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THE TOUGHNESS OF STEEL FIBRE REINFORCED CONCRETES

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Abstract

Preliminary comparison tests were carried out on fibre reinforced concretes (FRC) made with two types of well-known, well marketed foreign steel fibres and with a Hungarian one, used beforehand successfully in the industry to improve the toughness, of e.g. plain concrete SIOME tubes.

The evaluation of toughness indices I and residual strength factors R based on flexural data (ASTM C 1018) and equivalent strength (Japanese Standard) have shown that the Hungarian fibres are at least of the same quality as foreign ones, mainly in respect of overall toughness — nevertheless the near-after-crack behaviour (crack arrest) can be estimated correctly applying neither of these methods in itself. Splitting tests on cylinders and load-horizontal strain (or crack width increment) diagrams are helpful in estimating the overall toughness in cracked condition. The first crack load was not influenced by the fibres in any case, but moisture content and curing conditions were decisive factors.

Keywords: steel fibres, fibre reinforced concrete, flexural toughness, splitting tensile diagrams.

1. Introduction

In the last decade a lot of very thorough research work has been done concerning basic mechanical properties and industrial application of fibre reinforced concretes (FRC).

The domain of research extends from fracture mechanical approach to standardization and from production of fibres with sophisticated shape properties to ready dimensioning charts used for structural design of industrial floors (e.g. [10]), bridge decks, pavements of motorways and airfields, both for thick FRC and for thin repairing mortars.

The technical application system is complete — yet always arises the question, which fibre is better? This study is a practical approach to this question for a given case.

2. Freshly Mixed Concrete for Strength Tests Specimens and Compressive Strength Results

2.1 The Concrete Constituents

It was decided to make a heavy duty concrete with a low water/cement ratio possibly frost resistant, too, which is assumed if with w/c≈ 0.4 even without an air-entraining agent.

Ordinary portland cement OPC 45 (VÁC Factory) 400 kg/m^3 was used and a fibre (f) dosage of 50 kg/m^3, i.e. about 2 per cent by mass (fresh concrete base) and about 0.64 by volume was applied. The aggregate (a) was naturally rounded Danube sand and gravel in fractions of 0/4 (50 %) and 4/8, 8/16 mm (25 % each), respectively.

A high range water reducing admixture (HRWR) produced by KEMIKÁL (Budapest) on a license of MBT Austria (Rheobuild) was used as superplasticizer to improve workability. The dosage was constant (2 per cent by mass of cement) and the effect of fibres could be traced by changing numbers of consistence measured according to the BS 1881 (CF=compacting factor, or RILEM, or Glanville method which unfortunately is not incorporated in the new Euronorm). In the given w/c ratio the water content of the admixture was not taken into account.

A perfect compactibility resulted from the mix ratio w : c : a : f = 0.4:1:4.6:0.125 and the admixture. Even the technicians carrying out the work did not realize that a longer vibration (3000 rpm) time would have been necessary for fibre concretes, especially with 'fine' fibres.

In this preliminary test (as it is usual) only a restricted number of specimens was cast but they were prepared and tested with utmost care. The parallels lie very close to each other. A reference concrete (REF) and three fibre concretes were made (codes: EX, MM and BF. See *Table 1*). The MM fibres were produced by the D4D Wire Works (Miskolc, Hungary) and were either undulated in plane or helically shaped and are rather flexible due to the relative high aspect ratio l/d. The two other fibre brands — well known and well-marketed products — derive from abroad.

2.2 Specimens and Compressive Strength Results

150 × 150 × 700 mm beams were prepared for bending tests with net deflection measurements under third-point loading with a ratio $L/h = 600/150 = 4$ according to old Hungarian standard and ASTM C 1018 — although longer span L would eliminate the effect of shear forces and giving thus

Table 1
Fibre characteristics

Properties	Fibre code		
	EX	MM*	BF
raw material	block milled	cold drawn	cold drawn
length (mm) l	32.6	40.1 39.7	29.5
equivalent dia (mm)	0.8	0.67 0.52	0.5
aspect ratio l/d	40	60 76.3 / 66	59
tensile strength*** N/mm^2	800	1200 1600	$\geq$ 1100
specific number (n) of fibres n/kg	6220	8990 13980 / 10280	20280
mass of 100 pieces of fibres (g)	16.08	11.12 7.15 / 9.73	4.93
developed length m/kg	203	411	592
shape	HE**	undulated	BE**

* This fibre was a mixture of thinner and thicker fibres, so that out of 100 fibres, 65 were of nom. dia 0.7 mm and 35 of 0.5 mm, resp.
** He = hooked ends; BE = bent ends
*** Data delivered by the manufacturer

a more realistic view about the merits of a given fibre type, e.g. in crack arrest etc. (Longer spans were applied also in Sweden [1].)

Two beams from the four concrete mixes each were cast: one was kept continuously in water (W) another in water up to 9 days of age and thereafter in a relatively dry laboratory air (D): this latter case is the most disadvantageous concerning flexural strength — as it is well known. Beams were tested at an age of 14 days.

Two 150 mm cubes were cast from each concrete mix and soaked in water for 14 days (W) then tested (see *Table 2*). Two cylinders of dia 150, 300 mm long, were prepared and sawn into two halves later: the lower ones were subjected to splitting tensile test at 28 days of age until then kept in water. The horizontal strain (later crack width opening) was measured up to 0.4 per cent.

The upper halves of cylinders were tested at 28 days of age after 23 days of water soaking and 5 days of air curing, expected to give (theoretically) a more advantageous image about the compressive strength than only water cured 14 days specimens may do. In spite of such expectations (see *Table 3*) these values lie slightly lower than those for cubes, that may be attributed to the poorer compaction of concrete cast in slender cylinders

Table 2
Data of 150 mm cubes tested in compression at 14 days (water stored)*

Code	Fibres			Matrix density 14 *d*		Consistence	Cube strength	
	actual kg/m^3	aspect ratio l/d	n/kg	kg/m^3	per cent	CF BS 1881	N/mm^2	per cent
REF	–	–	–	2376	100	0.960	54.2	100
EX	49	40	6220	2371	99.8	0.902	52.7	97.2
MM	49.4	60–76*	10280	2390	100.6	0.974	54.8	101.1
BF	48.1	60	20280	2325	97.8	0.847	51.7	95.4

Note 1: Laboratory data are averages from two parallel specimens with results very close to another

Note 2: The fibre content was calculated supposing that the original mix ratio of the fresh concrete did not change during water storage

* See *Table 1*

Table 3
Compressive strength of 28 days cylinders

Code	Strength N/mm^3	Values per cent
REF	53	100
EX	53.4	100.7
MM	54.4	102.6
BF	49.2	92.8

Note: about 1:1 of dia : height ratios, air dry cylinders

than of that cast in cube moulds. In case BF more HRWR admixture ought to be used. The strength values are very near to each other (49 to 55) and their sequence follows strictly the matrix density, i.e. the compactibility (CF numbers).

The chosen concrete composition is very similar to that one used in Sweden for bridge decks, though there higher cement dosage (440 kg/m^3) and lower w/c (0.38) was used concluding in somewhat higher strength from 50 to 60 N/mm^2 [1].

3. Flexural Tests and Toughness of FRC Beams

3.1 Tests and Results

The beams were tested in an INSTRON machine with special 'cup-and-ball' joints to avoid any torsion. The loading was carried out under deflection control with a rate of 0.5 mm/min of the cross head till 4 mm max. net deflection which refers to $L/150$ of the span $L = 600$ mm thus enabling us to calculate the equivalent flexural strength according to Japanese prescriptions (JCI–SF: Japan Concrete Institute Standard for the Test Methods of Fibre Reinforced Concrete — June 1984, Standard SF4). The net deflections have been measured with a strain meter of type W10-TK (Hottinger). The INSTRON plotted curves are compiled in *Fig. 1* for water saturated beams (W) and in *Fig. 2* for wet-dry cured ones (D), respectively. The 'strength' values are to be found in *Table 4*.

In the evaluation of thoughness we followed the international 'State of the Art', i.e. the thoughness indices outlined in ASTM C 1018 (*Fig. 3*) but in order to get 'final' toughnesses, the deflections and the order of corresponding I-values taken into account have been extended up to I_{30} (belonging to 15.5 d_0), I_{40} (to 20.5 d_0) and I_{50} (to 25.5 d_0), respectively with possible maximum values for a perfect elasto-plastic behaviour of 30, 40 and 50 resp. The merits of I and R numbers are emphasized for different applications and design aims [2].

The residual strength factors R have been calculated from indices I (lower ones see in *Fig. 3*): $R_{10,30} = 5(I_{30} - I_{10})$, $R_{20,40} = 5(I_{40} - I_{20})$ and $R_{30,50} = 5(I_{50} - I_{30})$. (See *Table 5*). The necessity and usefulness of higher-order indices are emphasized also in [1] for evaluating or rating the compliance to service conditions involving greater deflections. The categories given in [3] and [9] for fibre reinforced shotcretes also require the knowledge of R_{10-30} values (*Table 6*). Some authors [7], [8] suggest other indices based on a deflection of $2d_0$ (where d_0 is the first-crack deflection) but as the first-crack deflections d_0 for FRC are very small numbers (see *Table 4*) and the accuracy of measuring is questionable (even the identification is sometimes dubious [2]) we have chosen the extended deflections with higher I_i and R_i values thus coming nearer to the background of $F_{equ} - f_{equ}$ values established in the Japanese Standard (mentioned above) and explained also in *Fig. 1*, curve MM-W, as an example.

The equivalent load and strength values do not contain the error in d_0 — they rather reflect the toughness of a strongly bent and deflected, seriously cracked beam on the one hand — but F_{equ} gives only *minimal information* about the behaviour of the FRC *just after the first crack* broadly speaking about the 'crack arrest' which is a disadvantage of the F_{equ} on

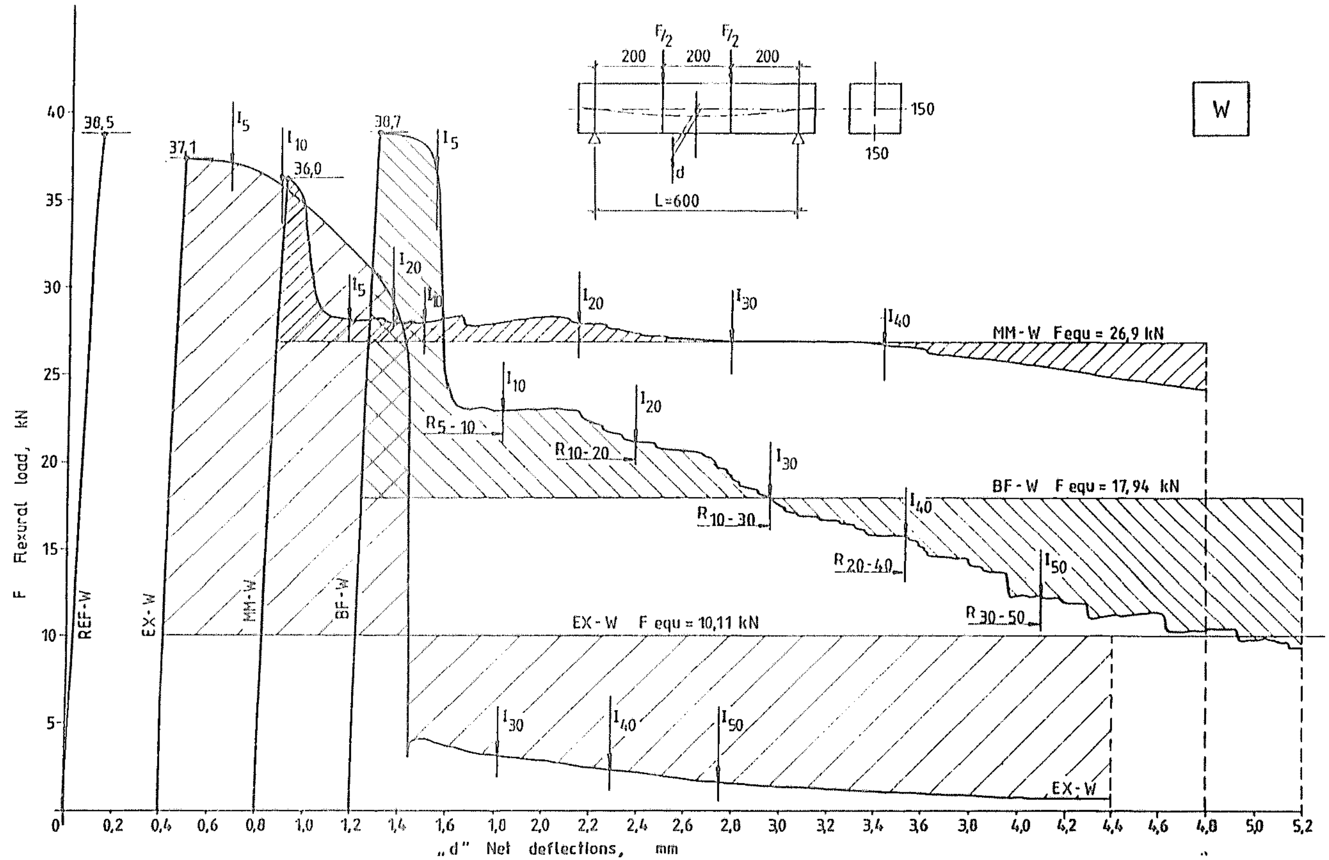

Fig. 1. Load-net deflection curves measured up to $d = L/150 = 4$ mm on 'wet' (W) beams

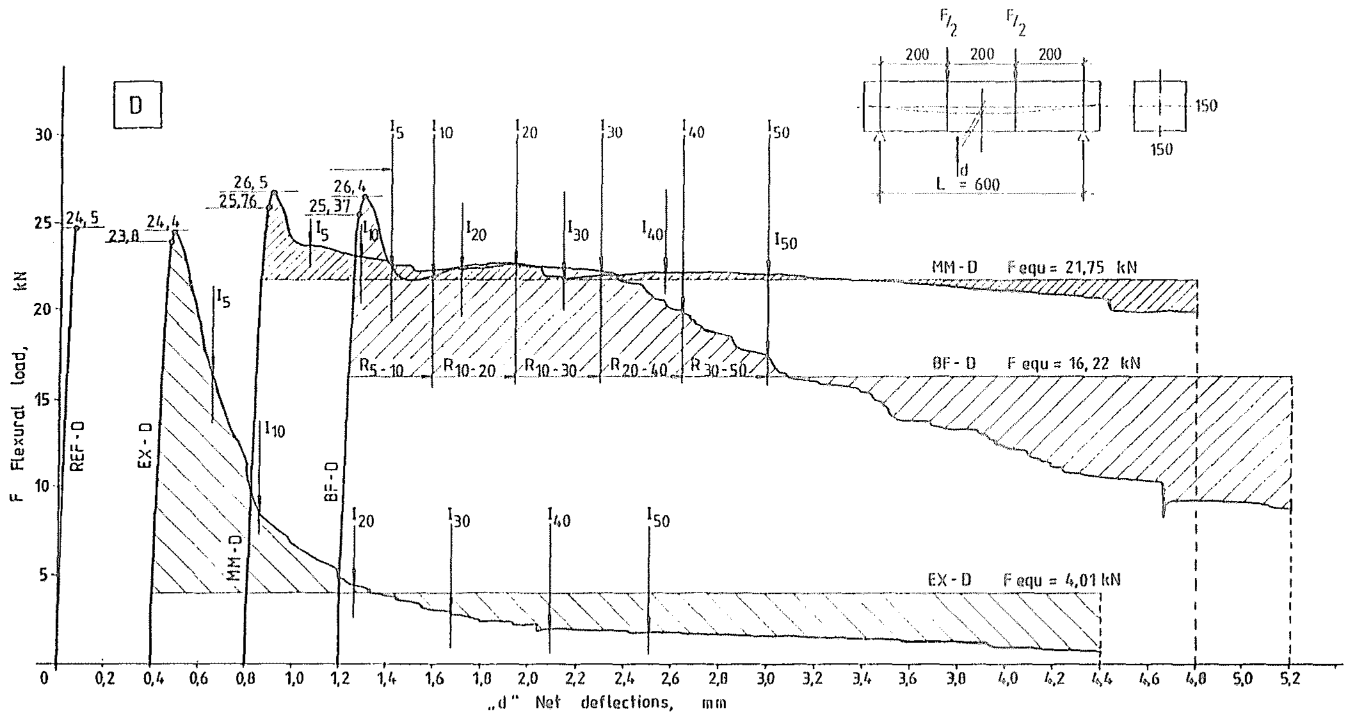

Fig. 2. Load-net deflection curves measured up to $d = L/150 = 4$ mm on 'dry' (D) beams.

Table 4

Results of flexural tests I (stress, strength) (14 days)

Code	First crack load, kN FCL	Max. load kN ML	Deflection at FCL, mm d_0	First crack strength f_f N/mm^2	Modulus of rupture (from ML) MOR, N/mm^2	Equivalent	
						load F_{equ} kN	strength f_{equ} N/mm^2
REF-W	38.5	38.5	0.133	6.60	6.60	–	–
REF-D	24.5	24.5	0.069	4.14	4.14	–	–
EX-W	37.1	37.1	0.093	6.43	6.43	10.11	1.75
EX-D	23.8	24.4	0.083	4.29	4.40	4.01	0.72
MM-W	36.0	36.0	0.129	6.17	6.17	26.9	4.61
MM-D	25.8	26.5	0.086	4.52	4.65	21.75	3.82
BF-W	38.7	38.7	0.114	6.50	6.50	17.94	3.01
BF-D	25.4	26.4	0.071	4.41	4.57	16.2	2.82

Note 1: REF=reference concrete without fibres
W=water stored till the test
D=water stored for 11 days, thereafter air stored

Note 2: The sequence of codes follows that of the load-deflection diagrams in *Fig. 1* and *Fig. 2*, resp.

Table 5

Results of flexural tests II (toughness etc. indices)

	I_5	I_{10}	I_{20}	I_{30}	I_{40}	I_{50}	$R_{5,10}$	$R_{10,20}$	$R_{10,30}$	$R_{20,40}$	$R_{30,50}$
Code	toughness indices ASTM C 1018 based on the net deflections						Residual strength indices (max. value 100) based on ASTM C 1018 method				
	$3d_0$	$5.5d_0$	$10.5d_0$	$15.5d_0$	$20.5d_0$	$25.5d_0$					
EX-W	4.8	9.5	17.8	19.6	20.4	20.8	93.4	83.4	50.9	12.7	6.0
EX-D	4.3	6.8	9.3	10.7	11.7	12.4	49.5	25.2	14.8	11.9	8.4
MM-W	4.2	7.9	15.3	22.4	29.5	36.3	73.7	73.5	72.6	71.0	69.3
MM-D	4.6	8.8	16.9	24.9	32.8	40.8	84.1	80.9	80.7	79.8	79.4
BF-W	4.8	7.8	13.3	18.1	22.2	25.5	59.8	55.2	52.0	44.5	37.0
BF-D	4.5	8.5	16.7	24.9	32.7	39.5	74.5	82.0	82.0	79.8	72.7

Note 1: The toughness index I for plain (reference) concrete equals 1 (by definition, see *Fig. 3*) and residual strength index R equals zero.

Note 2: The net deflection places where the indices belong to are indicated in *Fig. 1* and *Fig. 2*.

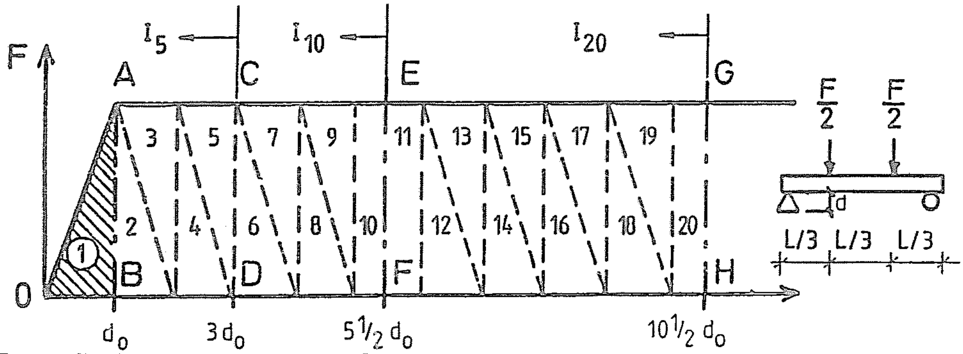

Fig. 3. Explanation of the ASTM C 1018 flexural toughness definition based on idealized load — deflection curve of elastic-plastic materials. Toughness indices: I_5=Area OACDO/Area OAB, I_{10}=Area OAEFO/Area OAB, I_{20}=Area OAGHO/Area OAB where OABO is the triangle belonging to the first crack deflection d_0.

Table 6
Quality categories of the FRC beams based on MORGAN's toughness rating ([3]; [9])

Category	Rating	I_{10}	I_{30}	R_{10-30}
I.	Marginal	< 4	< 12	< 40
II.	Fair	4	12	40
III.	Good	6	18	60
IV.	Excellent	8	24	80
Max.*)	–	10	30	100

*) Perfect elasto-plastic behaviour (See *Fig. 3*)

the other side. The German regulation for FRC industrial floors [10] with a slightly smaller final deflection of about $L/200$ doesn't give an essential change in this respect. Therefore

- the *crack arrest* properties and 'just after cracking' behaviour of FRC should be evaluated directly from load-deflection curves and from indices not above I_5 and I_{10};
- the *total toughness* up to failure should, however, be estimated from higher-order indices (I_{30}, I_{50}, R_{30-50} etc.) and from f_{equ} and F_{equ} (Japanese or German), resp.

In order to explain the necessity of this distinction let us see the curve EX-W (*Fig. 1*) which shows a very good toughness for small deflections and the referring I_5, I_{10} and even I_{20} (similarly to the corresponding R values) are very favourable, i.e. near 100 (*Table 5*), but that beam is considered to be very poor with its low $F_{equ} = 10.11$ kN for bigger deflections and wider cracks. On the contrary, MM-W (*Fig. 1*) is poorer in crack arrest ($R_{5,10}$ is abt. only 70) but that level of load capacity was maintained then until the max. deflection ($R_{30,50}$ also was about 70) and thus with $F_{equ} = 26.9$ kN this beam was the toughest as a whole. The case is similar with dry tested (D) beams (*Fig. 2*).

The *rating* established for fibre reinforced *shotcretes* (*Table 6*) and based on R_{10-30} gives an information roughly about the toughness behaviour of beams with *medium deflection and cracks*, resp.

Table 7

Comparable FRC toughnesses from our tests and reported in [1], respectively

Code	Aspect ratio	l mm	Specific number	Toughness indices I_5	I_{10}	I_{20}	Res. strength indices $R_{5,10}$	R_{10-20}
AM 30 [1]	125	30	100000	4.6	8.7	14.5	80.7	87
HE 30 [1]	60	30	22000	3.9	7.2	11.5	66	43
EE 25 [1]	45	25	18000	3.7	6.2	10.5	50	43
MS 32 [1]	37	32	7000	3.5	5.1	6.0	32	9
BF-W*	59	30	20280	4.8	7.8	13.3	59.8	55.2
MM-W*	66	40	10280	4.2	7.9	15.3	73.7	73.5
EX-W*	40	33	6220	4.8	9.5	17.8	93.4	83.4

Note 1: Values of [1] are not reported there but taken from their diagrams, for moist cured 28 days specimens with a span to height ratio of 7.5 and a fibre dosage 55 kg/m^3

Note 2: Values in our report refer to a span/height ratio of 4 for water cured specimens 14 days of age

A comparison with similar Sweedish FRC specimens is given is *Table 7*.

3.2 Evaluation, Assessments

Based on the results of flexural tests (*Tables 4* to 7, *Figs 1* and 2) we may conclude that

- continuously *water stored* (W) beams have less or more higher flexural strength or modulus of rupture (MOR, *Table 4*) and equivalent strength and a definitely higher first crack strength f_f than do water cured *dry tested* (D) beams: fibres *do not alter* this basic law;
- the first crack deflection d_0 is always bigger for W beams than for D beams, connected with the higher f_f;

- *first crack strength* is essentially not influenced by the fibres, neither with beams with W, nor D, but depends on the behaviour of the matrix, as stated also in [2];
- load-deflection curves W have *one* rather exact first crack load FCL which is the LOP (Limit of Proportionality) (*Fig. 1*, one-peak), the D curves (*Fig. 2*) have a lower LOP and a max. load ML slightly higher than FCL (*Table 4*). This may be attributed to the shrinkage micro-cracks due to air curing of 5 days;
- the Hungarian fibre MM gives the best *overall toughness* both in case W and D reflected also by the highest F_{equ} values, nevertheless *near-first-crack behaviour* (crack arrest) of the EX-W beam was the best one in the whole test ($R_{5,10}$-$R_{10,20}$ above 90 and 80, resp.);
- the first crack obviously occurs in the boundary layer where there are disturbances in the theoretically random fibre distribution which extends to about half of the wire length [4]: the 'anomaly' of EX (R factors worse in D bemas than in W ones) might be explained with the entirely different shape of fibre EX and must be cleared up by further tests (EX fibre had the smallest aspect ratio);
- a comparison with similar Swedish [1] FRC toughnesses (*Table 7* shows only W beams) indicates that our 'near crack' behaviour indices are slightly better or equal, not forgetting that the Swedish beams were more slender. The I and R numbers of [1] may be arranged in *regular sequence* according to aspect ratios and specific number of fibres n/kg — while our results don't obey this law: further tests are needed therefore concerning these factors;
- shape, length, aspect ratio, specific surface, developed length, etc., i.e. *fibre properties* have different effects on consistence (see *Table 2*), crack arrest and overall toughness of FRC — and differences are caused also by *curing* (W or D) which is of high practical significance;
- a rating according to [3] and [9] shows that FRC in dry condition made with the Hungarian fibre MM and with the foreign BF are in the 'excellent' range while MM-W is well above the 'good' limit (See *Table 6*);
- I and R values are *relative ones* referring only to their own d_0 and to the *shape* of their diagram, while F_{equ}, f_{equ} are *absolute terms* of overall load bearing and strength: neither of them alone or even both together cannot reflect all important properties of FRC;
- concerning only F_{equ} and f_f absolute equivalent strength values the FRC beams made with Hungarian MM fibres were superior to the two others.

4. Splitting Tensile Results

4.1 Tests

The ACI Committee 544 suggests the use of splitting tensile tests (carried out on cylinders) rather for routine test in quality control than for research and argues with the difficulties of the crack opening and strain measurement [6]. We tried to apply, however, this relatively simple method, too, on about 1:1 (dia : height) cylinders using a D3 Hottinger type strain meter with $L_0 = 80$ mm base length and a 0.5 mm/min velocity of the cross head of the INSTRON machine.

Table 8
Results of splitting tensile tests
(28 days, water-stored ⌀ 150 mm specimens)

Code	First crack load, kN	f_{split} N/mm^2 (f_s)	Max. load kN	(f_{max} N/mm^2)
REF 1	130	3.71	–	–
REF 2	131	3.62	–	–
BF 1	122	3.55	12*	(3.75)
BF 2	116	3.32	146	(4.18)
EX 1	122.5	3.66	125	(3.74)
EX 2	138	3.84	–	–
MM 1	149	4.26	181	(5.18)
MM 2	128	3.64	135	(3.83)

Note 1: The splitting tensile stresses have been calculated according to the usual formula $f_s = \frac{2F}{\pi dh}$ which may be valid till the first crack. (The results obtained from max. load on cracked cross section are in parentheses).

Note 2: The sequence of codes follows that of the splitting force — strain (crack width) diagrams in *Fig. 4*.

The measured *horizontal strain*–load curves are represented in *Fig. 4*, while the calculated f_{split} values in *Table 8*, based on the exact length and dia values of the cylinders.

The f_{split} results are nearly the same except the highest MM1 which we cannot explain. There is a *very slight* advantage for EX specimens against the others thus supporting an accordance with the assessment on the *good crack arrest* of EX fibres mentioned earlier.

After first crack (elastic strains hitherto) the strain meter essentially measures indirectly the *crack width increments* therefore we put a sec-

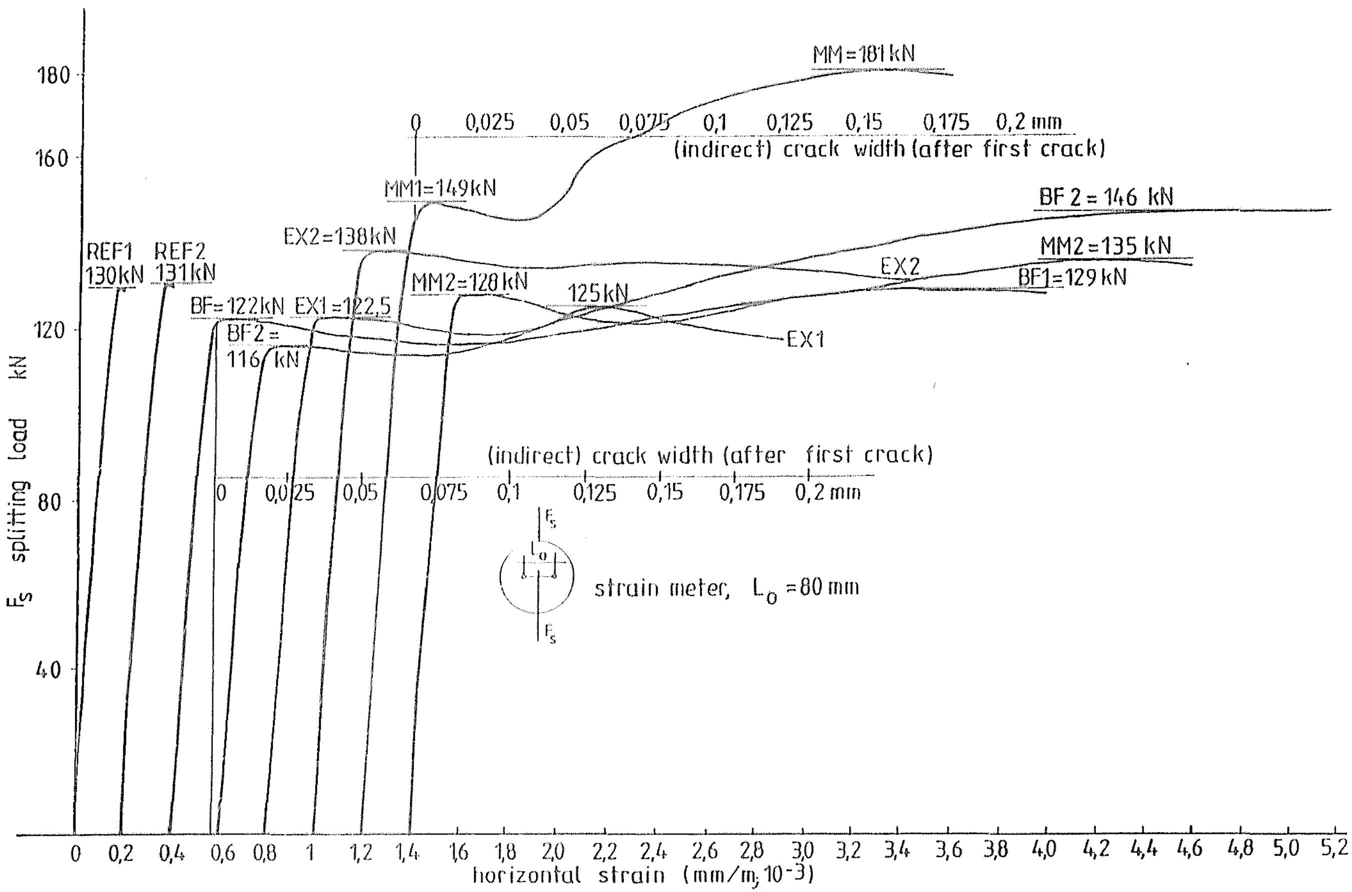

Fig. 4. Splitting load-horizontal strain diagrams measured on FRC cylinders

ondary scale on two of the diagrams in *Fig. 4*. The strains have been recorded till max. load was reached but at least till $2 \cdot 10^{-3}$.

Contrarily to load-deflection curves where FCL and ML have been reached close to another just at the beginning here, however, relatively higher max. loads (ML) have been reached later, in a 'well-cracked' stage.

4.2 Toughness

Nevertheless these diagrams (*Fig. 4*) are not suitable to calculate direct energy of the loaded specimens from the area below the curves yet it is evident that in cracked condition FRC can withstand to a certain horizontal tensile force after the first crack due to a practically constant or even increasing load with very *limited crack width* (e.g. up to 0.2 mm which often is considered as an allowed maximum for RC structures).

We are of the opinion therefore that splitting tests carried out with horizontal strain (indirectly: crack) measurement are simple and therefore also useful enough to give at least an idea about the probable toughness of FRC though it is known that regulations do not prefer this type of test [6]. Such tests are unavoidable, if we can check only drilled cores. Maybe better answers for real toughness are to be awaited from the splitting tests of notched cylinders following the methods of fracture mechanics.

5. Conclusions

We compared the flexural tensile (and shortly also the splitting tensile) behaviour of FRC beams (and cylinders, respectively) prepared with two well-known foreign made fibres and with a Hungarian one used already successfully in the concrete of SIOME pipes years ago in many 10 km-s long pipeline.

The *diagrams* have shown that neither the *indices I and factors R* (ASTM C 1018) in themselves, nor the *equivalent strength* in itself (Japanese, German regulations) are enough to judge both the near-first--crack behaviour and the overall toughness for well cracked (well deflected) beams: these two methods neglect the *absolute* strength values and *crack arrest* properties *near to the first crack*.

The Hungarian fibres turned out to be at least as good as the others, especially considering the overall toughness. The influence of *fibre characteristics* is obvious (some are better in crack arrest, other in rendering the final toughness) but the effect of concrete curing connected with the behaviour of fibres (e.g. slipping) both *in* (air) *dry and in water saturated* condition are of worth to study them further.

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