Fracture Energy of Water Saturated and Partially Dry Concrete at Room and at Cryogenic Temperatures

J. PLANAS, P. MATURANA, G. GUINEA and M. ELICES
Department of Materials Science, Escuela de Caminos, Universidad Politécnica de Madrid, 28040–Madrid, Spain

ABSTRACT

Fracture experiments on notched beams of partially dry concrete at 20 C and -170 C are compared with results for water saturated concrete. Drying slightly increases the fracture energy at room temperature. For -170 C the fracture energy of concrete displays a three-fold increase for saturated specimens and a two-fold increase for specimens with moisture contents as low as 1.8 per cent. Different procedures to estimate fracture energy are discussed.

KEYWORDS

Concrete; cryogenics; fracture energy; cracking failure; low-temperature.

INTRODUCTION

A knowledge of fracture behaviour of concrete at low and very low temperatures is of great interest, both from the practical point of view of the engineer, involved in liquified gas storage tanks or Arctic constructions, and for the researcher, in order to widen the range of analysis of such complex phenomenon.

In previous papers by the authors (Elices *et al.*, 1987, Maturana *et al.*, 1988), it was shown that for saturated concrete the fracture energy experienced a three-fold increase when cooling down to -170 C. This effect was atributted in Maturana *et al.* (1988) to the contribution of frozen water. While these results gave an optimistic picture for the fracture behaviour of storage tanks for criogenic fluids, it was logical to suspect, on the basis of the proposed mechanism, that the situation for partially dry structures would be less optimistic.

In this paper, unpublished results of fracture experiments on notched beams of partially dry concrete at 20 and -170 C, are compared with results for water saturated concrete of the same composition and geometry. The results are analysed following a recently proposed method (Planas *et al.*, 1988), already used in Maturana *et al.* (1988).

The results give further support to the method of analysis, which overcomes difficulties regarding the apparent size effect for fracture energy , and show that drying slightly increases the fracture energy at room temperature and that, even for moisture contents as low as 2 per cent, there is still a great increase of fracture energy when cooling to -170 C.

MATERIALS AND SAMPLE PREPARATION

Cement, aggregates and concrete mix

Concrete used in this research, as in previous ones (Elices *et al.*, 1987; Maturana *et al.*, 1988), is standard RILEM concrete, as described in RILEM (1974). Rapid hardening Portland cement (ASTM type III) was used. Natural rounded aggregates, classified as siliceous, were used. Grading of coarse and fine aggregates, as well as the resulting grading for the mix, are shown in Fig. 1.

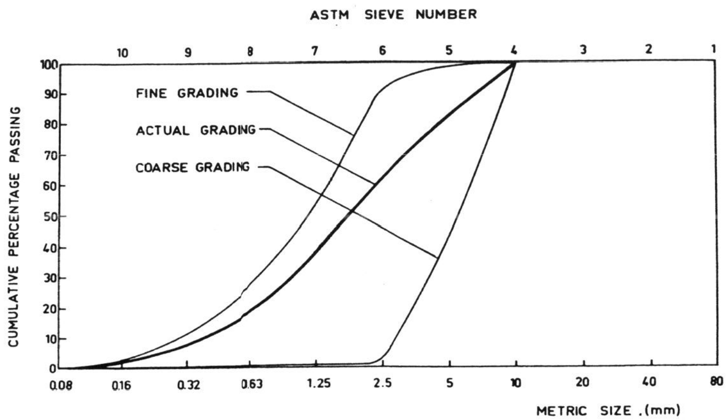

Fig. 1. Grading of concrete.

Table 1 summarizes the characteristics of concrete mix and Table 2 shows some concrete properties measured according to ASTM standards.

Table 1. Proportional mixing of concrete by weight

Cement*	Coarse aggregate	Fine aggregate	Water
1	1.35	3.02	0.55

* Cement content 400 kg/m3.

Table 2. Concrete properties

Slump (cm)	28 day strength (MPa) compressive	tensile	Tangent Modulus 28 days (GPa)
5	27.3	2.44	27.6

Concrete samples

Test specimens for fracture measurement were notched beams, as sketched in Figure 2. These beams were instrumented with five thermocouples, also shown in Figure 2, in order to ascertain the temperature distribution near the notched section during cooling and warming.

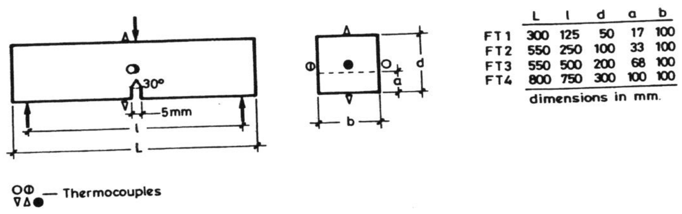

Fig. 2. Notched beam geometry and thermocouple arrangement.

All specimens were cast from a single batch in steel moulds and compacted by means of a vibrating table. After demoulding, samples were stored under lime saturate water at 20±3 C for 250 days, later oven dried according to the procedure described in the next paragraph, and finally sealed with a polymeric paint, to minimize water absorption from the environment.

EXPERIMENTAL PROCEDURE

Fracture tests were stable three point bend tests performed, essentially, following the tentative RILEM recommendation for the determination of the fracture energy of concrete (RILEM, 1985). The special features of the procedure used are briefly summarized:

Drying equipment

An electrical oven with forced convection, 600x600x820 mm in dimension, was used to partially dry the specimens. The electrical circuit of the oven was modified to accept the input from the temperature programmer in order to achieve controlled rates of heating and cooling. The temperature of the air in the chamber was monitored through a platinum resistor which gave the feed-back signal for the temperature controller. The temperature controller was a PID on-off controller with a variable set signal supplied by a digital function generator, which powered the heating resistor on and off, as needed, by means of a relay.

One of the specimens in the chamber was instrumented with five thermocouples as indicated in Fig. 2. The temperature of the air in the chamber was continuously recorded during all the process,and the temperatures of the five thermocouples were read at 2 min. intervals by an Automatic Data Acquisition System (ADAS) and plotted versus time. No digital data storage was performed.

Drying procedure

Since specimens of different in-plane dimensions, but of the same thickness, were used in the research, an attempt was made to achieve similar moisture profiles. Toward this end, the specimens were coated with a polymeric paint on the faces parallel to their thickness, including the notch, to reach essentially unidimensional through-the-thickness diffusion conditions.

After the specimens were coated, they were put into the oven, thermocouples were set in place and the temperature of the air in the oven was raised to 110 C at a constant rate of 7.2 C/hour. The temperature was maintained at 110 C for 4 days and, finally, the cooling process started at a controlled cooling rate of 7.2 C/hour. When the temperature of the specimens reached 25 C they were taken out of the oven and coated with a polymeric compound. The maximum temperature difference between the surface of the specimens and their centre was 6 C and the maximum temperature during the drying process was 103± 3 C.

Low temperature equipment

A specially built low temperature chamber, described elsewhere (Elices *et al.*, 1987; Maturana *et al.*, 1988), was used for low temperature tests. The temperature inside the chamber is lowered by spraying a mist of liquid nitrogen, controlled by an electromagnetic valve. The gas coolant temperature is continuously recorded during the cooling process as well as the temperatures of the five thermocouples attached to the specimen. The cooling rates ranged from 20 C/hour, for the largest specimens, to 28 C/hour, for the smallest specimens.

Stable bending tests of notched beams

The tests were performed in a 1 MN servohydraulic testing machine INSTRON 1275, run in CMOD control mode. Loads were measured by a 25/50 kN load cell with a resolution of 1.25/2.5 N and 0.5 per cent accuracy. CMOD was measured by a clip-on gauge MTS 632.03C-51, with 0.2 mm resolution and ±2 μm accuracy.

Deflection was measured as the relative displacement of the central loading head and the line defined by the points on the upper surface of the specimen located on the verticals of the lower supports. Such line was materialized by a rigid frame and a cross bar (a short bar crossing through the loading head), as depicted in Fig. 3. The displacement was measured by an extensometer located in a transverse hole in the loading head. The accuracy of the extensometer was better than 5 μm.

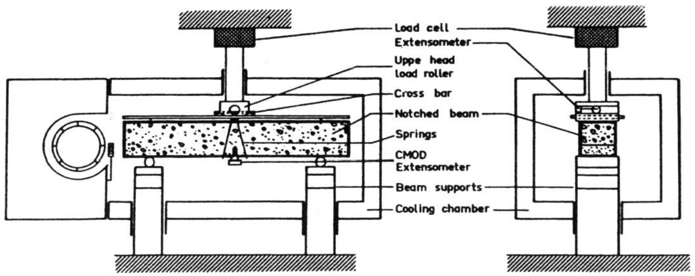

Fig. 3. Beam testing set-up.

In all tests weight compensation was used. This was automatically accomplished by using specimens twice as long as the loading span for the two smallest sizes. Prestressed springs on both sides of the notch provided the load compensation for larger specimens.

Load cell and extensometer outputs were continuously recorded and, simultaneously, readings were taken by the ADAS and stored as a 700 x 3 matrix. Force-deflection and force-CMOD curves and related fracture parameters were obtained by processing the stored data. All tests were run at the same rate of CMOD/depth ratio, namely 7 μm/(m s). With this condition the maximum load was reached in between 30 and 50 s in all cases.

Determination of water content

Immediately after performing the stable bending test, one of the halves of the specimen was fractured by percussion, a sample of approximatelly 1000 g was taken, weighed, and introduced into an oven at 120 C, where it was maintained until constant weight ± 0.2 g was reached as given by successive daily weighings.

EXPERIMENTAL RESULTS

Temperature gradients during specimen cooling

The maximum temperature difference between two points in a cross section during the cooling process is summarized in Table 3 for each specimen size. These temperature differences are very similar to those reported in previous work, (Elices *et al.*, 1987; Maturana *et al.*, 1988), and from the analysis performed in Elices *et al.* (1987) it may be concluded that the cooling conditions are adequate to avoid extensive diffuse microcracking and noticeable damage at the notch root.

Table 3. Maximum temperature difference during cooling

SPECIMEN	TEMPERATURE DIFFERENCE (C)
FT 1-LT	5
FT 2-LT	8
FT 3-LT	10
FT 4-LT	11

Moisture content of the partially dry specimens

From the samples taken after testing and dried at 120 C, until constant weight, it was found that the moisture content of the partially dried specimens was 1.8 ± 0,5 per cent by weight of dry concrete.

Fracture tests

These tests were performed on geometrically similar notched beams, of the same thickness but different sizes, as shown in Fig. 2. For completeness, we give in table 4 the results of a previous series of tests on saturated specimens of the same mix (same aggregates, cement, and mixing proportions, but different batch). The results of the present series are given in table 5. All the results are the mean of two specimens. Values in square brackets indicate half-range, and values in parentheses, where appropiate, are standard deviations.

The raw data to construct these tables are the dissipated energies in each test, W_F, which are given, per unit thickness, in column 4 of the tables. The fracture energies for each size according to RILEM procedure, G_F(RILEM), are obtained by dividing W_F by the ligament area:

$$G_F(\text{RILEM}) = W_F/(bc) \tag{1}$$

where c = d–a is the ligament length, and a, b, and d are defined in Fig. 2.

Table 4. Fracture tests on saturated notched beams

SPECIMEN	d (m)	Temperature (C)	W_F/b (N)	G_F(RILEM) (N/m)	G_F(PLM) (N/m)	l_p (mm)
FT-1-S- RT	0.05	20	1.9 [0.1]	57 [2]		
FT-2-S- RT	0.10	20	5.0 [0.9]	75 [13]	100	17
FT-3-S- RT	0.20	20	10.9 [0.2]	82 [2]	(5)	(6)
FT-4-S- RT	0.30	20	18.8 [1.1]	94 [5]		
FT-1-S- LT	0.05	-170	5.8 [0.6]	175 [17]		
FT-2-S- LT	0.10	-170	14.2 [0.1]	213 [2]	332	19
FT-3-S- LT	0.20	-170	38.5 [0.6]	289 [5]	(9)	(3)
FT-4-S- LT	0.30	-170	60.0 [-]	300 [-]		

d is as in figure 2. W_F is the dissipated energy. W_F/b is the dissipated energy per unit thickness. l_p is the perturbation length

Table 5. Fracture tests on partially dry notched beams (1.8 ± 0.5 per cent water content, by weight)

SPECIMEN	d (m)	Temperature (C)	W_F/b (N)	G_F(RILEM) (N/m)	G_F(PLM) (N/m)	l_p (mm)
FT-1-S- RT	0.05	20	2.5 [0.2]	75 [6]		
FT-2-S- RT	0.10	20	5.5 [0.3]	82 [5]	116	15
FT-3-S- RT	0.20	20	13.9 [1.0]	10 [8]	(6)	(5)
FT-4-S- RT	0.30	20	21.4 [1.2]	107 [6]		
FT-1-S- LT	0.05	-170	5.1 [0.5]	152 [14]		
FT-2-S- LT	0.10	-170	10.8 [0.7]	162 [10]	232	15
FT-3-S- LT	0.20	-170	27.5 [1.0]	206 [8]	(8)	(4)
FT-4-S- LT	0.30	-170	43.1 [1.4]	216 [7]		

d is as in figure 2. W_F is the dissipated energy. W_F/b is the dissipated energy per unit thickness. l_p is the perturbation length

As is clearly shown by the results in column 5 of the tables, G_F(RILEM) displays, for our tests (as well as for many other tests in the literature), an apparent size dependence, so that no single value of the fracture energy may be reasonably extracted by this classical method of analysis.

Based on reasonable physical assumptions regarding potential damage or perturbation over the ligament due to specimen manufacture, a model explaining this size effect was recently proposed by the authors (Planas *et al.*, 1988; Maturana *et al.*, 1988), and called the *Perturbed Ligament Model (PLM)*. The essential result is that, for not too small sizes, the dissipated energy for constant thickness specimens is linearly related to the length of the ligament by the equation

$$W_F/b = G_F(\text{PLM})\,[\,c - l_p\,] \tag{2}$$

where c is the ligament length, G_F(PLM) is a size independent fracture energy and l_p is a size independent constant called the *perturbation length.* Of course, when $l_p = 0$ it appears that G_F (RILEM) does not display size dependence and G_F (RILEM) = G_F (PLM).

The values of G_F (PLM) and l_p are shown in columns 6 and 7 of tables 4 and 5. They were obtained by linear regression of the experimental results assuming equal weight for all single measurements. The regression plots for saturated and partially dry specimens are shown in Figs. 5 and 6, respectively. Standard deviations for the results were estimated by conventional statistical analysis.

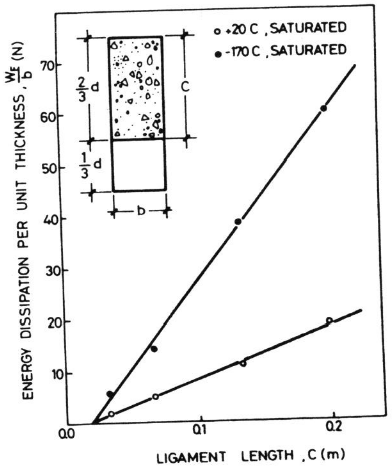

Fig. 4. Fracture tests of water saturated concrete.

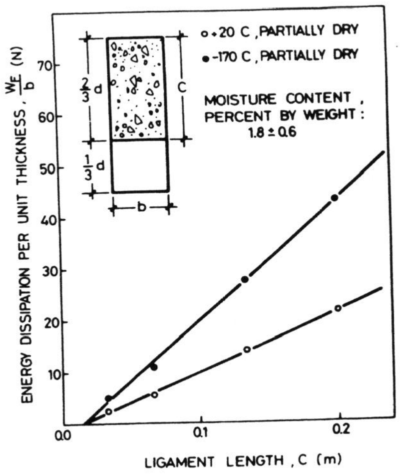

Fig. 5. Fracture tests of partially dry concrete.

DISCUSSION

Dependence of fracture energy on specimen size

RILEM procedure for the determination of the fracture energy of concrete rests upon the assumption that the fracture behaviour of concrete may be described by a Cohesive or Fictitious Crack Model, for which a size independent fracture energy is uniquely defined. But it also rests upon the implicit hypothesis that, for a given specimen, the fracture properties are essentially the same over the whole specimen ligament, i.e., that the bulk properties are unperturbed near the surface of the specimen. The present results, as well as those previously presented in Elices *et al.* (1987), Maturana *et al.* (1988), and in a number of other published works, show a definite effect of the specimen size on the values of the fracture energy computed according to the RILEM procedure.

In order to preserve the essential model for concrete, the Cohesive Crack Model, the hypothesis regarding the uniformity in concrete properties was relaxed by the authors to explain the apparent size dependence. In their PLM it is assumed that at the initiation of the test there are perturbed zones near the free surfaces of the specimen where the fracture energy is less than that in the bulk. Physically, those perturbed zones may arise due to structure modifications near the mould walls, to localised differential shrinkage near the free surfaces, or to some other local processes to be analysed in the future. The essential simplifying hypothesis is that the size and shape of the perturbed zones are size independent. With this hypothesis Eq. (2) above may be derived, in which, if the model is correct, G_F(PLM) would be the bulk fracture energy, and l_p a measure of the size of the perturbed zone.

A single look at the regression plots of Figs. 4 and 5 show that Eq. (2) agrees with the experimental results within the experimental scatter; hence, the present results lend further support to the Perturbed Ligament Model.

Moreover, within experimental accuracy, the values of the perturbation length are independent of temperature (within a given batch), which supports the idea that the size dependence is generated by processes arising during the manufacturing process, rather than in the course of the test.

Of course, further experimental and theoretical support is needed before the PLM physical bases may be widely accepted. Meanwhile, Eq. (2) may be a useful empirical expression to handle experimental results in a consistent way. Work is in progress to obtain direct experimental evidence of the existence of the perturbed zones.

Influence of low temperatures and moisture content

In the following discussion, G_F results obtained from the PLM approach will be compared. The first point to notice is that, owing to the standard deviations involved, the differences obtained at room temperature for saturated and partially dry concrete are not statistically significant for a 5 per cent confidence interval.

Moreover, while the concrete mix is the same for both moisture contents, the batch is not, and since scatter associated to batch change is not known, full confidence intervals cannot be constructed. Due to this fact, values of fracture energies at low temperature relative to those at room temperature will be used. The following values are obtained for the ratios of fracture energies at low temperature to the fracture energy at room temperature:

saturated specimens:	$G_F(-170)/G_F(20) = 3.3 \pm 0.2$
partially dry specimens:	$G_F(-170)/G_F(20) = 2.0 \pm 0.1$

These results show that, on cooling to -170 C, the fracture energy of concrete displays a three-fold increase for saturated specimens and a two-fold increase for specimens with moisture contents as low as 1.8 per cent. This allows two conclusions to be drawn.

First of all, it appears that concrete is tougher at low temperature than at room temperature even for low moisture contents (lower than those that can be expected, on average, in a cryogenic containment wall over its service life, see Elices *et al.*, 1982). This adds a strong argument to other more classical considerations regarding safety conditions of prestressed concrete structures operating in low temperature conditions as compared to metallic structures.

And second, the increase in toughness at low temperatures is significantly lower for low moisture contents, which supports the idea that a significant part of the fracture energy increase is due to freezing of water.

ACKNOWLEDGEMENT. The authors gratefully acknowledge financial support to this research provided by Comision Asesora de Investigación Cientifica y Tecnica, Spain, under grant PA85-0092.

REFERENCES

Elices, M., Rostásy, F.S., Faas, W.M. and Wiedemann, G. (1982), *Cryogenic Behaviour of Materials for Prestressed Concrete*, State of Art Report, Féderation Internationale de la Précontrainte, Wexham Springs, Slough, U. K

Elices, M., Planas, J. and Maturana , P. (1987), *Fracture of Concrete at Cryogenic Temperatures*, Proceedings SEM/RILEM Int. Conference. Houston (S.P. Shah and S.E. Swartz, Eds.), 159-169.

Maturana, P., Planas, J. and Elices, M. (1988), *Evolution of Fracture Behaviour of Saturated Concrete in the Low Temperature Range*, Proceedings Int. Conf. on Fracture and Damage of Concrete and Rock, Vienna (P. Rossmanith, Ed.).

Planas, J., Elices, M. and Guinea, G. (1988), *On the size dependence of G_F for concrete: Perturbed Ligament Model*, Department of Materials Science, Polytechnical University of Madrid, Report No. 88/01.

RILEM Reccomendation (1974), Materials and Structures, 39, pp. 207-224.

RILEM Committee 50-FMC (1985), *Determination of the Fracture Energy of Mortar and Concrete by Means of Three-Point Bend Tests on Notched Beams*, Materials and Structures, 18, No. 106, 285-224.

AFR-2—EE