FRACTURE BEHAVIOUR OF SELF-COMPACTING CONCRETE COMPARED TO VIBRATED CONCRETE

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ABSTRACT

Since the composition of vibrated concrete (VC) and self-compacting concrete (SCC) substantially differs, their mechanical properties, including fracture behaviour, might be different as well. Evaluating the fracture properties of heterogeneous materials, such as concrete, is usually done by experimental investigation. Three-point bending tests (3PBT) and wedge-splitting tests (WST), for instance, allow to examine the fracture process and crack propagation, even though these are not standardized methods. This paper compares the results of static 3PBTs and WSTs on notched specimens, made from both concrete types. Considering the ultimate load, fracture toughness and fracture energy, important differences between VC and SCC are observed.

Keywords: three-point bending test; wedge-splitting test; self-compacting concrete; fracture mechanics, crack growth

INTRODUCTION

Existing flaws in concrete structures, such as pores, inclusions, and micro-cracks are locations of crack initiation and can promote debonding of aggregate particles from the cement matrix. Further coalescence of these microscopic cracks due to external loading inevitably leads to macro-cracking [1], not only affecting the aesthetic look, but possibly jeopardizing the construction's stability, as well. However, concrete cracking is inherent to the material and it does not necessarily result in failure; stabilized cracks are not dangerous. But in order to make a correct judgement on this, it is important to fully understand the material's fracture behaviour. Three common test methods to investigate the fracture process of concrete, are the uniaxial tension test (UTT) on single or double notched cylindrical specimens, the three-point bending test (3PBT) on small, notched beams, and the wedge-splitting test (WST) on cubical samples with guiding groove and starter notch [2]. The first one, however, requires sophisticated testing equipment and is very time-consuming and not easy to carry out [3]. The 3PBT, which was originally introduced by Petersson in 1980 and later also recommended by the RILEM-Committee on Fracture Mechanics [4], is probably the most widespread method to obtain different fracture parameters. It has been extensively and successfully conducted by researchers, even though some drawbacks, such as the influence of the self-weight in case of large specimens, can be found in literature [1,2]. The more easy and stable WST, first proposed by Linsbauer and Tschegg [5] and subsequently refined by Brühwiler and Wittmann [6], is gaining interest recently and is being used for multiple purposes; determination of fracture properties and fatigue crack growth [2], examination of durability and corrosion resistance [7], etc.

In this study, 3PBTs as well as WSTs are performed on samples, made from VC and SCC. The fracture parameters, obtained from these experiments, allow to interpret and to compare the cracking behaviour of both concrete types. Since VC and SCC have a significantly different mix design, a different fracture behaviour can be expected, for it is not only the strength of the cement paste that influences the crack resistance. E.g. Issa et al. [8] pointed out that also the location and the size of the aggregates play an important role regarding crack propagation.

EXPERIMENTAL PROGRAM

Mixtures. The batches of VC and SCC were laboratory-made, using a planetary mixer. In both compositions (Cf. Tab. 1) the same cement type was used and also the aggregate types and sizes were identical.

Table 1. VC and SCC composition.

	VC [kg/m³]	SCC [kg/m³]
CEM III/A 42.5 LA	365	365
Water	175	194
Sand 0/4	726	808
Crushed limestone 2/6.3	652	451
Crushed limestone 6.3/14	434	265
Limestone filler (Calcitec)	/	235
Superplasticizer (Glenium 27)	2.9	8.0

Besides the beams and wedge-splitting samples, several control specimens were cast in order to determine the compressive strength of both concrete types. These standardized cubes (side 150mm) and cylinders (diameter 150mm and height 300mm) were demoulded after 24 hours and then stored under water at 20 ± 2°C. At the age of 28 days, they were tested according to EN 12390-3 [9]. The resulting experimental values of f_{cm} and $f_{c,cub,m}$ (Cf. Tab. 2) indicate that SCC has a higher compressive strength, compared to VC. The cubic compressive strength of SCC being smaller than the cylinder compressive strength, may be caused by the large scatter in the tests.

Based on these results, the average tensile strength f_{ctm} was calculated by Eq. 1 [10] and Young's modulus was obtained using Eq. 2 [10] As a direct consequence of the lower cylinder compressive strength, the tensile strength as well as Young's modulus is smaller in case of VC.

$$f_{ctm} = 0.3 f_{ck}^{\frac{2}{3}} \qquad (1)$$

with f_{ck} the characteristic cylinder strength, equal to f_{cm} – 1.64 s (deviation).

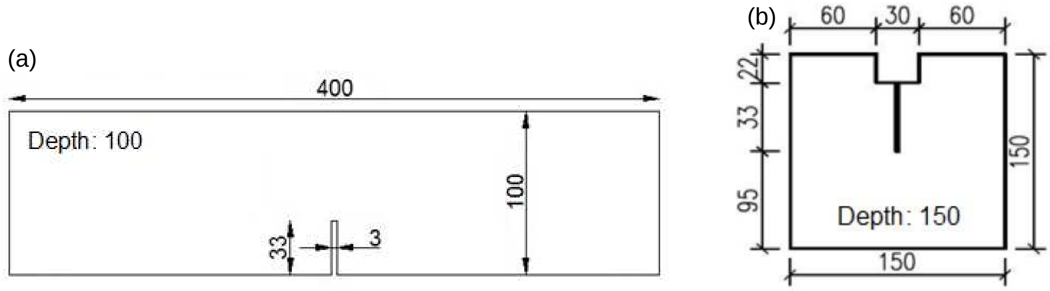
$$E_{cm} = 9500 f_{cm}^{\frac{1}{3}} \qquad (2)$$

Table 2. Main properties of VC and SCC.

	VC	SCC
f_{cm} [MPa]	68.0 ±6.1	77.9 ±6.0
$f_{c,cub,m}$ [MPa]	73.6 ±1.9	75.1 ±6.7
$f_{ctm,calc}$ [MPa]	4.5	5.0
$E_{cm,calc}$ [MPa]	40,235	41,915

Specimens. The 3PBT beams (Cf. Fig. 1a) were cast in moulds with rectangular section of 100x100mm and length of 400mm. In order to obtain the specific geometry of the WST specimens (Cf. Fig. 1b), standard cube moulds (side 150mm) were used, into which a wooden rod was placed, thus creating the guiding groove.

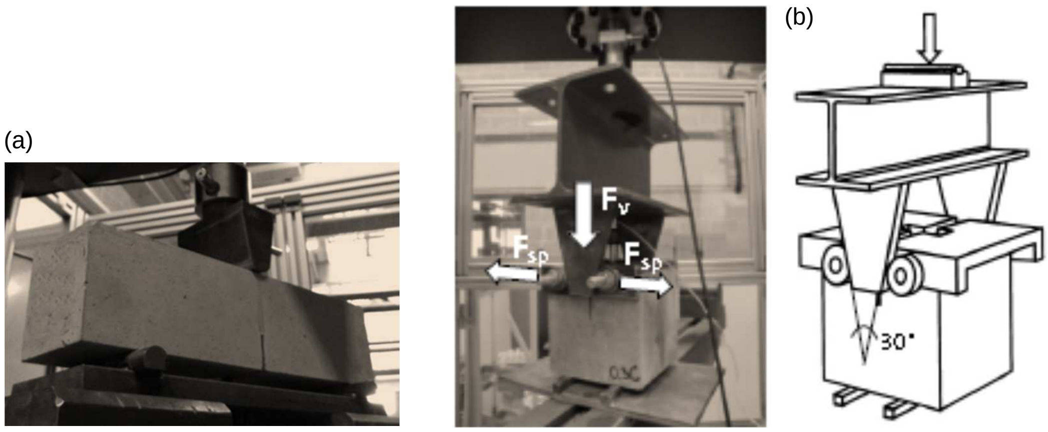
Figure 1. Specimens for 3PBT (a) and WST (b).



All of the samples were demoulded after curing for 24 hours and then stored in lab conditions (not under water) for several months. Approximately two days before testing, a 3mm wide notch was cut using a wet diamond saw. Considering the beams, the notch depth is 33mm, or 1/3rd of the beam's height, according to Rilem recommendations [11]. The dimensions of the WST cubes, on the other hand, are based on the findings of Löfgren et. al. [2].

Test procedure. A 25kN capacity compression test device was used to apply a static, vertical load (F_v). The beam-shaped specimens were placed in a regular three-point bending test setup (Cf. Fig. 2a). With regards to the WST, the vertical load is converted into two horizontal splitting forces (F_{sp}) due to the wedges moving between two roller bearings (Cf. Fig. 2b) and thus splitting the cubes. In both cases, a constant increment rate of the vertical displacement of 0.2mm/min was applied until the peak load was reached. Afterwards, this speed was lowered to a value of 0.02mm/min. During the tests, the exerted load (F_v) was registered continuously with a computer-controlled data acquisition system and the CMOD evolution was measured by a clip gauge, fixed at the notch end.

Figure 2. Test setup for 3PBT (a) and WST (b).



CALCULATIONS

In case of the 3PBT, the vertical load (F_v) was used in the load-CMOD curve. The recorded vertical load of the WST, however, was converted to the splitting force (F_{sp}) according to Eq. 3, in which α represents the wedge angle.

$$F_{sp} = \frac{F_v}{2\tan(\alpha/2)} \tag{3}$$

Based on the obtained graphs, the fracture energy (G_F) was calculated by Eq. 4. Furthermore the fracture toughness (K_{Ic}) and the characteristic length (l_{ch}) of the fracture process zone (FPZ) in front of the crack – which gives an indication of the material's brittleness – were determined using Eq. 5 and Eq. 6 respectively, where E symbolizes Young's modulus. These last two formula originate from Hillerborg's fictitious crack model, which asserts that the material gets damaged when the stress in the front of the crack tip reaches the tensile strength f_t, but that, along a certain distance of the crack path – the FPZ or the fictitious crack – so-called cohesive stresses can still be transferred [12,13].

$$G_F = \frac{surface\_under\_curve}{depth \cdot (height - notch\_length)} \tag{4}$$

$$K_{Ic} = \sqrt{E \cdot G_F} \tag{5}$$

$$l_{ch} = \frac{E \cdot G_F}{f_t^2} \tag{6}$$

Finally, the experimental results were put into numerical computation software and the so-called softening curve or σ-w relation was extracted using inverse analysis, based on the hinge model [3]. This method was chosen because of its simplicity and easy implementation. In the pre-crack phase, a linear elastic behaviour is assumed, while in the cracked state the stresses are calculated as a function of the crack width (w) and the uniaxial tensile strength (f_t). The coefficients, describing this function, allow to draw a bilinear stress-crack opening curve.

RESULTS AND DISCUSSION

Load-CMOD curve. The experimentally obtained load-CMOD curves (Cf. Fig. 3a and Fig. 3b) indicate, on average, lower maximum load values for SCC, despite its higher compressive strength. Regarding the two test setups, significant differences in peak load and curve shape are observed. The WST apparently generates a faster growth of the crack width as the load increases.

Fracture parameters. The fracture energy of the two concrete types, which is basically derived from the surface under the load-CMOD curves, differs little (Cf. Tab. 3). However, considering the strength difference of both batches, it can be stated that during the cracking process, more energy is released in the VC specimens, when compared to SCC. Regarding the fracture toughness and brittleness, a similar relation is observed. The samples made of VC are tougher than those made of SCC, or, in other words, VC is less brittle than SCC, since its FPZ, along which stresses can still be transmitted, is longer.

Figure 3. Load-CMOD curves for 3PBT (a) and WST (b).

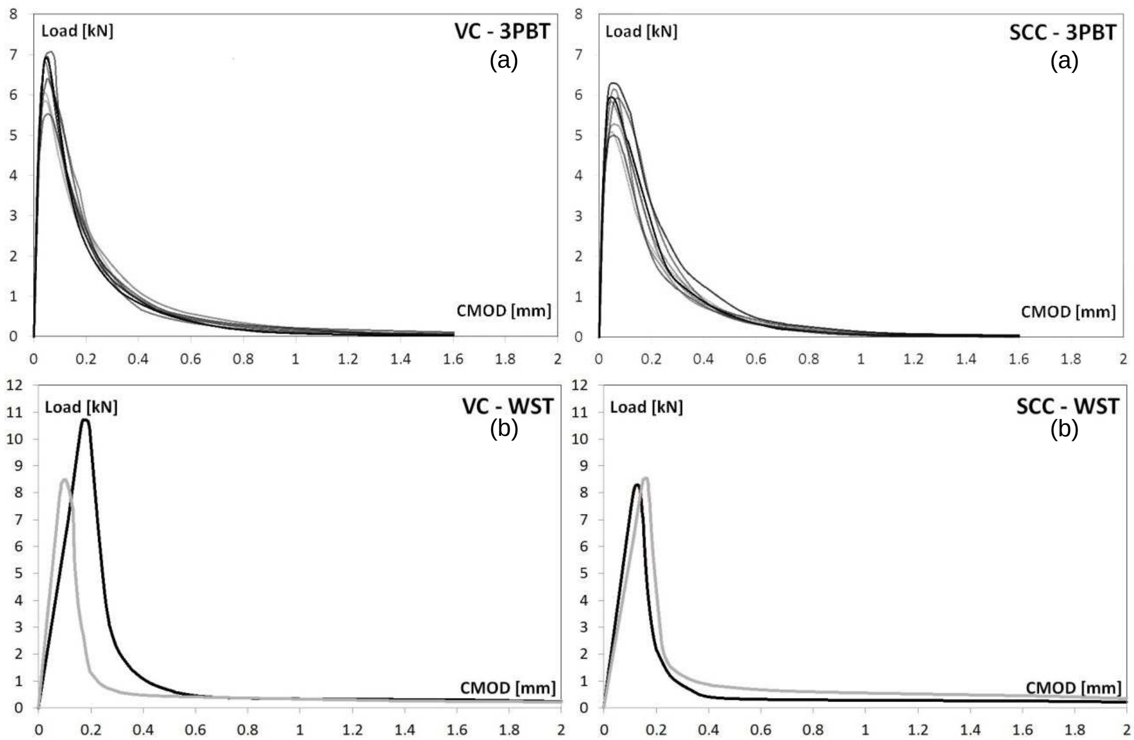


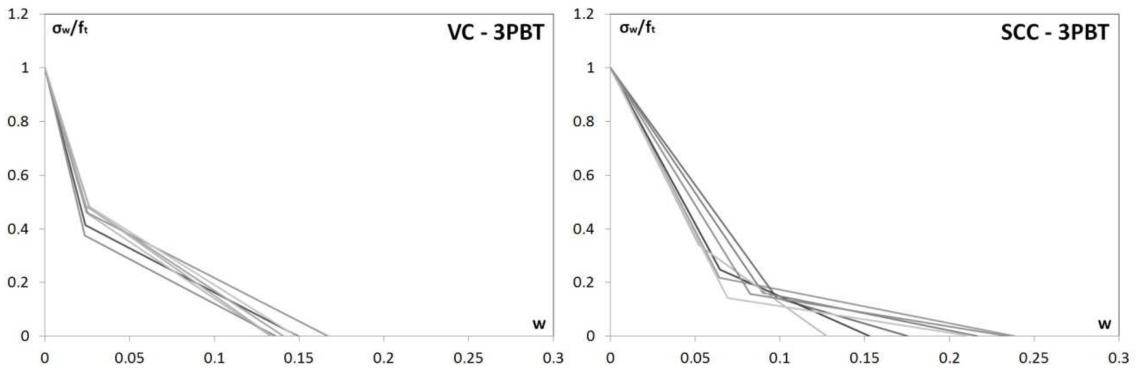
Table 3. Fracture properties of VC and SCC.

	3PBT		WST	
	VC	SCC	VC	SCC
F_{max} [kN]	6.46 ±0.57	5.71 ±0.49	9.81 ±1.57	8.86 ±0.02
G_F [N/m]	218.36 ±18.12	206.66 ±24.68	145.07 ±44.71	136.48 ±25.35
K_{IC} [x10^6 N/$m^{3/2}$]	2.90 ±0.12	2.89 ±0.17	2.35 ±0.37	2.34 ±0.22
l_{ch} [mm]	409 ±34	328 ±39	271 ±84	216 ±40

It can be noticed that the fracture parameters, calculated from the WST data strongly deviate from those obtained from the 3PBT. Inverse analysis also showed poor correspondence of the calculated and experimental P-CMOD curve, indicating that the data, derived from the WST, are not reliable.

σ-w curve. The stress-crack opening relationship represents the distribution of the cohesive stresses, which are transferred across the FPZ. A comparison of the σ-w curves of VC and SCC (derived from the 3PBT) affirms the earlier found results. In case of SCC, the crack width at maximum load is much larger. This means that more pre-peak damage occurs with more fracture energy being released and more stresses being transmitted along the shorter FPZ. Once the load-carrying capacity is reached, less energy is needed to further open the crack and the remaining small amount of stresses are transferred. As to the WST, inverse analysis showed poor correspondence of the calculated and experimental P-CMOD curve, indicating that the data, derived from the WST, are not reliable.

Figure 4. σ-w curves for 3PBT.



CONCLUSION

From the results, presented in this paper, it is clear that, despite its higher strength, SCC is less tough/more brittle and fails at a lower load, compared to VC. Due to the smaller amount of coarse aggregates in SCC, and the consequent limited presence of bridging elements, less cohesive stresses can be transferred along the FPZ, which is proven to be shorter than that of VC. In case of SCC, the largest portion of these stresses is transmitted before the maximum load is reached, where most of the damage occurs and most of the fracture energy (which is in total smaller than for VC) is released. The post-peak stress transmission and energy release is only 15% of the total energy, compared to 49% in case of VC.

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