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Fibre–matrix Adhesion in Fibre Reinforced CAC-MDF Composites

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Abstract

Macro-defect-free (MDF) cements are cement–polymer mixtures characterised by high tensile and flexural strengths. The use of fibres in the MDF cementitious matrices can further improve their mechanical properties. This paper covers a study of the adhesion between steel, polyethylene (PE) and polyvinylalcohol (PVA) fibres and calcium aluminate cement (HAC) MDF pastes. Properly processed, single fibre MDF samples were subjected to pull-out tests in order to estimate the interfacial shear stress between the fibre and the matrix. The analysis of the resulting pull-out curves for the three fibre–cement matrix pairs has also been performed, yielding interface strength values for fibre–cement interface. Among the polyethylene, polyvinylalcohol and steel fibres used for this study, the first ones turned out to be most promising to improve toughness and impact performance of CAC-MDF matrices. © 1997 Elsevier Science Ltd.

Keywords: MDF cement, fibres, pull-out tests, bonds strength, steel fibres, synthetic fibres, toughness.

NOMENCLATURE

L	embedded fibre length in pull-out test
ΔL	variation of the embedded fibre length
l_c	critical length in pull-out test
d	fibre diameter
λ	fibre perimeter
τ	interfacial shear stress
τ_{fu}	frictional shear stress
τ_{au}	adhesional shear bond stress
τ_{av}	average shear stress
P	pull-out load
P_{fu}	ultimate fibre load
P_A	maximum elastic load
P_M	maximum load
P_F	load at the debonding beginning
P_B	max pull-out load
Δ	pull-out displacement
σ_{fu}	ultimate tensile strength
σ_u	ultimate flexural strength

INTRODUCTION

The steady interest in cement-based materials is due to their widespread availability, low cost and recycling. Moreover, recent studies have showed that some mechanical properties of the cement paste, i.e. Young's modulus (E) and ultimate strength (σ_u), can be highly improved if the size of the residual pores or other macro defects were reduced. The addition of small amounts of certain polymers modifies rheological properties of the cement based paste, allowing their processing under high shear stresses, reduces the entrainment of air in the mixture so leading to macro-defect-free (MDF) cement composites.[1,2] The CAC-MDF have flexural strength of about 150 MPa and Young's modulus of about 40 GPa and are suitable for the production of laminates. Further improvement of both ultimate flexural strength and toughness of CAC-MDF matrix can be obtained by addition of inorganic or organic fibres to the paste. In every case, the fibre–cement matrix interface plays a determining role in enhancing strength and/or toughness: in fact the stresses acting on the matrix are transferred to the fibre across the interface. The fibre–cement adhesion is a very important factor: stiffness is enhanced by a strong bond at interfaces and an embedded length (L) to critical length ratio L/l_c much higher than 1, whereas weak interfacial bond and $L/l_c = 1$ are preferred to improve toughness.[3]

In order to improve toughness and impact performance, the MDF-cement, like other brittle matrices, can be reinforced by short fibres, the choice of which is dramatically dependent on the nature and strength of fibre–matrix interface. A pull-out test on a single-fibre-containing specimen provides an evaluation of debonding and pull-out processes and an estimation of interfacial parameters, from which the critical length (l_c), an important technological parameter, can be calculated.

In this paper the pull-out test results of MDF pastes containing a single fibre are reported. The results have been analysed according to the different theoretical approaches available in literature. Different kinds of fibre have been investigated such as polyethylene (PE), polyvinylalcohol (PVA) and steel. In addition, CAC-MDF composites containing short fibres were prepared and their flexural strength, modulus and fracture toughness were examined.

EXPERIMENTAL PART

Materials and specimens

The MDF material was produced premixing in a Hobart mixer calcium aluminate cement (Secar 71), Polyvinylalcohol–acetate polymer, glycerine and H_2O in 1/0.07/0.007/0.12 weight ratios, respectively. The mixture was then compounded in a twin roll mill and finally laminated. After this, the material could be cut in 50 × 100 mm strips. All the prepared samples underwent a pressing step at 80°C for 10 min and then the MDF sheets were cured in an oven at the same temperature for 24 h.

In order to obtain composite samples, the mixture composition was modified by adding short fibres and increasing the water–cement (w/c) ratio up to 0.14. The w/c ratio was increased for recovering the workability loss of the paste, caused by the addition of the fibres. Longer fibres could be incorporated in the cement paste during the calendering stage. The main properties of the fibres used for preparing the samples are illustrated in Table 1.

Specimens for pull-out tests were obtained by using a steel mold represented in Fig. 1, which allows fibre alignment during preparation. A monofilament fibre could be interposed between two fresh strips of MDF paste placed in the mold. In all the specimens the fibre extended across the matrix, so with both its ends emerging from it. After curing, the sheets were cut using a circular diamond saw to prepare specimens with different embedded lengths of the single fibre. As observed under the scanning electron microscope (SEM), the MDF paste surrounds the fibre perfectly.

Testing

Pull-out tests were carried out on monofilament fibre specimens by means of an INSTRON 4502 testing machine at a constant rate of cross-head travel of 1 mm/min. The fibre diameters were measured by SEM observations of pullout tested samples. Among the PVA fibres only the RF 350, as not available as monofilament, could not be used for pull-out tests.

Table 1. Main properties of the fibres

Fibres	*Diameter (mm)*	*Density (g/cm³)*	*Tensile strength (MPa)*	*Elastic modulas (GPa)*
PE (Spectra A-900)	0.04	0.97	2580	117
Steel (Fibraflex)	(*)	7.2	2000	140
PVA (RF350)	0.2	1.3	900	29
PVA (RF1500)	0.4	1.3	900	29
PVA (RF4000)	0.6	1.3	900	29

(*) Rectangular section: 1 mm width, 26 μm thickness.

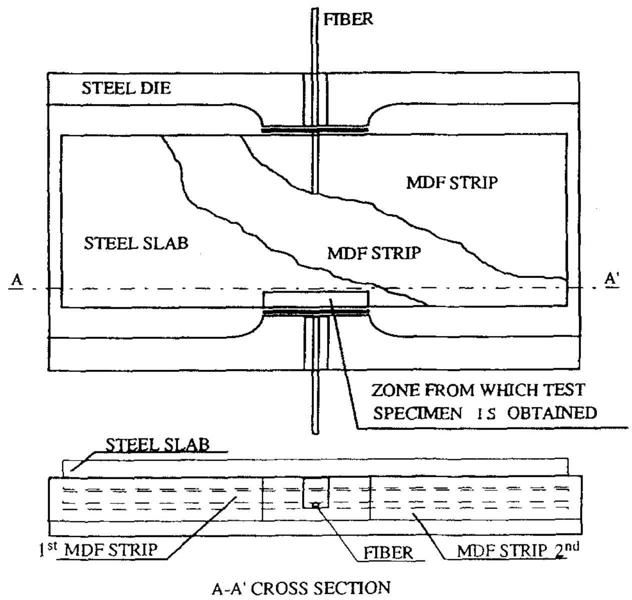

Fig. 1. Scheme of the mold.

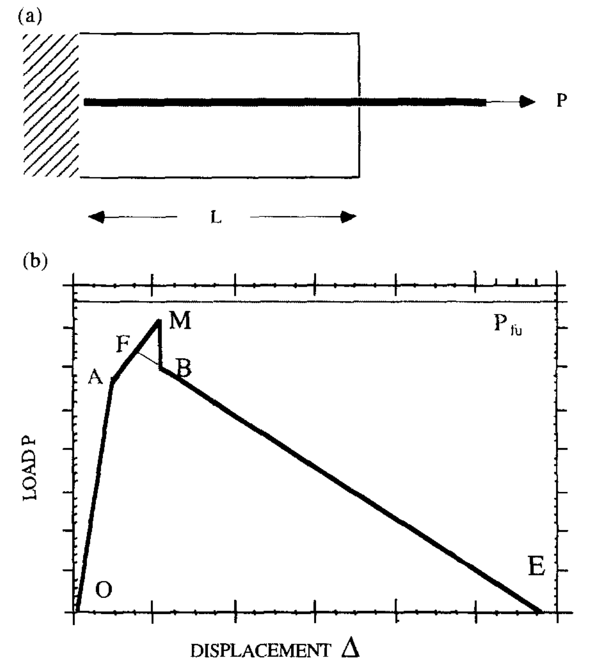

Fig. 2. (a)Pull-out test configuration; (b) typical pull-out load vs displacement relationship.

Before measuring the mechanical properties of fibre CAC-MDF composites, the samples were ground and dry-polished. Flexural strengths were determined by using a three point flexural test system (ASTM D-790 M-86) at a loading rate of 1 mm/min. Toughness was evaluated by dividing the area under the load–deflection curve by the nominal volume of specimen. The critical value for the stress intensity factor, K, in mode I was determined on single-edge-notched (SEN) beams (ASTM E 399-83), whereas the work of fracture, R, was calculated by dividing the area under the load–deflection curve by the nominal cross-sectional area of the beam. Unnotched samples were tested on Charpy impact machine with the fixed strain rate of 1.219 m/s.

RESULTS AND DISCUSSION

A typical pull-out test consists in applying a tensile force P to the tip of a fibre embedded over a length L in a MDF cement body according to the configuration depicted in Fig. 2(a). Figure 2(b) shows a theoretical pull-out curve for embedded fibre length $L < l_c$: the length and the slope of different lines, denoted by letters, vary according to the nature of the interface and the fibre embedded length. A monotonic increase in the value of P is accompanied by a displacement Δ at the tip of the fibre and leads to progressive debonding along the fibre–matrix interface. After the debonding begins, a dynamic mechanism of pull-out is observed.

Observing the curve of Fig. 2(b) (pull-out load vs displacement), it can be noted that the area below the ascending part of the curve is smaller than the descending portion: the occurrence of pull-out allows a great amount of energy to be absorbed. The ratio of adhesional shear resistance (τ_{au}) to frictional resistance (τ_{fu}) indicates, for each fibre–matrix pair, the predominant mechanism to dissipate fracture energy and whether the fibre can properly enhance the toughness of the CAC-MDF matrix.

In agreement with Greszczuk's theory,[5] an estimated value of the adhesional shear bond stress, τ_{au}, can be obtained by calculating average interfacial bond shear strength values using the equation $\tau_{av} = (P_M/\lambda L)$ and plotting them vs. the fibre embedment lengths and extrapolating back to $L = 0$ the fitting curve, conforming to the theoretical relationship developed

$$\tau_{av} = \frac{\tau_{au}}{\alpha L \coth \alpha L}$$

According to Bartos,[6] for each specimen failed by fibre pull-out, the maximum pull-out load, P_M, is plotted against the corresponding L. Then the slope of the straight line passing through a proper experimental value P', is equal to the frictional shear flow resistance to slipping at the interface $q_{fu} = P_F/L$. This value can be used in the analysis to calculate $\tau_{fu} = q_{fu}/\lambda$. The variation of P_M as a function of L for each experimental curve and for $L < L_P$, where L_P represents the maximum embedded fibre length at which complete debonding occurs instantaneously, is given by

$$P_M = \frac{\lambda \tau_{au}}{\gamma} \tanh \gamma L$$

and this curve at $L = L_p$ meets the straight line $P_F = \tau_{fu}\lambda L$. After Laws[5] at the point where debonding begins, denoted by letter A in Fig. 2(b), the load is

$$P_A = \frac{\lambda \tau_{au}}{\beta} \tanh(\beta L)$$

and at point where the debonding is finished, B in the Fig. 2(b), the load is

$$P_B = \tau_{fu} \lambda L$$

The expressions of the elastic constant α, γ and β are reported in several papers.[4–6]

The embedment lengths for PE fibres were between 0.70 and 4.5 mm. The specimens with embedment lengths above 2 mm did not show any pull-out and the fibres broke even if the load was lower than the failure load of a free single fibre. The fibres actually deteriorate because of surface defects produced under pressure at 80°C of the curing first stage of the micro-composites. The pull-out curves generally showed the expected shape of Fig. 2(b), although in some cases the first deviation from linearity was marked and in other cases it could not be so easily detected. After the maximum load (the value averaged out to 0.5 N) was reached, there was a slight drop of the load and then a more gradual decrease with apparently constant pull-out load. Actually, the details of this region reveal the occurrence of a phenomenon called 'stick-slip' relating to polymeric fibres protruded from an elastic matrix.[7] That phenomenon was also confirmed by SEM observation of the surface of a pulled-out fibre, the micrograph of which is reported in Fig. 3. The PE fibre withdrawn from the matrix has a waved external surface due to the frictional mechanism of the extraction.

Fig. 3. SEM micrograph of a PE fibre after extraction.

The pull-out curves for steel fibres in MDF cement were very similar to those showed by PE ones: also in this case the curves generally exhibited the 'progressive' failure pattern after the point related to maximum load. The embedment lengths varied between 1 and 2.3 mm and all the specimens showed pull-out with maximum load increasing from 23.3 up to 47.5 N, depending on the fibre length in the matrix. The realistic l_c value is likely to be higher than the superior limit of embedment length range used during the tests. However, compared with PE and PVA fibres, much research effort has not been devoted to study steel-CAC-MDF cement system. One of the reasons was that the steel fibres are not interesting from the practical point of view as reinforcement for the CAC-MDF matrix due to the difficulty to disperse them in MDF cement during the calendering process.

PVA RF 4000 fibres had embedment lengths from 0.4 up to 5 mm and the measured maximum pull-out loads increased accordingly from 12 up to 128 N. The typical pull-out test curve of PVA fibre-containing specimens is given in Fig. 4. The pull-out load increases linearly, with fibre displacement, up to the maximum applied load, then abruptly falls suggesting a catastrophic debonding has occurred. After that, the load does not decrease progressively, but with force fluctuations. This kind of pull-out curve is typically shown by a single fibre microcomposite in which strong chemical bonds occurred at the fibre–matrix interface, so that the elastic bond exceeds the frictional bond.[7] Also the SEM

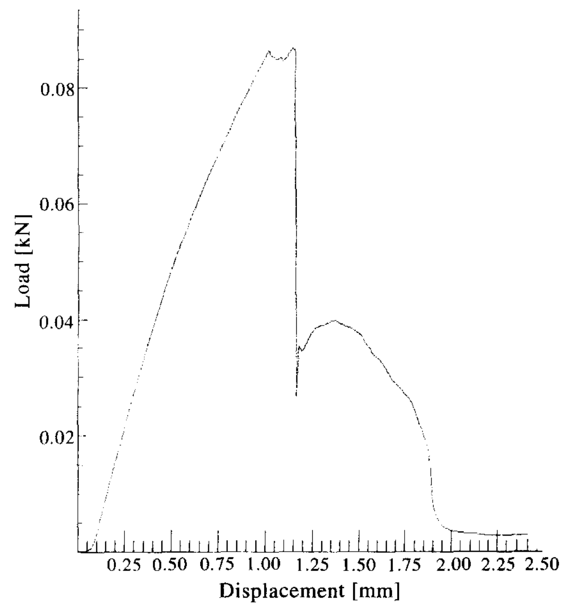

Fig. 4. Typical pull-out test curve for PVA fibres.

micrograph (Fig. 5), which shows a PVA fibre severely delaminated at the previous embedded ending after the extraction, suggests a strong interfacial bond. In fact, given that failure always occurs in the weakest point through which load is transferred between the matrix and fibre, in this case the failure is shifted to the fibres in proximity of the interface, as the fibre–matrix bond strength is greater than the fibre shear strength. In a few cases cement matrix on fibres pulled through the specimens observed. The existence of cross-linking bonds involving PVA chains, already considered a relevant aspect of MDF cement, could be the most likely explanation for these findings. As reported by Young *et al.*[8] when calcium aluminate cement is used the $Al(OH)_4^-$ ions are

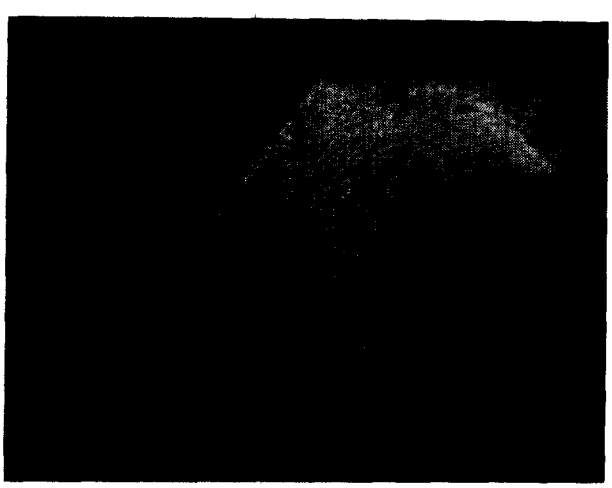

Fig. 5. SEM micrograph of a PVA fibre after extraction.

present and they can be involved in a cross-linking reaction with PVA chains as schematically reported in Fig. 6. The strong adhesion between fibre and matrix must determine a great quota of the interfacial shear resistence to debonding, as a consequence the τ_{au} value was expected to be far greater than τ_{fu}.

In Table 2 a summary of the interfacial parameters calculated from the experimental pull-out data of tested specimens containing different fibres is reported. For all the fibres some differences can be observed in the interfacial bond strength values calculated using various theories. It can be noticed that, even if the pull-out curves analyses provided a few discrepancies among the results, the bond strength values are affected by the method of analysis employed. All mathematical models of pull-out processes, developed for an idealised single fibre microcomposite, introduce simplifying assumptions that do not hold in the real material, even to a first approximation. In addition, specimens used for pull-out tests had fibres with too short embedment lengths, so a large uncertainity could affect the results. Another source of uncertainty was the difficulty in fixing exactly the characteristic points A, F, M, B, as in Fig. 2(b), and determining the corresponding load values as required for the application of the different methods. As an example, for pull-out curves of PVA and steel fibres, the P_A and P_F loads were calculated as 0.8 and $0.9\,P_M$, respectively. Moreover, the peculiar features of the pull-out curves of specimens containing PVA fibres made these calculations useless to provide indisputable results. Furthermore, as reported before, the τ_{au} and τ_{fu} parameters are not indeed related to the interface fibre–cement, but to that where the actual failure took place. Anyway, the τ_{au} value of 35 (MPa) for these fibres, as obtained through application of the Greszczuk' method, seems low to justify the findings. Among the values calculated with the different models, more realistic values of τ_{fu} and τ_{au} were obtained after the models of Laws and Bartos (see Table 2).

As for evaluation of the critical fibre length l_c, the interfacial bond strength values calculated from Laws' method were used for each fibre–matrix pair. The value of l_c corresponds to the minimum length of fibre, such that it will break rather than pull-out from the matrix. If

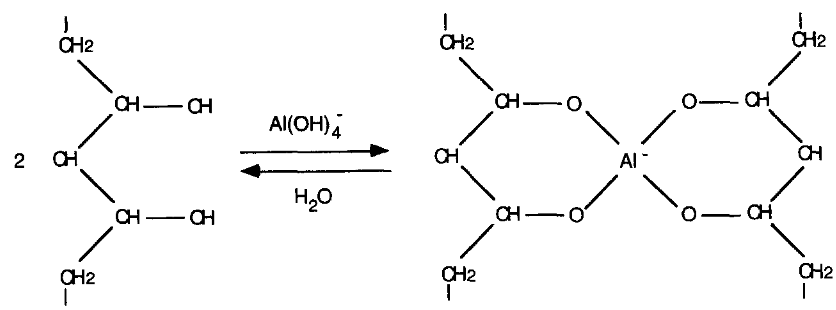

Fig. 6. Proposed cross-linking scheme for PVA fibres in a CAC-MDF cement (adapted from ref.[8]).

the frictional mechanism is prevalent, l_c is given[6] by:

$$l_c = \frac{\sigma_{fu}.\mathrm{d}}{2\tau_{fu}} \quad (1)$$

If the adhesional mechanism prevails and $l_c \geq x_{max}$, it ought to use the following eqn[6]:

$$l_c = \frac{1}{\lambda\tau_{fu}}\left(\sigma_{fu}A_f + \lambda\tau_{fu}x_{max} - \frac{\lambda\tau_{au}}{\beta}\tanh\beta x_{max}\right) \quad (2)$$

$$\text{where } x_{max} = \frac{1}{\beta}\cosh^{-1}\sqrt{\frac{\tau_{au}}{\tau_{fu}}}$$

In all the studied cases it verifies $l_c \geq x_{max}$. The σ_{fu} value for embedded fibre, depending upon the test conditions as on thermal treatments at which fibre underwent, was properly measured. Differently from the steel fibres, PE and PVA deteriorate during the specimens preparation and have σ_{fu} values of 995 and 500 MPa, respectively, far lower than those of integer fibres. The l_c for all fibres were calculated using eqn (2) and reported in Table 2. Such values do not fit the experimental results, except for PE fibres. Nevertheless, the l_c values as obtained from pull-out cannot be considered those in the composite, owing to the large differences existing between the single fibre configuration and the multi-fibre containing matrix. Actually also τ_{av} could be used to obtain a rough l_c value from eqn (1), provided τ_{av} is a sufficiently good estimate of τ_{fu}. In all the cases we studied, τ_{av} and τ_{fu} values proved to be the same within the experimental error, even when very short fibre lengths were used. Moreover the τ_{fu} calculated for each fibre–matrix pair using Bartos' and Laws' analysis do not show an appreciable differences. Rough l_c values of 6.5, 5, 3 and 2.7 mm were obtained using eqn (1) for PVA RF 4000, PVA RF 1500, steel and PE fibres, respectively. These results are in accordance with the experimental results and the important role the frictional bond plays in improving the composite properties like toughness. On the other hand the frictional bond, even being the more effective parameter in determining the energy to break of a composite, could be calculated just at the earlier stage of the fibre pull-out. The shape of the pull-out curves after P_{max} depends on the τ_{fu} changes during the slipping of the fibre and had shown

Table 2. Summary of calculated interfacial bond strength values*

Analytical method		Grezczuk	Bartos		Laws		
Fibres	τ_{av} (s.d.)	τ_{au}	τ_{fu} (s.d.)	τ_{au} (s.d.)	τ_{fu} (s.d.)	τ_{au} (s.d.)	l_c (mm)
PE	5(1)	13	4(1)	49(5)	4(1)	47(7)	2.1
STEEL (FIBREFLEX)	12(4)	40	11(3)	36(4)	9(3)	57(6)	1.9
PVA RF4000	19(4)	35	16(4)	80(17)	12(2)	129(26)	3.7
PVA RF 1500	19(4)	–	–	–	12(5)	101(9)	2.8

*The values are expressed in MPa.
(s.d.) standard deviation.

that the frictional bond strength is fairly constant in the PE fibres, unless the smallest changes that give the stick-slip phenomenon.

Table 3 summarizes the results of the flexural and impact tests performed on several composites with short randomly-arranged fibres. The fibres used to prepare the samples were PVA RF 350, PVA RF 1500 and PE SPECTRA A-900. In the last two cases the fibre lengths were much longer than the estimated l_c. PE fibres, being available as continuous monofilament, were cut into 12 mm long pieces, whereas the PVA 350 and 1500 fibres were available as short fibres 15 and 30 mm long, respectively.

Great effort was made in order to study PVA CAC-MDF system also in relation to volume percentage, due to their large availability and low cost. The values given in Table 3 indicate that the isotropic response of CAC-MDF is lost if PVA fibres are added. The results of the tests performed on PVA fibres composites depend on the volume percentage of the fibres and the orientation of the specimen with respect to the calendering direction of the composite paste. The Young's modulus decreases with increasing fibres' fraction, even though the E value of PVA fibres is rather similar to that of an MDF paste. Actually, the fibres are supposed to deteriorate in the composites because of water adsorption, so that their Young's modulus drop to an extent which is not immediately valuable.

As for 3% vol. RF 350 PVA fibres containing mix, a slight increase of the E value was recorded (Fig. 7b). This finding cannot be explained clearly. It could be suggested the MDF matrix of this composites batch was stiffer than the MDF paste used for comparison. In that case, a more noticeable decrease for E could be recorded and accounted for the larger surface area of RF350 PVA fibres available for water adsorption.

Figure 7(c,d) shows the flexural strengths obtained from the PVA fibres–CAC MDF composites. The fibre-containing specimens always have lower flexural strengths than that of plain CAC-MDF cement paste, in fact the fibres rising from the surface act like defects rather than a reinforcement. On the other hand, for any mix only a very slight improvement in K_{IC} was recorded and reported in Table 3, indicating the poor resistance to crack initiation of the materials containing PVA fibres. In the literature better improvements were recorded for rather similar materials,[9,10] which did not contain the same sort of fibres as used in the present paper.

Despite the composites containing PVA fibres looking less stress-resistant, the significant change of mechanical behaviour with respect to the CAC-MDF matrix is noteworthy. The typical stress–strain curve recorded for the PVA fibres reinforced CAC MDF composites (see

Table 3. Mechanical properties of HAC-MDF fibre composites

	σ_u(MPa) (s.d.)	E (GPa) (s.d.)	Toughness (mJ/m³) (s.d.)	R (KJ/m²) (s.d.)	K_{Ic}(MPa/m$^{1/2}$) (s.d.)	R_{Charpy} (KJ/m²) (s.d.)
MDF 14L	127(9)	28(2)	33(4)	1.6(0.2)	1.2(0.1)	5.6(0.3)
MDF 14T	119(9)	28(1)	29(4)	1.4(0.2)	1.2(0.2)	6(0.9)
PVA 350L 3%vol	103(2)	32(1)	37(4)	2(0.2)	1.6(0.1)	–
PVA 350T 3%vol	96(7)	31(2)	19(5)	1(0.2)	1.5(0.1)	–
PVA 350L 6%vol	92(3)	27(1)	105(11)	5.2(0.6)	1.8(0.1)	–
PVA 350T 6%vol	80(7)	26(1)	17(5)	2(0.1)	1.4(0.2)	–
PVA 350L 9%vol	94(9)	26(1)	115(8)	6(0.4)	2(0.1)	11(1)
PVA 350T 9%vol	77(9)	24(2)	75(13)	4(1)	1.5(0.1)	–
PVA 350L 12%vol	87(3)	23(1)	149(16)	8(1)	2(0.1)	–
PVA 350T 12%vol	71(4)	23(1)	94(27)	5(1)	2(0.1)	–
PVA 1500L 3%vol	82(4)	27(2)	75(25)	4(1)	1.5(0.3)	–
PVA 1500T 3%vol	77(9)	28(2)	–	–	1.4(0.2)	–
PVA 1500L 6%vol	88(8)	27(2)	68(15)	3(1)	2(0.3)	–
PVA 1500T 6%vol	86(10)	26(1)	61(18)	3(1)	2(0.3)	–
PVA 1500L 9%vol	84(12)	23(3)	227(30)	11(6)	2(0.3)	14(3)
PVA 1500T 9%vol	79(7)	25(2)	96(49)	5(2)	2(1)	–
PVA 1500L 12%vol	86(8)	23(3)	157(31)	8(2)	2(0.3)	–
PVA 1500T 12%vol	76(10)	23(1)	65(31)	–	1.6(0.04)	–
PE T 9% Vol	110(1)	29(1)	325(5)	16(0.3)	–	35(9)

(s.d.) = standard deviation.
the calendering direction of MDF paste.

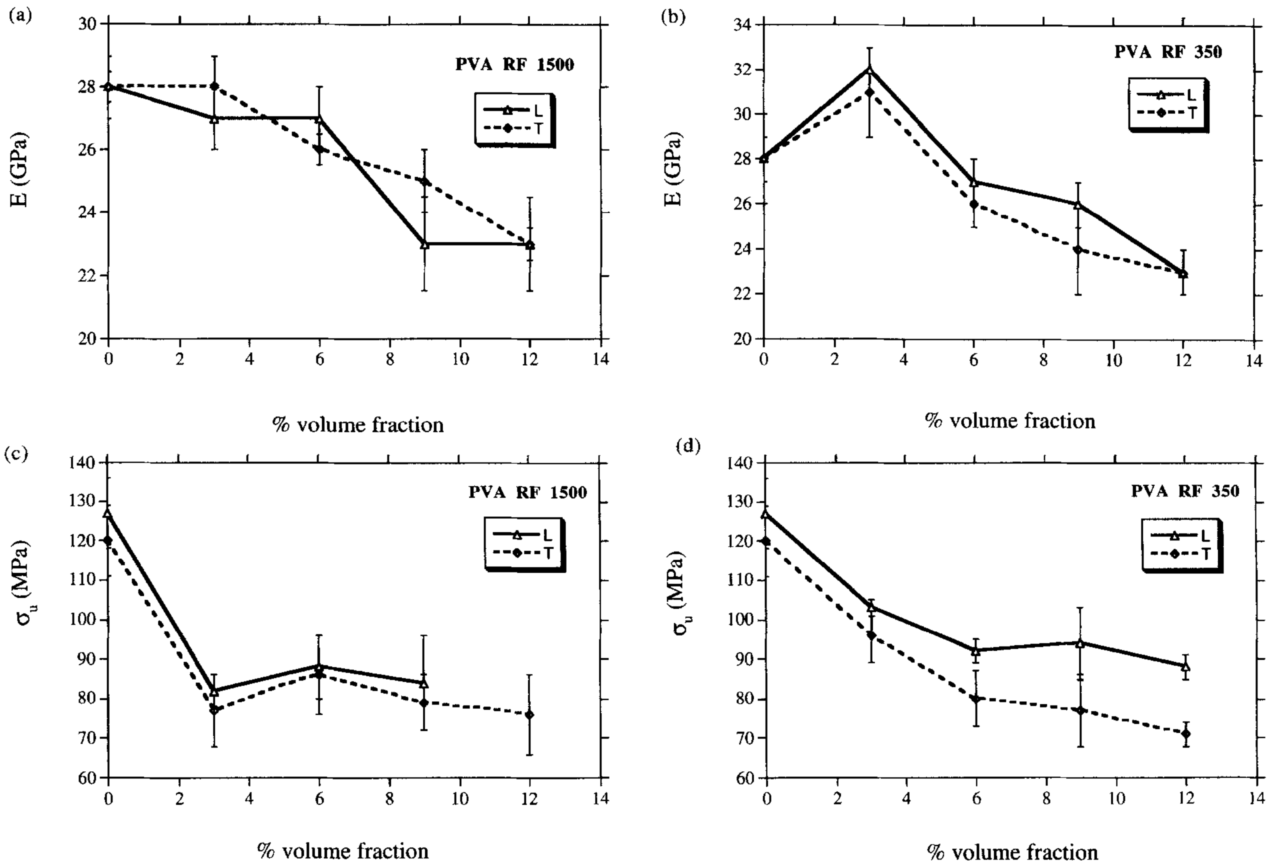

Fig. 7. Young's modulus of PVA RF 1500 (a) and PVA RF 350 (b) fibres — CAC MDF composite; flexural strength, s_u, of PVA RF 1500 (c) and PVA RF 350 (d) fibres-HAC MDF composite.

Fig. 8) denotes a pseudo-ductile behaviour with a great amount of strain after the fracture started. As a consequence, the major effect of the fibres addition is on the toughness, made out as energy per unit volume, on the work of fracture, R, and fracture toughness, K_{IC}. The experimental data demonstrated that the addition of fibres yield improvements for the most produced mix, where the maximum was obtained for the 12 and 9%vol mix, respectively, for RF 350 and RF 1500 PVA samples. Actually the maximum improvements recorded in this study are not as good as data available in literature,[9,10] although the results of the impact energies and fracture work cannot be compared immediately. Moreover, it seems the lengthwise calendering direction mostly takes advantage of the fibres addition, in fact the major improvements of mechanical values were recorded for mixes denoted by the letter L, as indicated in Table 3. This suggests the fibres are arranged according to a preferential orientation, because the calendering process makes them align.

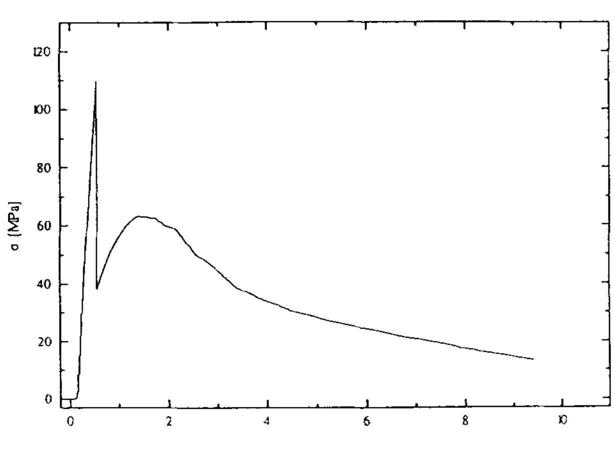

Fig. 8. Typical stress–strain curve for specimens containing PVA fibres tested in flexural mode.

As far as PE fibres are concerned, even though the mechanical properties of just one mix was evaluated, the results indicate that the PE-CAC-MDF composites are promising as structural material. Indeed, a slight increment of the Young's modulus and the maximum improvement of toughness were recorded for a PE fibre composite, without reducing the flexural strength of the non-reinforced matrix. This result is very noticeable and could become even greater, if fibres as long as the estimated values of l_c were used. As mentioned before, the calculation of this technological parameter is open to doubt, since interfacial bond strengths evaluation is a questionable issue. Anyway, the great improvement of toughness of PE fibres–CAC-MDF composite was promoted by the low cohesive bond strength and the constant slipping of the fibre throughout the pull-out. The PVA fibres did not have as interesting interfacial features, showing instead strong adhesion and a rather fast pull-out of the fibres after the debonding had been completed. Surface treatments limiting the reactivity of PVA fibres with the cementitious matrix could let them be accounted for as a good reinforcement.

CONCLUSIONS

Pull-out tests, performed on single-fibre CAC-MDF composites, enabled us to estimate the interfacial bond strengths between PE, PVA and steel fibres and CAC-MDF matrix. Among the theoretical methods used for the analysis of experimental pull-out curves, the Laws' theory appeared the most suitable to calculate realistic values of interfacial parameters, both τ_{fu} and τ_{au}, with a simplified analytical approach. Consequently, only these last values were used to calculate the l_c values.

The incorporation of PE, PVA short fibres into the CAC-MDF matrix brings about a composite material with an enhanced pseudo-ductile behaviour, even though the samples containing PVA fibres have a lower flexural strength. Despite their cost and the unavailability of short fibres, PE fibres are preferable to PVA ones, because of the higher improvement of the toughness, the fracture behaviour and the better *E*/*r* ratio. The PE fibre CAC-MDF composite showed the most relevant improvement of toughness. This could be related to the peculiar features of the PE fiber–cement interface.

REFERENCES

1. Di Maggio, R., Franchini, M., Guerrini, G., Poli, S. & Migliaresi, C., *MDF cement compositions with improved impact strength*, International Patent Publication no: WO96/01234, 18 January 1996.
2. Greszczuk, L. B., ASTM STP 452. American Society for Testing and Materials, Philadelphia, 1969, p. 42.
3. Bartos, P., Analysis of pull-out tests on fibres embedded in brittle matrices. *Journal of Material Science*, **15** (1980) 3122.
4. Gray, R. J., Analysis of the effect of embedded fibre length on fibre debonding and pull-out from an elastic matrix. Part 1 Review of theories. *Journal of Material Science*, **19** (1984) 861.
5. Gray, R. J., Analysis of the effect of embedded fibre length on fibre debonding and pull-out from an elastic matrix. Part 2 Application to a steel fibre–cementitious matrix composite system. *Journal of Material Science*, **19** (1984) 1680.
6. Laws, V., Micromechanical aspects of the fibre–cement bond. *Composites*, **13** (1982) 145.
7. Bartos, P., Review paper: bond in fibre reinforced cements and concretes. *The International Journal of Cement Composites*, **3** (1981) 159.
8. Young, J. F. & Berg, M., Macro-defect-free cement: a novel organoceramic composite. *Material Research Society Symposium Proceedings*, **271** (1992) 609.
9. Alford, N. McN. & Birchall, J. D., Fibre toughening of MDF cement. *Journal of Material Science*, **20** (1985) 37.
10. Park, C. K., Silabee, M. R. & Roy, D. M., Toughening of MDF-OPC composites. *Material Research Society Symposium Proceedings*, **211** (1991) 239.