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Effect of Fiber Modulus of Elasticity on the Long Term Properties of Micro-fiber Reinforced Cementitious Composites

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Abstract

Fibers for reinforcing cementitious composites are typically short and randomly dispersed in the matrix. Consequently, most of the fibers are inclined to the cracks that develop in the cement matrix and suffer from bending stress as these cracks open. For brittle fibers, such as carbon fibers, the bending stress may lead to flexural fiber rupture before the fiber attains its full capacity in direct tension. As a result, the efficiency of these fibers may be reduced. This phenomenon is not expected to occur in ductile fibers, which can yield locally rather than rupture. Predictions of a theoretical model show that the bending stress increases as the matrix becomes denser and stiffer (an event which occurs as the matrix ages or due to the addition of silica-fume) and decreases for fibers of lower modulus of elasticity. Therefore, a reduction in strength with time in composites with dense matrices is expected for very brittle fibers of high modulus, moderate or no reduction for low modulus brittle fibers, and no reduction in strength is expected for ductile fibers. The long term properties of cementitious composites reinforced with various microfibers was studied to validate the model; PAN and Pitch type carbon fibers represented brittle fibers of high and low modulus, respectively; polypropylene and polyacrylonitrile fibers represented ductile fibers. The results showed good agreement with the theoretical model. © 1997 Elsevier Science Limited

INTRODUCTION

The use of fibers to improve the properties of a cement based matrix has been known for many years. Lately, new developments in the fiber industry have led to the production of low cost carbon fibers. Generally speaking, two types of carbon fibers are produced, distinguished by their precursors: PAN type, based on polyacrylonitrile fiber; and Pitch type, based on petroleum and coal tar pitch. Generally, the PAN types are of high strength and modulus (1·68–3·16 and 186–517 GPa, respectively[1]) and also of high price. On the other hand, the Pitch type is of low strength and modulus (0·50–0·70 and 25–40 GPa, respectively) and relatively low cost. New techniques enable the production of Pitch type fiber at a wide range of strength and modulus values (0·59–2·76 and 28–830 GPa, respectively), but at higher price.

A previous study by Katz and Bentur[2] showed a reduction of up to 65% in the long term properties (strength and toughness) of CFRC (carbon fiber reinforced cements) reinforced by PAN type carbon fibers. The reduction in properties was greater for dense cementitious matrices aged in hot water (60°C) for a period of 230 days. This reduction in properties was attributed by Katz and Bentur[3] to the brittle nature of the carbon fiber, which tends to fail in flexure as it bends when the inclined fiber bridges over a matrix crack (see

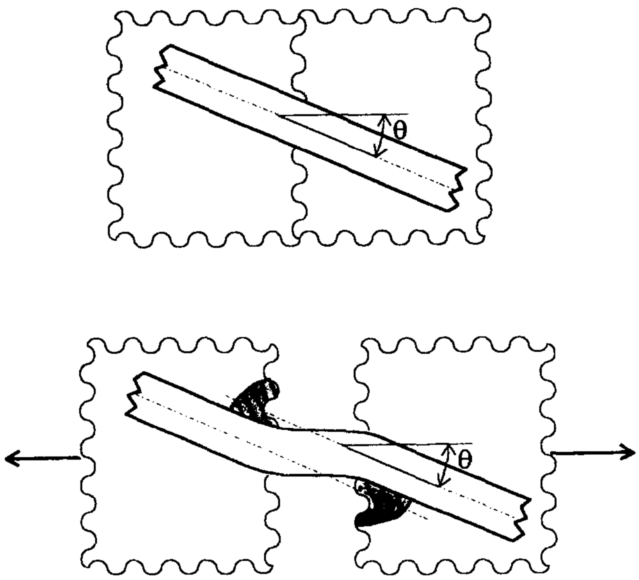

Fig. 1. Bending of inclined fiber bridging over a crack.

Fig. 1). In a dense matrix, the flexural stresses can be sufficiently high to lead to a premature failure of the fiber, before it attains its full capacity in direct tension.

According to Aveston *et al.*[4] the bending stress in inclined brittle fibers (such as glass and carbon) may cause a local increase in the fiber stress by a factor of up to 7–15 times the direct tensile stress of the aligned fiber. However, local yielding or crumbling of the matrix in the compressive zone around the fiber (the shaded area in Fig. 1) can reduce the bending stress. Recent research on modeling and calculation of the bending stress as a function of fiber and matrix properties has been reported by Katz,[5] Katz and Bentur[3] and Leung and Li[6] for brittle fibers in a brittle matrix. These models simulate the fiber as a cantilever beam laid on a foundation. Katz and Bentur[3] treated the fiber as a short beam laid on a foundation of plastic nature as Morton and Groves[7] assumed previously for ductile fibers, while Leung and Li[6] treated the fiber as a continuous beam on an elastic foundation, as discussed by Timoshenko,[8] taking into the calculations the case of a foundation of non-uniform stiffness and matrix spalling.

In spite of the differences between the models, the effect of the matrix seems to be the same: increasing the matrix strength and stiffness increases the bending stress in the fiber, leading to early failure of the fiber in bending, and to a general reduction in the composite properties. Katz and Bentur[3] used this model to explain the relatively low strength and toughness of PAN type CFRC of dense matrices. Matrices of such characteristics are obtained when silica-fume is present or when extended aging has occurred.

The extent of fiber breakage in bending was attributed to the properties of both matrix and fiber. Previous work[3] dealt only with the influence of matrix changes. The purpose of this paper is to study experimentally and theoretically the effect of fiber modulus of elasticity (E_f) and its failure mode (i.e. brittle vs ductile) on the long term properties of micro-fiber reinforced cementitious composites.

EXPERIMENTAL STUDY

In practice, there is rarely a situation where only one parameter, the modulus of elasticity, is changed. Production techniques adjusted for obtaining fibers of different properties (even for similar fiber composition) may lead at the same time to changes in fiber diameter, ultimate strength, ductility, bond, etc. In order to explore the significance of the model predictions discussed here, experimental tests were carried out with different types of micro-fibers as follows.

Materials

Four different micro-fibers were tested: two of them were carbon fibers which might be considered relatively brittle and two polymeric ductile fibers. Fiber properties are listed in Table 1.

Two matrices of water to binder (cement+silica-fume) ratio 0·40 were prepared: (a) ordinary paste without silica-fume; and (b) dense matrix where 21% of the cement was replaced by silica-fume. High dosage of superplasticizer (5% by weight of the binder) was used for all the composites. Fiber content was 6% by volume for all types of fibers, except for the Pitch type carbon fiber where only a maximum of 3·2% could be added without affecting the workability of the fresh mix. For comparison, another mix of 3·0% volume fraction of PAN type carbon fibers was also prepared.

Testing procedures

All the ingredients were mixed in a Hubart mixer. The matrix was prepared first and the fibers were gradually added into it.

Table 1. Fiber type and properties

Fiber type	*Abbreviation*	*Tensile strength (MPa)*	*Modulus of elasticity (GPa)*	*Strain capacity (%)*	*Diameter (μm)*	*Length (mm)*	*Volume fraction (%)*
Carbon (PAN)	C-PAN	2900	230	1·4	6·8	6	6
Carbon (Pitch)	C-Pitch	590	30	2	18	6	3·2
Polyacrylonitrile	PAN	570	13·5	13	16	6	6
Polypropylene†	PP	500	5	20	23	6	6

†Mono-filament.

Plates of 140 × 120 × 10 mm were prepared and kept sealed for 2 days until they were demolded. After demolding, the specimens were placed in water at 20°C for another day, and then moved to a hot water bath of 60°C until the testing day. This aging method was found to be satisfactory as it allows a great portion of the pore structure to develop under normal temperature,[9] whereas the aging temperature is sufficiently high to accelerate further development of hydration products, without drastically changing their nature. This aging temperature is recommended by the international standards (ISO/DIS 8366—Testing of Fiber Cement Flat Sheet, 1991).

On the testing day, the plate was saw-cut into six small beams of 20 × 10 × 120 mm. Each beam was tested in a four points bending test and the deflection at the center was monitored. The testing ages were 3, 7, 14, 56 and 120 days. After testing, the specimens were dried in an oven at 105°C for SEM (Scanning Electron Microscope) studies.

THEORETICAL MODEL

The theoretical model describing the bending stresses developed in a fiber is presented elsewhere.[3] A brief description of the model precedes the theoretical analyzis of the effect of fiber modulus on the composite strength.

Based on Morton and Groves[7] model, the problem of fiber bridging a matrix crack can be considered as a symmetric problem, as can be seen in Fig. 2(a). Therefore, the fiber can be divided into two separate parts. Each part of the fiber is then simulated as a cantilever beam, protruding out of the matrix at an angle θ (Fig. 2(b)). A bending load F is applied at the fiber end, in order to bend the fiber by a displacement δ, back to the midpoint, where it meets the other half of the fiber.

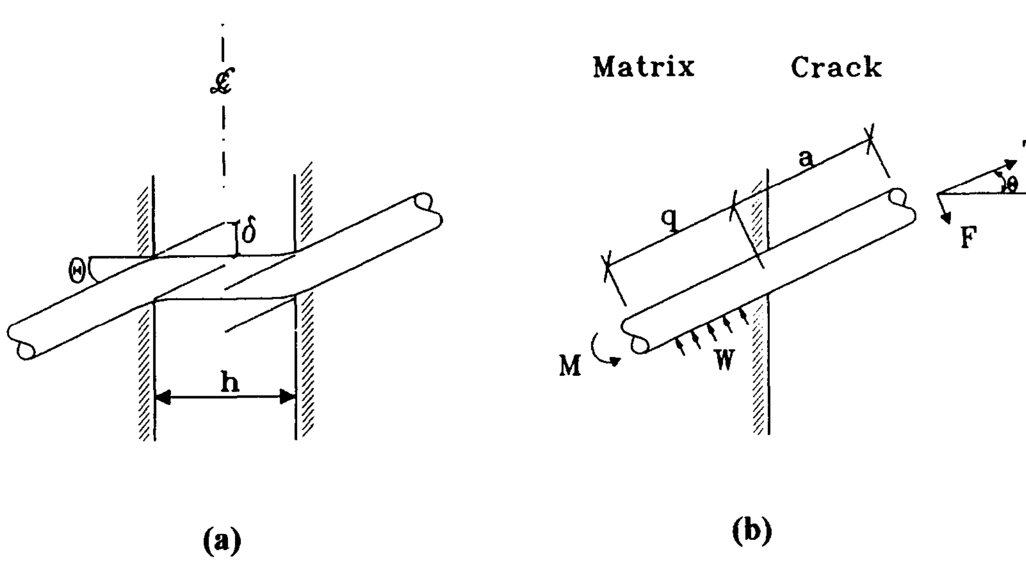

Fig. 2. A model to describe the bending of an inclined fiber.

The maximum bending stress σ_b developed in the fiber is given by:

$$\sigma_b = E_f \frac{\frac{1}{2} d\delta\left(a+\frac{1}{2}q\right)}{\frac{1}{3}(a+q)^3 - \frac{1}{8}q^3 - \frac{1}{6}q^2 a} \quad (1)$$

where:

E_f = fiber modulus of elasticity
d = fiber diameter
q = length of support
a = parameter which includes the following geometric parameters: u (crack width), θ (inclination angle), d (fiber diameter); $a = 0{\cdot}5u\cos\theta + 0{\cdot}5d\tan\theta$
$\delta = 0{\cdot}5u\tan\theta$

These parameters are shown in Fig. 2(b) which describes the general approach to the problem. The length of support q was shown to be a matrix parameter which is essentially related to its hardness: for a strong and stiff matrix, the value of length of support q is small, and it becomes larger for softer and weaker matrices.

It can be seen from eqn (1) that the fiber bending stress is proportional to the modulus of elasticity of the fiber; increasing the modulus will result in an increase in the bending stress. Generally in bending of beams, the flexural stress is proportional to the beam's EI product (I = moment of inertia). Thus, for a given fiber diameter and fiber deformation, an increase in the flexural stress with the increase in modulus of elasticity is expected.

The effect of matrix strength (represented by variation in the length of support q) on the bending stress as derived from the model is presented in Fig. 3 for particular crack width and fiber parameters, and for different fiber inclination angles.

By limiting the bending stress to the fiber strength (the dotted line in Fig. 3), it is possible to determine the angle at which fiber bending fracture occurs θ_b for a certain crack width. The active fiber fraction (AFF), defined as the fraction of fibers which do not break and continue to support bridging loads, was determined as the relative fraction of fibers inclined at angles smaller than θ_b. The fiber volume fraction multiplied by the AFF represents the actual active fiber fraction in the composite at any

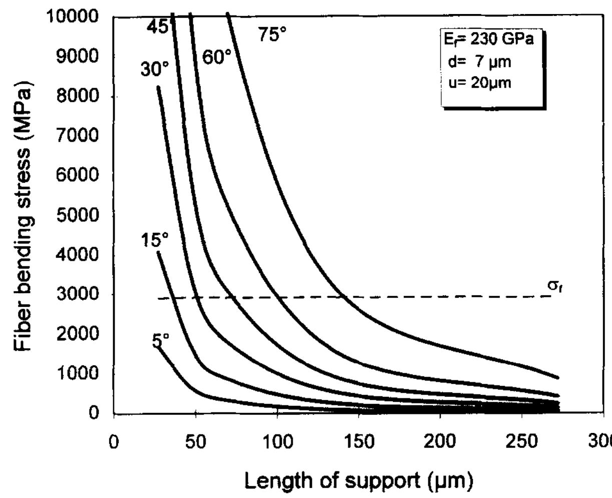

Fig. 3. Effect of length of support (matrix strength) on fiber bending stress for different inclination angles.

given conditions of fiber and matrix properties and crack width:

$$\text{AFF} = \frac{\theta_b}{\pi/2} \quad (2)$$

Figure 4 represents the effect of the length of support on the breakage angle and AFF value, for a micro-fiber with diameter of 7 μm, for a wide range of fiber modulus. In the calculations of the curves in this figure it was assumed that other parameters, such as crack width and fiber diameter remain constant.

As the length of support is related to matrix properties, Fig. 4 represents the effects of both matrix and fiber stiffness. For the same matrix, the use of fiber having high modulus results in a

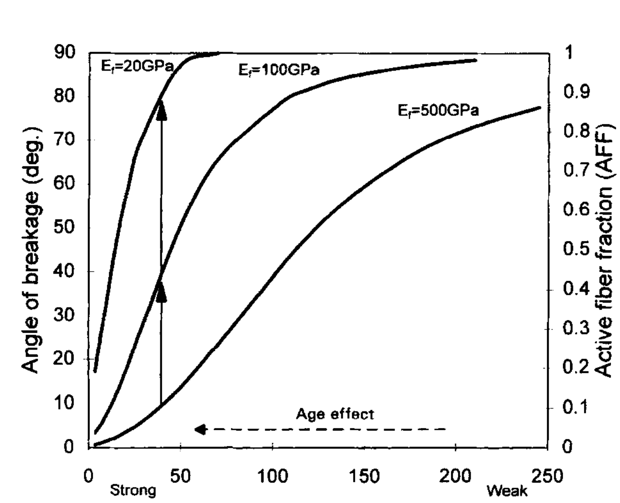

Fig. 4. Effect of matrix stiffness (represented by the length of support) on the breakage angle of the fiber, θ_b, and AFF.

low AFF value, thus leading to a low composite strength and toughness. Replacing the fibers with fibers of low modulus (the solid arrow in Fig. 4) may increase the efficiency of the fibers in the composite, by increasing the AFF, leading to a better composite. Changing the matrix from a weak one to a strong one, as may happen with time or by the effect of silica-fume incorporation, may lead to a reduction in the AFF and consequently to a reduction in the composite properties (the dashed arrow in Fig. 4).

In order to evaluate the effect of changes in the fiber modulus of elasticity on the composite strength, test results of the development of flexural strength (Fig. 5) published elsewhere[3] were analyzed analytically for new values of fiber modulus. Figure 5 presents the original results together with the analysis. Two opposing mechanisms were identified and analyzed: (i) increase in bond strength with time (represented by a thin line in Fig. 5); and (ii) reduction in the AFF with time (represented by a thin line in the figure). The combined effect (the thick line, AM, in the figure) is of an initial increase in the composite strength at an early age and a reduction thereafter, as indicated by the test results marked in Fig. 5.

Evaluation of the effect of changes in the fiber modulus of elasticity on the development of the composite strength, can be done by calculating new AFF–q relationships for different values of fiber modulus, using eqn (1). Based on the test results and the model analysis which is presented in Fig. 5, new values for the AFF were calculated for three levels of fiber modulus: $0{\cdot}1E_f$, E_f and $2E_f$, where $E_f = 230$ GPa (the modulus of the tested fibers). The combined influence of increase in bond (assuming the same development of bond for the three cases) and reduction in AFF was calculated again for the new AFF values and the results are presented in Fig. 6.

Also presented in Fig. 6 is a curve for a system with ductile fibers where it can be assumed that AFF = 1, i.e. the fiber is free to bend without being accompanied by flexural rupture.

Analysis of the AFF–q relationships for fibers of low modulus of elasticity showed that the reduction in the AFF with time is very small, and thus, a composite reinforced with this kind of micro-fiber may not show a reduction in properties with time, or just a moderate reduction (see Fig. 6). This can explain the small reduction of only 10% in flexural strength observed by Akihama *et al.*[10] for composite reinforced with Pitch type carbon fibers ($E_f = 37$ GPa) cured in hot water for 5 months, while the reduction in strength of PAN type carbon fibers composites, reported by Katz and Bentur[2] ($E_f = 230$ GPa), was of up to 65% after curing in hot water for 7 months.

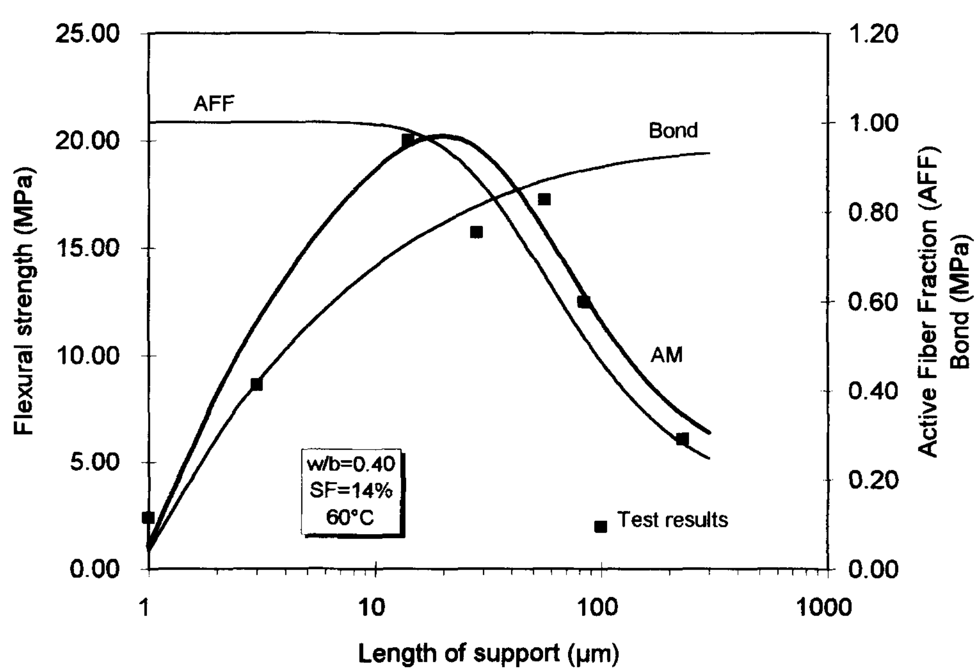

Fig. 5. Test results of the influence of aging on flexural strength and calculated curves of changes in bond and AFF factors together with the calculated flexural strength based on the combined changes of these two.

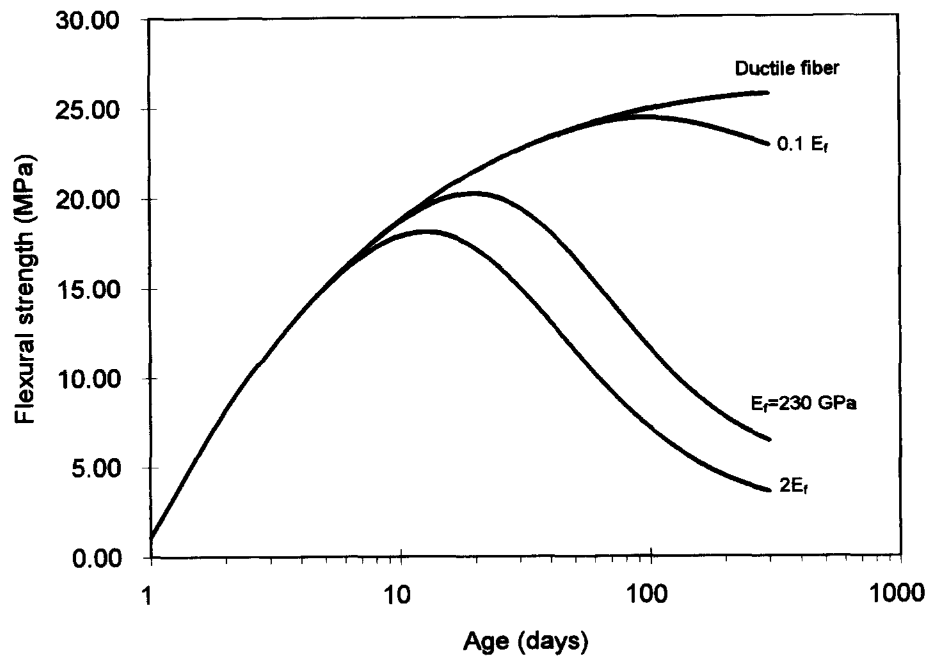

Fig. 6. Predictions of the age effect on the flexural strength of a composite reinforced with brittle micro-fibers of different modulus and a ductile micro-fiber.

Using fibers of high modulus increases the bending stress in the fiber at any time, leading to greater fiber rupture and a reduction in the AFF. More fibers break in bending and, thus, less fibers are available to support the load, leading to a composite of lower strength, as presented in Fig. 6.

For ductile fibers, no bending breakage is expected, and the composite strength is likely to develop with time without any reduction, as known for most of the ductile fibers used today (Hannant[11] and Khajira *et al.*[12]).

RESULTS AND DISCUSSION

Load–deflection behavior

Typical load–deflection curves for each micro-fiber type at the age of 8 weeks are presented in Figs 7(a)–(d) for 0 and 21% silica fume matrices.

It can be seen from Fig. 7 that C-PAN, C-Pitch and PAN specimens exhibited peak load at a deflection of 0·3–0·7 mm, with a reduction thereafter. The drop of loads at the postpeak zone was rapid for the C-PAN composite and moderate for the C-Pitch and PAN composites. The polypropylene specimens, though, maintained the maximum load for larger deflections exhibiting more ductility. Analysis of the effect of silica-fume showed rapid drop of loads for the C-PAN fibers at the post-peak zone when silica-fume was used; better ductility both in the pre-peak and post-peak zone was observed for the C-Pitch and polyacrylonitrile fibers with no significant change in the peak load; and a better first crack load behavior was observed for the polypropylene fibers composites when silica-fume was used.

The changes in the shape of the load–deflection curves of the C-PAN fibers composites as a result of the use with silica-fume (Fig. 7(a)) can be attributed to the change in fiber–matrix interaction due to stiffening of the matrix. This leads to more fiber rupture in bending as the cracks open, resulting in a rapid reduction in the load bearing capacity of the composite at the post peak zone. This effect was not observed for the other types of fibers and in some cases (Figs 7(b) and 7(c)), a better post-peak behavior was observed, probably due to a better fiber–matrix bond.

SEM observations

SEM observations were made on the fractured surfaces of the specimens and the results are presented in Fig. 8 for the silica-fume matrices. The differences in the lengths at which the various fibers protrude out of the matrix can be clearly seen. For the PAN type carbon fibers (C-PAN), the protruded length is relatively short and it becomes longer for the Pitch type carbon and polyacrylonitrile fibers, respectively (note the scale differences between the micrographs). This trend reflects possible differences in the mode of failure of these fibers; when the mode of failure of the fibers is mainly of bending, the observed protrusion length is short, as fiber rupture occurs close to the crack; when the mode of failure turns to be of pullout and tension failure, the protrusion length can be up to half the fiber length, thus longer fibers will be seen protruding from the fractured surface.

Age effect

Curves describing the effect of age on the flexural strength of the composites are shown in Fig. 9. Composites of 0% silica-fume content are presented Fig. 9(a), and composites of 21% silica-fume are presented in Fig. 9(b). Similar trends were also seen for the toughness (the area under the load–deflection curves). It seems that for composites of 0% silica-fume content the initial strength at 3 days was relatively high and the strength increased gradually with time for all the composites. For the dense matrix specimens containing silica-fume, a rapid increase of the strength was observed at an early age for all specimens. At later ages, a reduction of 30% after 56 days of aging was noted for the composite of the PAN type carbon fiber (C-PAN) while the strength of the other composites changed only slightly.

It seems that the pozzolanic reaction of the silica-fume in the composite was activated rapidly due to the high curing temperature, leading to high strength at 7 days and almost no change thereafter for most of the composites. The behavior of the C-PAN carbon fiber composite is different from the others. In these composites, a reduction in strength occurred after 7 days, probably due to the fiber bending breakage discussed and predicted by the theoretical model and previous results. As also

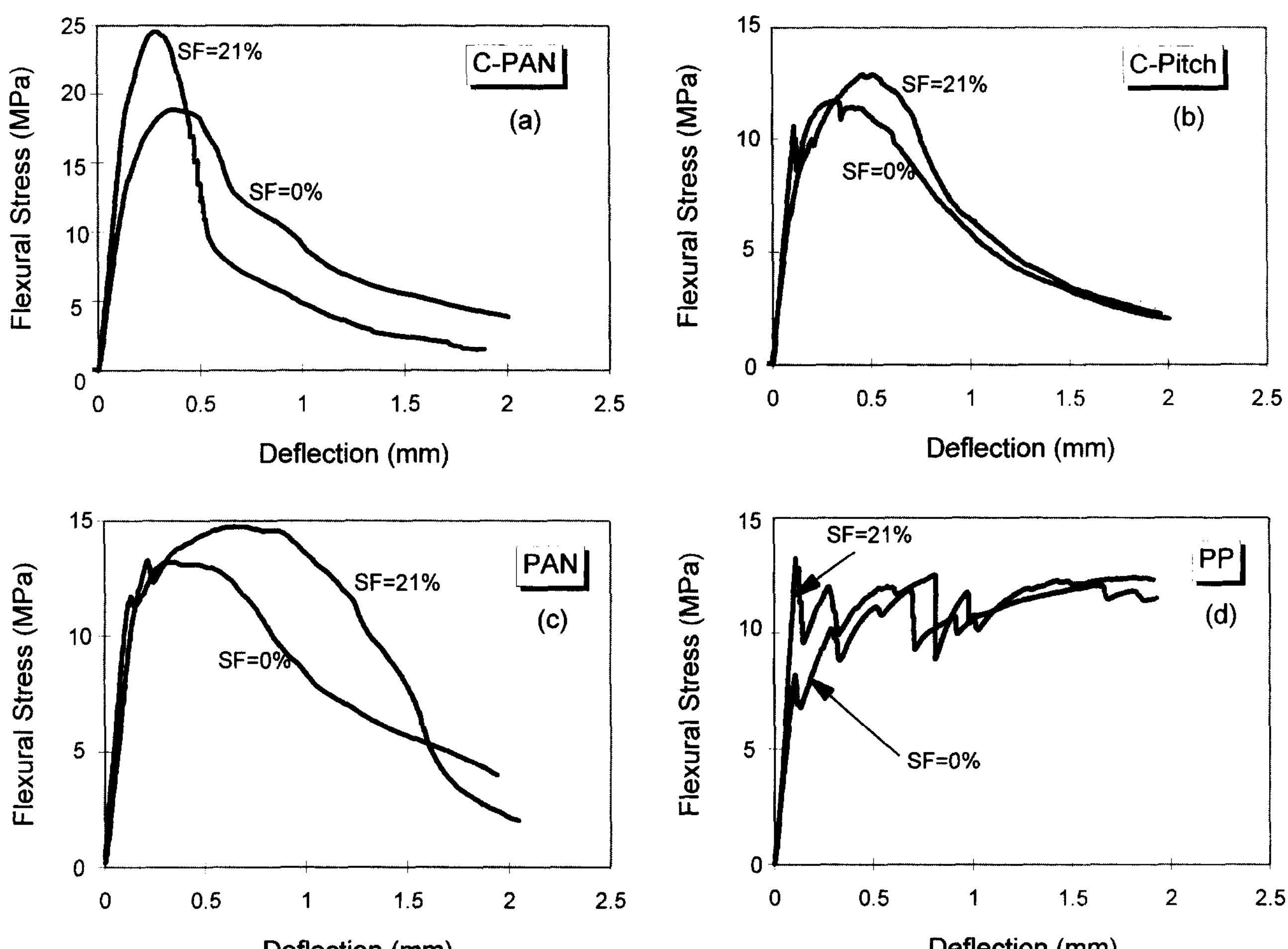

Fig. 7. Typical load–deflection curves for different fibers at matrices of 0 and 21% silica-fume, at 56 days: (a) PAN type carbon fiber; (b) Pitch type carbon fiber; (c) polyacrylonitrile fiber; and (d) polypropylene fiber.

Fig. 8. SEM micrographs of the fracture surface of matrices reinforced with: (a) PAN type carbon; (b) Pitch type carbon; and (c) polyacrylonitrile fibers.

predicted from the model (Fig. 6), the low modulus carbon fiber did not show signs of strength reduction as did the high modulus carbon fibers.

For the composites containing ductile fibers (polyacrylonitrile and polypropylene), no reduction in strength with time was predicted (Fig. 6), and none was observed in practice (Fig. 9).

A possible mechanism for the composite strength loss may be related to a deterioration of either the matrix or the fibers. However, it is noted that strength reduction in time was observed only for the C-PAN composite of high silica-fume content, while no reduction was observed for the other composites. This indicates that the strength reduction in time which was observed for the C-PAN composite cannot be related to any deterioration of the fiber or the matrix but only to the changes in fiber–matrix interaction described before.

Efficiency of the fibers

The presence of local flexure (i.e. reduction in the AFF values) may not necessarily show up as an overall reduction in strength, if fiber ultimate

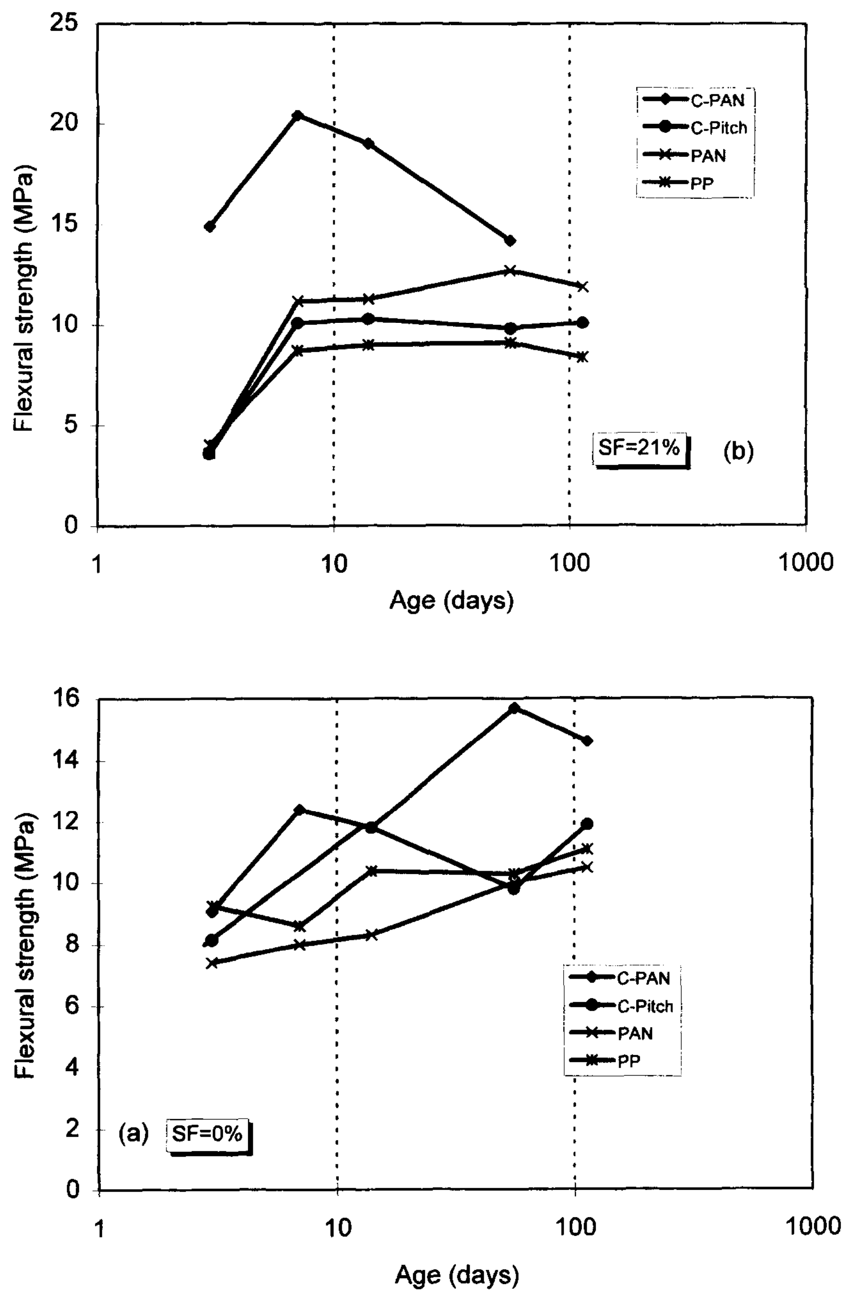

Fig. 9. Development of flexural strength of composites of 0 (a) and 21% of silica-fume (b) reinforced with the tested fibers.

strength is high enough to override the effect of strength loss due to fiber bending rupture. This effect may show up when calculating the efficiency factor, as defined commonly by eqn (3):

$$K = \frac{\sigma_c}{\sigma_f V_f} \quad (3)$$

Where σ_c and σ_f are the strength of the composite and the fibers, respectively, V_f is the fiber volume fracture and K is the efficiency factor which includes the effects of fiber orientation, fiber length and AFF. It was shown by Laws[13] that eqn (3) is applicable for analyzing the flexural strength of the composite.

The efficiency factor for the different fibers tested here was calculated for the 14 days flexural strength of the various composites, and the results are shown in Fig. 10. Included in Fig. 10 is additional data for C-PAN fiber composite having 3% fiber volume, which is similar to that of the composites with C-Pitch fiber. The efficiency factor of the 6% C-PAN composite is somewhat lower than the value obtained for the composite prepared with the same type of fiber but at lower fiber volume of 3%. Probably due to the adverse effect of increasing fiber volume, which damages the composite's properties at high fiber volumes.

It is interesting to note that the efficiency factors of the C-PAN composites were considerably lower, relative to the other fibers (at both fiber loads). This may be accounted for by the high local flexural stress predicted to be present in the fibers of this system, which inhibits the development of high tensile stress as a result of premature failure in bending rather than in direct tension as for the other fibers.

The somewhat lower values for the polymeric fibers compared to C-Pitch fibers might be the result of the higher fiber loads (6% compared with 3·2%) which lower the efficiency factors as discussed before for the C-PAN fibers, or lower fiber–matrix bond as is known for these fibers.[14] Yet, despite the high fiber load and the possible reduced bond, the efficiency factor of the polymeric fibers was much higher than the C-PAN fibers at both fiber loads, suggesting a continuous bridging of the crack as it opens, unlike the behavior of the brittle fiber.

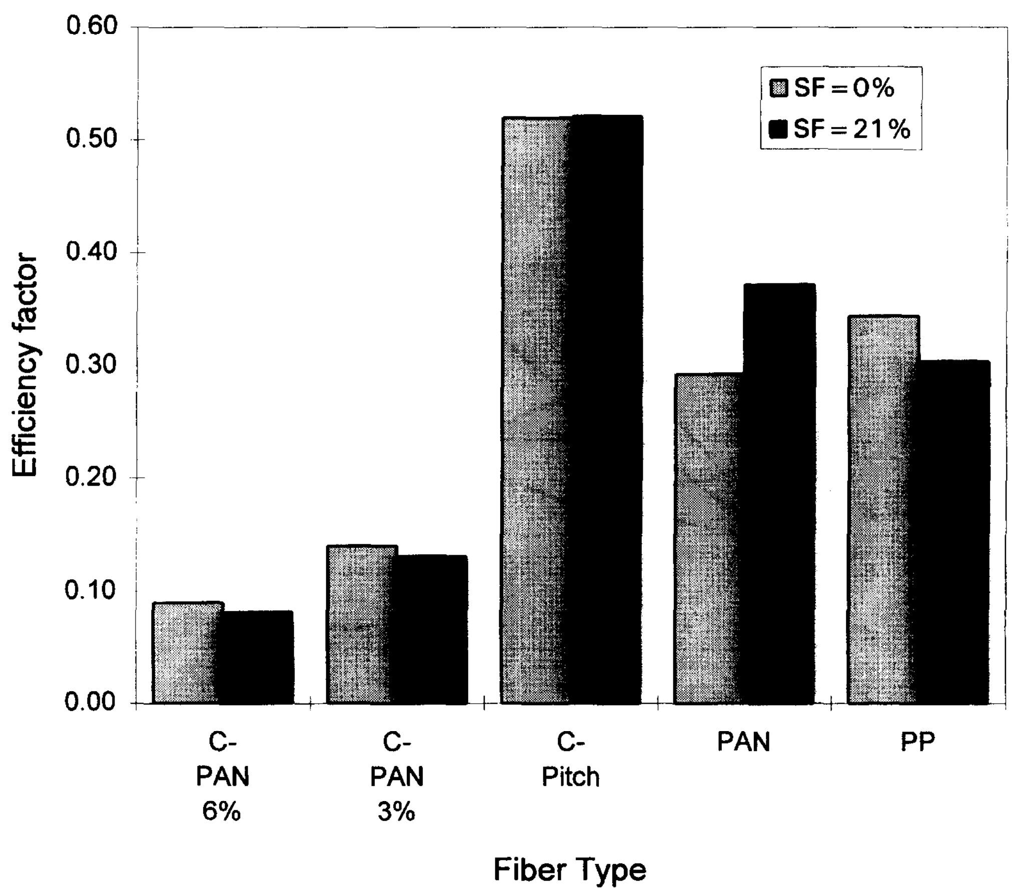

Fig. 10. The efficiency factor of the various composites at the age of 14 days.

CONCLUSIONS

Brittle micro-fibers might be significantly sensitive to bending failure which may be generated when brittle inclined fibers bridge over a matrix crack.

The extent of fiber bending failure depends on the fiber and matrix properties. An increase in the fiber modulus of elasticity may increase the bending stress developed in the fiber, leading to its premature breakage. An analytical model was developed to predict the extent of the bending rupture and its effect on the overall composite strength, taking into account changes in the fiber modulus and matrix stiffness, as it changes with age or by the addition of silica-fume.

The model was compared successfully with test results showing a marked reduction with time in the flexural strength of high modulus PAN type carbon fiber reinforcing a dense matrix of 21% silica-fume content. The reduction in flexural strength of the same matrix reinforced with low modulus Pitch type carbon fiber was small and can be considered negligible, and no reduction at all was observed for ductile polyacrylonitrile and polypropylene fibers.

Calculation of the efficiency factors of the composites, before decline in strength occurred, showed high values for the Pitch type carbon fiber, moderate values for the polymeric fibers and low values for the PAN type carbon fibers. This is attributed to the presence of local flexure in the latter.

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