higher resistance to fluid and chloride ingress [154].

Two non-reinforced concrete columns (6.0 m in height), cast with SCC or a VC, considered for high-level radioactive waste disposal purposes (using Portland cement class 42.5, limestone filler, sand and aggregates and a polycarboxylate ether superplasticiser (precise compositions mentioned in [289]) were tested to determine in situ properties of SCC and VC [290]. Compressive strength of drilled cores and precast cubes at 28 days, direct tensile strength of drilled cores at 56 days, and secant modulus of elasticity of drilled cores at 28 days are reported. Cores were drilled out of the columns at different heights (high, mid, and low levels at 5, 3, and 1 m, respectively, above the bottom surface). Three cubes were stored at 20 °C (>90 % RH). It is shown that the height of the extruded cores is of a great importance for SCC columns, which is less prominent for columns out of VC. Due to the self-compacting capacity, a greater degree of compaction was obtained for the SCC cores at the lower levels, hence resulting in increased compressive strength (3.6 % higher for cores at the lower level) and modulus of elasticity (10.8 % higher for cores at lower level). Cores from the lower parts also registered 3.8 % higher ultrasonic pulse velocity (NBN EN 12504-4) and significantly lower water permeability (NBN B 15-222) compared to cores from the upper parts of the wall elements. For the tensile behaviour, the position of the cores had no significant effect.

Full-scale reinforced columns (3.0 m in height) applying VC and SCC were tested by Sonebi et al. [291]. The investigated concrete mixtures were prepared with Portland cement, ground granulated blast slag and limestone filler as powder material, quartzite sand with continuously crushed granite aggregates (nominal particle size of 10 and 20 mm) were used as aggregates in combination with a copolymer-based superplasticiser: precise compositions mentioned in [291]. In total, eight columns were cast: two columns out of SCC and two with VC intended for housing purposes (strength of 35 MPa (C35)), and two columns with SCC and two with VC intended for civil engineering purposes (strength of 60 MPa (C60)). For the variation in situ strength of columns, the results obtained at the bottom are higher than those obtained at the top, except for the C60-VC mixture used for civil engineering purposes. The results also show that the strength variation within the column is less significant for C60 strength grade mixtures than for C35 mixtures, with slightly smaller variations obtained for SCC. The study also indicates that the in situ strength achieved in the columns varies between 80 and 100 % for all mixtures (SCC and VC), which is above the average value of 65 % reported in literature for such elements. In general, the in situ compressive strengths of SCC were closer to standard cube strength than those of VC. Moreover, the distribution of in situ properties was found to be more uniform in the case of SCC. Finally, the maximum load of the SCC column was slightly higher (4 %) but the SCC columns did not behave in the same manner as the VC columns in terms of initial stiffness and axial strain at maximum load, where the VC columns exhibited greater ductility.

Similar findings were reported by Zhu et al. [233], who tested realistic size columns (3.0 m in height) and beams (3.8 m in length), with different types of reinforcement depending on the chosen application: C35 strength class (housing) and C60 (civil engineering purposes). The investigated SCC and VC concrete mixtures were prepared with Portland cement (42.5 N strength class), ground granulated blast slag and limestone filler as powder material, locally available sand and crushed aggregates (nominal particle size of 10 and 20 mm) were used as aggregates: precise compositions mentioned in [291]. By means of precast cubes and withdrawn cores (compressive strength), pre-embedded inserts (pull-out tests) and rebound hammer values for near-surface properties, comparable conclusions regarding the behaviour of the columns and beams were drawn: (i) the strength-differences along the height of the columns were statistically significant for all mixtures. The strength of the used concrete, SCC and VC, increased from top to bottom, the difference between top and bottom being greater for C35 strength grading, (ii) the results from SCC mixtures were similar to those of the VC mixtures, although the properties of SCC were marginally more uniform.

Overall, it can be confirmed that SCC cast in situ could provide similar (or even slightly enhanced) properties compared to those obtained by means of properly compacted VC. However, the robustness of a SCC mixture, i.e. the stability of its properties when affecting the original mixture design by errors in weighing the constituents, is an important parameter that cannot be overlooked. According to Rigueira et al. [292], the tolerances known for VC have proved to be valid for SCC as well. Especially errors in weighing water (effective water and water transported by means of the aggregates) and fines contents are of capital importance for SCC, and are admissible up to ±6 % interval. Results of a pilot survey conducted by Ferrara [293] show that SCC can be reliably and robustly produced in precast plant for manufacturing precast pre-stressed elements.

2.8 Conclusions

Several studies have addressed the hardened properties of SCC. For the sake of providing a general view of obtained results, an extensive database was developed and analysed in the framework of the RILEM technical committee on mechanical properties of SCC rather than reviewing individual studies.

With respect to compressive strength, the influence of specimen size and shape is well documented in the case of VC. However, for SCC the data are limited. Based on the database, a tendency for the development of higher conversion factors, (f_{ccyl}/f_{ccub}) up to 0.90, is noticed in the case of SCC. With respect to the influencing factors on the obtained compressive strength, W/C and cement strength class does seem to affect the obtained strengths as they do for VC.

The most common addition types to produce SCC in the studies reported in the database are limestone filler, fly ash, and silica fume. Higher 28-day compressive strengths are obtained with fly ash and natural pozzolans compared to limestone filler, while maintaining C/P and the cement content. The influence of C/P was analysed in case of the addition of limestone filler, fly ash, slag, and silica fume. At a constant W/C, a higher C/P generally leads to lower strength. Increased air content decreases the compressive strength of SCC with about 4 MPa per 1 % increase in air content. No significant effect of the type, origin and shape of the aggregate was noted, except for some general trends. As in the case of VC, the higher the compressive strength is, the more critical is the compressive strength of the rock.

Different conclusions can be found in the literature concerning the stress-strain relationship of SCC, due to different test set-ups. However, they all show some differences between SCC and VC. For limestone filler-based SCC, the peak strain at different ages and concrete strengths is higher than for VC. Besides the influence of limestone filler, other filler materials resulted in higher peak strains as well.

The strain softening behaviour of SCC and VC is comparable for the same compressive strength level. The toughness of limestone filler-based SCC is slightly higher than that of VC made without limestone filler. The largest difference was found for the ascending branch of the stress-strain diagram, whereas the surface under the descending branch was comparable. However, the difference in toughness between VC and SCC does not seem to be significant.

The direct tensile strength tends to increase with increasing cube compressive strength. Based on limited results, no significant effect of the paste volume or filler type on the correlation between direct tensile strength and compressive strength is found. However, the C/P seems to have some visible effect, yielding lower direct tensile strength values in case of C/P $<$ 75 %, for a given strength.

An increasing trend of splitting tensile strength is also noticed for increasing compressive strength. Splitting tensile strength results of SCC using granite coarse aggregate lie in the upper half or above the ranges proposed by the EC2 and MC2010. This was not the case when limestone or gravel aggregates are used. Further analysis of available literature data shows that there is no significant effect of coarse aggregate size or paste volume on the correlation between splitting tensile strength and compressive strength. The influence of the C/P or filler type is also not significant according to the available data.

For the evaluation of the flexural tensile strength of SCC, only a limited amount of test results could be found in literature. A logically increasing trend of flexural strength is noticed for increasing cube compressive strength. As could be expected, higher values are found in case of 3-point bending tests, with most of the results lying above the mean value and even above the upper range proposed by EC2 and MC2010. In case of 4-point bending, the test results follow the mean value proposed by EC2 and MC2010, and all data are between the lower and upper range as proposed by the codes.

Due to the considerable contribution of aggregates to the overall stiffness of concrete, it is often assumed that SCC is characterised by a lower modulus of elasticity. Nevertheless, analysis of the data available in the RILEM database shows that the available results fit well into the range acceptable for design using the CEB-fib Model Code. The modulus of elasticity of SCC thus seems to be very similar to VC, with an important but similar scatter on the results for both types of concrete.

The denser microstructure of SCC in comparison with VC seems to be a disadvantage when exposed to fire, as it is the case for HPC. On average, the strength loss after heating of SCC is comparable to VC. The strength of SCC at fire temperature (hot strength) and the residual or post-cooling strength of SCC more or less follow the strength decrease as predicted by EC2. The strength decrease of SCC with temperature increase is less than what is observed for HPC.

The probability of spalling of SCC is higher compared to VC, although sometimes conflicting results are given in literature. The explosive fire spalling is mainly dependent on the stress in the concrete, the C/P, and the W/C.

In literature, several studies concerning the in situ properties of SCC can be found. Overall, it can be confirmed that SCC cast in situ can provide similar or even slightly better properties compared to VC.

References

1. Sonebi, M., Bartos, P.J.M., Zhu, W., Gibbs, J., Tamimi, A.: Brite-EuRam—Task 4-Properties of Hardened Self-Compacting Concrete—Final Report. p. 73 (2005)
2. Domone, P.L.: A review of the hardened mechanical properties of self-compacting concrete. Cement Concr. Compos. **29**, 1–12 (2007)
3. Holschmacher, K., Klug., Y.: A Database for the evaluation of hardened properties of SCC. LACER **7**, 123–134 (2002)
4. De Schutter, G., Bartos, P.J.M., Domone, P., Gibbs, J.: Self-Compacting Concrete, p. 293. Whittles Publishing, Caithness (2008)
5. Abdel-Jawad, Y., Dehn, F.: Self-healing of self-compacting concrete. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 1023–1029 (2005)
6. Abidelah, A., Bouchaïr, A., Kerdal, D., Ayed, K.: Characterization of a self-compacting sand concrete using the quarry waste. Can. J. Civ. Eng. **36**, 1773–1783 (2009)
7. Adam, T., Ruehl, M., Gruebl, P.: The effect of different binders and chemical admixtures on the early hardening of high-strength self-consolidating concrete. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 973–979 (2005)
8. Akalin, O., Ulas Akay, K., Sennaroglu, B.: Self-consolidating high-strength concrete optimization by mixture design method. ACI Mater. J. **107**(4), 357–364 (2010)
9. Akcay, B., Tasdemir, M.: Mechanical behaviour and fiber dispersion of hybrid steel fiber reinforced self-compacting concrete. Constr. Buil. Mater. **28**, 287–293 (2012)
10. Akram, T., Memon, S.A., Obaid, H.: Production of low cost self-compacting concrete using bagasse ash. Constr. Build. Mater. **23**, 703–712 (2009)
11. Almeida Filho, F.M., Barragán, B.E., Casas, J.R., El Debs, A.L.H.C.: Hardened properties of self-compacting concrete—a statistical approach. Constr. Build. Mater. **24**, 1608–1615 (2010)
12. Al-Tamimi, A.K., Sonebi, M.: Assessment of self-compacting concrete immersed in acidic solutions. J. Mater. Civ. Eng. **15**(4), 354–357 (2003)

13. Alyamaç, K.E., Ince, R.: A preliminary concrete mix design for SCC with marble powders. Constr. Build. Mater. **23**, 1201–1210 (2009)
14. Anagnostopoulos, N., Sideris, K.K., Georgiadis, A.: Mechanical characteristics of self-compacting concretes with different filler materials, exposed to elevated temperatures. Mater. Struct. **42**, 1393–1405 (2009)
15. Anagnostopoulos, N.S., Georgiadis, A.S., Sideris, K.K.: Carbonation of self-compacting concretes produced with different materials. In: 5th International RILEM Symposium on Self-Compacting Concrete, pp. 721–727 (2007)
16. Annerel, E., De Schutter, G.: Microstructure and aesthetic appearance of SCC. In: 5th International RILEM Symposium on Self-Compacting Concrete, pp. 381–386 (2007)
17. Arbelàez, J., Rigueira, V., Marti, V., Serna, R., Pinto, B.: Bond characteristics of prestressed strand in self-compacting concrete. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 684–691 (2003)
18. Assié, S.: Durabilité des Bétons Autoplaçants, PhD, Institut national des sciences appliquees de toulouse, p. 249 (2004)
19. Assié, S., Escadeillas, G.: Estimates of self-compacting concrete 'potential' durability. Constr. Build. Mater. **21**, 1909–1917 (2007)
20. Assié, S., Escadeillas, G., Waller, V., Marchese, G., Vachon, M.: Self-compacting and vibrated concrete compared by their physico-chemical durability properties. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp 373–379 (2005)
21. Audenaert, K., De Schutter, G.: Chloride penetration in self compacting concrete. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 818–825 (2003)
22. Audenaert, K., De Schutter, G.: Modelling the carbonation process of self-compacting concrete. In: 5th International RILEM Symposium on Self-Compacting Concrete, pp. 689–694 (2007)
23. Ayding, A.C.: Self compactability of high volume hybrid fiber reinforced concrete. Constr. Build. Mater. **21**, 1149–1154 (2007)
24. Barbhuiya, S.: Effects of fly ash and dolomite powder on the properties of self-compacting concrete. Constr. Build. Mater. **25**, 3301–3305 (2011)
25. Bassuoni, M.T., Nehdi, M.L.: Durability of self-consolidating concrete to sulfate attack under combined cyclic environments and flexural loading. Cem. Concr. Res. **39**, 206–225 (2009)
26. BBRI: Onderzoeksresultaten Prenormatief onderzoek: Mechanische prestaties van zelfverdichtend beton: naar een mogelijke toepassing van Eurocode 2, Biënnale 2008–2010, Conventie NBN: CC CCN/PB/NBN-513, Eindverslag, (2011)
27. Beaupré, D., Lacombe, P., Khayat, K.H.: Laboratory investigation of rheological properties and scaling resistance of air entrained self-consolidating. Mater. Struct. **32**(3), 235–240 (1999)
28. Boel, V., Audenaert, K., De Schutter, G.: Behaviour of self-compacting concrete concerning frost action with deicing salts. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 837–843 (2003)
29. Boel, V., Audenaert, K., De Schutter, G.: Gas permeability and capillary porosity of self-compacting concrete. Mater. Struct. **41**, 1283–1290 (2008)
30. Boel, V., Audenaert, K., De Schutter, G., Heirman, G., Vandewalle, L.: Experimental durability evaluation of self-compacting concrete with limestone filler. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 297–303 (2005)
31. Boel, V.: Microstructure of self-compacting concrete in relation to gas permeability and durability (in Dutch). PhD, Ghent University (2010)
32. Bokan Bosiljkov, V., Duh, D., Zarnic, R.: Salt frost scaling of SCC related to curing regime and air void system. In: 5th International RILEM Symposium on Self-Compacting Concrete, pp. 729–734 (2007)
33. Bokan Bosiljkov, V.: SCC mixes with poorly graded aggregate and high volume of limestone filler. Cem. Concr. Res. **33**, 1279–1286 (2003)

34. Boukendakdji, O., Kenai, S., Kadri, E.H., Rouis, F.: Effect of slag on the rheology of fresh self-compacted concrete. Constr. Build. Mater. **23**, 2593–2598 (2009)
35. Bouzoubaâ, N., Lachemi, M.: Self-compacting concrete incorporating high volumes of class F fly ash: preliminary results. Cem. Concr. Res. **31**(3), 413–420 (2001)
36. Braam, C.R.: Horizontale belasting door zelfverdichtende betonspecie. Cement **3**, 82–85 (2002)
37. Brewe, J.E., Myers, J.J.: High strength self-consolidating concrete girders subjected to elevated compressive fiber stresses, part 1: Prestress loss and camber behavior. PCI J. **3**, 59–77 (2010)
38. Brouwers, H.J., Radix, H.J.: Self-compacting concrete: theoretical and experimental study. Cem. Concr. Res. **35**, 2116–2136 (2005)
39. Brunner, M.: Durability of SCC with high water content. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 333–340 (2005)
40. Bui, V.K., Akkaya, Y., Shah, S.P.: Rheological model for self-consolidating concrete. ACI Mater. J. **99**(6), 549–559 (2002)
41. Byun, K.-J., Kim, J.-K., Song, H.-W.: Self-Compacting Concrete in Korea, International Workshop on Self-Compacting Concrete Japan, pp. 23–33 23–26 August 1998
42. Castel, A., Vidal, T., François, R.: Bond and cracking properties of self-consolidating concrete. Constr. Build. Mater. **24**, 1222–1231 (2010)
43. Castel, A., Vidal, T., Viriyametanont, K., François, R.: Effect of reinforcing bar orientation and location on bond with self-consolidating concrete. ACI Mater. J. **4**, 559–567 (2006)
44. Chopin, D., Francy, O., Lebourgeois, S., Rougeau, P.: Creep and shrinkage of heat-cured self-compacting concrete (SCC). In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 672–683 (2003)
45. Collepardi, M., Borsoi, A., Collepardi, S., Troli, R.: Strength, shrinkage and creep of SCC and flowing concrete. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 911–919 (2005)
46. Collepardi, M., Collepardi, S., Ogoumah Olagot, J.J., Troli, R.: Laboratory-tests and field-experiences of high-performance SCCs. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 904–912 (2003)
47. Collepardi, M., Passuelo, A.: The best SCC: stable, durable, colorable. In: 4th International ACI/CANMET Conference on Quality of Concrete Structures and Recent Advances in Concrete Materials and Testing (2005)
48. Coppola, L., Cerulli, T., Salvioni, D.: Sustainable development and durability of self-compacting concretes. In: 11th International Conference on Fracture (2005)
49. Corinaldesi, V., Moriconi, G.: Characterization of self-compacting concretes prepared with different fibers and mineral additions. Cement Concr. Compos. **33**, 596–601 (2011)
50. Corinaldesi, V., Moriconi, G.: Durable fiber reinforced self-compacting concrete. Cem. Concr. Res. **34**, 249–254 (2004)
51. Corinaldesi, V., Moriconi, G.: The role of industrial by-products in self-compacting concrete. Constr. Build. Mater. **25**, 3181–3185 (2011)
52. Craeye, B., De Schutter, G., Desmet, B., Vantomme, J., Heirman, G.: Effect of mineral filler type on autogenous shrinkage of self-compacting concrete. Cem. Concr. Res. **40**, 908–913 (2010)
53. Craeye, B.: Early-age thermo-mechanical behaviour of concrete supercontainers for radwaste disposal, Doctoral thesis, p. 376 (2010)
54. Daoud, A., Lorrain, M.: Influence de la position des armatures sur I'adhérence des bétons autoplaçants: interprétation par analyse d'image. Mater. Struct. **36**, 231–237 (2003)
55. Daoud, A., Lorrain, M., Laborderie, C.: Anchorage and cracking behaviour of self-compacting concrete. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 692–702 (2003)
56. de Almeida Filho, F.M., El Debs, M.K., El Debs, A.L.H.C.: Bond-slip behavior of self-compacting concrete and vibrated concrete using pull-out and beam tests. Mater. Struct. **41**, 1073–1089 (2008)

57. De Schutter, G., Audenaert, K., Boel, V., Vandewalle, L., Heirman, G., Dupont, D.: Transport properties in self-compacting concrete and relation with durability: overview of a belgian research project. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 799–807 (2003)
58. Dehousse, E., Marion, A.-M.: Early age compressive strength prediction of self-compacting concrete: first results. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 586–595 (2003)
59. Desmet, B., Atitung, K.C., Sanchez, M.A.A., Vantomme, J., Feys, D.: Monitoring the early-age hydration of self-compacting concrete using ultrasonic p-wave transmission and isothermal calorimetry. Mater. Struct. **44**, 1537–1558 (2011)
60. Desnerck, P.: Compression, bond and shear behaviour of powder-type self-compacting concrete. PhD Thesis (2011)
61. Desnerck, P., De Schutter, G., Taerwe, L.: Experimental determination of bond strength of reinforcing bars in self-compacting concrete. In: 5th International RILEM Symposium on Self-Compacting Concrete, pp. 659–664 (2007)
62. Dinakar, P., Babu, K.G., Santhanam, M.: Durability properties of high volume fly ash self-compacting concretes. Cement Concr. Compos. **30**, 880–886 (2008)
63. Dinakar, P., Babu, K.G., Santhanam, M.: Mechanical properties of high volume fly ash self compacting concrete. In: 5th International RILEM Symposium on Self-Compacting Concrete, pp. 651–657 (2007)
64. Ding, Y., Zhang, Y., Thomas, A.: The investigation on strength and flexural toughness of fiber cocktail reinforced self-compacting high performance concrete. Constr. Build. Mater. **23**, 448–452 (2009)
65. Druta, C.: Tensile Strength and bonding characteristics of self-compacting concrete. MSc Thesis, Louisiana State University-USA, p. 115 (2003)
66. El Chabib, H., Nehdi, M., El Naggar, M.-H.: Behavior of SCC confined in short GFRP tubes. Cement Concr. Compos. **27**, 55–64 (2005)
67. Emdadi, A., Libre, N.A., Mehdipour, I., Vahdani, M., Dara, S.: SCC mixtures with different aggregate gradation and limestone powder, 5th International RILEM Symposium on Self-Compacting Concrete, pp. 155–162 (2007)
68. Emdadi, A., Libre, N.A., Mohebbi, A.R., Yekta, S., Shekarchi, M.: Self-compacting concrete for developing countries using raw materials. In: 5th International RILEM Symposium on Self-Compacting Concrete, pp. 181–188 (2007)
69. Fantilli, A.P., Vallini, P., Chiaia, B., Chiaia, B.: Ductility of fiber-reinforced self-consolidating concrete under multi-axial compression. Cement Concr. Compos. **33**, 520–527 (2011)
70. Fares, H., Noumowe, A., Remond, S.: Self-consolidating concrete subjected to high temperature—mechanical and physicochemical properties. Cem. Concr. Res. **39**, 1230–1238 (2009)
71. Fares, H., Remond, S., Noumowe, A., Cousture, A.: High temperature behaviour of self-consolidating concrete microstructure and physicochemical properties. Cem. Concr. Res. **40**, 488–496 (2010)
72. Fava, C., Bergol, L., Fornasier, G., Giangrasso, F., Rocco, C.: Fracture behaviour of self compacting concrete. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 628–636 (2003)
73. Felekoglu, B.: A comparative study on the performance of sands rich and poor in fines in self-compacting concrete. Constr. Build. Mater. **22**, 646–654 (2008)
74. Felekoglu, B., Sarikahya, H.: Effect of chemical structure of polycarboxylate-based superplasticizers on workability retention of self-compacting concrete. Constr. Build. Mater. **22**, 1972–1980 (2008)
75. Felekoglu, B., Türkel, S., Baradan, B.: Effect of water/cement ratio on the fresh and hardened properties of self-compacting concrete. Build. Environ. **42**, 1795–1802 (2007)

76. Felekoglu, B., Yardimci, M.Y., Baradan, B.: A comparative study on the use of mineral and chemical types of viscosity enhancers in self-compacting concrete. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 446–456 (2003)
77. Floyd, R.W., Ruiz, E. D., Do, N. H., Staton, B. W., Hale, W. M.: Development lengths of high-strength self-consolidating concrete beams, PCI J. **52**(4), 44–57 (2011)
78. Georgiadis, A.S., Anagnostopoulos, N.S., Sideris, K.K.: Mechanical characteristics of self-compacting concrete produced with different filler materials. In: 5th International RILEM Symposium on Self-Compacting Concrete, pp. 611–618 (2007)
79. Georgiadis, A.S., Sideris, K.K., Anagnostopoulos, N.S.: Properties of SCC produced with limestone filler or viscosity modifying admixture viscosity modifying admixture. J. Mater. Civ. Eng. **22**(4), 352–360 (2010)
80. Gesoglu, M., Güneyisi, E.: Properties of self-compacting concretes made with binary, ternary, and quaternary cementitious blends of fly ash, blast furnace slag, and silica fume. Constr. Build. Mater. **23**, 1847–1854 (2009)
81. Ghoddousi, P., Javid, A.A.S.: Effect of reinforcement on plastic shrinkage and settlement of self-consolidating concrete as repair material. Mater. Struct. **45**, 41–52 (2012)
82. Giordano, L., Mancini, G.: Fatigue behaviour of bridge deck repaired with self compacting concrete. J. Adv. Concr. Technol. **7**(3), 415–424 (2009)
83. Girgis, A.F.M., Tuan, C.Y.: Bond strength of pretensioned bridge girders cast with self-consolidating concrete, PCI J, **50**(6), 72–87 (2005)
84. Gram, H.-E., Pentti, P., Properties of SCC—especially early age and long term shrinkage and salt frost resistance. In: 1st International RILEM Symposium on Self-Compacting Concrete, pp. 211–225 (1999)
85. Grünewald, S., Walraven, J.: Stabiliseerders in zelfverdichtend beton (in Dutch). Cement **1**, 87–91 (2006)
86. Grünewald, S., Walraven, J.C.: Parameter-study on the influence of steel fibers and coarse aggregate content on the fresh properties of self-compacting concrete. Cem. Concr. Res. **31**, 1793–1798 (2001)
87. Grünewald, S., Walraven, J.C.: The effect of viscosity agents on the characteristics of self-compacting concrete. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 9–15 (2005)
88. Güneyisi, E., Gesoglu, M., Özbay, E.: Evaluating and forecasting the initial and final setting times of self-compacting concretes containing mineral admixtures. Mater. Struct. **42**, 469–484 (2009)
89. Güneyisi, E., Gesoglu, M., Özbay, E.: Strength and drying shrinkage properties of self-compacting concretes incorporating multi-system blended mineral admixtures. Constr. Build. Mater. **24**, 1878–1887 (2010)
90. Güneyisi, E., Gesoğlu, M.: Properties of self-compacting Portland Pozzolana and limestone blended cement concretes containing different replacement levels of slag. Mater. Struct. **44**, 1399–1410 (2011)
91. Hammer, T.A.: The influence of some mix design parameters on drying shrinkage of SCC. In: 5th International RILEM Symposium on Self-Compacting Concrete, pp. 559–564 (2007)
92. Hassan, A.A.A., Hossain, K.M.A., Lachemi, M.: Behavior of full-scale self-consolidating concrete beams in shear. Cement Concr. Compos. **30**, 588–596 (2008)
93. Hassan, A.A.A., Hossain, K.M.A., Lachemi, M.: Bond strength of deformed bars in large reinforced concrete members cast with industrial self-consolidating concrete mixture. Constr. Build. Mater. **24**, 520–530 (2010)
94. Hassan, A.A.A., Hossain, K.M.A., Lachemi, M.: Corrosion resistance of self-consolidating concrete in full-scale reinforced beams. Cement Concr. Compos. **31**, 29–38 (2009)
95. Hauke, B., Self-compacting concrete for precast concrete products in Germany. In: 2nd International RILEM Symposium on Self-Compacting Concrete, pp. 33–642 (2001)
96. Hegger, J., Görtz, S., Will, N., Drössler, C., Tigges, C.: Tragfähigkeit von Bauteilen aus selbstverdichtendem Beton. Beton- und Stahlbetonbau **96**(11), 691–697 (2001)

97. Heirman, G., De Geyter, N.: De Invloed van Vulstoffen op de Eigenschappen van Zelfverdichtend Beton in Vloeibare en Verharde Toestand (in Dutch), Master thesis—KULeuven (2002)
98. Heirman, G., Hendrickx, R., Vandewalle, L., Van Gemert, D., Vantomme, J., Feys, D., De Schutter, G., Desmet, B.: Integration approach of the Couette inverse problem of powder type self-compacting concrete in a wide-gap concentric cylinder rheometer Part II: influence of mineral additions and chemical admixtures on the shear thickening flow behaviour. Cem. Concr. Res. **39**, 171–181 (2009)
99. Heirman, G.: Modelling and quantification of the effect of mineral additions on the rheology of fresh powder type self-compacting concrete, PhD, ISBN 978-94-6018-372-0, 202-206 (2011)
100. Heirman, G., Vandewalle, L.: Shrinkage, creep and frost resistance of self-compacting concrete. In: International CANMET/ACI/JCI Symposium on Sustainable Development of Cement, Concrete and Concrete Structures (2005)
101. Heirman, G., Vandewalle, L.: The influence of fillers on the properties of self-compacting concrete in fresh and hardened state. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 606–618 (2003)
102. Ho, D.W.S., Sheinn, A.M.M., Tam, C.T.: The sandwich concept of construction with SCC. Cem. Concr. Res. **31**, 1377–1381 (2001)
103. Hodgson III, D., Schindler, A.K., Brown, D.A., Gardiner, M.S.: Self-consolidating concrete for use in drilled shaft applications. J. Mater. Civ. Eng. **17**(3), 363–369 (2005)
104. Hoffmann, C., Leemann, A.: Homogeneity of structures made with self-compacting concrete and conventional concrete. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 619–627 (2003)
105. Hossain, K.M.A., Lachemi, M.: Bond behavior of self-consolidating concrete with mineral and chemical admixtures. J. Mater. Civ. Eng. **20**(9), 608–616 (2008)
106. Hossain, K.M.A., Lachemi, M.: Fresh mechanical, and durability characteristics of self-consolidating concrete incorporating volcanic ash. J. Mater. Civ. Eng. **22**(7), 651–657 (2010)
107. Hunger, M., Entrop, A.G., Mandilaras, I., Brouwers, H.J.H., Founti, M.: The behavior of self-compacting concrete containing micro-encapsulated phase change materials. Cement Concr. Compos. **31**, 731–743 (2009)
108. Hwang, S.-D., Khayat, K.H.: Comparison of in situ properties of wall elements cast using self-consolidating concrete. Mater. Struct. **45**, 123–141 (2012)
109. Hwang, S.-D., Khayat, K.H.: Effect of mix design on restrained shrinkage of self-consolidating concrete. Mater. Struct. **43**, 367–380 (2010)
110. Jau, W.-C., Yang, C.-T.: Development of a modified concrete rheometer to measure the rheological behavior of conventional and self-consolidating concretes. Cement Concr. Compos. **32**, 450–460 (2010)
111. Júlio, E., Dias, N., Lourenço, J., Silva, J.: Feret coefficients for white self-compacting concrete. Mater. Struct. **39**, 585–591 (2006)
112. Karatas, M., Turk, K.: Investigation of bond between lap-spliced steel bar and self-compacting concrete: the role of silica fume. Can. J. Civ. Eng. **37**, 420–428 (2010)
113. Khatib, J.M.: Performance of self-compacting concrete containing fly ash. Constr. Build. Mater. **22**, 1963–1971 (2008)
114. Khayat, K.H., Bickley, J., Lessard, M.: Performance of self-consolidating concrete for casting basement and foundation walls. ACI Mater. J. **97**(8), 374–380 (2000)
115. Khayat, K.H., Ghezal, A., Hadriche, M.S.: Factorial design models for proportioning self-consolidating concrete. Mater. Struct. **32**, 679–686 (1999)
116. Khayat, K.H., Manai, K., Trudel, A.: In-Situ mechanical properties of wall elements cast using self-consolidating concrete. ACI Mater. J. **94**(6), 491–500 (1997)
117. Khayat, K.H.: Use of viscosity-modifying admixtures to reduce top-bar effect of anchored bars cast with fluid concrete. ACI Mater. J. **95**(2), 158–167 (1998)

118. Kheder, G.F., Al Jadiri, R.S.: New method for proportioning self-consolidating concrete based on compressive strength requirements. ACI Mater. J. pp. 490–497 (2010)
119. Kim, J.-K., Han, S.H., Park, Y.D., Noh, J.H.: Material properties of self-flowing concrete. J. Mater. Civ. Eng. **10**(4), 244–249 (1998)
120. Kim, Y.H., Hueste, M.B.D., Trejo, D., Cline, D.B.H.: Shear characteristics and design for high-strength self-consolidating concrete. J. Struct. Eng. **136**(8), 989–1000 (2010)
121. Kim, Y.J., Choi, Y.W., Lachemi, M.: Characteristics of self-consolidating concrete using two types of lightweight coarse aggregates. Constr. Build. Mater. **24**, 11–16 (2010)
122. König, G., Holschemacher, K., Dehn, F., Weisse, D.: Verbundverhalten von Betonstahl in selbstverdichtendem Beton. Beton- und Stahlbetonbau **96**(3), 124–132 (2001)
123. König, G., Holschemacher, K., Dehn, F., Weiβe, D.: Bond of reinforcement in self-compacting concrete (scc) under monotonic and cyclic loading. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 939–947 (2003)
124. König, G., Holschemacher, K., Dehn, F., Weiβe, D.: Self-compacting concrete-time development of material properties and bond behaviour. In: 2nd International RILEM Symposium on Self-Compacting Concrete, pp. 507–516 (2001)
125. Kou, S.C., Poon, C.S.: Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates. Cement Concr. Compos. **31**, 622–627 (2009)
126. Kraus, R.N., Naik, T.R., Ramme, B.W., Kumar, R.: Use of foundry silica-dust in manufacturing economical self-consolidating concrete. Constr. Build. Mater. **23**, 3439–3442 (2009)
127. Kumar, R., Kumar, R., Kumar, N.: In situ performance of self-compacting concrete in T-beams. J. Mater. Civ. Eng. **21**(3), 103–109 (2009)
128. Kwan, A.K.H., Ng, I.Y.T.: Improving performance and robustness of SCC by adding supplementary cementitious materials. Constr. Build. Mater. **24**, 2260–2266 (2010)
129. Lachemi, M., Hossain, K.M.A., Lambros, V., Bouzoubaa, N.: Development of cost-effective self-consolidating concrete incorporating fly ash Slag Cement, or Viscosity-Modifying Admixtures. ACI Mater J **100**(5), 419–425 (2003)
130. Lachemi, M., Hossain, K.M.A., Lambros, V., Nkinamubanzi, P.C., Bouzoubaa, N.: Self-consolidating concrete incorporating new viscosity modifying admixtures. Cem. Concr. Res. **34**, 917–926 (2004)
131. Lachemi, M., Hossain, K.M.A., Lambros, V.: Shear resistance of self-consolidating concrete beams—experimental investigations. Can. J. Civ. Eng. **32**, 1103–1113 (2005)
132. Leemann, A., Hoffmann, C.: Properties of self-compacting and conventional concrete—differences and similarities. Mag. Concr. Res. **57**(6), 315–319 (2005)
133. Leung, H.Y., Nadeem, A., Tse, G.K.W.: Permeability of OPC-FA-SF self-compacting concrete. Struct. Concr. **10**(1), 15–19 (2009)
134. Liu, M.: Incorporating ground glass in self-compacting concrete. Constr. Build. Mater. **25**, 919–925 (2011)
135. Liu, M.: Self-compacting concrete with different levels of pulverized fuel ash. Constr. Build. Mater. **24**, 1245–1252 (2010)
136. Loser, R., Leemann, A.: Effects of curing time and drying behaviour of scc in case of restrained shrinkage deformations. In: 5th International RILEM Symposium on Self-Compacting Concrete, pp. 539–544 (2007)
137. Loser, R., Leemann, A.: Shrinkage and restrained shrinkage cracking of self-compacting concrete compared to conventionally vibrated concrete. Mater. Struct. **42**(1), 71–82 (2009)
138. Lowke, D.: Effect of powder content and viscosity agents on creep and shrinkage of self-compacting concretes. BFT **08**, 50–60 (2007)
139. Lowke, D., Schmidt, K., Schiebl, P., Heinz, D.: Dauerhaftigkeitspotentiale selbstverdichtender Betone. Beton- und Stahlbetonbau **103**(5), 324–333 (2008)
140. Ma, J., Dietz, J., Dehn, F.: Ultra high performance self compacting concrete. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 136–142 (2003)
141. Ma, J., Dietz, J.: Ultra high performance self compacting concrete. Lacer **7**, 33–42 (2002)

142. Maeda, M.K., Yamada, K., Uchida, A.: Evaluation on the practicability of SCC. In: 1st International RILEM Symposium on Self-Compacting Concrete, pp. 617–628 (1999)
143. Marquardt, I., Vala, J.: Optimization of self-compacting concrete mixes. In: 2nd International RILEM Symposium on Self-Compacting Concrete, pp. 295–302 (2001)
144. Melo, K.A., Carneiro, A.M.P.: Effect of Metakaolin's finesses and content in self-consolidating concrete. Constr. Build. Mater. **24**, 1529–1535 (2010)
145. Memon, S.A., Shaikh, M.A., Akbar, H.: Utilization of rice husk ash as viscosity modifying agent in self compacting concrete. Constr. Build. Mater. **25**, 1044–1048 (2011)
146. Mnahoncakova, E., Pavlıkova, M., Grzeszczyk, S., Rovnanıkova, P., Cerny, R.: Hydric, thermal and mechanical properties of self-compacting concrete containing different fillers. Constr. Build. Mater. **22**, 1594–1600 (2008)
147. Mortsell, E., Rodum, E.: Mechanical and durability aspects of SCC for road structures. In: 2nd International RILEM Symposium on Self-Compacting Concrete, pp. 459–467 (2001)
148. Nachbaur, L., Waller, V., Haddad, O., Aggoun, S.: Estimating SCC early ages strength through simple tests. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 757–763 (2005)
149. Nachbaur, L., Waller, V., Haddad, O., Vachon, M.: Extension of concrete equivalent mortar (CEM) method to self-compacting concrete. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 1235–1241 (2005)
150. Naito, C.J., Parent, G., Brunn, G.: Performance of bulb-Tee girders made with self-consolidating concrete. PCI J. **51**(6), 72–85 (2006)
151. Nedhi, M., El Chabib, H., Hesham El Naggar, M.: Predicting performance of self-compacting concrete mixtures using artificial neural networks. ACI Mater. J. **98**(5), 394–401 (2001)
152. Nehdi, M., Pardhan, M., Koshowski, S.: Durability of self-consolidating concrete incorporating high-volume replacement composite cements. Cem. Concr. Res. **34**, 2103–2112 (2004)
153. Nguyen-Minh, L., Rovnak, M.: Shear resistance of GFRP-reinforced beams. Mag. Concr. Res. **63**(3), 215–233 (2011)
154. Nunes, S., Figueiras, H., Coutinho, J.S., Figueiras, J.: SCC and conventional concrete on site: property assessment. Ibracon Struct. Mater. J. **2**(1), 25–36 (2009)
155. Opçu, I.B., Bilir, T., Uygunoglu, T.: Effect of waste marble dust content as filler on properties of self-compacting concrete. Constr. Build. Mater. **23**, 1947–1953 (2009)
156. Pandurangan, K., Kothandaraman, S., Sreedaran, D.: A study on the bond strength of tension lap splices in self-compacting concrete. Mater. Struct. **43**, 1113–1121 (2010)
157. Panesar, D.K., Shindman, B.: Elastic properties of self-consolidating concrete. Constr. Build. Mater. **25**, 3334–3344 (2011)
158. Parra, C., Valcuende, M., Gómez, F.: Splitting tensile strength and modulus of elasticity of self-compacting concrete. Constr. Build. Mater. **25**, 201–207 (2011)
159. Paultre, P., Khayat, K.H., Cusson, D., Tremblay, S.: Structural performance of self-consolidating concrete used in confined concrete columns. ACI Struct. J. **102**(4), 560–568 (2005)
160. Persson, B.: Chloride migration coefficient of self-compacting concrete. Mater. Struct. **37**(2), 82–91 (2004)
161. Persson, B.: Creep, shrinkage and elastic modulus of self-compacting concrete. In: 1st International RILEM Symposium on Self-Compacting Concrete, pp. 239–250 (1999)
162. Persson, B.: Fire Resistance of Self-Compacting Concrete. SCC Mater. Struct. **37**(11), 575–584 (2004)
163. Persson, B.: Internal frost resistance and salt frost scaling of self-compacting concrete. Cem. Concr. Res. **33**, 373–379 (2003)
164. Persson, B.: Sulphate resistance of self-compacting concrete. Cem. Concr. Res. **33**, 1933–1938 (2003)
165. Peter, J.A., Lakshmanan, N., Manoharan, P.D.: Investigations on the static behavior of self-compacting concrete under-reamed piles. J. Mater. Civ. Eng. **18**(3), 408–414 (2006)

166. Piérard, J., Dieryck, V., Desmyter, J.: Autogenous shrinkage of self-compacting concrete. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 1013–1021 (2005)
167. [167] Pineaud, A., Cabrillac, R., Rémond, S., Pimienta, P., Rivillon, P.: Mechanical properties of self-compacting concrete—influence of composition parameters. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 863–868 (2005)
168. Pons, G., Mouret, M., Alcantara, M., Granju, J.L.: Mechanical behaviour of self-compacting concrete with hybrid fiber reinforcement. Mater. Struct. **40**, 201–210 (2007)
169. Pons, G., Proust, E., Assié, S.: Creep and shrinkage of self-compacting concrete: a different behaviour compared with vibrated concrete? In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 645–654 (2003)
170. Poon, C.S., Ho, D.W.S.: A feasibility study on the utilization of r-FA in SCC. Cem. Concr. Res. **34**, 2337–2339 (2004)
171. Poppe, A.-M., De Schutter, G.: Creep and shrinkage of self-compacting concrete. In: 1st International Symposium on Design, Performance and Use of Self-Consolidating Concrete, pp. 329–336 (2005)
172. Poppe, A.-M., De Schutter, G.: Effect of limestone filler on the cement hydration in self-compacting concrete. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 558–566 (2003)
173. Pozolo, A., Andrawes, B.: Analytical prediction of transfer length in prestressed self-consolidating concrete girders using pull-out test results. Constr. Build. Mater. **25**, 1026–1036 (2011)
174. Radix, H.J., Brouwers, H.J.: Zelfverdichtend beton volgens de Chinese methode—Deel 2: Proeven op mortel en betonspecie. Cement **6**, 104–108 (2004)
175. Radix, H.J., Brouwers, H.J.: Zelfverdichtend beton volgens de Chinese methode—Deel 3: Proeven op verhard beton. Cement **7**, 76–79 (2004)
176. Prasad, Raghu: B.K., Eskandari, H., Venkatarama Reddy, B.V.: Prediction of compressive strength of SCC and HPC with high volume fly ash using ANN. Constr. Build. Mater. **23**, 117–128 (2009)
177. Reinhardt, H.W., Jooss, M.: Permeability and diffusivity of self-compacting concrete as function of temperature. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 808–817 (2003)
178. Reinhardt, H.W., Wüstholz, T.: Tensile deformation behaviour of self-compacting concrete under sustained loading. In: 5th International RILEM Symposium on Self-Compacting Concrete, pp. 591–598 (2007)
179. Reza Esfahani, M., Lachemi, M., Reza Kianoush, M.: Top-bar effect of steel bars in self-consolidating concrete (SCC). Cement Concr. Compos. **30**, 52–60 (2008)
180. Reza Esfahani, M., Reza Kianoush, M., Lachemi, M.: Bond strength of glass fiber reinforced polymer reinforcing bars in normal and self-consolidating concrete. Can. J. Civ. Eng. **32**, 553–560 (2005)
181. Rols, S., Ambroise, J., Péra, J.: Effects of different viscosity agents on the properties of self-leveling concrete. Cem. Concr. Res. **29**, 261–266 (1999)
182. Roussel, N., Staquet, S., D'Aloia Schwarzentruber, L., Le Roy, R., Toutlemonde, F.: SCC casting prediction for the realization of prototype VHPC-precambered composite beams. Mater. Struct. **40**(9), 877–887 (2007)
183. Rozière, E., Granger, S., Turcry, Ph, Loukili, A.: Influence of paste volume on shrinkage cracking and fracture properties of self-compacting concrete. Cement Concr. Compos. **29**, 626–636 (2007)
184. Rozière, E., Turcry, P., Loukili, A., Loukili, A.: Influence of paste volume, addition content and addition type on shrinkage cracking of self-compacting concrete. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 945–951 (2005)
185. Safawi, M.I., Iwaki, I., Miura, T.: The segregation tendency in the vibration of high fluidity concrete. Cem. Concr. Res. **34**, 219–226 (2004)

186. Safiuddin, M., West, J.S., Soudki, K.A.: Hardened properties of self-consolidating high performance concrete including rice husk ash. Cement Concr. Compos. **32**, 708–717 (2010)
187. Sahmaran, M., Keskin, S.B., Ozerkan, G., Yaman, I.O.: Self-healing of mechanically-loaded self-consolidating concretes with high volumes of fly ash. Cement Concr. Compos. **30**, 872–879 (2008)
188. Sahmaran, M., Yaman, I.O.: Hybrid fiber reinforced self-compacting concrete with a high-volume coarse fly ash. Constr. Build. Mater. **21**, 150–156 (2007)
189. Sahmaran, M., Yaman, I.Ö., Tokyay, M.: Transport and mechanical properties of self-consolidating concrete with high volume fly ash. Cement Concr. Compos. **31**, 99–106 (2009)
190. Sahmaran, M., Yaman, O., Tokyay, M.: Development of high-volume low-lime and high-lime fly-ash-incorporated self-consolidating concrete. Mag. Concr. Res. **59**(2), 97–106 (2007)
191. Sahmaran, M., Yurtseven, A., Yaman, I.O.: Workability of hybrid fiber reinforced self-compacting concrete. Build. Environ. **40**, 1672–1677 (2005)
192. Schindler, A.K., Barnes, R.W., Roberts, J.B., Rodriguez, S.: Properties of self-consolidating concrete for prestressed members. ACI Mater. J. **104**(1), 53–61 (2007)
193. Siad, H., Mesbah, H.A., Khelafi, H., Kamali-Bernard, S., Mouli, M.: Effect of mineral admixture on resistance to sulphuric and hydrochloric acid attacks in self-compacting concrete. Can. J. Civ. Eng. **37**, 441–449 (2010)
194. Siddique, R.: Properties of self-compacting concrete containing class F fly ash. Mater. Des. **32**, 1501–1507 (2011)
195. Sideris, K.K.: Mechanical characteristics of self-consolidating concretes exposed to elevated temperatures. J. Mater. Civ. Eng. **19**(8), 648–654 (2007)
196. Sonebi, M., Bartos, P.J.M.: Filling ability and plastic settlement of self-compacting concrete. Mater. Struct. **35**(5), 462–469 (2002)
197. Sonebi, M., Bartos, P.J.M., Zhu, W., Gibbs, J., Tamimi, A.: SCC: Properties of Hardened Concrete (Task 4), Brite EuRam Proposal No. BE96-3801, 73 (2000)
198. Sonebi, M., Cevik, A.: Genetic programming based formulation for fresh and hardened properties of self-compacting concrete containing pulverised fuel ash. Constr. Build. Mater. **23**, 2614–2622 (2009)
199. Sonebi, M., Cevik, A.: Prediction of fresh and hardened properties of self-consolidating concrete using neurofuzzy approach. J. Mater. Civ. Eng. **21**(11), 672–679 (2009)
200. Sonebi, M.: Medium strength self-compacting concrete containing fly ash: Modelling using factorial experimental plans. Cem. Concr. Res. **34**, 1199–1208 (2004)
201. Sonebi, M., Tamimi, A.K., Bartos, P.J.M.: Performance and cracking behavior of reinforced beams cast with self-consolidating concrete. ACI Mater. J. **100**(6), 492–500 (2003)
202. Söylev, T.A., François, R.: Effect of bar-placement conditions on steel-concrete bond. Mater. Struct. **39**, 211–220 (2006)
203. Soylev, T.A., François, R.: Quality of steel-concrete interface and corrosion of reinforcing steel. Cem. Concr. Res. **33**, 1407–1415 (2003)
204. Sua, N., Hsub, K.C., Chaic, H.W.: A simple mix design method for self-compacting concrete. Cem. Concr. Res. **31**, 1799–1807 (2001)
205. Sukumar, B., Nagamani, K., Raghavan, R.S.: Evaluation of strength at early ages of self-compacting concrete with high volume fly ash. Constr. Build. Mater. **22**, 1394–1401 (2008)
206. Tam, C.T., Sheinn, A.M.M., Teng, S. Swaddiwudhipong, S.H.N., Teng, S.H.N.: Comparing the volume change between scc and conventional slump concrete. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 997–1002 (2005)
207. Tao, J., Yuan, Y., Taerwe, L.: Compressive strength of self-compacting concrete during high-temperature exposure. J. Mater. Civ. Eng. **22**(10), 1005–1011 (2010)
208. Terpstra, J.: Stabilizing low-viscous self-compacting concrete. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 47–53 (2005)

209. Terpstra, J., Stabilizing self-levelling concrete with polysaccharide additives. In: 1st International Symposium on Design, Performance and Use of Self-Consolidating Concrete, pp. 207–213 (2005)
210. Topçu, I.B., Uygunoglu, T.: Effect of aggregate type on properties of hardened self-consolidating lightweight concrete (SCLC). Constr. Build. Mater. **24**, 1286–1295 (2010)
211. Turcry, P., Loukili, A.: A study of plastic shrinkage of self-compacting concrete. In: 3rd International RILEM Symposium on Self-Compacting Concrete, 576–585 (2003)
212. Turcry, P., Loukili, A.: Evaluation of plastic shrinkage cracking of self-consolidating concrete. ACI Mater. J. **103**(4), 272–279 (2006)
213. Turcry, P., Loukili, A., Haidar, K., Pijaudier-Cabot, G., Belarbi, A.: Cracking tendency of self-compacting concrete subjected to restrained shrinkage: experimental study and modeling. J. Mater. Civ. Eng. **18**(1), 46–54 (2006)
214. Turk, K., Karatas, M., Ulucan, Z.C.: Effect of the use of different types and dosages of mineral additions on the bond strength of lap-spliced bars in self-compacting concrete. Mater. Struct. **43**, 557–570 (2010)
215. Türkel, S., Kandemir, A.: Fresh and hardened properties of scc made with different aggregate and mineral admixtures. J. Mater. Civ. Eng. **22**(10), 1025–1032 (2010)
216. Türkmen, I., Kantarci, A.: Effects of expanded perlite aggregate and different curing conditions on the physical and mechanical properties of self-compacting concrete. Build. Environ. **42**, 2378–2383 (2007)
217. Uygunoglu, T., Topçu, I.B.: Thermal expansion of self-consolidating normal and lightweight aggregate concrete at elevated temperature. Constr. Build. Mater. **23**, 3063–3069 (2009)
218. Uysal, M., Yilmaz, K.: Effect of mineral admixtures on properties of self-compacting concrete. Cement Concr. Compos. **33**, 771–776 (2011)
219. Valcuende, M., Parra, C.: Bond behaviour of reinforcement in self-compacting concretes. Constr. Build. Mater. **23**, 162–170 (2009)
220. Valdez, P., Barragán, B., Girbes, I., Shuttleworth, N., Cockburn, A.: Use of waste from the marble industry as filler for the production of self-compacting concretes. Materiales de Construcción **61**(301), 61–76 (2011)
221. Vejmelková, E., Keppert, M., Grzeszczyk, S., Skalinski, B., Cerny, R.: Properties of self-compacting concrete mixtures containing metakaolin and blast furnace slag. Constr. Build. Mater. **25**, 1325–1331 (2011)
222. Vieira, M., Bettencourt, A.: Deformability of Hardened SCC. In: 3rd International RILEM Symposium on Self-Compacting Concrete, pp. 637–644 (2003)
223. Wang, H.-Y., Huang, W.-L.: Durability of self-consolidating concrete using waste LCD glass. Constr. Build. Mater. **24**, 1008–1013 (2010)
224. Weiβe, D., Holschemacher, K.: Sandreiche Selbstverdichtende Betone. Beton **3**, 122–127 (2004)
225. Whitcomb, B.L., Kiousis, P.D.: Development of self-consolidating concrete for thin wall applications including validation. J. Mater. Civ. Eng. **21**(10), 587–593 (2009)
226. Xie, Y., Liu, B., Yin, J., Zhou, S.: Optimum mix parameters of high-strength self-compacting concrete with ultrapulverized fly ash. Cem. Concr. Res. **32**, 477–480 (2002)
227. Yadegaran, I., Mahoutian, M., Shekarchi, M., Libre, N.A.: Effect of polypropylene fibers on shrinkage of self-compacting concrete. In: 5th International RILEM Symposium on Self-Compacting Concrete, pp. 707–713 (2007)
228. Yazici, H.: The effect of silica fume and high-volume Class C fly ash on mechanical properties, chloride penetration and freeze–thaw resistance of self-compacting concrete. Constr. Build. Mater. **22**, 456–462 (2008)
229. Yin, J., Yu, Z., Xie, Y.: Research on the influence of different curing condition on the peformance of the self-compacting high-performance concrete. In: 1st International Symposium on Design, Performance and Use of Self-Consolidating Concrete, pp. 439–447 (2005)

230. Yurtdas, I., Burlion, N., Shao, J.-F., Li, A.: Evolution of the mechanical behaviour of a high performance self-compacting concrete under drying. Cement Concr. Compos. **33**, 380–388 (2011)
231. Zhu, W., Bartos, P.: Microstructure and properties of interfacial transition zone in SCC. In: 1st International Symposium on Design, Performance and Use of Self-Consolidating Concrete, pp. 319–327 (2005)
232. Zhu, W., Bartos, P.: Permeation properties of self-compacting concrete. Cem. Concr. Res. **33**, 921–926 (2003)
233. Zhu, W., Gibbs, J.C., Bartos, P. J.M.: Uniformity of in situ properties of SCC in full-scale structural elements. Cement Concr. Compos. **23**(1), 57–64 (2001)
234. Zhu, W., Gibbs, J.C.: Use of different limestone and chalk powders in self-compacting concrete. Cem. Concr. Res. **35**, 1457–1462 (2005)
235. Zhu, W., Quinn, J., Bartos, P.: Transport properties and durability of self-compacting concrete. In: 2nd International RILEM Symposium on Self-Compacting Concrete, pp. 451–458 (2001)
236. Zhu, W., Sonebi, M., Bartos, P.J.M.: Bond and interfacial properties of reinforcement in self-compacting concrete. Mater. Struct. **37**, 442–448 (2004)
237. Powers, T., Brownyard, L.: Studies of the physical properties of hardened Portland cement paste (nine parts). J. Am. Concr. Inst. **43**, 101–132 (1946)
238. Zsigovics, I.: Effect of limestone powder on the consistency and compressive strength of SCC. In: 4th International RILEM Symposium on Self-Compacting Concrete, pp. 173–180 (2005)
239. European Committee for Standardization: EN 206-9: Concrete—Part 9: Additional Rules for Self-Compacting Concrete (SCC), p. 27 (2010)
240. European Committee for Standardization: EN 197-1: Cement. Composition, specifications and conformity criteria for low heat common cements, p. 52 (2002)
241. ASTM C150/C150 M: Standard Specifications for Portland Cement, p. 9 (2012)
242. European Committee for Standardization: EN 206-1: Concrete—Part 1: Specification, Performance, Production and Conformity, p. 72 (2000)
243. Khayat, K., Mitchell, D.: NCHRP report 628: Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements, National Cooperative Highway Research Program, p. 99 (2009)
244. Vandegrift, D. Jr., Schindler, A.K.: The effect of test cylinder size on the compressive strength of sulfur capped concrete specimens. Highway Research Center and Department of Civil Engineering at Auburn University, p. 83 (2006)
245. Elwell, D.J., Fu, G.: Compression testing of concrete: cylinders vs. cubes, Report FHWA/NY/SR-95/119, special report 119. Transportation Research and Development Bureau New York State Department of Transportation (1995)
246. EFNARC: The European Guidelines for Self-Compacting Concrete, p. 63 (2005)
247. European Committee for Standardization: EN 12390-3: Testing hardened concrete. Compressive strength of test specimen, p. 22 (2009)
248. ASTM C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, p. 7 (2012)
249. American Association of State and Highway Transportation Officials, AASHTO T 22-06: Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens, p. 11 (2006)
250. Neville, A.M.: A general relation for strengths of concrete specimens of different shapes and sizes. J. Am. Concr. Inst. **63**(10), 1109–1195 (1966)
251. Belgian Institute for Normalisation (BIN), NBN B15-220: Concrete testing—Compressive strength: Addendum 1 (In Dutch) (1973)
252. UNESCO: Reinforced Concrete : An International Manual, p. 20. Butterworths, Sydney (1971)
253. American Concrete Institute, ACI 318-08: Building Code Requirements for Structural Concrete and Commentary (2008)

254. Klug, Y., Holschemacher, K.: Comparison of the Hardened Properties of Self-Compacting and Normal Vibrated Concrete. In: 3rd International RILEM Symposium on Self-Compacting Concrete (Reykjavik 2003), pp. 596–605 (2003)
255. Van Itterbeeck, P., Cauberg, N., Parmentier, B., Vandewalle, L., Lesage, K.: Eurocode 2 predictions vs. mechanical properties of self compacting concrete. In: CD Proceedings of Design, Production and Placement of Self-Consolidating Concrete (SCC2010), Montreal, Canada (2010)
256. Boel, V., Craeye, B., Desnerck, P., Van Der Vurst, F., De Schutter, G.: Influence of specimen shape and dimension on the compressive strenght of self-compacting concrete. In: Proceedings of SCC2013, Paris, France (2013)
257. European Committee for Standardization: EN 1992-1-1, Eurocode 2: Design of concrete structures—Part 1-1: General Rules and Rules for Buildings, p. 225 (2004)
258. RILEM, Report 038: Durability of Self-Compacting Concrete—State-of-the-Art Report of RILEM Technical Committee 205-DSC, p. 208 (2007)
259. Schiessl, A, Zilch, K.: The effects of the modified composition of SCC on shear and bond behaviour. In: Proceedings of the second RILEM international symposium on self-compacting concrete, Japan, COMS Engineering Corporation, pp. 501–506 (2001)
260. Hewlett, P.: Lea's Chemistry of Cement and Concrete. Arnold Publishers, London (1998)
261. Feret, R.: Sur la compacité des mortiers hydrauliques, Annales des Ponts et Chaussées. Série **7**(4), 5–164 (1892)
262. ASTM C109: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars, p. 10 (2012)
263. Domone, P.: Self-compacting concrete: An analysis of 11 years of case studies. Cement Concr. Compos. **28**, 197–208 (2006)
264. Dewar, J.D.: Computer Modeling of Concrete Mixtures, ISBN 0-419-23020-3 (1999)
265. Poppe, A.-M.: Influence of fillers on hydration and properties of self-compacting concrete (in Dutch). PhD, Ghent University (2004)
266. Lambotte, H.: Rheologie (in Dutch). Ghent University (1979)
267. RILEM, TC 148-SSC: Test method for measurement of the strain-softening behaviour of concrete under uniaxial compression. Mater. Struct. **33**, 347–351 (2000)
268. CEB-FIP: Bulletin 55: Model Code 2010—First complete draft, CEB-FIP, vol. 1, p. 292 (2010)
269. Comite Euro-International du Beton: CEB-Fib model code 1990: Design Code. Thomas Telford, London (1993)
270. Comite Euro-International du Beton: CEB-Fib model code 1978: Design Code. Thomas Telford, London (1978)
271. Annerel, E.: Assessment of the residual strength of concrete structures after fire exposure. PhD thesis, Ghent University (2010)
272. Liu, X.: Microstructural behaviour of self-compacting concrete during hydration and after exposure to high temperatures. PhD thesis, Ghent University (2006)
273. Uysal, M., Yilmaz, K., Ipek, M.: Properties and behavior of self-compacting concrete produced with gbfs and fa additives subjected to high temperatures. Constr. Build. Mater. **28**, 321–326 (2012)
274. Sashar, R., Khoury, G.A.: Material and environmental factors influencing the compressive strength of unsealed cement paste and concrete at high temperatures. Mag. Concr. Res. **45**, 51–61 (1993)
275. Bamonte, P., Felicetti, R., Gambarova, P.G.: Mechanical properties of self-compacting concrete at high temperature and after cooling. In: The Third North American Conference on the Design and Use of Self-Consolidating Concrete (2008)
276. Craeye, B., De Schutter, G., Wacquier, W., Van Humbeeck, H., Van Cotthem, A., Areias, L.: Closure of the concrete supercontainer in hot cell under thermal load. Nucl. Eng. Des. **241**, 1352–1359 (2011)

277. Khaliq, W., Kodur, V.: Thermal and mechanical properties of fiber reinforced high performance self-consolidating concrete at elevated temperatures. Cem. Concr. Res. **41**, 1112–1122 (2011)
278. Uysal, M.: Self-compacting concrete incorporating filler additives: performance at high temperatures. Constr. Build. Mater. **26**, 701–706 (2012)
279. Ye, G., Liu, X., De Schutter, G., Taerwe, L., Vandevelde, P.: Phase distribution and microstructural changes of self-compacting cement paste at elevated temperature. Cem. Concr. Res. **37**, 978–987 (2007)
280. Bhal, N.S., Jain, J.P.: Compressive strength of concrete subjected to elevated temperatures. Indian Concr. J. **73**(8), 503–507 (1999)
281. Chan, Y.N., Peng, G.F., Anson, M.: Residual strength and pore structure of high strength concrete and normal strength concrete after exposure to high temperatures. Cement Concr. Compos. **21**(1), 23–27 (1999)
282. Khoury, G.A.: Compressive strength of concrete at high temperatures: reassessment. Mag. Concr. Res. **44**(161), 291–309 (1994)
283. Malhorta, H.L.: Spalling of Concrete in Fire, Construction Industry Research and Information Association, Technical Report, No. 118 (1984)
284. Jansson, R.: Liquid/steam pressure measurement inside concrete exposed to fire. In: Proceedings of the 4th International Workshop on Structures in Fire, Aveiro, Portugal (2006)
285. Norling-Mjörnell, K.: Uttorkning av bygfukkt i självkompakterande betong, Report White Arkitekter AB (2003)
286. Domone, P.L.: Self-compacting concrete: an analysis of 11 years of case studies. Cement Concr. Compos. **28**, 197–208 (2006)
287. Sonebi, M., Rooney, M., Bartos, P.: In-situ compressive strength of self-compacting concrete. Concrete **36**(3), 48–49 (2002)
288. Khayat, K.H., Trembley, S., Paultre, P.: Structural response of self-compacting concrete columns. In: Proceeding of the First International RILEM Symposium on Self-Compacting Concrete, Stockholm, pp. 291–306, (1999)
289. Craeye, B., De Schutter, G., Van Humbeeck, H., Van Cotthem, A.: Early age behaviour of concrete supercontainers for radioactive waste disposal. Nucl. Eng. Des. **239**, 23–35 (2009)
290. Piérard, J., Pollet, V.: Testing of cores and precast samples out of cast column in SCC and VC. Belgian Building Research Institute, Report DE611XB050, Belgium, p. 23 (2007)
291. Sonebi, M., Bartos, P.: Performance of reinforced columns cast with self-compacting concrete. In: Proceedings of the 5th CANMET/ACI International Conference on Recent Advances in Concrete Technology, SP 200-25, Singapore, pp. 415–431, (2001)
292. Rigueira, J.W., Garcia-Taengua, E., Serna-Ros, P.: Self-consolidating concrete robustness in continuous production regarding fresh and hardened state properties, ACI Mater. J. **106**(3), 301–307 (2009)
293. Ferrara, L.: Statistical properties of steam-cured-plant produced SCC for prestressed precast applications. In: Proceedings of the 2nd International Symposium on Design, Performance and Use of Self Consolidating Concrete, Bejing, China, pp. 483–494, (2009)

Springer

http://www.springer.com/978-3-319-03244-3

Mechanical Properties of Self-Compacting Concrete
State-of-the-Art Report of the RILEM Technical Committee 228-MPS on Mechanical Properties of Self-Compacting Concrete
Khayat, K.; De Schutter, G. (Eds.)
2014, XIX, 271 p. 184 illus., 1 illus. in color., Hardcover
ISBN: 978-3-319-03244-3