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Research Article

Determination of Toughness Characteristics of Concretes

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Abstract

This paper is on experimental works related to the determination of concretes toughness characteristics (K_{IC} and G_{IC} in the framework of Linear Fracture Mechanics theory), in mode I of cracking. They are determined by performing fracture mechanic test on very large DCB (Double Cantilever Beam) specimens. In parallel, and for the same concretes, splitting tensile and compressive strengths are determined by performing tests on standardized cylindrical specimens. The interest of this work is 1) to propose intrinsic (and not scale effect sensitive) values of toughness characteristics related to three very different concretes (whose an ultra-high strength concrete) 2) to propose load-notch opening curves related to mode I macrocrack propagation over more than one meter. These last experimental results are very useful to validate numerical models devoted to fracture mechanics of concrete.

Keywords: Concretes; Fracture Mechanics Test; Toughness Characteristics; Tensile Splitting Strength; Compressive Strength

Introduction

Some numerical models, related to mode I cracking of concretes, use toughness parameter as K_{IC} or G_{IC} (in the framework of Linear Fracture Mechanics theory) as main material characteristic [1-3]. The principal problem is the difficulty to determine experimentally these toughness characteristics. Indeed, it has been clearly demonstrated that experimental tests have to be performed on large concrete specimens to get it [1, 4-14]. This is due to the high level of heterogeneity of concrete linked to the larger aggregate size. Thus, the dimension of the process zone at the macrocrack front tip which propagates reaches about 30 cm [14]. In the past, this type of test on large Double Cantilever Beam (DCB) specimen was performed [11, 13, 14]. This DCB specimen had the following dimensions: 3.5m long, 1.1m large and 0.3m width.

It is important to point out that this DCB test on very large specimen is the only one performed on current concretes (with larger aggregate diameter larger than 10 cm and without fibers) that allowed to get real and intrinsic values of K_{IC} or G_{IC} [11-14]. It means that the large majority of the others experimental studies led to K_{IC} or G_{IC} that was not intrinsic but scale effect sensitive [11-14]. This type of DCB test on so huge specimen being difficult to perform and time consuming, only one concrete, called concrete 1 in this paper, was studied [11,13,14]. In parallel to this DCB test, 6 standardized compressive and splitting tests (Brazilian tests) were performed on 16 cm (diameter) x 32 cm (length) cylindrical specimens [14]. The objective of the present work is to perform the same program of tests (DCB, compressive and Brazilian tests) on two more concretes very different compared with the previous one and try to find general relations between toughness parameters and tensile and compressive strengths.

Previous experimental test on large DCB specimen

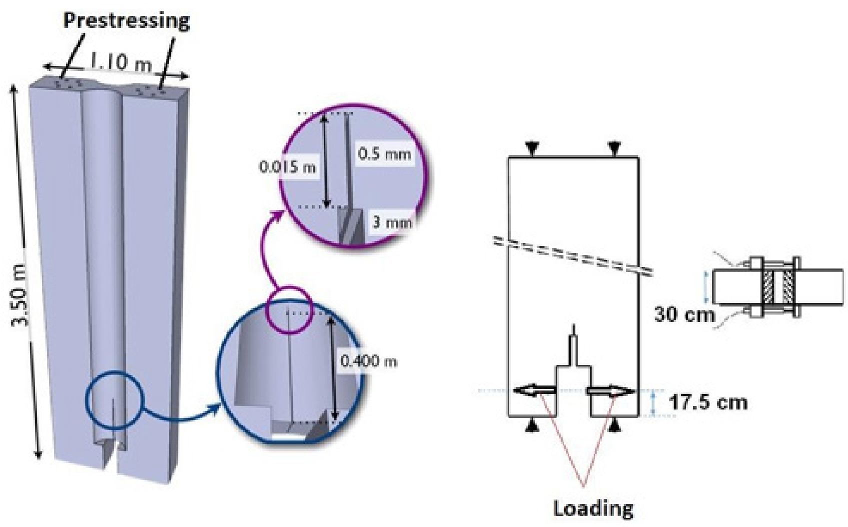


Figure 1: Detail of the geometry and of the loading conditions related to the DCB specimen.

The geometry and the loading conditions are given in Figure 1.

The test is controlled by applying a constant notch displacement rate of 25 μm/min. The test is fully detailed in [11, 14]. The *load/notch* opening curve is recorded during the test. After the peak load, that corresponds to the macrocrack initiation, several *notch closing/opening* cycles are imposed at the same frequency. These cycles permit to follow the stiffness evolution of the specimen that is used to calculate K_{IC} (mode I critical intensity factor) and G_{IC} (mode I specific fracture energy) using the classical and well known (in linear fracture mechanics theory) compliance method [11-16].

Table 1 presents the concrete 1 mix design [11, 13, 14]. The average compressive, f_c, and splitting tensile strengths, f_{ts}, of concrete 1 are given in Table 2.

Table 1: Concrete 1 mix design.

Constituent	Quantity
Aggregate 4/12 mm	1105 kg/m^3
Sand 0/5 mm	700 kg/m^3
Cement	400 kg/m^3
Water	190 l/m^3

Table 2: Average compressive and splitting tensile strengths of concrete 1.

Compressive strength	54 MPa
Splitting tensile strength	4.1 MPa
Young modulus*	35.5 GPa

*The average young modulus was determined during the compressive tests.

Figure 2 presents the load/notch opening curve related to concrete 1. The analysis of the DCB test by using the compliance method leads to get K_{IC} versus equivalent crack length curve. This equivalent crack length is the idealized crack length (straight and smooth crack in a linear elastic material) that leads to the same specimen compliance than the experimental one. Very commonly, the evolution of the specimen compliance with the idealized crack length (analytical relation) is obtained by performing linear elastic finite element analysis [11,13,14].

In figure 3, this K_{IC} versus equivalent crack length curve related to concrete 1 is presented. In this Figure, it can be noted that K_{IC} fluctuates between a minimum and a maximum with a constant evolution. This fluctuation is the result of the material heterogeneity. The fact that a constant evolution of K_{IC} with the equivalent crack length is observed proves that the DCB specimen used is large enough to get characteristic K_{IC} value. In other words, the length of the crack propagation is so large, more than 1.0 m, that one DCB test is sufficient to get a precise information about the dispersion related to K_{IC} of a given concrete. It is not necessary, as for others concrete mechanical characteristics, to perform several tests. From the K_{IC} fluctuation a mean value can be easily determined (Figure 3).

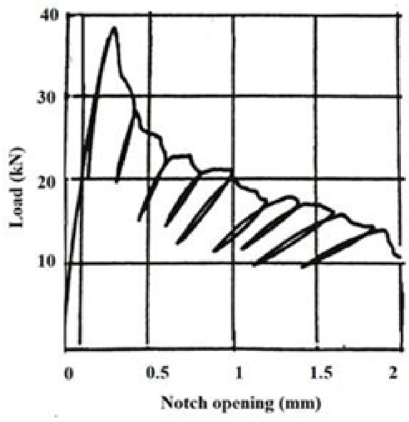


Figure 2: Load/notch opening curve related to concrete 1 (from [12,14]).

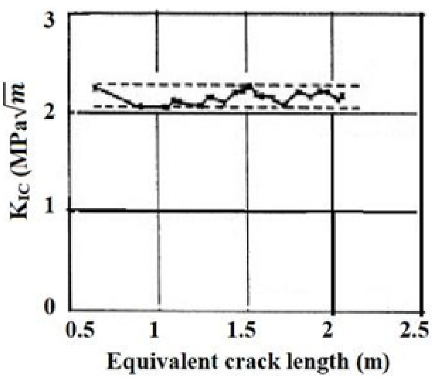


Figure 3: K_{IC} versus equivalent crack length curve related to concrete 1(from [12,14]).

Table 3: K_{IC} and G_{IC} mean values related to concrete 1.

K_{IC}	2.16 $Mpa\sqrt{m}$
G_{IC}	131 J/m^2

K_{IC} and G_{IC} mean values related to concrete 1 are presented in Table 3.

Note that the relation between K_{IC} and G_{IC} is very well known in Linear Elastic Fracture Mechanics:

$$K_{IC} = \sqrt{E\,G_{IC}} \qquad (1)$$

This relation (1) is relevant for stresses plane conditions that is the case with the DCB specimen.

Experimental Campaign on Other Concretes

The same program of tests, described in chapter I, have been performed in this new experimental campaign. The mix design of these two concretes, concrete 2 and concrete 3, are given in table 4.

The average compressive and splitting tensile strengths and young modulus of concretes 2 and 3 are given in Table 5.

Table 4: Mix designs of concretes 2 and 3.

	Concrete 2	Concrete 3
Constituent	**Quantity**	
Aggregate 5/20 mm	1265 kg/ m^3	1265 kg/ m^3

Sand 0/5 mm	652 kg/ m^3	652 kg/ m^3
Cement	425 kg/ m^3	421 145 l/ m^3
Water	145 l/ m^3	112 l/ m^3
Silica fume		42.1 kg/ m^3
Superplasticizer (dry powder)	6.75 kg/ m^3	7.6 kg/ m^3

Table 5: Average compressive and splitting tensile strengths and young modulus of concretes 2 and 3.

Characteristic	Concrete 2	Concrete 3
Compressive strength	76 MPa	105 MPa
Splitting tensile strength	5 MPa	6.4 MPa
Young modulus*	48.3 GPa	53.4 GPa

Table 6: K_{IC} and G_{IC} mean values related to concretes 2 and 3.

	Concrete 2	Concrete 3
K_{IC}	2.55 $Mpa\sqrt{m}$	2.85 $Mpa\sqrt{m}$
G_{IC}	135 J/m^2	152 J/m^2

Figures 4 and 5 present the *load/notch opening* curves related respectively to concrete 2 and 3. K_{IC} and G_{IC} mean values related respectively to concretes 2 and 3 are presented in Table 6.

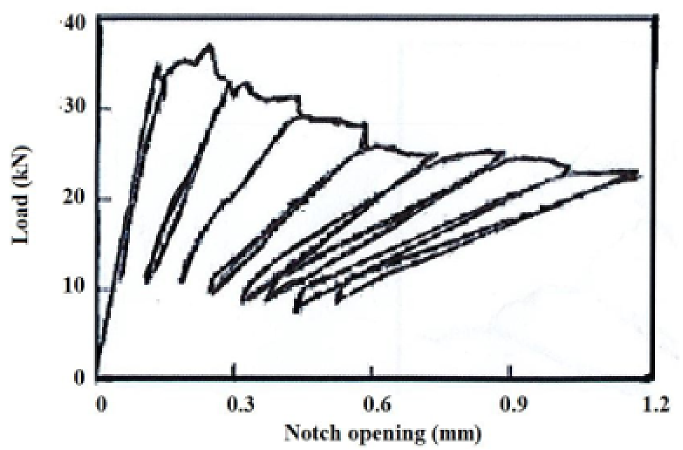
Analytical relations between toughness characteristics and splitting tensile and compressive strengths

From tables 2, 3, 5 and 6, it is interesting to draw the following curves:

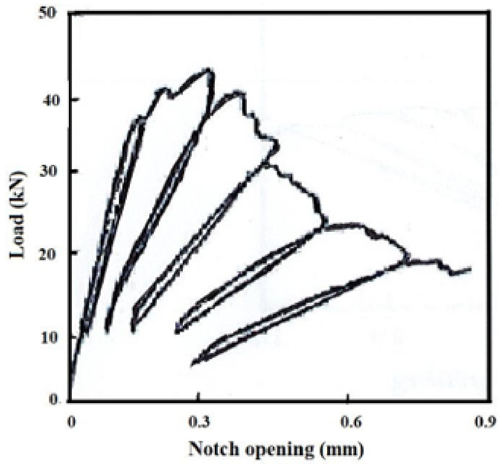
- K_{IC} versus f_{ts} and f_c.
- G_{IC} versus f_{ts} and f_c.

Figures 6 and 7 present respectively the curves K_{IC} versus f_{ts} and K_{IC} versus f_c.

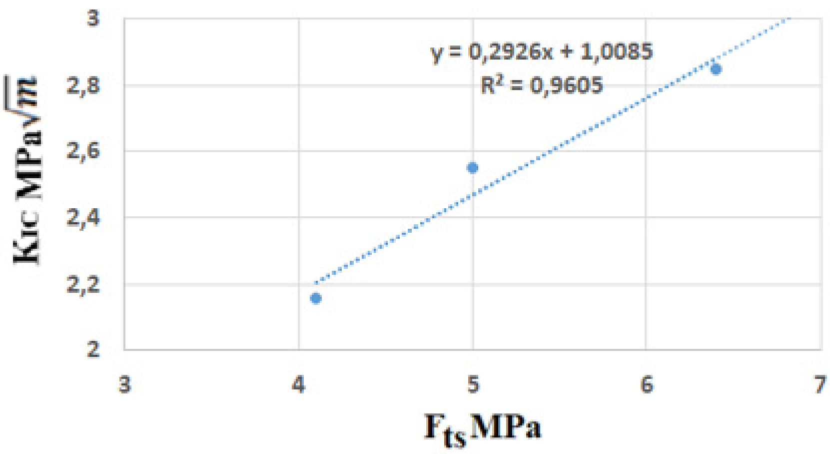
Figures 8 and 9 present respectively the curves G_{IC} versus f_{ts} and G_{IC} versus f_c. From Figures 6 to 9, it appears that the links between K_{IC} and G_{IC} with fts and f_c. are strong. From curves 6 to 9 the following relations can be proposed:



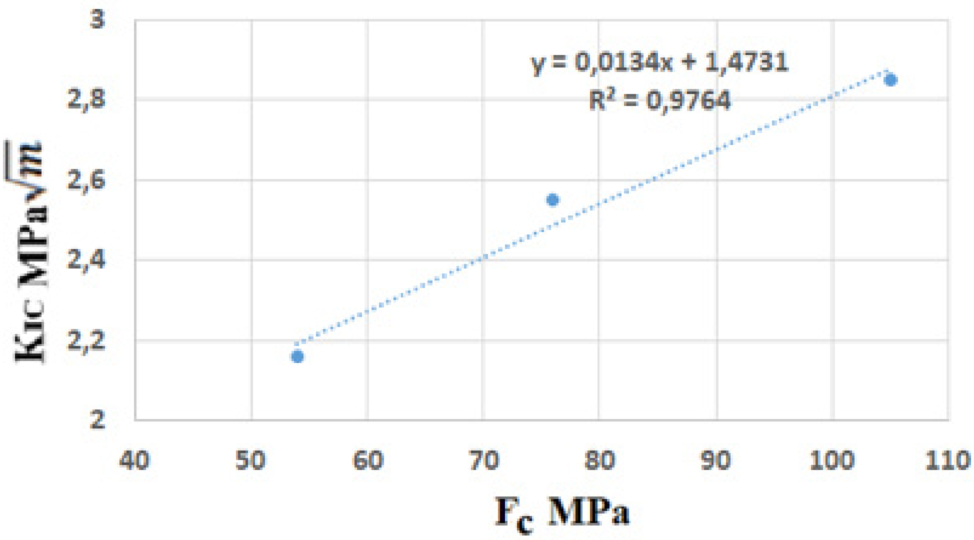
Figures 4: Load/notch opening curve related to concrete 2.



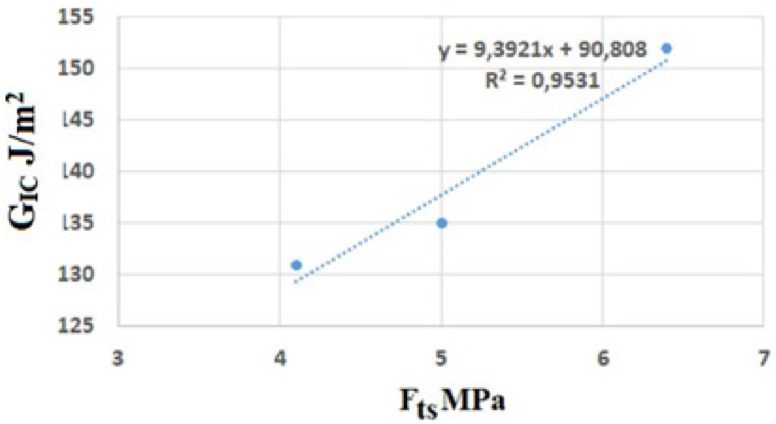
Figures 5: Load/notch opening curve related to concrete 3.



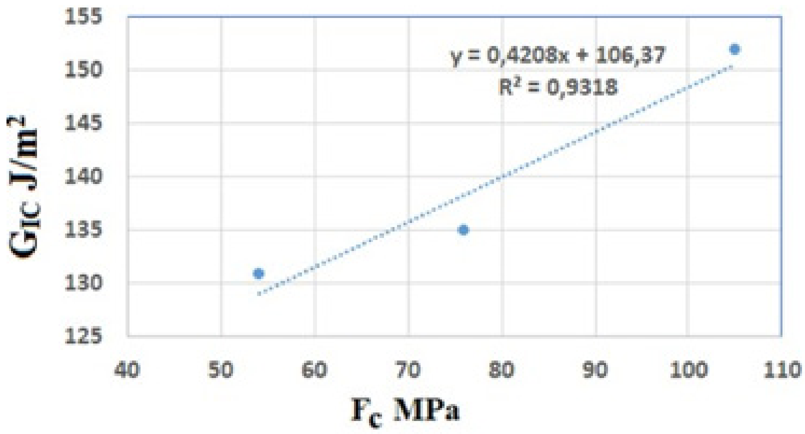
Figures 6: K_{IC} versus f_{ts} curve.



Figures 7: K_{IC} versus f_c curve.



Figures 8: G_{IC} versus f_{ts} curve.



Figures 9: G_{IC} versus f_c curve.

$$K_{IC} = 0.2926 f_{ts} + 1.0085 \quad (2)$$

$$K_{IC} = 0.0134 f_c + 1.4731 \quad (3)$$

$$G_{IC} = 9.3921 f_{ts} + 90.808 \quad (4)$$

$$G_{IC} = 0.4208 f_c + 106.37 \quad (5)$$

All these relations above being the consequence of experimental imprecisions, it is acceptable to simplify them as following:

$$K_{IC} = 0.3 f_{ts} + 1.0 \quad (6)$$

$$K_{IC} = 0,01 f_c + 1.5 \quad (7)$$

$$G_{IC} = 9.5 f_{ts} + 90 \quad (8)$$

$$G_{IC} = 0.4 f_c + 110 \quad (9)$$

In relations (2) to (9):

- K_{IC} is in $Mpa\sqrt{m}$.
- G_{IC} is in J/m^2.
- f_{ts} and f_c are in MPa.

If relations (6) to (9) are concerned, it can be noted that K_{IC} is always superior to 1.5 $Mpa\sqrt{m}$ and G_{IC} is always superior to 110 J/m^2. Indeed, f_{ts} and f_c cannot be equal to zero.

It is important to recall that these relations have been determined for concretes having:

- $4 \le f_{ts} \le 6.5$ MPa

➢ $50 \le f_c \le 105$ MPa

Discussion

It can be argued that making a direct link between toughness and compressive or tensile strength is too simplistic because other parameters than compressive (or tensile) strength influence this toughness, such as, for example, the water/cement ratio or the larger aggregate size. In fact, this link is possible and relevant because the physical mechanisms at the origin of these three mechanical characteristics are similar. Indeed, these three mechanical characteristics are the result of the passage from a diffuse microcracking to a localized macrocracking, it means the localization process of the cracking. This is obvious and well known for the compressive and the tensile strengths. Concerning K_{IC} or G_{IC}, it exists a microcracked zone at the front tip of the macrocrack in propagation, called process zone. The macrocrack can propagate only when the total dissipative energy in this process zone (microcracked zone) is achieved. The fact that parameters like water/cement ratio and larger aggregate have the same type of influence on the localization process related to the three mechanical characteristics can explain the good correlation between them and the linear relations obtained, even only three points are concerned. There are no physical and mechanical reasons that prevent extending the domain of validity of relations (6) to (9) to concretes having smaller compressive and tensile strengths. On the other hand, these relations are not valid for fibre reinforced concretes [12].

To conclude this chapter on discussion, it can be affirmed without any ambiguity, that the use of the analytical relations 6 to 9, as simplistic as they are, leads to a better prediction of the toughness of a given concrete than the usual use of small (a lot of smaller than the DCB specimen of the present study) laboratory test specimens.

Conclusion

This paper is related to experimental works concerning the possible link between toughness characteristics (K_{IC} and G_{IC}, determined by performing fracture mechanic test on large DCB specimens) and splitting tensile and compressive strengths (determined by performing tests on standardized cylindrical specimens) of several concretes. These experimental works were carried out during two campaigns of test:

➢ A past one, yet published, on one type of concrete.

➢ The present one on two more and different concretes.

These campaigns of test have the following interests:

➢ They permit to get intrinsic values of the toughness (defined in the framework of the Linear Fracture Mechanics) of three different concretes with different mechanical properties (compressive and tensile splitting strengths).

➢ They propose load-notch opening curves related to mode I macrocrack propagation over more than one meter. These results are very important and useful for researchers who want to validate their numerical models related to this problem.

➢ They propose to engineers and/or researchers, using numerical models based on fracture mechanics, simple analytical relations permitting to get real and intrinsic K_{IC} and G_{IC} values from simple and standardized tests.

Acknowledgement

None.

Conflict of Interest

No conflict of interest.

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