Concrete fracture energy tests performed by 9 laboratories according to a draft RILEM recommendation : Report to RILEM TC50-FMC

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1. Background

Within RILEM TC 50-Fracture Mechanics of Concrete different methods for measuring the fracture mechanics parameters of concrete have been discussed. It has been concluded that tests where the evaluation is based on linear elastic fracture mechanics only can give valid results if the specimens are so large, that they allow a crack growth in the order of one meter or more for normal concrete qualities. Such large specimens give great manufacturing and handling problems and are therefore not suited for a standardised testing procedure.

Therefore the committee has in the first place choosen to study an other type of test, viz the determination of the fracture energy which is absorbed per unit area of the fracture plane when a specimen is tested to complete failure /1/. The quantity that is measured is denoted G_F, and its definition is

$$G_F = \frac{\text{absorbed fracture energy}}{\text{fracture area}}$$

The fracture area is the projected area on a plane parallell to the crack direction.

One single value can not adequately describe the fracture properties of a material like concrete. Detailed calculations of the fracture process are however possible if, besides G_F, also the modulus of elasticity E, the tensile strength f_t and the shape of the descending branch of the tensile stress-deformation diagram are known.

The modulus of elasticity and the tensile strength can be determined for example by means of RILEM Recommendations CPC 8 and CPC 6 or CPC 7 respectively.

It is also possible to determine the modulus of elasticity and the tensile strength from the same test as G_F, but these values are rather approximate.

The shape of the descending branch seems to be rather constant for ordinary concrete and mortar /3, 4/. It does not seem necessary to determine this shape by means of tests in each individual case.

2. Short description of the proposed test method

In principle the fracture energy G_F shall be determined in a test where complete fracture (separation) occurs in the specimen. The test shall be so arranged, that it is possible to measure the energy absorption and so that this absorption as far as possible is associated with tensile fracture.

The measurement of energy absorption is only possible if the test is stable, i e without sudden jumps in deformations or stresses. If the test is unstable some energy will be absorbed in dynamic processes. The total measured energy absorption then will be to great.

The energy absorption can be measured in a direct tensile test. It is however very difficult to meet the stability requirement in a tension test. This is only possible with a special testing equipment, which is not available in most laboratories. Direct tensile tests are therefore unsuitable as standard tests for the determination of fracture energy.

Tensile stresses also occur in bending. Thus the fracture energy G_F can be determined by means of a stable bending test, provided that the fracture takes place along one reasonably well-defined plane and that the energy absorption in other processes than tensile fracture is negligible.

One well defined plane for bending fracture can be achieved by means of a notch in the tension side.

Energy absorption other than as tensile fracture can occur e g as irreversible deformations outside the fracture zone and as compressive fracture.

In order to minimise irreversible deformations outside the fracture zone it is important to avoid large parts with high stresses outside this zone. This is achieved if the notch is deep enough, i e at least 0.3-0.4 times the beam depth.

In order to avoid energy absorption within the compression zone the material in compression should not be stresses above the elastic limit. This can only be the case if the compressive strength is much higher than the tensile strength. The required minimum ratio between compressive and tensile strength depends on the size of the beam and on the toughness of the material. For ordinary concrete this ratio is of the order 5-10. Such a ratio has been judged to be sufficient, but no investigation has been performed in order to verify this.

It must however be noted that the test method proposed here is not suitable for materials with a low ratio between compressive and tensile strength, e g metals and many types of fibre reinforced materials.

A stable bending test on a notched beam with a notch depth of at least 0.3-0-4 times the beam depth thus seems to be suitable for the determination of G_F.

The test will be stable only if the testing mashine has a sufficient stiffness with regard to the properties of the specimen. As many laboratories do not have very stiff mashines the test should preferably be such, that the demand on stiffness is not too high. For this reason it is suitable to

1. use a tree-point bend test and not a four-point bend test,
2. use a rather deep notch,
3. use a small specimen,
4. use a span/depth ratio which is not too small.

There are however also other things to take into account, which partly act in the opposite direction to the above statements. One essential factor is that the ratio between the size of the fracture plane and the size of the maximum aggregate may not be too small, as this causes an increased scatter. This means that the beam may not be too small and the notch not too deep.

Another essential factor is that the beam should be easy to handle. Thus it should preferably have a weight of not more than 15-25 kg in order to be manageable by hand. If the notch is too deep or if the beam is too slender it will easily break during handling.

As a compromise between all these requirements a beam with a square section 100 x 100 mm^2 and a span of 800 mm (total length 840 mm) with a 50 mm deep notch has been proposed as the standard test beam, Fig 1. Such a beam will have a weight of about 20 kg. The formal stress at the tip of the notch, caused by this weight, is about 0.45 MPa, i e about 10-20 percent of the stress at failure.

The cross section of the fracture plane will be 50 x 100 mm^2. This has not been estimated to be suitable if the maximum aggregate size exceeds 32 mm. In that case the size of the test beam has to be increased. According to the draft recommendation all sizes should be increased in the same proportion. This has however proved to be unsuitable, because the stress due to the weight of the beam increases. For this reason it is better to increase the depth, the width, and the notch depth with the same factor k, but the span only with a factor $\sqrt{k}$, although this will increase the requirement on the stiffness of the testing mashine.

In the test the force-deformation is determined. The area W_0 below this diagram gives the energy supplied by the mashine. The weight of the beam also supplies energy when the beam deflects. It can be demonstrated that this energy approximately amounts to mg δ_0, where m is the mass of the beam between the supports, g is the acceleration due to gravity and δ_0 is the deformation when the force has fallen to zero.

The fracture energy G_F per unit area is calculated as

$$G_F = \frac{W_0 + mg \cdot \delta_0}{A_{lig}}$$

where A_{lig} is the projection of the fracture area on a plane perpendicular to the beam axis (the ligament area).

Tests carried out at different laboratories according to the draft recommendations

The draft recommendations were based on extensive tests at the university of Lund /2/. In order to get a broader judgement of the suitability of the method a number of laboratories in 1982 were requested to apply the method and to report their results and experience in the spring 1983.

Thus the following laboratories and persons reported tests, which were discussed at a meeting of RILEM TC 50-FMC on June 6, 1983. For the further discussions the abbreviations within parentheses are used.

Bundesanstalt für Materialprüfung (BAM, Berlin), H. Winkler.

Ecole Polytechnique de Lausanne (EPFL, Lausanne), I. Georghita and F.H. Wittmann.

Eidgenössige Technische Hochschule (ETH, Zürich), E. Brühwiler, A. Rösli.

Ente Nazionale per l'Energia Elettrica (ENEL, Milano), G. Ferrara.

Istituto Sperimentale Modelli e Strutture s.p.a (ISMES, Bergamo), L. Imperato.

Institut für Massivbau und Baustofftechnologie, Universität Karlsruhe (MPA, Karlsruhe), H.K. Hilsdorf.

Tohoku University (TU, Japan), H. Mihashi, N. Nomura.

Universidad Politêcnica de Madrid (UP, Madrid), M. Elices, J. Planas, H, Corres.

University of British Columbia (UBC, Vancouver), S. Mindess.

The results of the tests are summarized in Table 1.

Many of the tests were made with other beam sizes, spans and notch depths than according to the draft recommendation. Thus BAM, Berlin, and MPA, Karlsruhe, used German standard moulds for modulus of rupture tests, giving a suitable span of 600 mm and a beam depth of 100 or 150 mm.

At ISMES, Bergamo, beams with a span/depth ratio of 4 (instead of 8 for the proposed standard beam) and different notch depths were tested. Some of the beams were very large. This combination of a small span/depth ratio, a small notch/depth ratio and a large beam requires a very stiff testing mashine for a stable test. In spite of this these tests have been stable, i e the testing mashine evidently has been very stiff.

At UBC, Vancouver, beams have been tested where all sizes have been increased in the same proportion, i e according to the recommendations. These tests showed that such a simple scaling is unsuitable, as the influence of the weight of the beam becomes too dominant for large beams.

At EPFL, Lausanne, all tests were carried out with beams of the standard cross section 100 x 100 mm^2 but with some variations in notch depth, beam length and span. The variation in span can be seen in the span/depth ratio. The beams denoted "double length" had a length twice the span, so that the weigth of the beam had no influence on the energy supplied to the fracture plane. In this case the approximate correction for the weight in the formula above shall be deleted, which could theoretically give more accurate result. In practice this test method however has the disadvantage that the load approaches zero in an asymptotic way as the deformation increases, which makes the evaluation uncertain and sensible to unbalance, friction at the supports etc.

Intable I only such tests have been included, where there were no clear indication of instability. In spite of that some slight instability may have occured in some tests, especially where the span/depth ratio is small or where the notch/depth ratio is small. Instability leads to too high values of G_F.

It is impossible to make a direct comparison between the results of tests performed in different laboratories and also between tests performed in the same laboratory with different conrete mixes. The type of aggregate has e g a great influence on G_F. Some general trends may however be noted, e g that G_F increases with an increasing maximum aggregate size.

All reported values seem to be of an order of magnitude, which is in agreement with previously known results, where such exist. Some results fall outside this range, particularly the results from ISMES, Bergamo, where the age 700 days and maximum aggregates of 120 mm have been tested.

The scatter in the results within each series is in many cases very small in in most cases within the limits that can be expected from previous experience /3/. The only evident exception from this is the result from UBC, Vancouver, which shows a rather great scatter. The number of specimens was however very limited in this case.

The influence of the beam depth on the G_F-values can be studied in two of the test series. According to earlier experience /3/, an increase in the beam depth with a factor 4 will give an increase in G_F with a factor of about 1.2. This value is in a reasonable agreement with the tests at UBC, Vancouver, taking into account also the big scatter in these tests and the unsuitability of the largest of these beams, discussed above.

The tests at ISMES, Bergamo, showed an increase in G_F with a factor of about 1.6 when the depth was increased with a factor of about 3. This great influence of the depth makes a further investigation desirable. It is possible that the influence of the depth is very different for different concrete qualities, curing conditions etc.

Observations during the tests

In the test reports some observations have been made regarding the suitability of the recommendations.

It has already been pointed out that it is unsuitable to make larger beams just by increasing uniformly all the dimensions of the beam. The length and the span should preferably be increased in proportion to the square root of the other dimensions.

Some laboratories have experienced a fragility of the beams, sometimes causing fracture already during handling. This seems to have happened mainly where the notch has been cast and not sawn. In the recommendations it is said that "the notch shall preferably be sawn" and that casting of the notch "is only recommended where a suitable saw is not available".

In order to avoid the problem of fragility with cast notches the recommendations may be supplemented with an advise of how a cast notch can be made. The insert forming the notch may not be such, that it gives rise to any separating forces. A piece of wood is often unsuitable. Two thin plastic sheets with a layer of a soft plastic foam between is a suitable material. The loosening from the mold must be made very carefully.

If sawing would be the only recommend way of making the notch, this would presumably prevent some laboratories from using the test method.

One laboratory has noted that 15 minutes may be a too short time from removing the specimen from the water until the testing is performed. Thus maybe this time has to be increased.

One laboratory has reported that they had to decrease the speed of deformation during one part of the test in order to avoid instability. This observation may have to do with the definition of stability. There does not seem to be any cause to change the recommendations for this reason.

In evaluating the tests from the different laboratories it has been very helpful to see the load-deformation diagram from all the tests. These have been reported by only a few of the laboratories. It is recommended that copies of these diagrams are always included in the reports.

Possible further development of the test method

In the preceeding section some possible changes in the recommendations have been discussed. No arguments have been forwarded for any other essential changes. In spite of this, the suitability of some details can of course be discussed, e g if the size of the beam should be made to coincide with some other standard test beam.

It is also possible to make a further analysis of the test results in order to determine also the modulus of elasticity and the tensile strength.

In principle the modulus of elasticity can be determined from the initial slope of the load-deformation curve.

Calculations based on the theory of elasticity show that the modulus of elasticity can be calculated from the following equation /3/:

$$E = \left[1 + 3.15\left(\frac{d}{\ell}\right)^2 + 8\,\frac{d}{\ell}\,g\left(\frac{a}{d}\right)\right] \cdot \frac{1}{4b}\left(\frac{\ell}{d}\right)^3 \cdot \frac{dF}{d\delta}$$

Where

d = beam depth

ℓ = span

a = notch depth

b = beam width

$dF/d\delta$ = initial slope of F-δ-curve

$g(\frac{a}{d})$ a function of a/d, which for $0.45 < a/d < 0.55$ has the approximate value

$$g(\frac{a}{d}) = \frac{0.15}{(1-\frac{a}{d})^3}$$

Thus it should be possible to determine E from the observations during the test, provided that δ is measured as the true deflection of the center of the beam with respect to the supports. If the deflection is measured e g as the movement of the mashine, some corrections have to be introduced, which make the values more uncertain.

If G_F, E, and the maximum load are known, it is also possible to calculate an approximate value of the tensile strength f_t. Then the net bending strength corresponding to the maximum load is first determined from

$$f_{net} = \frac{6P_{max} \cdot \ell}{4b(d-a)^2}$$

An approximate value of f_t can then be determined by means of the diagram of Fig 2, which is based on values in /4/. As this diagram is based on a specific assumption regarding the shape of the descending stress-deformation diagram, it involves a rather great approximation and it can only be used for normal concrete qualities.

It is thus possible to determine values of E and f_t from the G_F-tests, provided these are performed in a suitable way. The values obtained must however be regarded as rather approximate, and there is some doubt regarding the suitability of recommending the evaluation methods.

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TABLE I. Summary of tests and test results.

Institution	Watercement-ratio	Age days	D_{max} mm	Span/Depth	Notch/Depth	Number	δ_0[1] mm	G_F[3] N/m	
BAM, Berlin	(B25)[2]	38	16	6	0.5	8		93±16	0.15 x 0.1 x 0.6 m
	(B45)	37	16	6	0.5	12		113±21	" "
EPFL, Lausanne	0.58	7	30	8	0.5	6	1.0±0.1	87±11	
	0.58	7	30	4.2	0.5	6		110±25	double length
	0.58	28	30	8	0.5	10		150±20	
	0.45	3	30	4.2	0.5	3		170±12	double length
	0.45	7	30	4.2	0.5	4		210±10	double length
	0.45	28	30	4.2	0.5	3		250±7	" "
	0.45	28	30	2.5	0.5	5		320±8	" "
	0.45	28	30	4.2	0.33	5		270±8	" "
	0.45	28	30	5	0.33	5		270±12	
ETH, Zürich	0.50	28	16	8	0.5	11	1.8±0.2	141±25	
ENEL, Milano	0.48	28	20	8	0.5	4	1.1±0.1	94±12	
	0.48	28	20	8	0.4	4	1.1±0.1	88±8	
	0.47	28	10	8	0.5	3	0.64±0.03	65±2	
	0.47	28	10	8	0.4	4	0.70±0.07	69±5	
	0.47	28	10	8	0.3	4	0.72±0.05	70±4	
ISMES, Bergamo		700	25	4	0.5	3		187±22	0.16 x 0.16 x 0.64 m
		700	25	4	0.4	2		192±15	" " "
		700	25	4	0.2	3		147±10	" " "
		700	25	4	0.5	3		223±21	0.5 x 0.5 x 2.0 m
		700	25	4	0.4	3		324±30	" " "
		700	25	4	0.2	3		310±21	" " "
		700	120	4	0.5			373±84	" " "
		700	120	4	0.4			467±71	" " "
		700	120	4	0.2			442±19	0.5 x 0.5 x 2.0 m
		700	120	4	0.02			448±43	" " " m
MPA, Karlsruhe	0.40	7	16	4	0.5	12		175±9	0.1 x 0.15 x 0.6 m
	0.40	28	16	4	0.5	12		161±16	" " "
TU, Japan	0.60	28	25	8	0.5	10	1.1±0.2	92±21	
UP, Madrid	0.58	28	20	8	0.5	13	1.4±0.3	124±22	
UBC, Vancouver	0.38	36	13	8	0.5	2	0.9±0.1	82±32	
	0.38	36	13	8	0.5	3		83±30	0.2 x 0.2 x 1.6 m
	0.38	36	13	8	0.5	3		115±55	0.4 x 0.4 x 3.2 m

1) Only for beams with standard depth and span

2) Quality given as compressive strength

3) Mean value and standard deviation

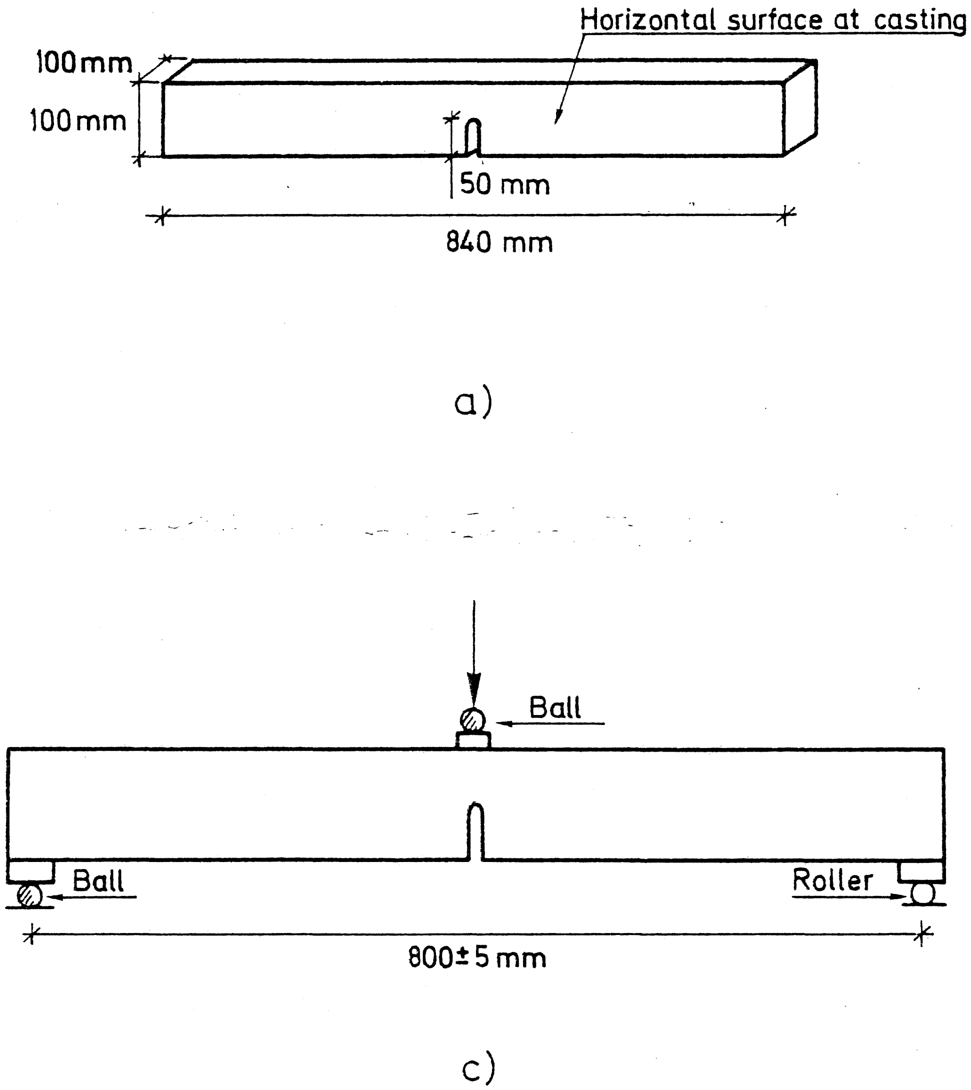

Fig 1. Specimen and support conditions according to /1/.

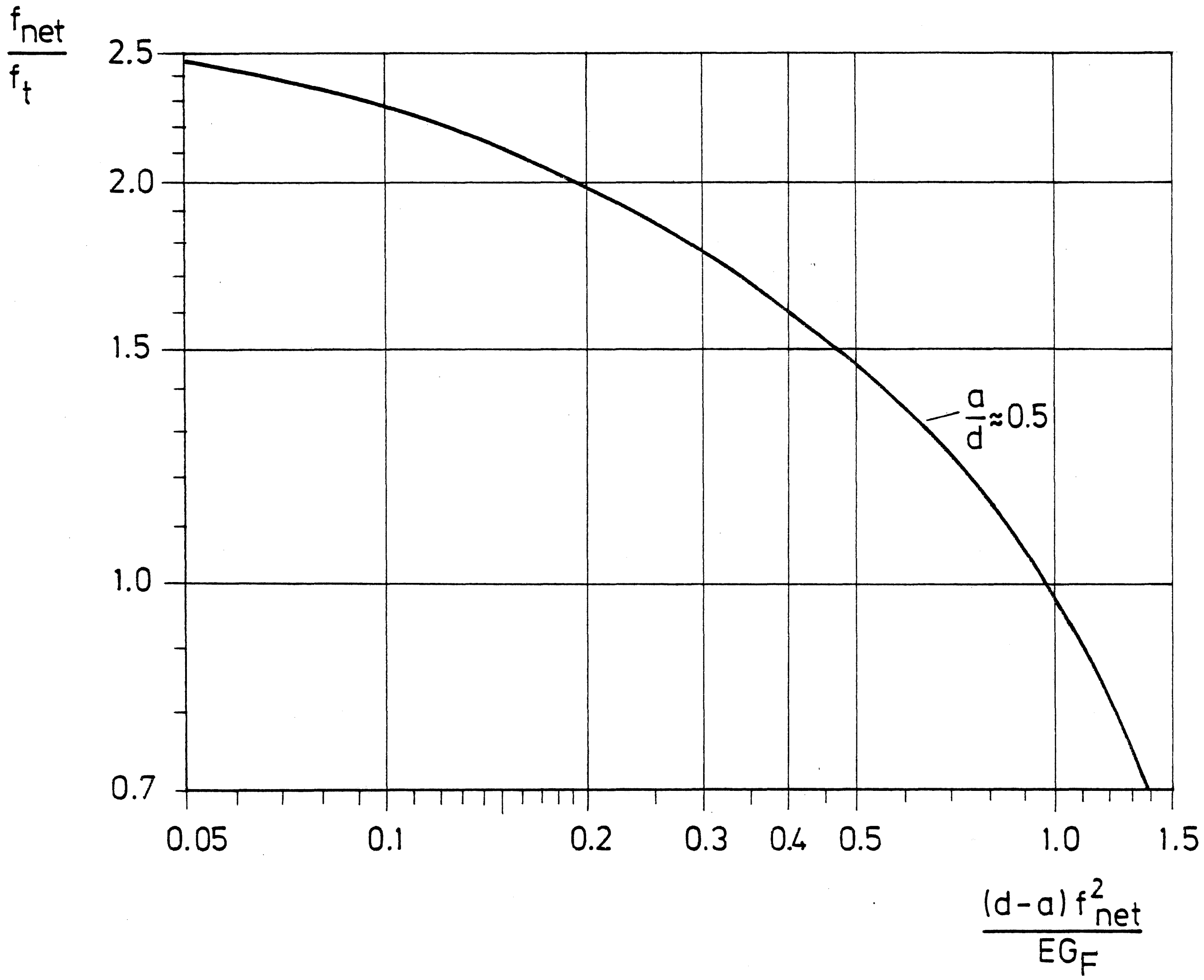

Fig 2. Curve for the determination of f_t when f_{net}, E and G_F are known.