

Fracture behaviour of high-strength concrete at different loading rates

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ABSTRACT: This research deals with the sensitivity of eight types of performance-designed high-strength concretes to the loading rate. Variations in concrete composition produce the desired performance, for instance, having null shrinkage or being able to be pumped at elevated heights without segregation, but also produce variations in the fracture properties that are reported in this paper as well. The tests were performed at five loading rates (loading point displacement rates) spanning six orders in magnitude, from 1.74×10^{-5} mm/s to 17.4 mm/s. Load-displacement curves show that the peak load increases with an increase in loading rates, whereas the corresponding displacement almost keeps constant. Fracture energy is not sensitive with the loading rates first when it is less than 0.01 mm/s, later, the rate effect on the fracture energy is quite remarkable. A formula with a cohesive term based on a cohesive law was adopted to analyze the results. This formula is in a good agreement with the experimental results and it allows obtaining the theoretical value of the fracture energy under strictly static condition.

1 INTRODUCTION

Compared with the extensive research into the static fracture behaviour of high-strength concrete, much less information is available on its dynamic fracture behaviour (Schuler & Hansson 2006, Mindess et al. 1987, Müller 2008, Zhang et al. 2009). Schuler and Hansson (Schuler & Hansson 2006) measured the tensile strength and the fracture energy of high-strength concretes at high strain rates between 10 s^{-1} and 100 s^{-1} with spalling tests. A three-fold increase in the fracture energy was observed at a crack opening velocity of 1.7 m/s. Nevertheless, the experimental data in scientific literature on the rate-sensitivity of the fracture behaviour of high-strength concrete is scarce.

In the case of conventional concrete, however, there is abundant information on the subject. The fracture energy varies slightly under quasi-static loading if there is a variation in the loading rate, while it changes dramatically under dynamic loading (Oh 1990). Thus some researchers deduce that the fracture energy is constant and independent of the loading rate (Challamel et al. 2005, Jansen et al. 1995, Yon et al. 1992). However, the fracture energy increases by approximately 50% when the loading rate increases until about 1 mm/s (RILEM 1990). Under high loading rates, the fracture energy greatly exceeds the static value, mainly due to structural causes, such as inertia

and the geometry of the structure (Lu & Xu 2004, Toutlemonde 1994, Van Doormaal et al. 1994).

In addition, results and conclusions obtained with conventional concretes are not directly applicable to high-strength concrete, as the type and extent of the fracture process zone varies with the increasing strength of the material. In general, cracks tend to propagate around aggregates in conventional concrete, whereas in high-strength concrete, they usually go through them (Choi et al. 1996, Caliskan et al. 2002). According to Carpinteri and Paggi (Carpinteri & Paggi 2007), the super-singular behaviour of transgranular cracks may be a possible reason of the less pronounced effect of crack arrest by aggregates and a more brittle global behaviour of high-strength concrete. This fact implies that we should review the formulations obtained in the study of the fracture of conventional concrete when it will be used in high-strength concrete.

Therefore, in this research we want to study the variation of fracture energy in eight types of high-strength concretes designed for performance. By this we mean that besides being of high strength the concrete is required to have a special feature. Both requirements determine the mixture components of the concrete and its strength. The variations in the composition of the concrete, while providing the desired benefit, also produce changes in mechanical properties in fracture and, therefore, another objective of

this study is to ascertain the relationship between the composition of high-strength concrete and its properties in fracture. The process of design, fabrication and the curing state of the material (for example, properties in fresh state, especially the thixotropic changes characteristic of the use of additives) is complementary to this research and, of course, is of great technological interest. However, they are located outside of the limits of the fracture mechanical characterization of materials and therefore we have excluded this part in our work. We will only consider, as a complement to our primary objective, the influence of the composition of the concrete on the mechanical properties in fracture.

This article is structured as follows. Below, in Section 2 we describe the experimental program conducted. First the characteristics of the concrete used are explained, and then the way the tests were performed on fracture energy. Section 3 presents the results, which are analyzed and discussed with the help of an analytical model in Section 4. Finally, in Section 5 we summarize our research and draw the most relevant conclusions.

2 EXPERIMENTAL PROGRAM

2.1 High-strength concrete

The concretes studied in this investigation were designed and manufactured by Composites ID in its factory in Alpedrete (Madrid). The provision of design and nomenclature adopted for each of them are shown in Table 1 (in the nomenclature there is a gap from H03 to H05, this is because H04 was planned but not made in the end, nevertheless we respected the initial name of the concrete that Composites ID had agreed to). From a mechanical point of view its composition can be characterized by the type of coarse aggregate used, by its maximum size and compressive strength (Alexander & Mindess 2005), this information is also included in Table 1. In addition this table provides the results of standard mechanical characterization tests (elastic modulus, E_c , compressive strength, f_c , and indirect tensile strength, f_t , besides the average value of these four tests, in brackets, it shows the standard deviation). For the compressive tests, we used 75×150 mm cylinders (diameters $\times$ height) and followed the recommendations of ASTM C39. Right before testing,

the bases of the cylinders were surface-ground with a wet diamond wheel to ensure perfectly-plane and parallel surfaces. The elastic modulus was measured using two clip strain gages centered in opposite generatrices. The span of the clips was 50 mm so that local constriction caused by the friction between the steel plates and the concrete surfaces was not influencing the measurement of the elastic modulus (Indelicato & Paggi 2008).

2.2 Test for fracture energy

In this work we measured the fracture energy, GF, through three-point bending tests with the procedure recommended by RILEM (RILEM 1985) and with the improvements proposed by Planas, Guinea and Elices (Elices et al. 1992, Guinea et al. 1992, Planas et al. 1992). In particular, the dimensions of the specimen are 100×100 mm in cross section and 400 mm in total length, the initial notch-depth ratio is approximately 0.5. The tests were conducted in position control at five loading rates: 17.4 mm/s (very fast), 0.55 mm/s (fast), 1.74×10^{-2} mm/s (intermediate), 5.5×10^{-4} mm/s (slow) and 1.74×10^{-5} mm/s (very slow). In the case of slow and very slow tests loading rates displayed were the first 0.25 mm of loading-point displacement.

This displacement always includes peak load in the first ramp. Then the test is accelerated by multiplying the rate by five to 0.75 mm of loading point displacement, and then, multiplying by five again until the end of the test. The slowest tests last about 8 hours while the fastest tests last approximately 1/5 th of a second. Figure 1 shows a photo of the specimens to be tested. Four samples were tested for each type of concrete and loading rate (but for H01, which was not tested at the very fast rate), in other words, there have been 156 such trials in this investigation.



Figure 1. Test for fracture energy.

Table 1. Performance of design, type of aggregate used and mechanical properties of high strength concretes.

features	nomenclature	Coarse aggregate	d_{max} (mm)	f_c aggregate (MPa)	E_c (GPa)	f_c (MPa)	f_t (MPa)
Conventional plant	H01	silicious	20	130	32 (2)	78 (4)	6.3 (0.4)
Pumpable	H02	andesite	12	250	30 (2)	88 (4)	5.8 (0.7)
Without retraction	H03	andesite	12	250	34 (1)	97 (6)	6.1 (0.5)
Very high strength	H05	porphyry	12	200	43 (2)	127 (11)	6.3 (0.6)
High early strength	H06	mylonite	6	150	34 (1)	71 (11)	4.9 (0.3)
Low heat of hydration	H07	andesite	12	250	29 (4)	96 (14)	5.3 (0.7)
Light	H08	arlite	10	10	20 (1)	57 (5)	3.0 (0.4)
Heavy	H09	barite	10	12	34 (1)	60 (1)	3.7 (0.4)

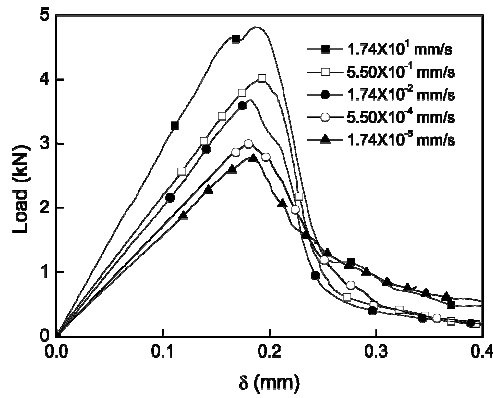


Figure 2. Curves P- δ for concrete H03 at different loading rates (without retraction).

Table 2. Variation of fracture energy with loading rates. G_F (N/m) to loading rate v_D (mm/s)

v_D	1.74×10^{-5}	5.5×10^{-4}	1.74×10^{-2}	0.55	17.4
H01	211 (13)	200 (41)	197 (26)	249 (35)	—
H02	121 (28)	108 (13)	119 (11)	156 (16)	177 (9)
H03	134 (14)	126 (6)	124 (8)	155 (12)	198 (23)
H05	181 (43)	156 (20)	187 (12)	215 (18)	252 (39)
H06	245 (22)	213 (9)	254 (42)	285 (24)	328 (62)
H07	149 (16)	137 (11)	157 (3)	158 (7)	204 (25)
H08	120 (3)	100 (8)	97 (5)	113 (12)	111 (2)
H09	153 (11)	138 (13)	139 (25)	169 (40)	201 (19)

3 RESULTS

Figure 2 shows the typical load-displacement curves (P- δ) of the concrete H03 at each loading rate. Each curve produces a value of G_F . The average values of

G_F and the loading rate for each concrete are provided in Table 2 (in the case of H01-mixed in a pre-cast plant- G_F was not measured for the very fast loading rate). The standard deviation of each measurement is shown between brackets.

4 DISCUSSION

4.1 Variation of the mechanical properties depending on aggregate type

Figure 3 represents the relation between the concrete's mechanical properties and the compressive strength of coarse aggregates. It is clear that the compressive strength of the concretes increases almost in a linear way (except H05) with an increase in the compressive strength of aggregates. As concerns the tensile strength of the concretes, the increase is significant at first and slight later with increases in the compressive strength of aggregates. For the concrete H05 (very high strength), the increase is more pronounced for both properties. It could be that it was produced with a high quantity of additives (microsilica) (Del Viso 2008).

With regard to the variation of the elastic modulus with aggregates strength, Table 1 shows that the modulus is kept in an interval between 30 and 35 GPa approximately, except for the H08 concrete (light) and the H05 concrete (very high strength). The H08 concrete (light) is composed of an artificial

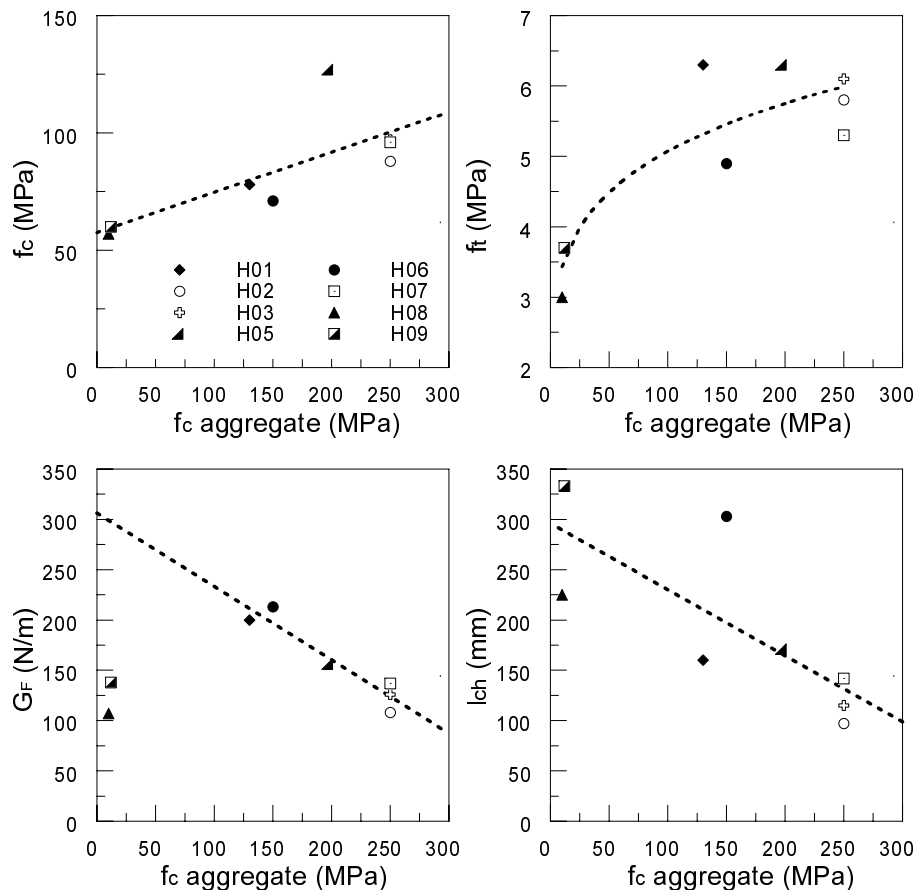


Figure 3. Variation of the mechanical properties in relation to the compressive strength of coarse aggregates.

aggregate, arlite, this is an expanded clay and has an elastic modulus far lower than the rest of the aggregates. The increase in the elastic modulus of the H05 concrete (very high strength) is attributable partially to the porphyry aggregate that is used in its composition and partially to the fact that the matrix is more rigid and resistant (Del Viso 2008).

Regarding the variation of the specific fracture energy G_F with aggregate strength, Figure 3 clearly shows that G_F decreases with an increase in the compressive strength of the aggregate, except in the case of concretes with aggregates of a weaker strength (H08 and H09). Figure 3 also shows that the characteristic length, ℓ_{ch} , decreases with increases in coarse-aggregate strength. It confirms, from a fracture mechanics view point, that the strongest concretes are the most fragile. It is important to remember that the length of fracture process and the release of fracture energy in concrete are proportional to ℓ_{ch} . Therefore, two similar structures that have the same proportion of their dimensions with ℓ_{ch} are going to generate similar crack processes with proportional dimensions and, in this respect, ℓ_{ch} characterizes the ductility or intrinsic brittleness of concrete.

4.2 Variation of fracture energy with loading rate

Figure 2 shows typical load-displacement curves, $P-\delta$ under different loading rates for the concrete H03 (without retraction). The peak load increases with an increase in the loading rate, whereas the displacement in maximum load remains practically constant. Regarding the stiffness of the beam, it is observed that, as with the peak load, it also increases with increases in the loading rate.

In Table 2 we arrange the values of G_F obtained from fracture energy tests for all of the concretes at the five loading rates next to their corresponding

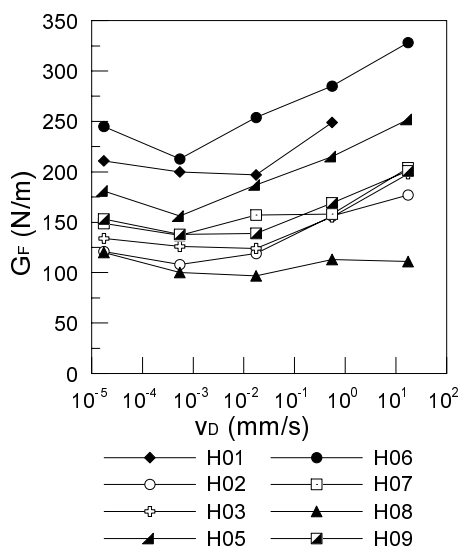


Figure 4. Variation of fracture energy with loading rate.

standard deviation in brackets, in contrast Figure 4 represents average values graphically. It is observed that the fracture energy remains practically constant for quasi-static loading rates but increases in value for dynamic loading rates. For all of the concretes, note that the value of G_F at the lowest loading rate is slightly greater than that obtained for the following two loading rates (slow and intermediate loading rates). A possible explanation for this recovery of G_F can be in the humidity loss of the specimen during the slowest test, since the duration of the fracture process was approximately eight hours. On the other hand, the increase of G_F with increases in loading rate is attributable to a major extension of the microcracking zone around the principal fracture (Bischoff et al. 1991, Brara & Klepaczko 2007, Vegt et al. 2007). Nevertheless, a visual inspection of the fracture surface of our specimens does not allow us to deduce that there is an increase in microcracking with increases in the loading rate. To illustrate this, Figure 5 shows the fracture surfaces of two specimens of concrete H03 tested to the extreme loading rates. Both surfaces are similar in spite of the fact that there is a difference of six orders of magnitude in the loading rates.

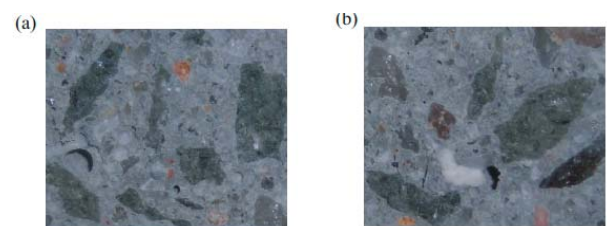


Figure 5. Fracture surface of two specimens of concrete H03 tested to the loading rates of (a) 1.74×10^{-5} mm/s and (b) 17.4 mm/s.

It is clear that, for static and quasi-static loading rates, from 1.74×10^{-5} mm/s up to 1.8×10^{-2} mm/s, the fracture energy scarcely changes -though the maximum load changes (See Fig. 2)-, which would explain why some researchers should have thought that fracture energy is independent from loading rate (Challamel et al. 2005, Jansen et al. 1995, Yon et al. 1992). For higher loading rates G_F increases sensitively (with the exception of H08 - light-, probably due to the different nature of its coarse aggregate). We think that the movement of water through the network of pores of material, and the formation of a new surface of water in the way of spread of the fissures, have an influence on the variation of the peak load and the fracture energy with the loading rate that is shown in the experimental results. The aforementioned variation reproduces correctly using a cohesive model which includes a term dependent on the loading rate (Ruiz et al. 2008). This approximation allows us to deduce that the adjustment to the

experimental results would be of the type:

$$\frac{G_F}{G_F^S} = 1 + \left(\frac{v_D}{v_0} \right)^n \quad (1)$$

where G_F is the fracture energy, G_F^S is a parameter of adjustment with dimensions of fracture energy, v_D is the loading rate, v_0 is another parameter of adjustment, with rate dimensions, and n is a non-dimensional exponent which describe the degree of viscosity of the material, obtained from fitting (1) to the experimental results.

In Table 3 we present the parameters that fit Equation (1) to each type of concrete. The regression coefficients turn out to be almost 1 except in the case of H01 (mixed in a pre-cast plant), due to the fact that G_F did not measure for the very fast rate, and also in the case of H08 (light), due to its anomalous behavior; for this reason, the parameters corresponding to these two concretes are not displayed in Table 3.

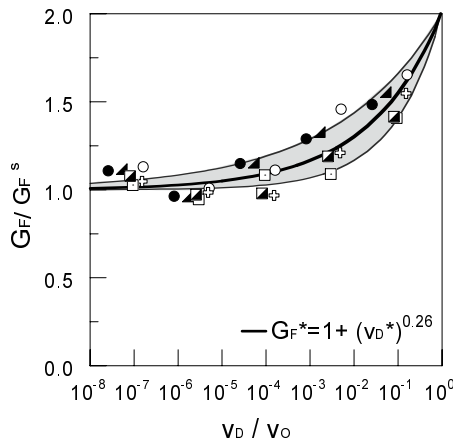


Figure 6. Non-dimensional representation of the fracture energy with regard to the loading rate.

It is necessary to emphasize that G_F^S can be understood as the value of the fracture energy for strictly static conditions ($v_D = 0$). It can be observed that the aforementioned parameter practically coincides, in all cases, with the fracture energy measured at slow velocity, which is habitually considered to be an intrinsic material property. On the other hand, v_0 is a parameter that represents the displacement rate that would produce a 100% increase in the fracture energy, compared with the static value; it is a parameter whose value may be between 10^2 and 10^3 mm/s and its average is 284 mm/s. The exponent n changes from between 0.2 and 0.4, and its average value is 0.27.

Figure 6 represents the experimental results of non-dimensional way. The x-axis corresponds to the non-dimensional velocity v_D/v_0 and the y-axis corresponds to the non-dimensional fracture energy with regard to G_F^S . In this figure, each concrete has been

represented using its corresponding parameters indicated in Table 3. Two fitting curves bridged by the shaded zone are intended to cover most of the experimental data points. A new fit (the thick line) Equation (1) to pass the center of the shaded zone gives an n of 0.26, which is very close to the value average found above (0.27). This fit represents the non-dimensional average behaviour of the high-strength concretes in this study.

Table 3. Parameters of the equation of adjustment for each concrete.

	G_F^S (N/m)	v_0 (mm/s)	n
H01	—	—	—
H02	106	125	0.18
H03	126	91	0.33
H05	162	317	0.20
H06	221	733	0.19
H07	145	180	0.39
H08	—	—	—
H09	142	256	0.32

5 SUMMARY AND CONCLUSIONS

In this research we have investigated the loading-rate sensitivity of the fracture energy of eight high-strength concretes designed for benefits, such as being pumped or without retraction.

With each type of concrete we performed tests to measure fracture energy at five different loading rates, including six orders of magnitude from 1.74×10^{-5} mm/s to 17.4 mm/s. Load-displacement curves show that the maximum load increases with an increase in loading rates, yet the corresponding displacement remains almost constant. The fracture energy value increases with the loading rate from 0.01 mm/s. The results fit perfectly with a formula based on a cohesive model with a viscous term. With this adjustment we have obtained the theoretical value of fracture energy in strictly static loading conditions.

We have also investigated the changes that the variations in the composition of the concretes produced in the fracture properties. In particular, both the fracture energy and the characteristic length fall in proportion with an increase in the compressive strength of the aggregates used in the research.

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