Impact properties of steel fibre reinforced concrete in bending

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SYNOPSIS
The effects of strain rate of loading including impact on the bending properties of steel fibre reinforced mortar are studied using an instrumented drop-weight impact machine. Particular emphasis is put on clarifying the influence of the fibre reinforcing parameters and matrix strength. The parameters investigated in the experimental programme include three volume fractions of fibres (1%, 2% and 3%), three fibre aspect ratios (47, 62 and 100, two mortar mixes and four strain rates of loading ranging from 0.5×10^{-5} to 1.2 strains per second. It is found that depending on the fibre reinforcing parameters the energy absorbed by the composite at static loading rates can be one to two orders of magnitude higher than that of the unreinforced matrix. Moreover, up to a three-fold increase is observed in the modulus of rupture and the energy absorbed by the composite when the strain rate increases from 0.5×10^{-5} to 1.2 strain per second.

KEYWORDS
Fibre reinforced concrete, impact studies, energy dissipation, toughness, surface energy, composite materials, metal fibres, impact tests, strain rate, modulus of rupture, cracking (fracturing), bond stress, strength of materials.

INTRODUCTION

Studies on the dynamic properties of fibre reinforced concrete are rather limited in comparison to studies on their static properties [1–3]. Dynamic loading implies high strain rates such as under impact or earthquake loading. It is generally agreed that the most significant property needed by a material subjected to impact loading is its energy absorbing capability or toughness; it is also generally agreed that adding fibres to a concrete matrix leads to a significant increase in its toughness, hence impact resistance. Increasing attempts are being made to determine reliably the impact properties of fibre reinforced concrete [4–15].

Although various types of impact test (Charpy, Izod) have been long used as standard toughness tests for many materials, only recently the development of instrumented impact testing has made it possible to rationally analyse material response by isolating it from that of the test setup. Instrumented impact testing was successfully used to study the dynamic behaviour of metal alloys [16]. However, it has made little progress in the study of brittle materials such as cementitious composites. This can be attributed to inherent problems associated with brittleness and the relatively low strength-to-weight ratios of these composites.

A research conducted at the University of Illinois at Chicago under a grant from the US Army Research Office has shown that instrumented impact testing methods can be successfully applied to cementitious composites. Earlier related publications have dealt with the analysis of inertial effects in the instrumented impact testing of fibre reinforced concrete [17], the effect of strain rate on the pull-out behaviour of fibres in

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mortar [11], and a general review of strain rate effects on concrete and fibre reinforced concrete [12,15,18]. This paper summarises the influence of the fibre reinforcing parameters and matrix properties on the flexural behaviour of steel fibre reinforced mortar subjected to high strain rates of loading. Parameters investigated in the experimental programme include three volume fractions of fibres, three aspect ratios, two mortar mixes and four loading velocities. It is observed that depending on the fibre reinforcing parameters a threefold increase in energy absorption under bending can be expected at high strain rates of loading in comparison to static rates of loading. A brief review of previous work is presented first.

SOME BACKGROUND ON FIBRE REINFORCED CONCRETE UNDER IMPACT LOADING

Comprehensive surveys of existing know-how on strain-rate effects on concrete and fibre reinforced concrete have been recently published [13,18,19,20]. Discussion in this section is restricted to instrumented impact tests on fibre reinforced cementitious composites. Background on instrumented impact testing can be found in literature [21–23].

Hibbert [5] modified a conventional Charpy type test by instrumenting the pendulum striker. He obtained continuous load-time and energy-time histories for plain and fibre reinforced concrete beams (100 × 100 × 500 mm) and reported a ten-fold increase in peak load carrying capacity of fibre reinforced concrete beams under impact as compared to the static peak load. Using specially designed supports he was able to compute the kinetic energy imparted to the broken halves of the specimen on impact and thus obtain the fracture energy of plain concrete. The value he reported is an order of magnitude higher than the energy absorbed by plain concrete when fractured under static loading. It is believed that this unusual difference can be attributed largely to specimen inertial effects particularly since Hibbert's specimens were relatively heavy. This also led Hibbert to conclude that the energy absorbed by the fibre reinforced concrete specimens under impact was not significantly different from that under static loading.

Kobayashi and Cho [24] studied strain-rate effects on the flexural behaviour of polypropylene fibre reinforced concrete beams using an Instron testing machine. For specimens containing 4% fibres by volume, they reported a 25% increase in modulus of rupture when the crosshead velocity was increased from 1 to 200 mm/min. Little information was given on the energy absorption capacity of the material at increasing loading rates.

Radomski [9] used a rotating impact machine for performing instrumented tests on fibre reinforced concrete. Impact was simulated by releasing a striker from a rotating flywheel when it has attained the desired velocity. On release, the striker hits a simply supported beam specimen (15 × 15 × 105 mm). The load-time response is recorded using piezoelectric gauges at one of the specimen supports. The author does not report details of such load histories. However, he observes that measurements of energy absorption obtained from his tests do not correlate with those obtained from conventional Charpy tests. This emphasizes the growing need for an impact test where the recorded material properties are independent of the test setup.

Butler and Keating [10] used a hydraulic ram to study the effect of loading rate on the flexural strength of steel fibre reinforced concrete beams tested in four-point bending. The volume fraction of fibres was 1.2% and their aspect ratio 100. They reported a 35% increase in the modulus of rupture when the calculated equivalent stress rate was increased from 0.017 to 170 MPa/sec.

To the best of the authors' knowledge no systematic investigation has so far been undertaken to study the effects of the fibre reinforcing paramenters on the impact properties of fibre reinforced concrete using an instrumented impact testing method. The study reported here is a summary of bending behaviour [13]. A similar investigation on tensile behaviour will be reported elsewhere.

EXPERIMENTAL PROGRAM

A flowchart summarising the experimental program and test series designation is presented in Figure 1. The parameters studied include four strain rates, two matrix strengths (mortar mixes), three volume fractions and three aspect ratios of fibres. Brass coated smooth steel fibres (supplied by National Standards Company) were used throughout. Information on the mortar mixes and the fibres is given in Tables 1 and 2.

A rotating Hobbart food-type vertical mixer was used to mix all constituent materials. Sand and cement were dry mixed first before part of the water (mixed with the superplasticizer) was added to obtain a workable mix. The fibres were then gradually dispensed simultaneously with the remaining water while the paddle was in operation.

The specimens were cast in vertical plexiglass moulds in two layers, each layer being vibrated for about one minute. All flexural specimens were 0.5 in (12.5 mm) thick, 3 in (75 mm) wide and 12 in (300 mm)

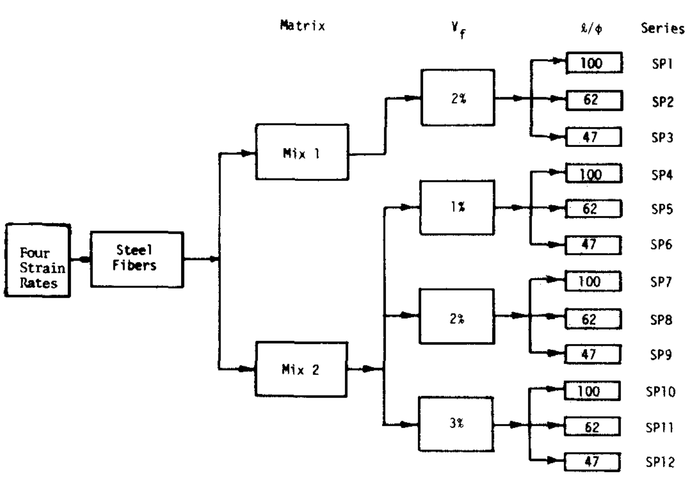

Figure 1 Details of the experimental program

Table 1 Mortar composition by relative weight and properties

	Mix 1	Mix 2
Cement	1	1
Sand	2	1.5
Water	0.50	0.40
Superplasticizer (Melment)	0.024	0.024
Average compressive strength	For SP1 to SP3 8134 psi (56 MPa)	For SP4 to SP12 9380 psi (64.7 MPa)
Average modulus of rupture (plain mortar)		975 psi (6.7 MPa)
Energy absorbed to fracture (plain mortar in bending)		0.67 lb-in (0.075 Nm)

Table 2 Properties of steel fibres used

Brass-coated smooth steel fibres used for all the series of specimen.

Ultimate tensile strength: ≃90 to 120 ksi

Modulus of elasticity: 29×10^6 (psi 2×10^5 N/mm^2)

Aspect ratio (ℓ/d)	Length (in-mm)	Diameter (in-mm)
100	1.00–25.00	0.010–0.25
62	1.00–25.00	0.016–0.40
47	0.75–18.75	0.016–0.40

long. For each series, a 3 × 6 in (75 × 150 mm) cylinder was also cast as control to determine the compressive strength of the mix. Every 12 test series corresponding to one loading rate were prepared simultaneously and later tested simultaneously. The specimens were covered with a polyethylene sheet for 24 hours before demoulding. They were then placed in a curing room (100% RH) for 21 days, then removed and kept at room temperature until they were tested at the age of about two months.

Three-point bending tests were conducted at four different rates of loading. The loading velocities were 0.1, 20, 1670 and 2360 in/min (4.23×10^{-3}, 0.846, 70 and 100 cm/sec), respectively. Corresponding strain rates were 0.5×10^{-5}, 0.01, 0.8 and 1.2 strain per second. Tests at the smaller two velocities were conducted on an Instron universal testing machine while tests at the higher two velocities were performed using an instrumented Tinius Olsen Dynatup drop-weight tower. Figures 2 and 3 show a global view of these two setups. Figure 4 shows the loading configuration and the displacement measuring fixture. The impact face of the instrumented tup was rounded and a ⅛ in (3 mm) strip of rubber pad was placed on top of the specimen to avoid causing local damage to the specimen on

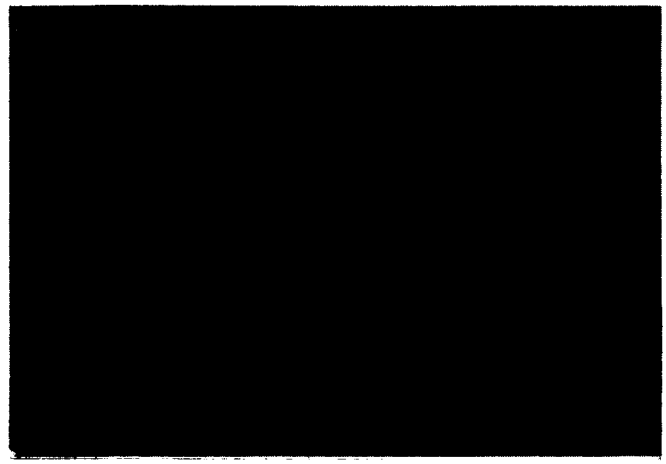

Figure 2 Test setup for the lower two rates of loading (Instron machine).

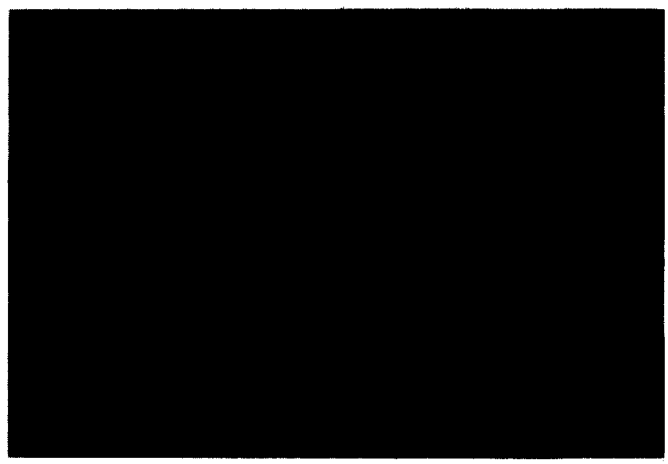

Figure 3 Test setup for the higher two rates of loading (Dynatup system)

impact. All bending test measurements were carried until a midspan deflection of 0.5 in (12.5 mm).

In order to reduce inertial effects on the load recorded, one of the anvil supports was instrumented. Records of anvil load versus midspan deflection were directly obtained on a Tektronix 3C66 dual trace storage oscilloscope and their traces were photographed. In the dynamic tests using the Dynatup-500 system, the tup load versus time was also recorded but it was used only to determine the time to the peak load. Other details related to the testing procedure and instrumentation can be found in [13].

RESULTS AND DISCUSSION

Detailed experimental results are given in [13] where computations from the raw data are explained. Here only their main interpretation is briefly discussed.

For both the static and dynamic tests identical specimens were used in similar loading and support conditions. Tests of the fibre reinforced specimens at all loading rates were limited to a midspan deflection of 0.5 in (12.5 mm) much prior to which the peak load was

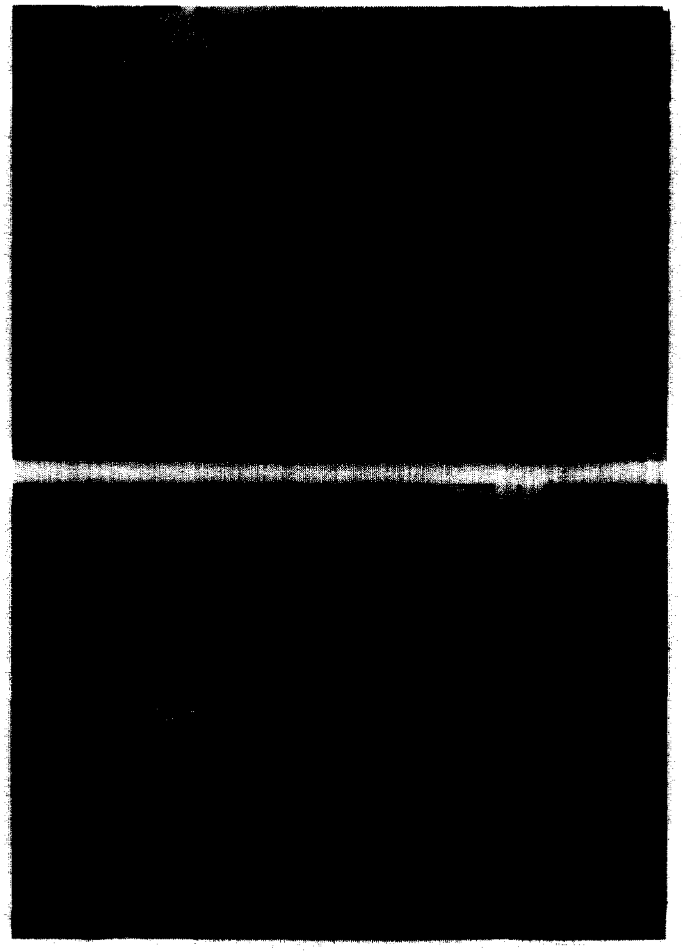

Figure 4 A view of the loading configuration and displacement measuring fixture

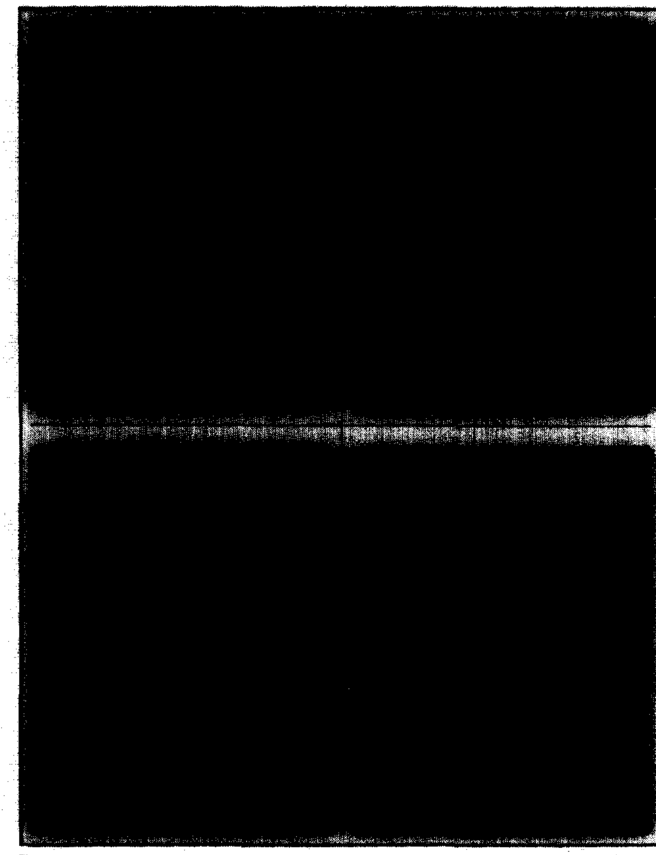

Figure 5 Typical load-deflection traces for series SP1
a. $\dot{\epsilon} \simeq 5 \times 10^{-5}$ strain/sec.; load scale = 18.75 lbs/division (83.4 N/division)
b. $\dot{\epsilon} \simeq 0.01$ strain/sec.; load scale = 18.75 lbs/division (83.4 N/division)
c. $\dot{\epsilon} \simeq 0.8$ strain/sec.; load scale = 48 lbs/division (213.5 N/division)
d. $\dot{\epsilon} \simeq 1.2$ strain/sec.; load scale = 48 lbs/division (213.5 N/division)
a,b,c,d. Deflection scale = 0.05 in/division (1.25 mm/division)

attained. Representative photographic records of the load-deflection curves at each of the four loading rates are shown in Figure 5. Note that the scales for each record are different. A typical set of load-deflection curves at the four loading rates are plotted to scale in Figure 6.

The modulus of rupture was computed from the peak load assuming elastic behaviour. The energy absorbed by the composite up to 0.5 in (12.5 mm) deflection was computed from the area under the load-deflection curve. A single through crack was generally observed at or near the section of maximum moment. The crack was more branched and tortuous at the lower rates than at the higher rates of loading.

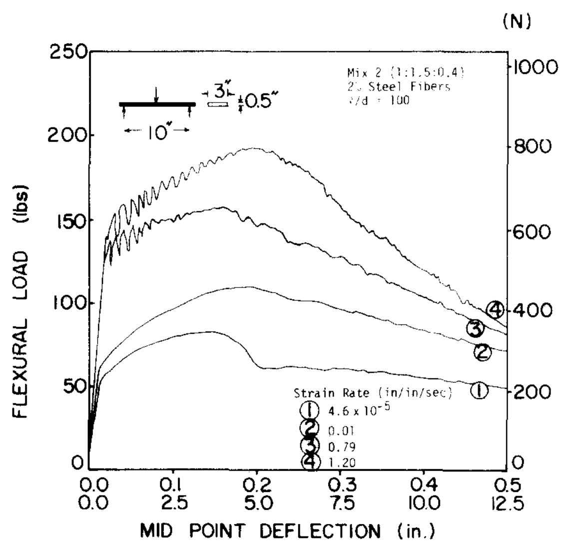

Figure 6 Typical set of load-deflection curves plotted to the same scale at the four strain rates

Effect of strain rate on composite properties
Average values of the observed modulus of rupture (MOR) and energy absorbed up to 0.5 in (12.5 mm) deflection are plotted in Figures 7 to 10 versus the strain rate of loading for all series of tests. Similarly, the average relative values of the ratios MOR dynamic/MOR static and corresponding energy ratios are plotted in Figures 11 and 12. By convention the lowest rate of loading was defined as the static loading.

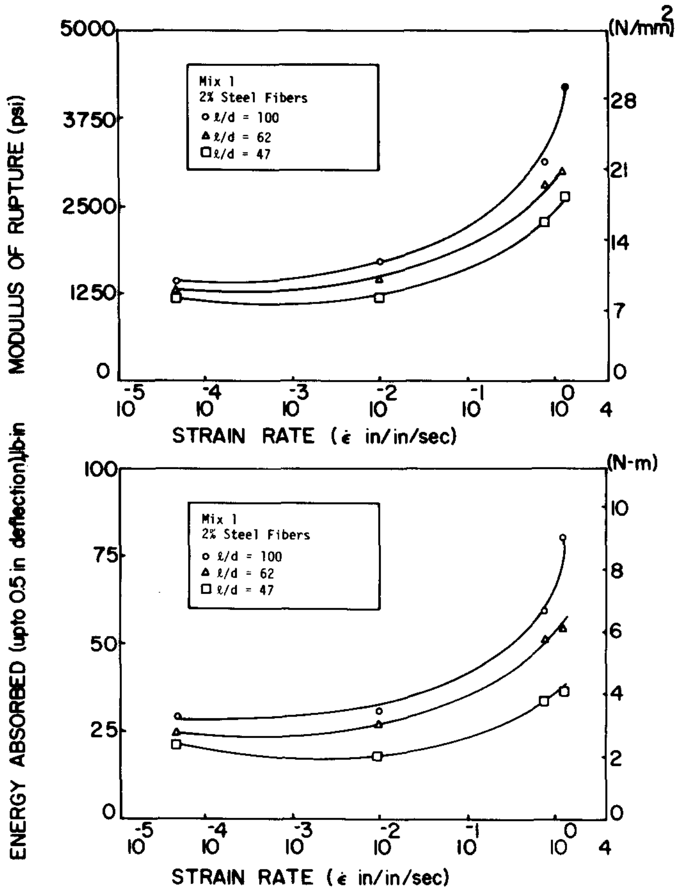

Figure 7 Modulus of rupture and energy absorbed versus strain rate (series SP1 to SP3)

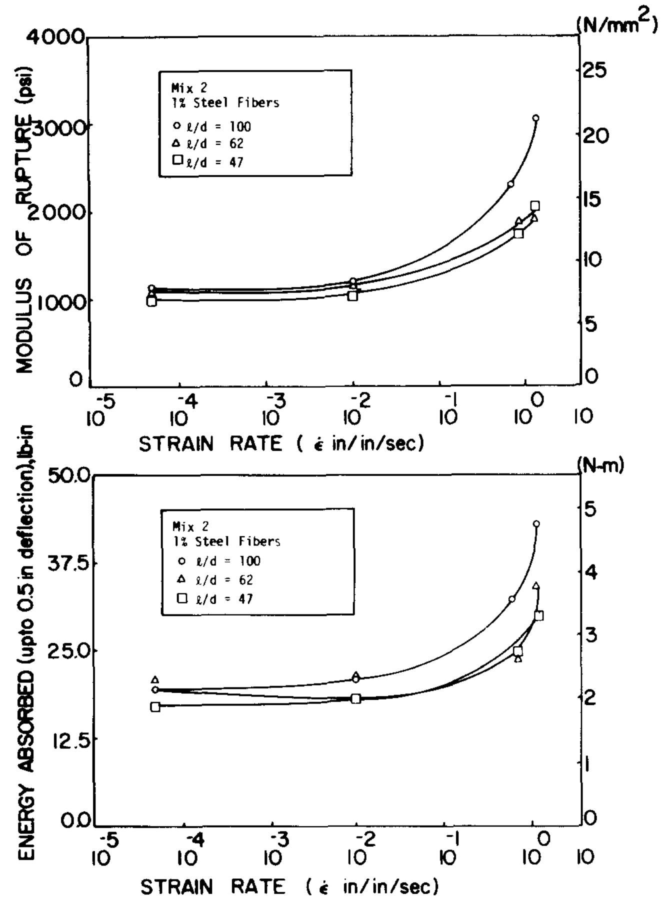

Figure 8 Modulus of rupture and energy absorbed versus strain rate (series SP4 to SP6)

It can be observed that little increase in modulus of rupture occurs when the strain rate increases from 0.5 $\times\ 10^{-5}$ strain/second to 10^{-2} strain/second; however, depending on the fibre reinforcing parameters, up to a three-fold increase in modulus of rupture can be observed when the strain rate increases from 10^{-2} to 1.2 strain/second. Similar observations can be made regarding the effect of strain rate on the energy absorbed.

The relative influence of the fibre reinforcing parameters at any strain rate is described in Figure 11. It can be seen that the higher the volume fraction of fibres or the higher their aspect ratio, the higher the modulus of rupture and the energy absorbed. Finally, it is interesting to point out that the highest ratio of dynamic to static results was obtained for the series of tests made with the weaker matrix (Figure 12).

Effect of strain rate on pull-out energy The two main energy absorbing components in the fracture process of steel fibre reinforced mortar are the work to fracture of the matrix and the frictional work to pull out the fibres from the matrix.

It has been shown that the strength in tension, compression and flexure of plain mortar and concrete is strain rate sensitive, that is, it shows a substantial increase with an increase in loading rate [18,25,26]. This observation may explain the observed increase in cracking strength (or modulus of rupture) in this study but does not explain the substantial increase in the energy absorbed. The energy absorbed is generated mostly in the post-cracking stage and is associated with the pull-out behaviour of the fibres. As only one major crack was generally observed, the energy values recorded can be divided by 3 in^2 (1935 mm^2) to obtain as a first approximation the equivalent surface energy of the material.

The bond strength at the interface between fibre and matrix is the weakest link in a typical steel fibre cementitious composite. For composites made with similar fibres, the post-cracking behaviour is directly related primarily to the amount of bonded area and the matrix properties. Weaker matrices exhibit inferior bonding properties than stronger matrices. Similarly for identical matrix strengths, the higher the bonded area (larger volume content of fibres or higher fibre aspect ratios) the larger the resistance to fibre pull out. Consequently, the larger are the load-carrying and energy absorption capacities. Thus lesser cracking of the matrix at higher rates of loading should provide superior pullout load hence enhanced post-cracking strength and energy absorption.

It may be concluded that the bond strength (which is related to the pull-out strength) is rate sensitive. This

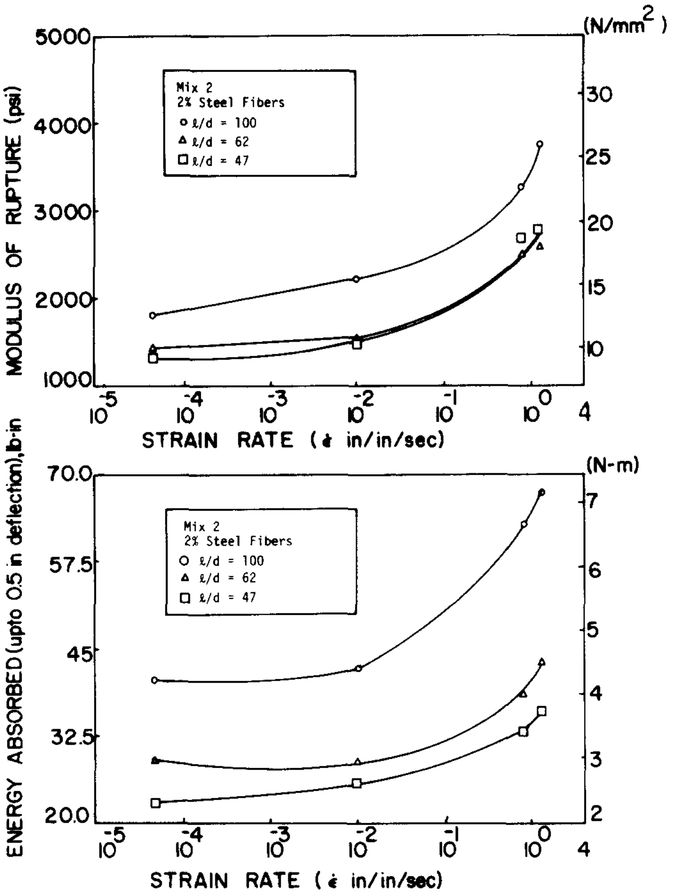

Figure 9 Modulus of rupture and energy absorbed versus strain rate (series SP7 to SP9)

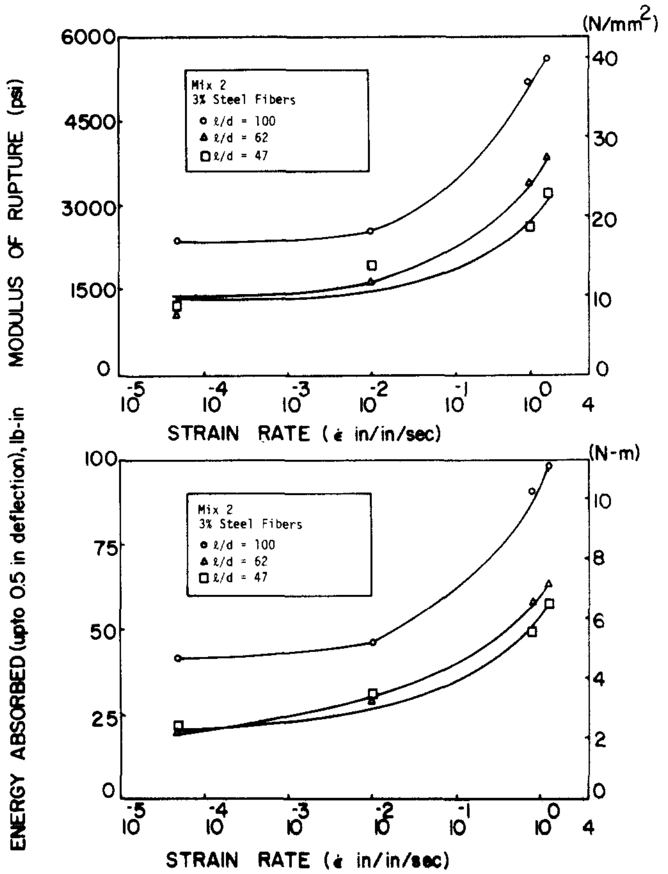

Figure 10 Modulus of rupture and energy absorbed versus strain rate (series SP10 to SP12)

conclusion seems in disagreement with the findings of Gokoz and Naaman [11] and Vos and Reinhardt [27] on smooth fibres and plain reinforcing bars. In the above investigations pull-out tests were conducted in direct uniaxial tension (fibres or bars aligned with the direction of loading). In both studies cracking of the matrix transverse to the steel-matrix interface was not likely to be present. Consequently, little improvement in bond strength was observed at higher rates of loading. The significant increases in modulus of rupture of fibre reinforced mortar composites with strain rates as observed here may be attributed to several parameters (other than the extent of transverse matrix cracking) associated with the measurement of an apparent bond strength. For instance, when fibres are pulled out at an angle, a mechanical bond component is added to the frictional bond component due to the bearing of the fibre on the matrix [28]. This is quite similar to the pullout behaviour of deformed bars where the lugs of the bars bear on the matrix. Indeed, Vos and Reinhardt [27] report significant increases in the pull-out load of deformed bars at high rates of loading. Pull-out loads in this case and the apparent bond strength are strain rate sensitive.

In addition, it was shown in [28] that when non-aligned steel fibres are pulled out, they undergo at the crack surface continuous bending which enhances their pull-out resistance. As steel is rate sensitive, this effect should increase with increases in loading rates. Hence in view of all the above factors, it can be said that the pull-out resistance of steel fibres and their apparent bond strength are strain rate sensitive.

Analytical estimate of surface energy It was pointed out earlier that under loading only one major crack was observed in the matrix followed by fibre pull out. The area under the load-deflection curve up to 0.5 in (12.5 mm) deflection was converted to an equivalent surface energy of pull out $(\gamma_f)^*$. The average values of $(\gamma_f)^*$ for 48 series of tests were correlated with the product $(V_f(\ell^2/\phi))$ which was found important in the analytical prediction of surface energy in tension [14,15,29]. V_f is the volume fraction of fibres, ℓ their length and ϕ their diameter. Regression lines were derived [15] between $(\gamma_f)^*$ and $(V_f(\ell^2/\phi))$. A single linear relation was sought for strain rates between 0.5 $\times$ 10^{-5} and 0.01 strain/second to reflect the observed results (Figures 7–13). For the nominal strain rates of 0.8 and 1.2 strain/second, the two linear equations obtained were not sufficiently different to warrant a separate analysis. Hence a single fitting line was used for both. The corresponding least square equations are [15]:

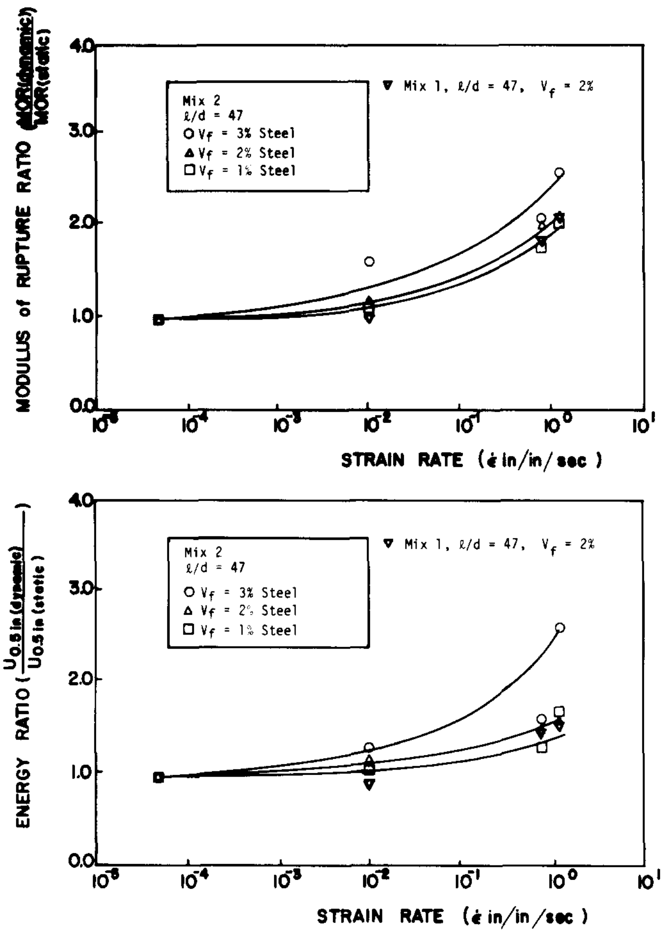

Figure 11 **Normalised modulus of rupture and energy absorbed versus strain rate (series SP6, SP9 and SP12)**

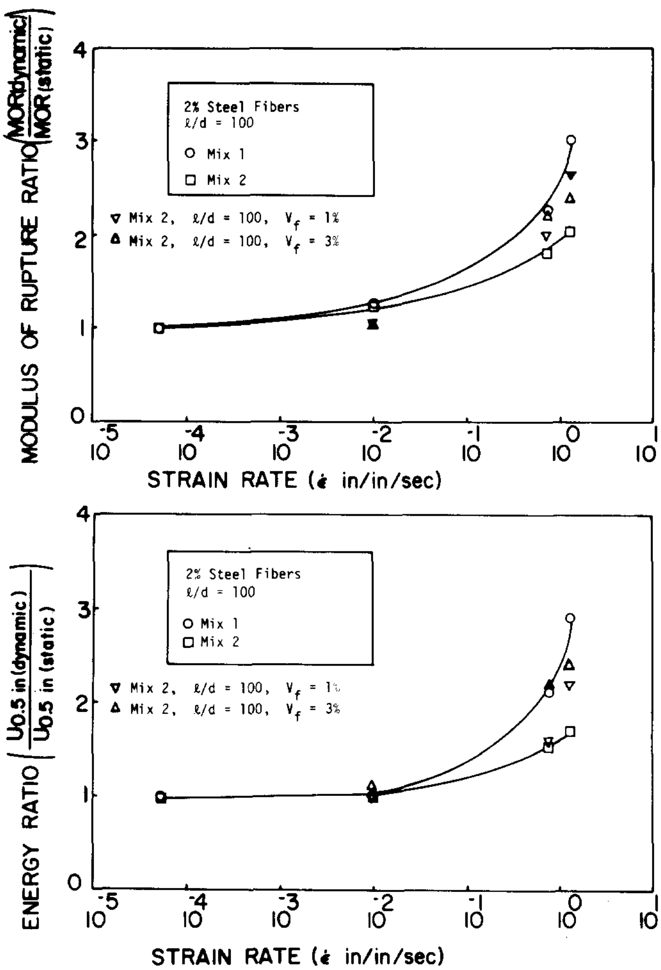

Figure 12 **Normalised modulus of rupture and energy absorbed versus strain rate for two different mortar mixes**

For strain rates between 5×10^{-5} and 0.01 strain/second:

$$(\gamma_f)^* = 5.2 + 2.95\, V_f \frac{\ell^2}{\phi},\ \text{lb in/in}^2 \qquad (1)$$

$$(\gamma_f)^* = 912 + 20.3\, V_f \frac{\ell^2}{\phi},\ \text{Nm/mm}^2$$

For strain rates between 0.8 and 1.2 strain/second:

$$(\gamma_f)^* = 5.5 + 8.55\, V_f \frac{\ell^2}{\phi},\ \text{lb in/in}^2 \qquad (2)$$

$$(\gamma_f)^* = 962 + 59\, V_f \frac{\ell^2}{\phi},\ \text{Nm/mm}^2$$

These equations are valid for $(V_f(\ell^2/\phi))$ ranging from 0.35 to 3 in (9 to 76 mm).

An observation is in order. The surface energy γ_m of the unreinforced mortar matrix at the static loading rate was found equal to about 0.22 lb in/in^2 (38 Nm/mm^2). The intercepts of Equations (1) and (2) which correspond theoretically to an unreinforced matrix $(V_f(\ell^2/\phi) = 0)$ suggest surface energies substantially higher than γ_m. This suggests that the mere presence of the fibres even in very small volumes tend to dramatically increase the energy absorbing capacity of the composite. It also explains why the addition of fibres to concrete in very small volumes (0.1 to 0.5%) is found effective in applications such as piles.

CONCLUSIONS

Based on the results obtained in this investigation, the following conclusions can be drawn.

1. Reliable material behaviour in form of continuous load-deflection records without parasitic inertial effects can be successfully obtained for steel fibre reinforced concrete at reasonably high rates of loading ($\dot{\epsilon} \leq 1.5$ strain/second).

2. The equivalent bond strength of the fibres, their volume fraction and aspect ratio influence the behaviour of the composite at dynamic rates of loading in a manner similar to that at static loading rates.

3. The higher the volume fraction of fibres and the higher their aspect ratio the more sensitive is the composite to the rate of loading.

4. Unreinforced mortar matrices showed a surface energy to failure in bending of the order of 0.22 lb-in/in^2 (38 N m/mm^2) at static rates of loading. At similar loading rates mortar matrices reinforced with smooth steel fibres showed an equivalent surface energy (up to 0.5 in (12.5 mm) deflection) in the range of 5.8 lb-in/in^2 to 32.6 lb-in/in^2 (998 N m/mm^2 – 5631 N m/mm^2) for volume fraction of fibres ranging from 1% to 3% and fibre aspect ratios ranging from 47 to 100.

5. Everything else being equal, a three-fold increase in composite flexural strength and energy absorption can be expected when the strain rate varies from 5×10^{-5} strain/second to 1.2 strain/second.

6. Composites made from weaker matrices exhibit a higher sensitivity to loading rate than those made with stronger matrices.

7. The increase in composite flexural strength and energy absorbed with loading rates is attributed primarily to the strain rate sensitivity of both the matrix and the pull-out resistance of the fibres. As in an earlier study [11] frictional bond was found to show little sensitivity to strain rate, the increase in fibre pull-out resistance is believed to be due to the strain sensitivity of the fibre and the mechanical components of bond. For smooth fibres the bearing of the fibres not aligned with the direction of loading and plastic bending of the fibres during pull out are considered equivalent to mechanical bond components.

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