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Fracture energy of concrete at early ages

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ABSTRACT

This contribution focuses on the evolution of the fracture energy of concrete at early ages. It is examined whether the degree of hydration can be used as the parameter for the description of the softening behaviour of early-age concrete submitted to tensile forces. For the experimental investigation of the evolution of the fracture energy during hardening, three-point bending tests are performed on unnotched prisms whose age ranges from 1 to 28 days. Three different cement types are considered. The development of fracture energy during hardening can be described by a degree of hydration-based formulation. This confirms once more the fundamental character of the degree of hydration.

RÉSUMÉ

Cette contribution étudie l'évolution de l'énergie de rupture du béton en cours de durcissement. On y examine si le degré d'hydratation est un paramètre fondamental en ce qui concerne le comportement au-delà de la charge maximale d'un béton soumis à la traction. Sur la base de plusieurs essais en flexion effectués sur trois différents types de béton pendant leur phase d'hydratation (1 jour jusqu'à 28 jours), on peut conclure que le développement de l'énergie de rupture peut effectivement être relié au degré d'hydratation. Ceci confirme de nouveau le caractère fondamental du degré d'hydratation pendant la phase de durcissement du béton.

1. INTRODUCTION

In order to study the problem of early-age thermal crack formation in hardening concrete, an extensive research program is going on at the University of Ghent, Belgium. Based on isothermal and adiabatic hydration tests, a new general hydration model was developed, valid for both Portland cement and blast furnace slag cement [1]. This hydration model enables the calculation of the heat production rate as a function of the actual temperature and the degree of hydration. By means of improved test methods, a degree of hydration-based description of the thermal characteristics of the hardening concrete was also elaborated [2]. The degree of hydration also proved to be a very fundamental parameter for the description of the development of strength and deformability of early-age concrete [3]. This contribution focuses on the evolution of the fracture energy during hardening. It is examined whether the degree of hydration can also be used as the parameter for the description of the softening behaviour of early-age concrete submitted to tensile forces.

2. TEST METHOD

For the experimental investigation of the evolution of the fracture energy of hardening concrete, a three-point bending test [4] on unnotched prisms of 150 mm x 150 mm x 600 mm is used. The span length is 500 mm. The bending tests are performed with a controlled and constant rate of increase of deflection of 0.033 mm/min at mid-span of the specimen. During each test, a load-deflection curve is recorded, with the deflection being measured at mid-span.

In order to study the evolution of the softening behaviour during hardening, bending tests are performed at different concrete ages, ranging from 24 hours

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Prof. Dr. Ir. L. Taerwe is a RILEM Senior Member. He was awarded the Robert l'Hermite Medal for 1988.

to 28 days. The corresponding degree of hydration r can be calculated as the fraction of heat released, using a newly-developed hydration model [1, 3].

The experiments were carried out on concrete with the following composition per m^3: 300 kg cement, 150 kg water, 670 kg sand 0/2 and 1280 kg gravel 4/14. Three different kinds of cement were used: Portland cement CEM I 52.5, and blast furnace slag cements CEM III/B 32.5 and CEM III/C 32.5. The chemical composition and the fineness of the cements are given in Table 1. Some characteristics of the fresh and hardened concrete are mentioned in Table 2. The concrete specimens were stored at 20°C and 95% relative humidity. Six test series were considered, as indicated in Table 3.

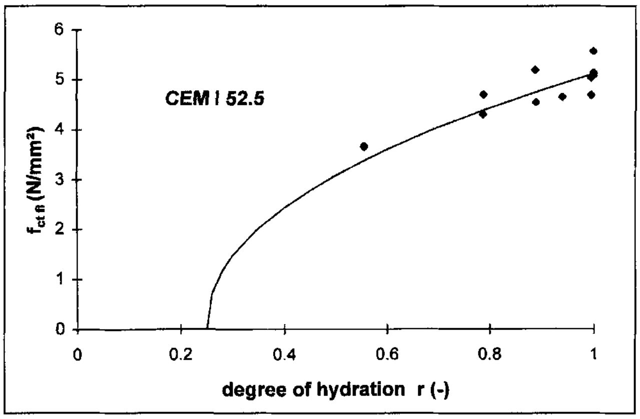

Figure 1 – Flexural tensile strength development CEM I 52.5.

Table 1 – Chemical composition (in %) and fineness

	CEM I 52.5	CEM III/B 32.5	CEM III/C 32.5
SiO_2	19.74	26.15	27.12
Al_2O_3	5.04	7.93	9.40
Fe_2O_3	3.27	2.57	1.63
CaO	62.95	48.96	42.95
MgO	0.93	5.07	7.23
Blaine (cm2/g)	5320	3920	4180

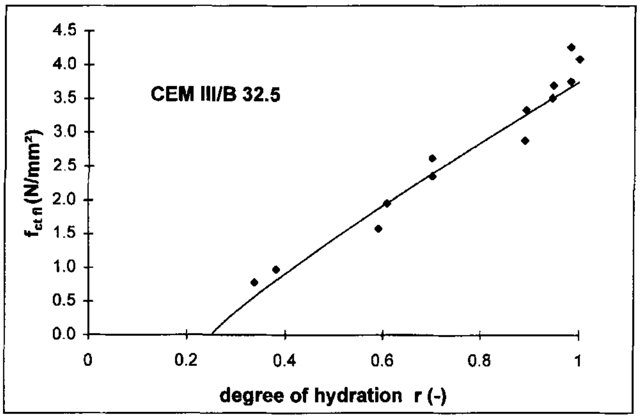

Figure 2 – Flexural tensile strength development CEM III/B 32.5.

Table 2 – Concrete properties

Cement type	Fresh concrete			Hardened concrete	
	Slump (mm)	Flow (-)	Density (kg/m³)	Density (kg/m³)	Mean 28-day cube strength (N/mm²)
CEM I 52.5	20	1.32	2390	2420	60.3
CEM III/B 32.5	25	1.42	2410	2410	41.8
CEM III/C 32.5	55	1.69	2420	2430	34.8

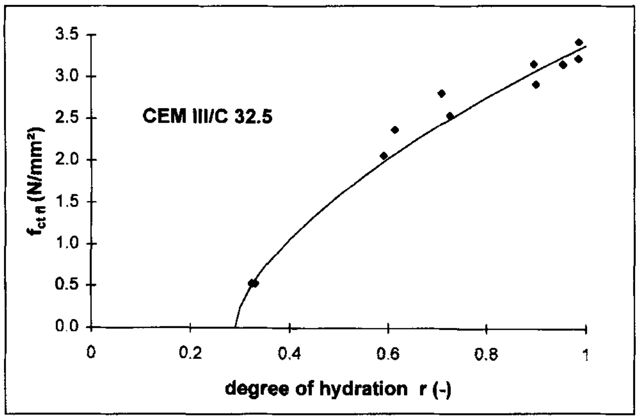

Figure 3 – Flexural tensile strength development CEM III/C 32.5.

Table 3 – Test Series

Cement type	Series	1d	2d	3d	4d	7d	10d	14d	28d
CEM I 52.5	I	x	x	x	x	x		x	x
	II	x	x	x	x	x		x	x
CEM III/B 32.5	I	x	x	x		x	x	x	x
	II	x	x	x		x	x	x	x
CEM III/C 32.5	I	x	x	x		x	x	x	x
	II	x	x	x		x	x	x	x

Since the aim of the experimental program was to study the evolution of the softening behaviour during hardening, and not to verify the size effect, only one size of concrete prisms was used. Unnotched prisms were used instead of notched prisms for practical reasons: the preparation of a sawcut or precast notch is very difficult in the case of early-age concrete.

3. RESULTS

3.1. Flexural tensile strength

The evolution of the flexural tensile strength $f_{ct\,f\ell}$ is shown in Figs. 1 to 3 for the three different cement types used. As already mentioned in [3], the flexural tensile strength development can be described by means of the degree of hydration in the following way:

$$\frac{f_{ct\,f\ell}(r)}{f_{ct\,f\ell}(r=1)} = \left(\frac{r-r_0}{1-r_0}\right)^c \qquad (1)$$

with
r = degree of hydration
$f_{ct\,f\ell}(r=1)$ = flexural tensile strength at degree of hydration r = 1
r_0, c = parameters.

In this formulation, it has been assumed that below a certain datum value r_0 for the degree of hydration, no strength development occurs. This assumption is based on the strength results obtained, as well as on theoretical considerations based on percolation theory [5]. The existence of a datum value r_0, below which no strength development occurs, seems to be widely accepted in the literature [5, 6].

Regression based on the obtained experimental results yields the parametric values given in Table 4. The datum value r_0 is also based on compressive strength results obtained from an earlier research program [3]. The resulting model (1) is also shown in Figs. 1 to 3.

From earlier research [3], it is known that the tensile strength develops faster than the compressive strength, but slower than the Young's modulus.

Table 4 - Parametric values

Cement type	$f_{ct\,f\ell}(r=1)$ (N/mm^2)	r_0 (-)	c (-)	$G_f(r=1)$ (N/m)	d (-)
CEM I 52.5	5.10	0.25	0.46	100	0.46
CEM III/B 32.5	3.75	0.25	0.88	92	1.10
CEM III/C 32.5	3.40	0.29	0.78	112	1.05

3.2. Fracture energy

Fig. 4 shows a typical load-deflection curve for an unnotched beam tested at an age of 2 days. The softening curve can be described numerically by means of an empirical model based on Li et al. [7]. In this model, the load F can be expressed as a function of the deflection y:

$$F = \frac{F_{max}}{1 + \left(\frac{y - y_1}{y_0 - y_1}\right)^n} \qquad (2)$$

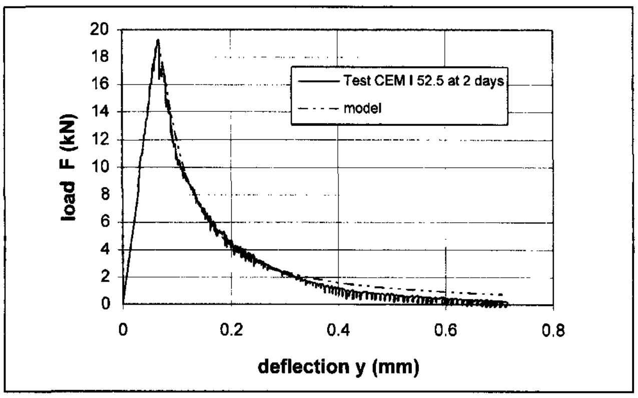

Figure 4 – Load-deflection curve CEM I 52.5 at 2 days.

where F_{max} is the maximum load at a deflection $y = y_1$. The parameter n describes the shape of the softening branch. The parameter y_0 corresponds to the deflection occurring when the load F has dropped to half of F_{max}.

By means of the obtained results, it was verified that equation (2) fits the experimental data extremely well. At all ages, the parameter n was found to be equal to 1.25. In Fig. 4, equation (2) is compared with the experimental curve obtained for one of the specimens.

At very early ages in particular, it was not always possible to obtain a stable crack growth. The recorded part of the softening curve can then be extrapolated by means of equation (2), as shown in Fig. 5. Since equation (2) was verified at different ages by means of the test results with stable crack growth, the extrapolation could be performed with good confidence.

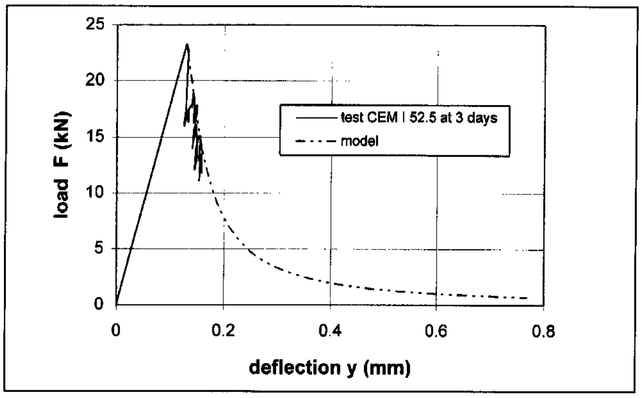

Figure 5 – Load-deflection curve CEM I 52.5 at 3 days.

The area under the softening function is the energy needed to completely break the beam section. From this, the specific fracture energy G_f can be calculated as being the energy needed to completely break a unit area. From the experimentally-obtained softening curves, which in some cases were partly based on extrapolation as explained above, the specific fracture energy G_f can be calculated. For the different cement types used, the result is shown in Figs. 6 to 8, as a function of the degree of hydration. The values for G_f are calculated based on the softening curves limited to a deflection equal to y_1 + 0.7 mm. The influence of the self-weight of the prisms can be neglected.

In the literature, very few results are available concerning the fracture energy at early ages. Brameshuber and Hilsdorf [8] give some results for Portland cement-based concrete, using three-point bending tests on notched and unnotched beams. They come to the conclusion that the development of G_f and of the flexural strength $f_{ct\,f\ell}$ with age are similar. The result from Brameshuber and Hilsdorf, an experimentally-generated function of time $G_f(t)$, is used by de Borst and van den Boogaard [9] for the finite-element modelling of deformation and cracking in early-age concrete. Zollinger et al. [10] study the critical stress intensity factor (or fracture toughness) K_{If} of hardening concrete. They conclude that the critical stress intensity factor K_{If} increases with concrete age. The critical stress intensity factor K_{If} is related to the fracture energy G_f in the following way [10]:

$$G_f = \frac{K_{If}^2}{E} \tag{3}$$

where E is the Young's modulus. In the often-mentioned state-of-the-art report on the properties of concrete at early ages [11], nothing can be found concerning the fracture energy. Even at some major international conferences concerning early-age concrete [12, 13], no attention is paid to the experimental study of the evolution of the softening behaviour during hardening, except in [14] where the results from Brameshuber and Hilsdorf are mentioned once again.

Based on the concept of the datum value r_0 (see Section 3.1) the following degree of hydration-based formulation for the evolution of the specific fracture energy G_f can be given:

$$\frac{G_f(r)}{G_f(r=1)} = \left(\frac{r - r_0}{1 - r_0}\right)^d \tag{4}$$

where $G_f(r = 1)$ is the specific fracture energy at a degree of hydration r = 1, and d is a parameter. The datum value r_0 takes the same value as for the flexural tensile strength description given in equation (1). According to the CEB-FIP Model Code 1990, the fracture energy would be more or less proportional to the tensile strength. Although for Portland cement CEM I 52.5 not many test results have been obtained for lower values of r, a value of $d \approx 0.46$ cannot be rejected. This d-value, equal to the c-value for the tensile strength development given in equation (1), would indeed indicate a similar development of G_f and $f_{ct\,f\ell}$, as was also found by Brameshuber and Hilsdorf for Portland cement. For the blast furnace slag cement CEM III/B 32.5 and CEM III/C 32.5 however, the d-values resulting from the experimental G_f-values are higher than those obtained for the parameter c, as shown in Table 4. This would indicate that for these cements, the fracture energy develops in a slower fashion than does the tensile strength.

Zollinger *et al.* [10] have already found that the critical stress intensity factor K_{If} develops somewhat faster than the compressive strength f_c. This can be confirmed by means of our test results, when considering the relation (3) together with the development of f_c and E as given in [3]. Another frequently used fracture mechanics parameter is the characteristic length ℓ_{ch}, defined by:

$$\ell_{ch} = \frac{G_f \cdot E}{f_{ct}^2} \tag{5}$$

Brameshuber and Hilsdorf [8] report a minor decrease in ℓ_{ch} during hardening, which can also be confirmed by means of our test results, using equation (5) together with the development of E given in [3].

The formulation (4) is shown in Figs. 6 to 8. The reasonably high level of scatter in the test results, especially for CEM I 52.5, is not uncommon, as indicated in [15]. More test results, especially for low r-values, may slightly change the parametric values given in Table 4.

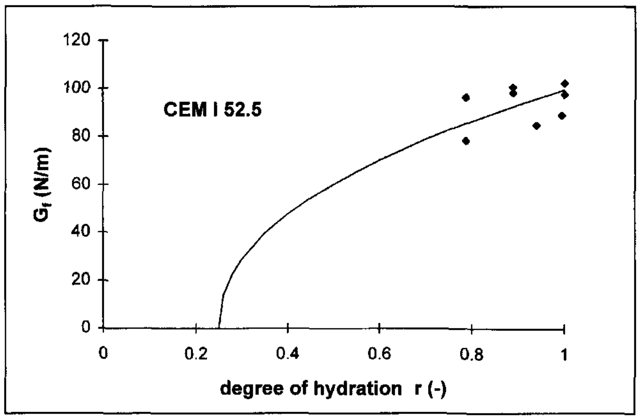

Figure 6 – Fracture energy development CEM I 52.5.

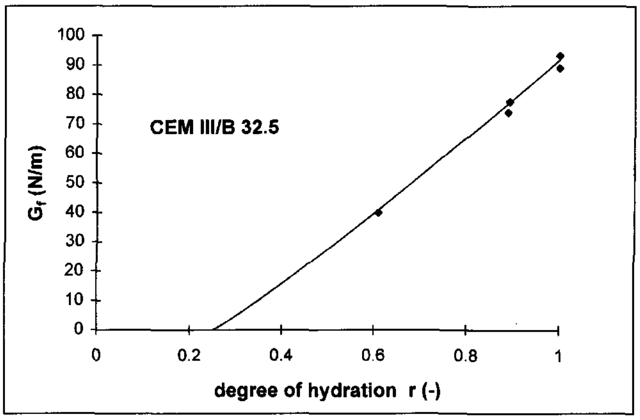

Figure 7 – Fracture energy development CEM III/B 32.5.

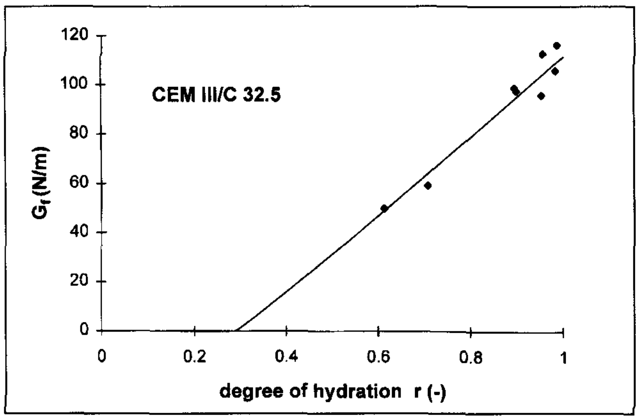

Figure 8 – Fracture energy development CEM III/C 32.5.

For practical calculations using finite element programs, the specific fracture energy $G_f(r)$ can be introduced in a widely-accepted bilinear softening function [16]. In this way, together with the degree of hydration-based description of other mechanical properties of early-age concrete [3], a most fundamental evaluation of the early-age thermal crack formation can be carried out.

4. CONCLUSIONS

The evolution of the fracture energy of concrete during hardening was studied experimentally by means of a three-point bending test on unnotched prisms. For Portland cement CEM I 52.5, the development of fracture energy seems to be proportional to the flexural tensile strength development. For the blast furnace slag cements CEM III/B 32.5 and CEM III/C 32.5, the fracture energy seems to develop in a slower way than the flexural tensile strength. The development of the fracture energy during hardening can be described by a degree of hydration-based formulation. This confirms once more the fundamental character of the degree of hydration.

5. ACKNOWLEDGEMENTS

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