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# Static and fatigue fracture mechanics properties of self-compacting concrete using three-point bending tests and wedge-splitting tests

Sara Korte [a,b,*], Veerle Boel [a,b], Wouter De Corte [a,b], Geert De Schutter [b]

[a] Department of Industrial Technology and Construction, Faculty of Engineering and Architecture, Ghent University, Valentin Vaerwyckweg 1, 9000 Ghent, Belgium
[b] Magnel Laboratory for Concrete Research, Department of Structural Engineering, Faculty of Engineering and Architecture, Ghent University, Technologiepark 904, 9052 Zwijnaarde, Belgium

## HIGHLIGHTS

- An altered outcome is found from the static 3PBT, compared to the WST.
- In the static tests, SCC1 is the most brittle concrete type and VC the toughest.
- SCC2 has the highest overall fatigue resistance in the dynamic 3PBTs.
- VC can sustain the most load cycles to failure in the dynamic WSTs.
- The numerically determined fracture parameters differ from the experimental ones.

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## ABSTRACT

This paper compares the results of static and dynamic three-point bending tests and wedge-splitting tests on specimens, made from VC (vibrated concrete) and two types of SCC (self-compacting concrete). Different fracture parameters are derived from the experimentally obtained load–CMOD curves (load versus crack mouth opening displacement) and the softening curve is extracted, using inverse analysis. The outcome depends on the test setup, but SCC with equal compressive strength compared to VC, is generally the most brittle concrete type and performs worst in the cyclic experiments, whereas VC is the toughest and has the best fatigue resistance.

## 1. Introduction

Due to the heterogeneous nature of concrete and its inherent flaws (e.g. pores, water inclusions, microscopic cracks due to shrinkage, etc.), its failure mechanism essentially involves a rather complex process of crack formation and crack growth [1]. Typical phenomena, such as softening behaviour, caused by distributed cracking, transition of micro-cracks to macro-cracks prior to failure, and bridging stresses along the fracture process zone (FPZ[1]) can be explained by applying NLFM [2][2]. In order to do so, the experimental determination of several fracture parameters is required. Even though no standardized test methods exist, the 3PBT[3] and the WST[4] on notched specimens are commonly used [3].

The inevitable macro-cracking mechanism in concrete structures, caused by the coalescence of microscopic imperfections, may seriously affect the aesthetic look, but may also jeopardize the construction's stability. Hence it is crucial to fully understand the fracture behaviour of the different concrete types used worldwide in the civil engineering industry. Since VC[5] and SCC[6] have a significantly different mix design different material characteristics are affected, as well. Already a considerable amount of research has been carried out on the fresh, mechanical and transport properties and on the durability of SCC [4–6], showing some remarkable

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* Corresponding author at: Department of Industrial Technology and Construction, Faculty of Engineering and Architecture, Ghent University, Valentin Vaerwyckweg 1, 9000 Ghent, Belgium. Tel.: +32 92488816.

*E-mail addresses:* Sara.Korte@UGent.be (S. Korte), Veerle.Boel@UGent.be (V. Boel), Wouter.DeCorte@UGent.be (W. De Corte), Geert.DeSchutter@UGent.be (G. De Schutter).

[1] FPZ: fracture process zone.

[2] NLFM: non-linear fracture mechanics.

[3] 3PBT: three-point bending test.

[4] WST: wedge-splitting test.

[5] VC: vibrated concrete.

[6] SCC: self-compacting concrete.

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differences, compared to VC. For instance, the higher content of fine particles (e.g. by adding fillers) influences the whole microstructure, making the interfacial transition zone of SCC stronger and consequently increasing the compressive and tensile strength, compared to VC with similar w/c ratio [4]. Furthermore, the reduction in the amount of coarse aggregates in SCC contributes to a lower stiffness, when compared to VC of equal strength [4,7]. As a result, a distinct fracture behaviour of both concrete types can be expected, for it is both, the strength of the cement paste, and the location and size of the aggregates that play an important role regarding crack resistance [8,9].

Therefore, in this study 3PBTs and WSTs are performed, both statically and dynamically, on samples, made from VC and two SCC mixtures (one with similar compressive strength and another with equal w/c ratio). The static and dynamic fracture parameters, obtained from these experiments, allow to interpret and compare the cracking behaviour of the different concrete types.

## 2. Materials and methods

### 2.1. Concrete mixtures

Table 1 displays the concrete compositions used in this study. They were provided by a ready-mix concrete company. VC, a traditional vibrated concrete mix, functions as a reference for comparison with two self-compacting concrete mixtures: one with similar compressive strength (SCC1) and another with equal w/c ratio (SCC2). As can be seen, the cement type and the aggregate sizes are identical for the three mixtures, thereby excluding these as possible influencing factors for the cracking resistance.

Different experiments were performed on the freshly-mixed concrete batches. First, the air content was measured using the pressure method as described in the European Standard EN 12350-7 [10]. Additionally, workability tests were carried out to ensure a good consistency and a proper filling ability of the formwork. In case of VC, slump and flow tests were performed, according to EN 12350-2 [11] and EN 12350-5 [12], respectively. Both SCC mixtures underwent slump-flow tests and V-funnel tests, defined in EN 12350-8 [13] and EN 12350-9 [14]. All the results are displayed in Table 2.

Afterwards, per batch several beams and wedge-splitting samples were cast, along with at least six control specimens (cubes with side 150 mm and cylinders with diameter 150 mm and height 300 mm) in order to determine the compressive strength of each concrete type. After a sealed curing period of 24 h, these standardized cubes and cylinders were demoulded and stored under water at 20 ± 2 °C. Then, they were tested at different ages, following the guidelines of EN 12390-3 [15]. $f_{cm}$ represents the mean value of the cylindrical compressive strength, $f_{c,cub,m}$ is the average cubical compressive strength, and the index '$k$' is used to indicate the corresponding characteristic values. Based on the resulting strengths at 28 days, the average tensile strength $f_{ctm}$ was calculated by Eq. (1) [16]. Furthermore, Young's modulus $E_{cm}$ was obtained experimentally by deformation measurements on axially, in compression loaded cylinders of diameter 150 mm and height 300 mm, according to the National Belgian Application Document NBN B15-203 [17]. These findings are also listed in Table 2.

$$f_{ctm} = 0.3 f_{ck}^{\frac{2}{3}} \tag{1}$$

The consistency classes, shown in Table 2, demonstrate a sufficiently fluid and workable character for all of the three concrete mixtures. Hence, no problems regarding workability or compaction during casting were reported. When considering the air content, the highest value is noticed in case of VC, followed by SCC2 and SCC1, respectively. The results of the compressive strength measurements, however, are not affected by these different amounts of air, since VC and SCC1 show a similar strength (class C35/45, as was aimed for), whereas SCC2 is classified in the higher strength class C45/55 (as could be expected). The values of Young's modulus for VC and SCC1 are comparable. In case of SCC2, the large variation does not allow to draw clear conclusions concerning its Young's modulus. SCC2 does show the largest tensile strength, followed by VC and SCC1, for which the values are similar.

**Table 1**
Concrete compositions.

| COMPOSITION | VC (kg/m$^3$) | SCC1 (kg/m$^3$) | SCC2 [kg/m$^3$] |
|---|---|---|---|
| CEM III/A 42.5 LA | 360 | 293 | 360 |
| Water | 161 | 161 | 161 |
| Sand 0/4 | 759 | 651 | 651 |
| Crushed limestone 2/6.3 | 433 | 523 | 523 |
| Crushed limestone 6.3/14 | 610 | 321 | 321 |
| Limestone filler | 0 | 377 | 317 |
| Superplasticizer (PCE) | 2.7 | 9.0 | 9.5 |
| Retarding agent | 1.2 | 0.0 | 0.0 |

**Table 2**
Fresh and hardened properties of the concrete mixtures.

| Main properties | VC | SCC1 | SCC2 |
|---|---|---|---|
| Air content (%) | 3.95 | 2.20 | 2.65 |
| Workability | S3 | SF2 | SF2 |
| | F3 | VF2 | VF2 |
| $f_{cm}$ (MPa) | 53.4 ± 2.3 | 51.3 ± 5.1 | 60.0 ± 6.5 |
| $f_{c,cub,m}$ (MPa) | 54.3 ± 4.7 | 53.9 ± 0.0 | 63.8 ± 4.8 |
| $f_{ck}$ (MPa) | 45.4 | 43.3 | 52.0 |
| $f_{c,cub,k}$ (MPa) | 46.3 | 45.9 | 55.8 |
| $f_{ctm,calc}$ (MPa) | 3.8 | 3.7 | 4.2 |
| $E_{cm}$ (MPa) | 38,400 ± 300 | 38,100 ± 500 | 35,300 ± 4200 |

### 2.2. Specimens

#### 2.2.1. Three-point bending test specimens

The 3PBT specimens were cast in beam-shaped moulds with dimensions 100 × 100 × 400 mm (see Fig. 1), and sealed for 24 h. After demoulding, they were stored in lab conditions for about five months. Approximately two days before testing, a notch of width 3 mm was made in the middle of the beam's side surface, using a wet diamond saw. This way, a smooth top and bottom surface could be assured. According to RILEM recommendations [18] the notch depth must be 1/3rd of the beam's height in order to ensure the location of crack initiation. Consequently, the notch length was chosen 33 mm.

#### 2.2.2. Wedge-splitting test specimens

The geometry and dimensions of the cubical WST specimens, as depicted in Fig. 2, are based on the findings of Löfgren et al. [19]. Additional information and other dimensions can be found in [20–22]. The samples were made using a standard cube mould (side 150 mm), into which a wooden bar with rectangular section (30 × 22 mm) was placed. The bar was attached to the side of the mould in order to obtain a plain top surface with guiding groove. After sealed curing for 24 h, the specimens were demoulded and also stored in lab conditions for several months. Again, two days prior to testing, a 3 mm wide and 33 mm long starter notch was cut by wet diamond sawing.

### 2.3. Test procedure

#### 2.3.1. Three-point bending test

Fig. 3 illustrates the 3PBT setup for both static and dynamic tests, where a vertical, linear load was applied onto the middle of the beams' top surface, using a compression test device. With the beams resting on two line supports with a span length of 300 mm, the specimens started cracking at the notch tip as the load increased. During the entire loading process, the load ($F$) was continuously registered with a computer controlled data acquisition system and the opening of the notch or the crack mouth opening displacement (CMOD) was measured by a clip gauge. In case of the static tests, a constant increment rate of the CMOD of 0.0005 mm/min was applied. The dynamic tests were conducted load-controlled with a speed of 1.5 kN/s resulting in a frequency of approximately 0.33 Hz. The lower limit of the sinusoidal load function was chosen 10% of the average static ultimate load, for the upper limit various percentages were selected: 90%, 80%, 75% and 70%.

#### 2.3.2. Wedge-splitting test

For the WSTs, the concrete cubes were placed onto a steel plate with two linear supports. At the top, the compression test device applied a vertical, static or dynamic load onto a transfer beam with two metal wedges (angle 30°). These wedges move between two roller bearings, mounted on two metal caps, which rest on the edges of the specimen's guiding groove (Fig. 4). The vertical displacement ($F_v$) was thus transformed into two horizontal splitting forces ($F_{sp}$), which caused the specimen to crack, also starting at the notch tip. Again, the load ($F_v$) was continu-

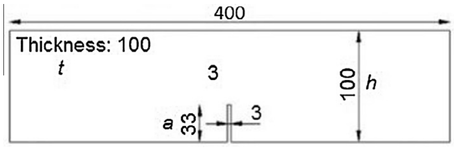

**Fig. 1.** 3PBT specimen's geometry and dimensions (mm).