INFLUENCE OF SPECIMEN SHAPE AND DIMENSIONS ON THE COMPRESSIVE STRENGTH OF SELF-COMPACTING CONCRETE

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ABSTRACT

Standard EN 12390-4 specifies the shape and dimensions of concrete test specimens for the strength tests and the methods of casting and curing in order to determine the strength class. For design purpose mostly 150x300mm cylinder compressive strength is used. However, depending on the country, other standards and subsequently other dimensions and shapes might be used as well, e.g. 100x200mm cylinders as stated in ASTM C39. Besides, even other types of test specimens than defined in the standards are used depending on local tradition, practice and research purpose.

In order to compare all measured strengths on different samples from different researchers and to convert the measured strength into the design strength, conversion formulas are needed. Those formulas are well-known for normal strength vibrated concrete (VC), whereas this is not the case for self-compacting concrete (SCC). From literature it was found that the conversion formulas of VC are not always applicable for SCC, and as such the way to convert stays rather unclear causing uncertainties. In this paper the strength results of different powder-type SCC mixtures are analyzed taking into account mixture parameters like type of cement, aggregate, filler, superplasticiser, powder content and the water-to-cement and water-to-powder ratio. Cylinders and cubes of various dimensions are used to determine the compressive strength. Finally, the conclusions will lead to some suggestions for new conversion formulas.

Keywords: self-compacting concrete; compressive strength; strength ratio; shape factor; conversion factor

INTRODUCTION

In practice different standards can be followed for the compressive testing of concrete e.g. EN 12390-3, ASTM C39 and AASHTO T 22. These standards in total allow the testing of a wide variety of specimens with different shapes and sizes. In order to compare the measured strengths on different samples and to convert into a design strength as prescribed in the standards, conversion formulas are needed. In case of vibrated concrete (VC) the influence of specimen size and shape on the measured compressive strength is well documented in various papers and books [1,2]. This is however not yet the case for SCC. By the difference in mixture composition between SCC and VC, changes in the conversion formulas might be expected. Tab.1 lists some strength conversion factors utilised in practice for VC, originating from different sources, [2,3].

Table 1. Strength ratios [2,3].

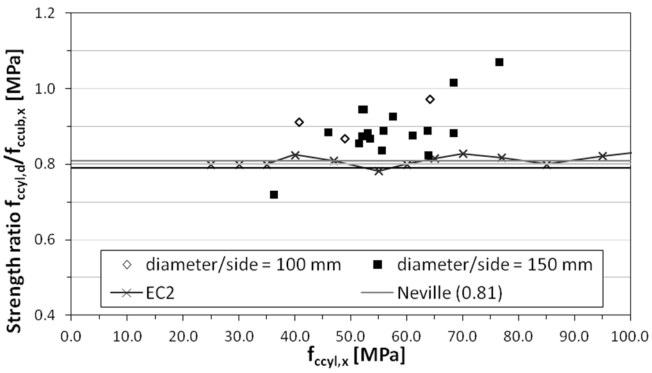
Side x [mm]	$f_{ccub,x}$ / $f_{ccub,150}$ [-]				
	Neville	NBN B15	UNESCO	AASHTO	ACI
100	1.02	1.06	1.00	-	-
120	1.01	1.04	1.00	-	-

Diameter d [mm]	Height h [mm]	$f_{ccyl,d}$ / $f_{ccyl,150}$ (h/d=2) [-]				
		Neville	NBN B15	UNESCO	AASHTO	ACI
100	200	1.03	1.03	1.03	1.00	1.00
110	220	1.02	1.03	1.02	1.00	-

$f_{ccyl,150}$ / $f_{ccub,150}$ [-]				
Neville	NBN B15	UNESCO	AASHTO	ACI
0.81	0.79	0.80	-	-

In literature nine papers have been found in which the compressive strength of SCC has been determined on cubes as well as on cylinders [4-12]. Only 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 EFNARC (2005). In Fig.1 the experimental strength conversion factors $f_{ccyl,d}/f_{ccub,x}$ are plotted in function of the cylinder compressive strength $f_{ccyl,d}$ and compared to the conversion factors of Tab.1 and Eurocode 2. The analysis is based on cubes 100 and 150 mm and the corresponding cylinders 100/200 mm and 150/300 mm. The mean value of the obtained strength ratio is 0.90 with a standard deviation of 0.07. The information is based on only a limited amount of results and further research on this matter is needed. It can nonetheless be stated that a first observation seems to indicate that the conversion factors $f_{ccyl,150}/f_{ccub,150}$ and $f_{ccyl,100}/f_{ccub,100}$ may be higher for SCC than reported for VC (cf. Tab.1). In [13], based on [14], an increase from 0.8 to near 1 is reported. Besides, in [13] an increasing strength ratio with increasing strength is noticed. Taking into account the limited amount of the data from [4-12] no dependency on the compressive strength was found.

Figure 1. Strength ratio $f_{ccyl,100}$ / $f_{ccub,100}$ and $f_{ccyl,150}$ / $f_{ccub,150}$ vs cube compressive strength $f_{ccyl,x}$.



MATERIALS AND METHODS

Mix design - In total 24 powder-type SCC mixtures and 2 VC mixtures have been designed (mixed in three different laboratories: lab A-B-C) in order to analyze 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), addition (limestone fillers with different fineness, quartz filler, fly ash), aggregate (gravel, calcareous rubble, porphyry rubble) and superplasticiser (2 types of polycarboxylic ether with different dry particles concentration (PCE1 35% vs. PCE2 30 %), NFS: naphtalene formaldehyde sulphonate, MFS: melamine formaldehyde sulphonate). The influence of the water-to-cement ratio (W/C), the cement-to-powder ratio (C/P) and the powder content (P) is investigated as well. The mixtures are listed in Tab.2.

Test methods - The fresh concrete properties are summarized in Tab.2 (slump, slump-flow, V-funnel, air content, density (EN 12350)). In order to determine the shape factors compared to a reference cylinder with a diameter of 150 mm and a height of 300 mm, cubes with 100 mm and 150 mm were cast and stored until testing according to the European standards [EN 12390 and EN 12504]. The compressive strength was determined according to the European standard 12390-3. Each time the same mix procedure is applied in the three laboratories.

RESULTS AND DISCUSSION

General strength ratio - In Fig.2 (a-c) the strength ratios $f_{ccyl,150}/f_{ccub,100}$, $f_{ccyl,150}/f_{ccub,150}$ and $f_{ccub,100}/f_{ccub,150}$ are plotted together with the mean value of the ratios, respectively 0.86±0.06, 0.90±0.06 and 1.03±0.05. The strength ratio $f_{ccyl,150}/f_{ccub,150}$ fits well with the analysis based on [4-12] and is also corresponding with the findings of [13]. As such, the ratio is indeed higher for SCC than for VC (Cf. Tab.1).

[kg/m^3]	TVC CEM I	TVC CEM III	SCC ref	SCC WC0.45	SCC WC0.50		SCC CP0.45	SCC CP0.55	SCC CP0.60	SCC P520	SCC P560	SCC P640
CEM I 52.5 N	360	-	300	300	300	300	270	330	360	260	280	320
CEM III/A 42.5 N LA	-	-	-	-	-	-	-	-	-	-	-	-
CEM III 42.5 N LA	-	360	-	-	-	-	-	-	-	-	-	-
Limestone Filler 1	-	-	300	300	300	300	330	270	240	260	280	320
Limestone Filler 2	-	-	-	-	-	-	-	-	-	-	-	-
Quartz Filler	-	-	-	-	-	-	-	-	-	-	-	-
Fly Ash	-	-	-	-	-	-	-	-	-	-	-	-
River sand 0/5	640	640	853	913	890	850	890	850	829	944	905	835
Gravel 2/8	462	462	263	281	274	262	274	262	255	290	278	257
Gravel 8/16	762	762	434	463	452	431	452	431	421	479	459	424
Calcareous rubble 2/7	-	-	-	-	-	-	-	-	-	-	-	-
Calcareous rubble 6/14	-	-	-	-	-	-	-	-	-	-	-	-
Porphyry rubble 2/7	-	-	-	-	-	-	-	-	-	-	-	-
Porphyry rubble 6/14	-	-	-	-	-	-	-	-	-	-	-	-
Water	165	165	165	135	150	180	148.5	181.5	198	143	154	176
Superplasticiser (PCE1)	-	-	3.0	4.7	3.1	2.0	3.4	2.0	2.0	3.7	-	2.3
Superplasticiser (PCE2)	-	-	-	-	-	-	-	-	-	-	-	-
Superplasticiser (MFS)	-	-	-	-	-	-	-	-	-	-	-	-
Superplasticiser (NFS)	-	-	3.0	4.7	3.1	2.0	3.4	2.0	2.0	3.7	-	2.3
W/C [-]	0.46	0.46	0.55	0.45	0.50	0.60	0.55	0.55	0.55	0.55	0.55	0.55
W/P [-]	0.46	0.46	0.275	0.225	0.250	0.300	0.248	0.303	0.330	0.275	0.275	0.275
C/P [-]	1.00	1.00	0.50	0.50	0.50	0.50	0.45	0.55	0.60	0.50	0.50	0.50
P [-]	360	360	600	600	600	600	600	600	600	520	560	640
Slump [mm]	45	35	-	-	-	-	-	-	-	-	-	-
Slump-flow [mm]	-	-	721	700	675	570	758	660	708	755	733	608
V-funnel [s]	-	-	11.6	36.2	20.7	8.5	19.9	7.3	6.2	15.1	8.9	9.8
Air content [%]	2.2	2.5	2.4	2.1	2.9	2.2	2.1	2.3	1.9	1.3	2.4	2.1
Density [kg/m^3]	2384	2375	2376	2424	2400	2369	2419	2350	2481	2419	2375	2369
$f_{ccyl,150}$ [N/mm^2]	55.7	53.5	56.7	71.2	62.1	48.6	62.6	49.8	49.4	57.2	58.2	54.4
$f_{ccub,100}$ [N/mm^2]	58.9	63.0	65.4	78.7	72.0	55.6	73.0	60.9	59.2	69.2	70.1	63.4
$f_{ccub,150}$ [N/mm^2]	60.2	60.2	61.3	75.4	68.0	52.8	71.0	56.9	56.3	68.2	65.4	58.6
$f_{ccyl,150}/f_{ccub,100}$ [-]	0.946	0.849	0.867	0.905	0.863	0.874	0.858	0.818	0.834	0.827	0.830	0.858
$f_{ccyl,150}/f_{ccub,150}$ [-]	0.925	0.889	0.925	0.944	0.913	0.920	0.882	0.875	0.877	0.839	0.890	0.928
$f_{ccub,100}/f_{ccub,150}$ [-]	0.978	1.047	1.067	1.044	1.059	1.053	1.028	1.070	1.052	1.015	1.072	1.082

[kg/m^3]	SCC CEMIII/A 42.5 N LA	SCC CEMI 52.5 R HES	SCC limestone	SCC porphyry
CEM I 52.5 N	-	-	300	300
CEM III/A 42.5 N LA	300	-	-	-
CEM III 42.5 N LA	-	300	-	-
Limestone Filler 1	300	300	300	300
Limestone Filler 2	-	-	-	-
Quartz Filler	-	-	-	-
Fly Ash	-	-	-	-
River sand 0/5	860	860	871	871
Gravel 2/8	265	265	-	-
Gravel 8/16	437	437	-	-
Calcareous rubble 2/7	-	-	261	-
Calcareous rubble 6/14	-	-	449	-
Porphyry rubble 2/7	-	-	-	258
Porphyry rubble 6/14	-	-	-	451
Water	165	165	165	165
Superplasticiser (PCE1)	3.0	3.0	3.0	3.0
Superplasticiser (PCE2)	-	-	-	-
Superplasticiser (MFS)	-	-	-	-
Superplasticiser (NFS)	-	-	-	-
W/C [-]	0.55	0.55	0.55	0.55
W/P [-]	0.275	0.275	0.275	0.275
C/P [-]	0.50	0.50	0.50	0.50
P [-]	600	600	600	600
Slump [mm]	-	-	-	-
Slump-flow [mm]	640	733	655	693
V-funnel [s]	-	-	-	-
Air content [%]	-	-	-	-
Density [kg/m^3]	-	-	-	-
$f_{ccyl,150}$ [N/mm^2]	55.6	44.5	47.2	47.5
$f_{ccub,100}$ [N/mm^2]	54.1	57.1	57.5	58.1
$f_{ccub,150}$ [N/mm^2]	50.9	55.8	55.7	53.0
$f_{ccyl,150}/f_{ccub,100}$ [-]	1.028	0.778	0.822	0.818
$f_{ccyl,150}/f_{ccub,150}$ [-]	1.093	0.796	0.848	0.897
$f_{ccub,100}/f_{ccub,150}$ [-]	1.063	1.024	1.032	1.096

[kg/m^3]	SCC LF50%	SCC LF100%	SCC QF50%	SCCQF100%	SCCFA10%	SCCFA20%	SCCFA30%	SCC MFS	SCC NFS	SCC PCE
CEM I 52.5 N	300	300	300	300	300	300	300	300	300	300
CEM III/A 42.5 N LA	-	-	-	-	-	-	-	-	-	-
CEM III 42.5 N LA	-	-	-	-	-	-	-	-	-	-
Limestone Filler 1	150	-	150	-	268	239	210	300	300	300
Limestone Filler 2	150	300	-	-	-	-	-	-	-	-
Quartz Filler	-	-	150	300	-	-	-	-	-	-
Fly Ash	-	-	-	-	25	50	75	-	-	-
River sand 0/5	871	869	871	863	864	868	871	860	858	866
Gravel 2/8	268	267	268	266	266	267	268	265	264	267
Gravel 8/16	442	441	442	438	439	441	442	437	436	440
Calcareous rubble 2/7	-	-	-	-	-	-	-	-	-	-
Calcareous rubble 6/14	-	-	-	-	-	-	-	-	-	-
Porphyry rubble 2/7	-	-	-	-	-	-	-	-	-	-
Porphyry rubble 6/14	-	-	-	-	-	-	-	-	-	-
Water	165	165	165	165	165	165	165	165	165	165
Superplasticiser (PCE1)	3.0	2.7	3.0	5.6	3.4	3.0	3.5	-	-	-
Superplasticiser (PCE2)	-	-	-	-	-	-	-	-	-	7.8
Superplasticiser (MFS)	-	-	-	-	-	-	-	22.1	-	-
Superplasticiser (NFS)	-	-	-	-	-	-	-	-	13.2	-
W/C [-]	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
W/P [-]	0.275	0.275	0.275	0.275	0.278	0.280	0.282	0.27	0.275	0.275
C/P [-]	0.50	0.50	0.50	0.50	0.51	0.51	0.51	0.50	0.50	0.50
P [-]	600	600	600	600	593	589	585	600	600	600
Slump [mm]	-	-	-	-	-	-	-	-	-	-
Slump-flow [mm]	785	720	675	670	640	735	785	690	705	718
V-funnel [s]	10.9	19.5	10.6	6.4	18.7	12.2	18.0	9.0	10.3	7.8
Air content [%]	2.0	2.5	2.2	2.2	2.7	2.3	1.9	1.6	2.6	2.2
Density [kg/m^3]	2383	2386	2368	2391	2374	2391	2380	2361	2360	2368
$f_{ccyl,150}$ [N/mm^2]	50.6	42.8	-	-	50.6	-	-	42.0	44.3	49.4
$f_{ccub,100}$ [N/mm^2]	55.0	56.5	65.6	73.3	59.1	55.5	58.6	49.3	48.9	56.7
$f_{ccub,150}$ [N/mm^2]	54.3	52.8	61.4	70.8	55.3	60.6	61.9	52.3	47.5	57.8
$f_{ccyl,150}/f_{ccub,100}$ [-]	0.919	0.758	-	-	0.856	-	-	0.852	0.906	0.871
$f_{ccyl,150}/f_{ccub,150}$ [-]	0.931	0.810	-	-	0.915	-	-	0.802	0.932	0.855
$f_{ccub,100}/f_{ccub,150}$ [-]	1.013	1.069	1.068	1.034	1.069	0.915	0.947	0.941	1.029	0.981

Table 2. Mix design and results of lab A (left), lab B (middle), lab C (right)

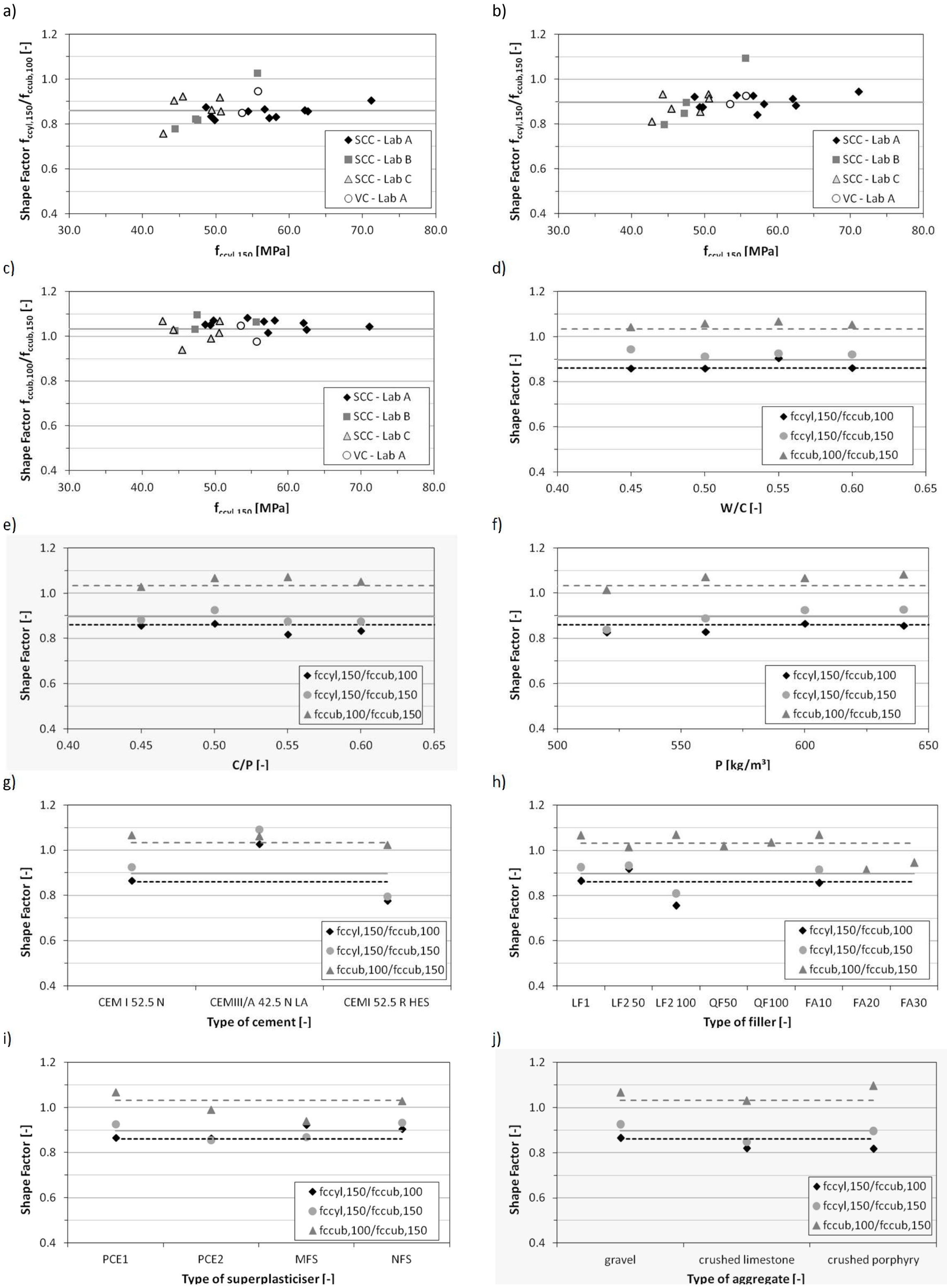
The ratio of $f_{ccub,100}/f_{ccub,150}$ however falls within the values proposed for VC (Cf. Tab.1). Among the influencing factors of the strength ratio mentioned in [1] three factors might be responsible for the difference between VC and SCC. The denser microstructure of SCC and enhanced bonding to the aggregates [15,16] 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 0.866d 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 more 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.

Influence of the W/C ratio and C/P ratio - The mixtures SCC ref, SCC WC.45, SCC WC.50 and SCC WC.60 vary in W/C ratio while maintaining the W/P ratio, superplasticiser type, aggregate type, powder content and filler type. The resulting shape factors are illustrated in Fig.2d. As in a study performed by [17], no clear influence of the W/C ratio is observed on the conversion factors between $f_{ccyl,150}$, $f_{ccub,150}$ and $f_{ccub,100}$. The self-compacting mixtures SCC CP.45, SCC ref, SCC CP.55 and SCC CP.60 have a different C/P ratio, while the powder content and W/C ratio remain constant. Also the applied superplasticiser, cement and filler type were kept constant. In Fig.2e, the corresponding shape factors are plotted in relation to their cement-to-powder ratio. No big influence can be observed.

Influence of the powder content P - In the mixtures SCC P520, SCC P560, SCC ref and SCC P640, the powder content varies, while the C/P ratio and W/C ratio were kept constant. The resulting shape factors as a function of the powder content are shown in Fig.2f. Although a linear trend can be observed, there are too few experimental data to draw general conclusions. For the tested mixtures the shape factors are slightly increasing for increasing powder contents.

Influence of the type of cement and type of filler - In Fig. 2g. is observed that in case of SCC CEMIII/A 42.5 N LA significantly higher values are obtained for $f_{ccyl,150}/f_{ccub,150}$ and $f_{ccyl,150}/f_{ccub,100}$ compared to the proposed ratio of 0.90 and 0.86 respectively. In case of SCC CEMI 52.5 R HES the opposite is noticed. The cube conversion factor remains close to 1.03 for the different cement types. The cube conversion factor $f_{ccub,100}/f_{ccub,150}$ is not affected significantly by replacing the fine limestone filler LF1 (Fig. 2h), except in case more than 10% of the limestone powder is replaced by fly ash: the cube conversion ratio decreases significantly in those cases due to a decrease of $f_{ccub,100}$ compared to an uninfluenced mean value of $f_{ccub,150}$. The cylinder-to cube conversion factors are not affected significantly by varying the filler type, except for SCC-LF2 100. Replacing 100% of the limestone filler of the reference mix (LF1) by LF2, wich is more coarse, a 25% strength loss for $f_{ccyl,150}$ is obtained, while for $f_{ccub,100}$ and $f_{ccub,150}$ the strength loss is 14%. As a concequence, $f_{ccyl,150}/f_{ccub,150}$ and $f_{ccyl,150}/f_{ccub,100}$ is affected: the obtained conversion factors lay 0.09 and 0.10 respectively beneath the proposed strength ratios for SCC, and tend to follow the strength ratios for converting cylinder strenght into cube strength of VC .

Figure 2. Parametrical study of the strength ratios.



Influence of the type of superplasticiser - To obtain comparable slump-flow values, respectively 22.1 kg/m³, 13.2 kg/m³ and 7.8 kg/m³ of MFS (melamine), NFS (naphtalene) and PCE2 (30% dry particles) is needed, compared to 3.0 kg/m³ of PCE1 used for the reference mix SCC ref. Regarding the compressive strength of the mixes with altered type of superplasticiser: (i) A decrease of 26%-25%-15% for $f_{ccyl,150}$, $f_{ccub,100}$ and $f_{ccub,150}$ respectively is obtained in case MFS is used, (ii) a decrease of 22%-25%-23% for $f_{ccyl,150}$, $f_{ccub,100}$ and $f_{ccub,150}$ respectively is obtained in case NFS is used, and (iii) a decrease of 13%-13%-6% for $f_{ccyl,150}$, $f_{ccub,100}$ and $f_{ccub,150}$ respectively is obtained using PCE2 (30 con%). However, regarding the shape factors, no significant trends are found by means of this research study, except for the cube conversion factor that lies 0.09 beneath the proposed ratio of 1.03 in case MFS is used. (Cf. Fig.2i)

Influence of the type of aggregate - In Fig.2j the effect is studied by replacing gravel by crushed limestone or crushed porphyry. No significant influence was noticed on the shape factors, except for the cube conversion factor when crushed porphyry was used (0.07 higher as the proposed 1.03).

CONCLUSION

In this paper, strength ratios of SCC are compared to those proposed for VC by different standards. 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, 1.03 (±0.05), is found in agreement with those proposed for VC (cf. Tab.1). As such there is a difference between the strength ratio $f_{ccyl,150}/f_{ccub,150}$ of SCC mixtures and the theoretical proposed ratio of VC mixtures.

Besides, the influence however of the water-to-cement ratio, the cement-to-powder ratio, the powder content, the type of cement, filler, superplasticiser and aggregate, and compressive strength seems to be insignificant or too scattered to be considered.

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