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FRACTURE MECHANICS CHARACTERISTICS AT CRACK INITIATION AND PROPAGATION AND THEIR DEPENDENCE ON STRUCTURE OF CONCRETE

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Abstract

The structure of hardened cement paste (HCP), mortars and concretes was varied by a certain rule: by introducing fine and coarse aggregates into the HCP matrix. The changes of the fracture mechanics characteristics, determined separately for ascending and descending parts of the load-displacement curve, were analyzed. The possible physical causes of these changes are discussed. It is argued, that the fracture energy G_F, determined by the area under complete load-displacement diagram, is integral parameter of cracking resistance and does not take into account the different peculiarities of material response at crack initiation and growth.

1 Introduction

Concrete materials can be divided into the two groups by their abilities to absorb large or small amounts of energy during crack propagation. This distinction is not adequately reflected in conventional test data as a prepeak stress-strain curve. It is usually accepted that the most of the energy absorbed occurs within so-called descending branch of this curve, and this can be found by the area under the post-peak branch of the diagram. An area under the ascending branch responds to the deformation energy required for the crack initiation which is usually takes place in the vicinity of the peak load. Thus the mechanical properties of the material should be characterized, at least, by the two groups of FM parameters describing the different peculiarities of material resistance within the stages of crack initiation and further stable propagation.

The integral fracture energy, G_F, determined by the area under complete load-displacement curve at bending, cannot be considered as sufficiently accurate parameter for characterizing concrete cracking resistance. This issue becomes clear to the international concrete fracture community mostly because of its sound dependence on specimen size and geometry. The second aspect of the correctness in using G_F, which is discussed in the present work, is the integral method of G_F determination.

At the same time the practicing engineer can be attracted by the simple concepts of the G_F test. As far as materials absorbing large amounts of energy at crack propagation are concerned, e.g. fibre reinforced concretes, when the difference between the integral energy and that determined in the post-peak region is small, the G_F approach can be used without any change. However, it should be used only as first approximation for such material as plain concrete, which absorbs a small amount of energy, is much more brittle, and in some cases is sensitive to specimen dead weight.

These considerations were experimentally proved when macrostructure of plain concrete was varied by a certain rule. The changes of the FM characteristics, determined separately for ascending and descending parts of load-displacement diagram, were analyzed.

2 Experimental

The structure of concrete was varied by changing the number of components and their relative contents. The mechanical properties of hardened cement paste (HCP) matrix remained constant for all mixes. This was ensured by the constancy of the effective water/cement ratio (0.236) in the HCP matrix, bearing in mind the water requirements of the aggregates. The raw materials were: Portland cement, quartz sand with a fineness modulus of 2.18 and water requirement of 7.5%, crushed granite stone with particle size of 5-10 mm (20%) and 10-20 mm (80%) and water requirement of 0.7%. The concrete compositions are assembled in Table 1.

Table 1. The concrete compositions

Material	Weight content (cement units)			Volume content (%)		
	Fine aggregates	Coarse aggregates	Water	Fine aggregates	Coarse aggregates	HCP
HCP	0	0	0.24	0	0	100
Mortar A	0.5	0	0.30	23	0	77
Mortar B	1	0	0.35	36	0	64
Mortar C	2	0	0.44	50	0	50
Mortar D	4	0	0.64	61	0	39
Concr. A1	0.5	0.5	0.27	19	19	62
Concr. A2	0.5	1.1	0.28	16	34	50
Concr. A3	0.5	2	0.28	12	48	40
Concr. C1	2	2	0.40	34	33	33
Concr. C2	2	3	0.41	29	43	28
Concr. C3	2	4	0.44	25	50	25

Prismatic specimens of 70x70x280 mm and cubes of 70x70x70 mm were cast, cured for 28 days at air relative humidity of 95-98% and temperature of 18-22°C, then isolated from water exchange with an ambient air until testing at 1 year age. The specimens were tested at 3-point bending and tension (prisms) and compression (prisms and cubes).

The fracture mechanics characteristics were measured at 3-point bending on notched beams with relative crack length of 1/8, 1/4, 3/8 and 1/2.

Load-line deflection gauges were mounted in support sections on the special frame which excluded the influence of irregular movement. A swinging knife-edge support was used instead of a roller to exclude horizontal support reactions and a fixed spherical hinge was used to prevent torsional moments.

Each specimen was tested in bending 3 times, accordingly to Kovler et al. (1988). For this aim special extenders were mounted on the two halves of the beam. The extenders had counterweights for taking specimen dead weight into account.

3 Results and discussion

3.1 Strength

The strengths at compression (both for cubes and prisms), bending and axial tension are in detail reported by Kovler and Zaitsev (1994). The compressive strengths in mortars regularly decrease with a growth in aggregate content, due to the increasing number of initial contact defects.

The strengths at bending and axial tension change with the increase of aggregate in a different manner: both of them have a typical maximum for the certain aggregate content of the mortars. It may be explained by the superposition of the two tendencies: on one hand the increase in the aggregate content making easier formation of contact zones having poor bonding; on the other hand a higher probability of matrix microcracking breaking on aggregates, which play a role of crack stoppers, produces an increased tensile strength.

3.2 Fracture mechanics characteristics on the stage of crack initiation

The critical stress intensity factor K_{Ic}, defined by the maximum load and the initial crack length, and the critical J-integral value J_c, defined by the doubled area under the ascending branch of the load-displacement diagram reduced to the initial net section of bend beam (so called Rice's formula) were used as fracture mechanics characteristics at crack growth.

Both of them are shown in Fig. 1 vs. HCP content. The dependencies are similar to those of tensile strength. It proves the conclusion of Bazant (1984) and Zaitsev and Kovler (1985) that K_{Ic} should be proportional to tensile strength. As far as J_c is concerned, it should depend also on the elasticity modulus. It is clearly seen in Fig. 1 for the mixes C...C3 with high elasticity modulus. The data on elasticity moduli of the materials studied were reported by Kovler and Zaitsev (1994).

3.3 Fracture mechanics characteristics at stable crack propagation

The resistance of concrete to stable crack propagation may be characterized by the specific fracture energy G_s defined by the energy increment dW that is expanded for crack surface increase b(dl), where b is beam thickness:

$$G_s = \frac{1}{b} \cdot \frac{dW}{dl} \qquad (1)$$

The problem here is to measure the crack increment during stable crack propagation because, as was shown by Kovler (1986), Swartz and Refai (1989) and others, the crack front is not exactly planar.

There are typical load-displacement curves shown in Fig. 2. The size of related tensile zone was measured by means of strain gauges having different base, according to Kovler (1986a), and is shown for the concrete A2 as an example. The tensile zone increases linearly with the energy defined by the area under load-displacement curve (Fig. 3).

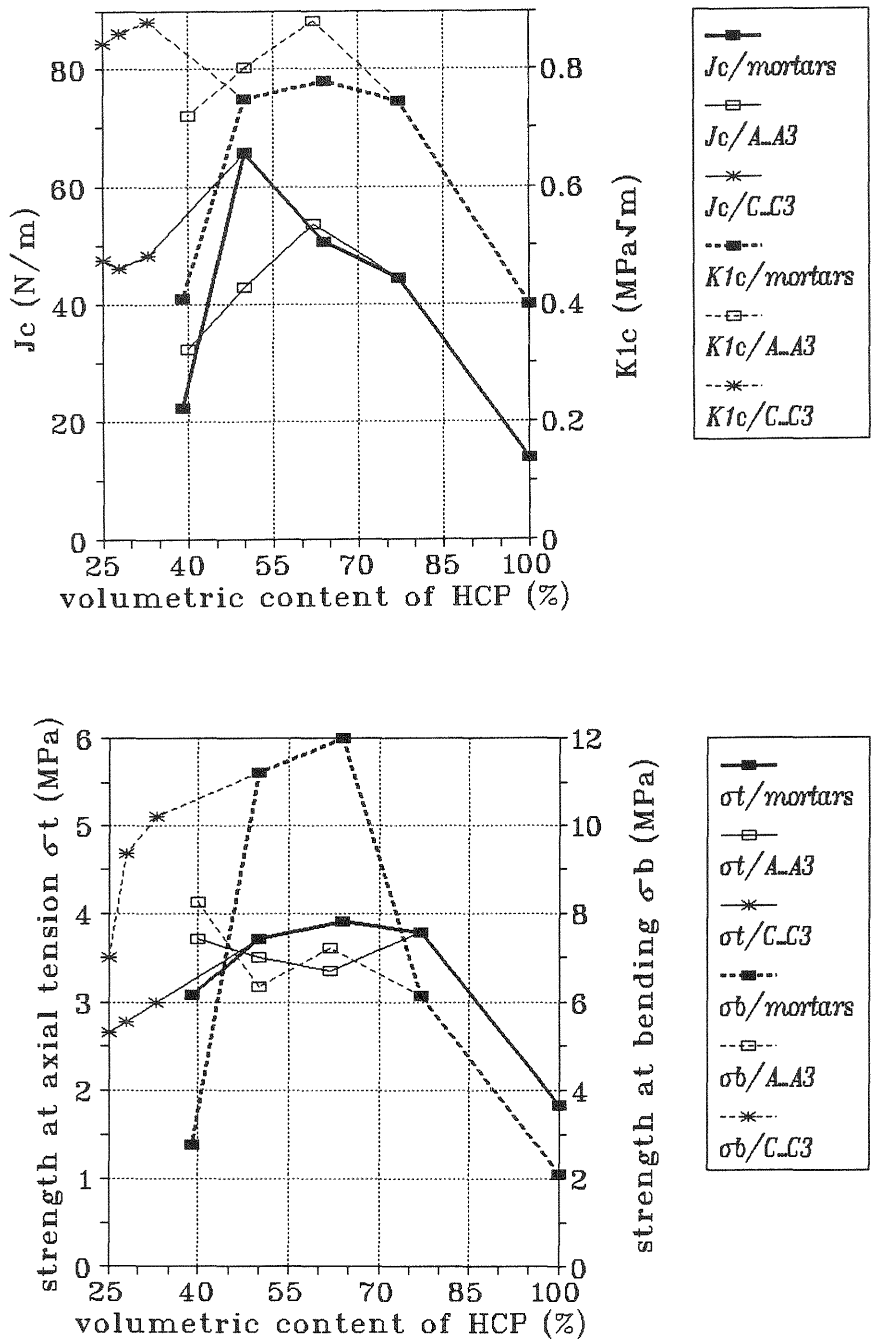

Fig. 1. K_{Ic} and J_c (top) and tensile strengths (bottom) vs. content of HCP

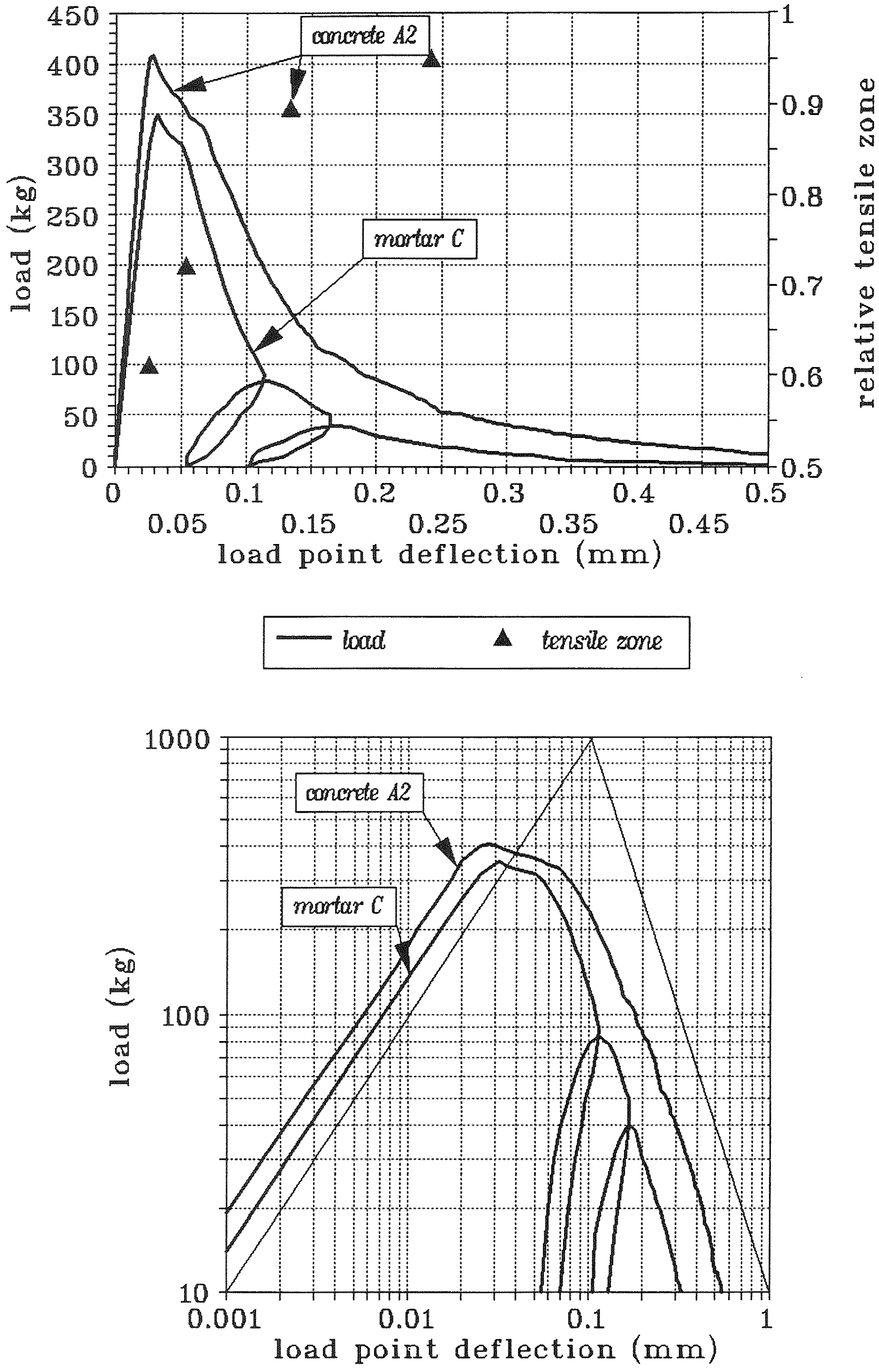

Fig. 2. Typical load-displacement curves in normal (top) and logarithmic (bottom) coordinates

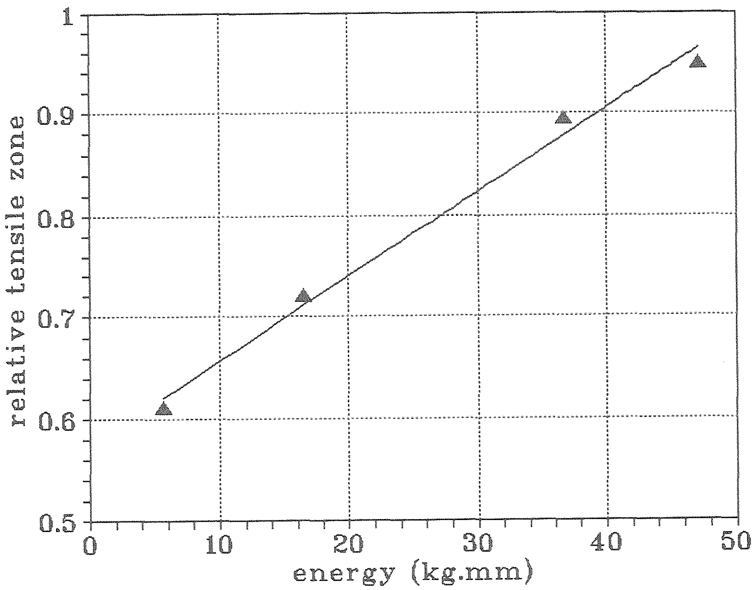

Fig. 3. Relative tensile zone vs. energy for concrete A2

It can be assumed also that the size of tensile zone is linearly proportional to the crack length. Therefore G_s can be measured as average value over the whole crack extension h-l (h is beam depth):

$$G_s = \frac{W_s}{b(h-l)} \qquad (2)$$

where W_s is the area under descending branch.

Other proof of the correctness in using G_s as average value is the fact of its constancy within the post-peak region, revealed in the following way.

It was observed by Zaitsev et al. (1988) and Elices et al. (1992), that ascending and descending branches of the load-displacement curve for plain concrete in logarithmic coordinates may be described by two straight lines with the slope of 1 and 2 respectively, and joined to each other by a short intermediate part. It means that the descending branch is a square hyberbola in normal coordinates (see Fig. 2).

On the other hand, from Fig. 4 it follows:

$$tg(\theta/2)=2f/L = \frac{\delta_c}{2r(1-\mu)h} = \frac{v}{2[r(1-\mu)+\mu]h} \qquad (3)$$

where v and δ_c are, respectively, crack opening displacement and its critical value; μ is relative crack length; f, L, Θ and r are load-line displacement, beam span, crack opening angle and turning factor.

As was shown by Zaitsev et al. (1989), v ≅ f. Therefore,

$$1-\mu = \frac{L\delta_c}{4h} \cdot \frac{1}{f} \qquad (4)$$

$$\frac{d\mu}{df} = \frac{L\delta_c}{4h} \cdot \frac{1}{f^2} \qquad (5)$$

$$G_s = \frac{1}{bh} \cdot \frac{dW}{d\mu} = \frac{F}{bh} \cdot \frac{df}{d\mu} = \frac{4hFf^2}{\delta_c Lbh} = \frac{Ff^2}{\delta_c bh} \qquad (6)$$

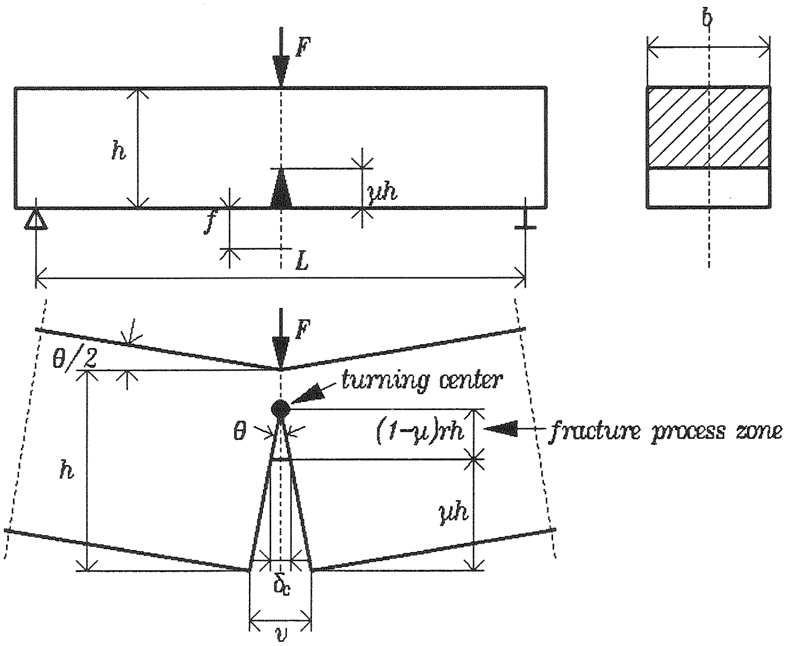

Fig. 4. Simplified scheme of deformed beam at bending

From the observed fact that load F is inversile proportional to f^2 it follows that $G_s \cdot \delta_c$ should be constant. It is also true separately for G_s and δ_c because the energy and deformation criteria should be independent. Knowing the crack kinetics from (4) it is possible to find also the force fracture mechanics parameter, K_{Ic}. Thus all the main fracture mechanics characteristics at stable crack growth (force, energy and deformation criteria) can be determined from the F-f diagram.

The dependence of G_s on the concrete macrostructure is not similar to that of J_c (Fig. 5). G_s increases monotonically with an addition of aggregates, and for coarse concretes its growth is higher. This is explained by the greater total fracture surface developing around the aggregate grains.

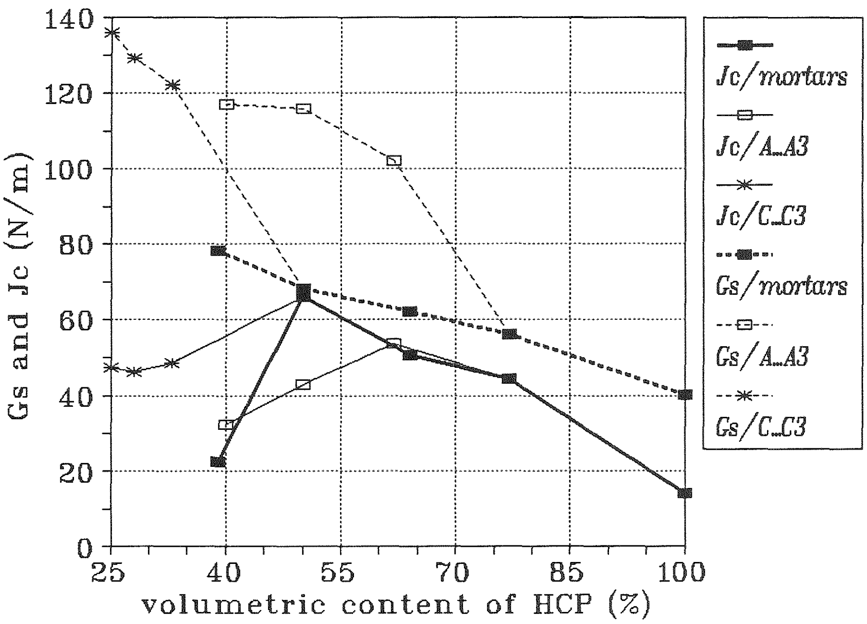

Fig. 5. J_c and fracture energy at stable crack growth G_s vs. content of HCP

The two kinds of characteristics, describing both crack initiation and crack growth, do not practically depend on the kind of mortar matrix in coarse concretes, but only on the content of coarse aggregate.

4 Conclusions

The mechanical properties of concrete (compressive and tensile strengths, FM parameters at crack initiation and growth) change differently with increase in aggregate content, that proves their independent character. It is argued that the integral fracture energy G_F is not a sufficiently accurate characteristic, because it does not take into account the different physical peculiarities of destructive process at crack initiation and growth.

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