# ENERGETIC APPROACH TO FRACTURE TOUGHNESS ESTIMATION OF HARDENED CEMENT PASTE AND CONCRETE

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ABSTRACT

It is shown that fracture mechanics methods can be used for fracture energy $G_c$ and critical stress intensity factor $K_c$ determination of hardened portland cement paste and concrete. However at the experimental determination of $G_c$ and $K_c$ it is necessary to take into account formation of fracture (process) zone in front of the microcrack tip at specimens testing. The direct method of fracture energy determination provides the stable character of specimen fracture. The influence of fine-ground additives quantity, types of aggregates and heating temperature on cracking resistance changing of hardened portland-cement paste, ordinary and high-temperature concretes has been established.

KEYWORDS

Fracture energy, stress intensity factor, mechanical properties, cracks, process zone, portland cement paste, concrete under heating.

INTRODUCTION

It is known that concrete destruction under mechanical loading is taking place as a result of cracks formation. The estimation of fracture toughness of hardened cement paste based on fracture mechanics methods is usually performed by means of stress criteria $K_{IC}$ - critical stress intensity factor and energy criteria $G_c$ - specific fracture energy. At present the concrete fracture toughness test methods have not been standardized and are made by various methods. The correct value determination is still a problem. The tests series carried out on large concrete notched specimens showed the presence of fracture zone reaching up to 100-300 mm at the crack tip in the process of its developing that greatly exceeds the length of the initial crack (notch) and as a rule the size of specimens usually used in the laboratory practice (Entov, Yagust, 1975; Sok,1978). The tests show that $K_{IC}$ increases with the increase of the crack length. The values of $K_{IC}$ and $G_c$ that were obtained on the basis of linear elastic fracture mechanics methods correspond to 35-65% and to 15-40% of their real values respectively (Hillerborg A., Petersson P.E.,1981).

## METHODS OF RESEARCH, TEST PROCEDURES AND DISCUSSION OF RESULTS

It is known that at the fracture tests elastic energy is stored in the specimen as well as in the testing machine. The criterium of the fracture characteristics is
$\Delta U = U_0 - U_r$ ($U_0$ - is the elastic energy stored in the system "specimen - machine"; $U_r$ - is the fracture energy). If $\Delta U > 0$ - the fracture has a sudden brittle character, if $\Delta U \leq 0$ it is stable that gives the possibility of obtaining complete stable stress-strain diagramme (with falling branch) for hardened cement paste, mortar and concrete. Fig.1 shows the diagramme $P - f$ obtained from testing the beam specimens (50x50x320 mm) with a 25 mm notch depth at three-point bending cured during 28 days in normal conditions.
Concrete composition is 1:1, 56:3,29; $W/C$ = 0,5. The diagramme area (Fig.1) is equal to the energy consumed in producing new fracture. So, $G_c$ may be obtained by dividing the area under the force-displacement curve by the area over which the crack front passes. For the given concrete



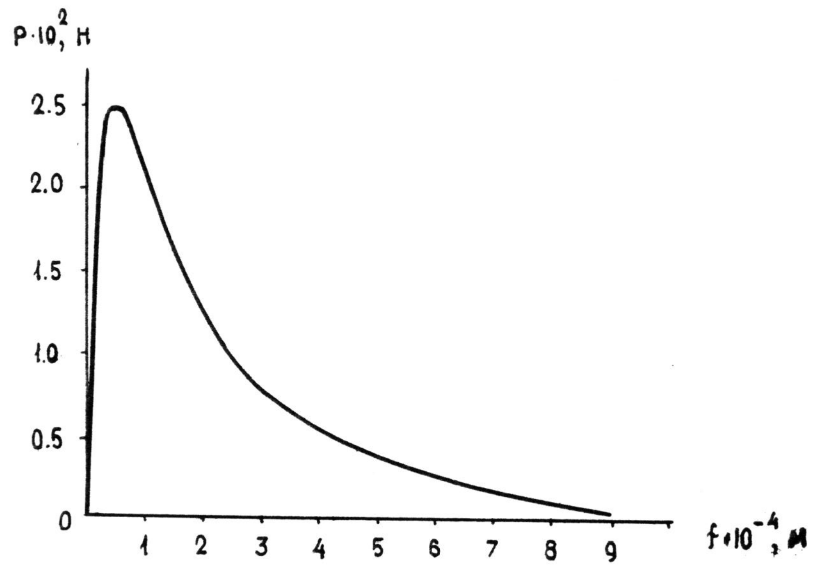


Fig.1. Complete bending diagramme of ordinary concrete.

composition the value of specific fracture energy $G_c$ = = 65 N/m . The dynamic modulus of elasticity determined by resonant method is equal to $36 \cdot 10^3$ MH/m$^2$. Then $K_{IC}$ = = 1.52 MH/m$^{3/2}$. This value of $K_{IC}$ corresponds to the results of the tested concrete specimen-slabs with central and side notches (1,1-2,3 MH/m$^{3/2}$) and greatly exceeds the data obtained on small specimens (0,4-0,8 MH/m$^{3/2}$) according to the linear fracture mechanics equations. The direct method of fracture energy determination provides the stable character of specimens fracture. For this purpose a special device to the standard testing machine was developed. Complete diagrammes with falling branch may also be obtained at the constant speed of specimen deformation during testing when the testing machine stiffness corresponds to the specimen size. It is possible to obtain the specimen length for specimens having equal cross-sectional area which will ensure the stable character of fracture. In investigation (Lebedev A.A., Chausov N.G., 1983) the length of the speci-

men working part is determined as the average value of specimens lengths the least one of which corresponds to the stable fracture and the largest one corresponded to the non-stable one. The specimen length which gives the stable character of fracture may be determined on the basis of the test methods (Shevchenko V.I., 1988).
The critical specimen length is

$$\ell_{cr} = \frac{G_c E}{R_{Bt}^2} = \left(\frac{K_{IC}}{R_{Bt}}\right)^2 , \qquad (1)$$

where $E$ is modulus of elasticity and $R_{Bt}$ is tensile strength of material.
Equation (1) corresponds to the requirements for metal specimens sizes when their fracture toughness is tested.
Equation (1) coincides with the criterium

$$R^{IV} = \frac{E\gamma}{G_t^2} , \qquad (2)$$

where $\gamma$ is specific surface energy and $G_t$ is tensile strength which takes into account the kinetic cracks growth in materials when determining their thermo-shock resistance (Hasselman D.P.H., 1963). In (Hillerborg A., Petersson P.E., 1981) according to the ficticious crack model the parametre $\ell_{ch} = G_c E/R_{Bt}^2$ ($\ell_{ch}$ - is the characteristic length) is introduced for estimating fracture zone at the local macrocracking development. $\ell_{ch}$ is also the measurement of materials brittleness.
When supposing that the rising and falling parts of stress-strain diagrammes are linear and $R_{Bt}$, $E$ and $G_c$ are known, then it is possible to obtain complete curves for concrete deformations. In this case the relative deformation on the rising branch of the curve is determined by parametres $R_{Bt}$ and $E$, and the local deformation in the fracture zone (falling branch) is determined by equation

$$\Delta\ell_p = 2G_c/R_{Bt} \qquad (3)$$



Tests were made on high temperature cement paste with fine-ground fireclay additives of compositions $C:A$ = 1:0,3 ($W/C$ = 0,36) and 1:1 ($W/C$ = 0,68), as well as on high temperature concretes of composition 1:0,2:1,75:1,6; $W/C$ = 0,73) with fireclay aggregates cured during 28 days. Binding matrix - Portland cement produced by "Sebryakovsky" plant had the standard strength "500". The initial humidity of materials was 17,44; 22,98 and 12,62% respectively. To determine the dynamic modulus of elastisity $E_d$, $R_{Bt}$ at the uniaxial tension and bending diagrammes, specimens with the size of 50x50x320 mm were used. Having obtained $E_d$ by resonant method, a 25 mm depth notch was made on the specimens and then they were tested at three-point bending.For porosity determination samples.the mass of which reached 80-100 gr were watersaturated in vacuum. The tests were made on the specimens having natural humidity, and after heating them up to 110,300 and 800°C. The rate of heating was 100°C/h, exposure at given temperature 5 h (at 110°C during 5 days) and then cooling together with cooling of the oven.
The complete bending diagrammes of materials are given on Fig.2, which shows that the increase of fine-ground additives quantity in the cement paste, sand and aggregates introducing cause the increase of fracture process duration what is clearly shown by the smooth character of the falling branch.
The analysis of diagrammes also testifies that concrete being more heterogenious material in comparison with the cement paste is a less brittle and must be more inclined to the redistribution of stresses.
Table 1 shows that when passing from the cement paste having composition 1:0,3 to the composition 1:1 and then to concrete the fracture energy increase (especially for concrete). The increase of the quantity and aggregate size also leads to the critical crack length and local deformation increasing.Consequently the cracking resistance of concretes is essentially higher than that of the cement

paste having the composition 1:0,3 and 1:1.

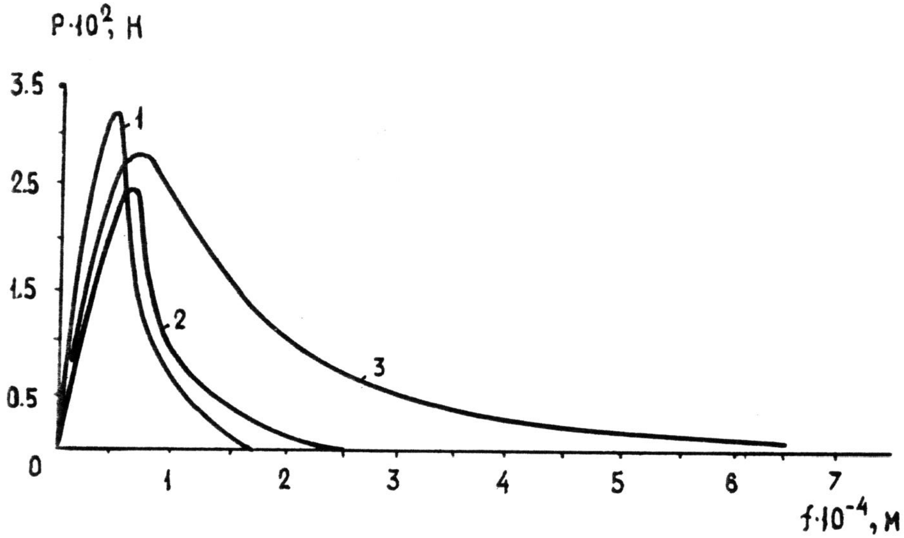


Fig.2. Complete bending diagrammes of high-temperature cement pastes of compositions: 1 - 1:0,3; 2 - 1:1; 3 - for refractory concrete non heated.

Table 2 presents the results of fracture toughness of refractory concrete depending on the heating temperature. It shows that the mostly efficient changes take place after the temperature heating at 100° and 800°C. As a whole the temperature raising leads to the decrease of concrete brittleness. Table 2 also shows that the fracture toughness increase of refractory concrete depending on heating temperature may be achieved by the rational choice of its composition ensuring, together with the optimum strength properties, high values of $G_c$ and $E$ . The optimum strength is ought to be considered the initial strength, ensuring the maximum remain strength after concrete heating.



Table 1

| Material | $R_{bt}$, $MH/m^2$ | $E_d \cdot 10^3$, $MH/m^2$ | $G_c$, N/m | $K_{IC}$, $MH/m^{3/2}$ | $\ell_{cr}$, m | $\Delta\ell_p \cdot 10^{-6}$, m | P, % |
|---|---|---|---|---|---|---|---|
| Cement paste | 2,40/1,85 | 29,75/22,61 | 15,51/19,05 | 0,68/0,65 | 0,080/0,125 | 13,00/20,59 | 33,15/39,50 |
| High temperature concrete | 1,96 | 26,88 | 47,18 | 1,12 | 0,330 | 48,14 | 28,88 |

Table 2

| Heating Temperature, °C | $R_{bt}$ $MH/m^2$ | $E_d \cdot 10^3$, $MH/m^2$ | $G_c$, H/M | $K_{IC}$, $MH/m^{3/2}$ | $\Delta\ell_p \cdot 10^{-6}$, m | P, % |
|---|---|---|---|---|---|---|
| 20 | 1,96 | 26,88 | 47,18 | 1,12 | 48,14 | 28,88 |
| 110 | 1,72 | 21,77 | 102,40 | 1,49 | 119,06 | 26,15 |
| 300 | 1,70 | 14,67 | 90,60 | 1,15 | 106,58 | 29,62 |
| 800 | 0,40 | 4,74 | 45,40 | 0,46 | 227,00 | 32,67 |

## CONCLUSIONS

The methods suggested allow to obtain complete (with falling branch) diagrammes of deformation and on their basis to obtain the values of parametres of concrete fracture toughness.

$G_c$ values allow to estimate the influence of various technological factors on concrete crack resistance and to find the ways of its raising.

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