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Determination of size-independent specific fracture energy of normal- and high-strength self-compacting concrete from wedge splitting tests

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HIGHLIGHTS

- Wedge splitting tests have been conducted on two different self-compacting concrete.
- SCC showed a lower size-independent fracture energy than similar vibrated concrete.
- The Young's modulus of the self-compacting concrete mixes is higher.
- The higher proportion of fine particles decrease ductility of SCC concrete mixes.

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ABSTRACT

Wedge splitting tests have been conducted on two different self-compacting concretes (normal- and high-strength) and the size-dependent fracture energy G_f determined from the measured RILEM work of fracture. Then the specific size-independent fracture energy, G_F, has been determined using the boundary effect (BE) method of Hu and Wittmann and the simplified boundary effect (SBE) method proposed by Abdalla and Karihaloo. Tests on specimens of three different sizes and four different relative notch depths have shown that a unique value of G_F can be obtained irrespective of the specimen size and relative notch depth. The results by both the BE and SBE methods are in very good agreement. A comparison with previous results from Abdalla and Karihaloo for normal- and high-strength vibrated concretes tested under the same conditions in the same laboratory shows that the SCC has a lower specific size-independent fracture energy than the vibrated concrete of the same strength.

1. Introduction

Wedge splitting tests were developed by Linsbauer and Tschegg in 1986 [1] and subsequently modified by Bruhwiler and Wittmann in 1990 [2]. It is a very stable test for determining the fracture energy of concrete. The specimens used are very compact and require small amounts of material as compared to the notched beams employed in three-point bending tests. However, the implementation of this type of test requires more sophisticated tools than the three-point bending test and the number of results available in the literature obtained using the wedge splitting test of concrete is very limited.

The specific fracture energy of concrete measured using the RILEM work-of-fracture procedure by both the wedge splitting and the three-point notched beam tests shows a size dependency [3].

Hu and Wittmann [4] developed the boundary effect (BE) method that considers the influence of the back free boundary of the uncracked ligament area on the fracture process zone of concrete based on the concept of the local fracture energy. By means of this method it is possible to obtain a size-independent specific fracture energy of concrete based on the measured fracture energy of specimens of one size but different relative notch depths. Elices and co-workers [5–7] proposed an alternative method to obtain a size-independent specific fracture energy value, which consists of the identification of the sources of experimental error in the RILEM three-point bending method. They proposed a methodology for eliminating the major source of error, namely by including the work-of-fracture that is not measured in the RILEM method due to practical difficulties in capturing the tail part of the load–deflection plot. In a recent paper Cifuentes et al. [8], showed that if the size-dependent G_f is corrected following the methods of Elices and co-workers [5–7] and of Hu and Wittmann [4], then the resulting specific fracture energy G_F is very nearly the same.

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Nomenclature

G_F	specific size-independent fracture energy	$CMOD$	crack mouth opening displacement
WS	wedge splitting	F	vertical force at bearings
BE	boundary effect	P	horizontal force at bearings
SBE	simplified boundary effect	θ	half-angle of the wedge
FPZ	fracture process zone	h	height of the groove on top of wedge splitting specimen
G_f	measured size-dependent fracture energy	$CMOD_c$	crack mouth opening displacement at the end of test
g_f	local fracture energy	COV	coefficient of variation
x	distance along the uncracked ligament	f_c	compressive strength
a	initial notch depth	f_{st}	splitting tensile strength
W	depth of the specimen	E_c	Young's modulus
α	relative notch depth	l_{ch}	characteristic length
a_l	ligament transition length		

Abdalla and Karihaloo [3] and Karihaloo et al. [9] extended and confirmed the boundary effect hypothesis of Hu and Wittmann [3] and observed that a size-independent specific fracture energy G_F of concrete could be obtained by testing three point bend (TPB) or wedge splitting (WS) specimens containing either a very shallow or a deep starter notch. This observation was based on TPB and WS tests, and they proposed the simplified boundary effect (SBE) method [9] that greatly reduces the number of specimens to be tested. Abdalla and Karihaloo [3] carried out a comprehensive experimental study of normal- and high-strength vibrated concrete using the WS test for three different specimen sizes (W = 100, 200 and 300 mm) and four different relative notch depths ($\alpha = a/W$ = 0.2, 0.3, 0.4 and 0.5) [3].

It is the aim of the present paper to show the results of a new set of wedge splitting tests carried out on normal- and high-strength self-compacting concretes and to compare the fracture behavior of these self-compacting concretes with that of vibrated normal- and high-strength concrete made and tested in the same laboratory and under the same test conditions.

Ninety-six notched specimens were tested according to the WS test method to determine the size-dependent fracture energy from the RILEM work-of-fracture. The geometry of the specimens was the same as employed by Abdalla and Karihaloo [3] for vibrated concrete. The BE and SBE methods were applied to obtain an estimate of the size-independent fracture energy and the ligament transition length of concrete. The results show a good agreement between the BE and the SBE methods for the size-independent specific fracture energy and the ligament transition length of self-compacting concrete. A comparison with previous results for normal- and high-strength vibrated concretes tested under the same conditions in the same laboratory shows that the SCC has a lower specific size-independent fracture energy than the vibrated concrete of the same strength.

2. Theoretical background

Hu and Wittmann [4,10–13] argued that the effect of the free boundary is felt in the fracture process zone (FPZ) ahead of a real crack so that the energy required to create a fresh crack decreases as the crack approaches the free boundary. Initially, when the crack growths from a pre-existing notch, the rate of decrease is moderate, almost a constant, but it accelerates as the crack approaches the end of the un-cracked ligament. They represented the transition from the moderate decrease to the rapid decrease by a bi-linear approximation (Fig. 1). The bi-linear function consists of a horizontal line with the value of G_F and a descending branch that reduces to zero at the back surface of the specimen [10]. The intersection of these two straight lines is defined as the transition ligament size a_l or the crack reference length [11]. The transition ligament size a_l is a parameter depending on both the material properties and the specimen geometry.

On the basis of the BE method of Hu and Wittmann [4] the size-dependent measured fracture energy, G_f, represents the average value of the variable local fracture energy, g_f, which depends on the distance, x, along the un-cracked ligament length (Fig. 1)

$$G_f(a) = \frac{1}{W-a}\int_0^{W-a} g_f(x)dx \tag{1}$$

Substituting the bi-linear approximation for the local fracture energy variation (Fig. 1) into Eq. (1) and introducing the dimensionless ratios $\alpha = a/W$ and $\alpha_l = a_l/W$, a relation between the measured fracture energy, G_f, the transition length, a_l and the size-independent fracture energy, G_F is obtained

$$G_f(\alpha) = \begin{cases} G_F\left[1-\frac{1}{2}\frac{\alpha_l}{1-\alpha}\right] & 1-\alpha > \alpha_l \\ G_F\frac{1}{2}\frac{1-\alpha}{\alpha_l} & 1-\alpha \le \alpha_l \end{cases} \tag{2}$$

Making use of Eq. (2), the size-independent fracture energy of concrete and the transition length can be back-calculated from the size-dependent fracture energy $G_f(\alpha)$. To do that, it is necessary to get the size-dependent fracture energy of a specimen of a given size with a full range variation of the relative notch depth α. Usually, the number of the measured $G_f(\alpha)$ values is therefore much larger than the two unknowns G_F and a_l in Eq. (2). For this reason, the over-determined system of equations is solved by a least squares method to obtain the best estimates of G_F and a_l. Duan [14] showed that although the measured values $G_f(\alpha)$ depend on α (and of course on the specimen size), the above procedure indeed leads to a G_F value that is essentially independent of the specimen size and relative notch depth [13].

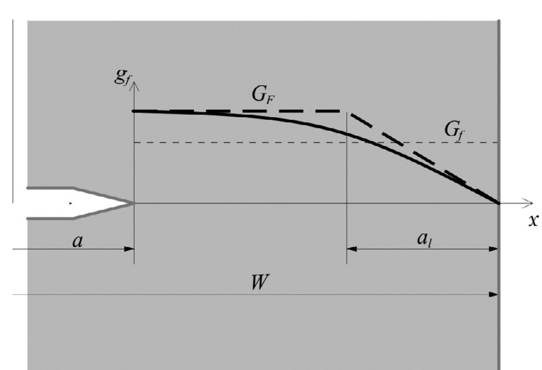

Fig. 1. Bi-linear approximation of the local fracture energy of concrete according to Hu [10].