

LATEX MODIFIED MORTAR REINFORCED WITH PLASTIC FIBRES - SYNERGISTICAL EFFECTS WITH RESPECT TO FRACTURE MECHANICAL PROPERTIES.



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ABSTRACT

Cement mortars (1:3) were reinforced with polyacrylonitrile (PAN) fibers at the dosages 0, $\frac{1}{2}$, 1 and 2 vol% of the mortar. In order to improve the adhesion between the PAN fibres and the cement minerals, 5 % of latexes based on the polymers styrene/butadiene-rubber, poly(vinyl acetate/versatic ester) and poly-(butylacrylate/methylmethacrylate) with a functional monomer capable of forming chemical bonds with the cement minerals were added to the mortars. It was shown directly by SEM-investigations, and indirectly through improvements of mechanical properties, that the adhesion of the fibres to the paste matrix was greatly improved. The best results were obtained with the special designed acrylic latex. However, the latex additions lead to an unusual high air entrainment when used together with the fibres. The latter effect was avoided by addition of extra anti-foamer at the end of the mixing periode.



Key-words: Polymer Cement Concrete, Fibre reinforcement, Latex, Plastic fibres, Interface, Fracture energy.

1. INTRODUCTION

Eventhough plastic fibres have been used for reinforcement in mortars and concrete for several years, the authors are not aware of any studies on the improvement of adhesion between plastic fibres and matrix. One reason may be that plastic fibres in general have been used to avoid plastic shrinkage of concrete /1/, where good adhesion is not needed due to the low forces in action. Other plastic fibres have been fibrillated /2/ in order to achieve better adhesion.

The general idea of this study was that the similarity in molecular structure of the plastic fibres and the polymer in the latex would lead to an intimate contact with strong interactions of van der Waal type bonds. On the other hand, the functional groups, or more sticky character, of the polymer in the latex would in addition secure a good contact with the cement minerals in the inorganic matrix of the PCC. In other words, the latex would act as an adhesion bridge between the plastic fibre and the matrix. Since latex in general is cheaper than fibres, the combination may be beneficial if the interface is improved to such an extent that a lesser amount of fibres is needed in order to obtain the wanted properties of the composite.

2. EXPERIMENTAL

2.1 Materials and mixing procedure

The plastic fibres in this study were made of polyacrylonitrile (PAN) with characteristics as given in Table 1.

Table 1 : Characteristics of PAN-fibres

Parameter	Value
Diameter	104.0 μm
Length	6.0 mm
Cross section	Kindney shaped
Density	1.180 g/cm^3
Tensile strength	410 - 530 MPa
Elongation at break	6 - 9 %
Elasticity modulus	14200 -16500 MPa
Alkali/acid resistance	Very good

The cement was an ordinary Portland cement type, and the composition of the reference mix is given in Table 2. Fibres were added to the reference mix in $\frac{1}{4}$, 1 and 2 vol% of the total mortar volume, while the the latex was added so that 5 vol% polymer replaced an equal volume of cement paste (cement + water). The

water in the latex was included in the w/c-ratio, which was kept constant to 0.50. Two commercial latexes, and an experimental latex as described by Justnes and Dennington /3/, were evaluated. One of the commercial ones was based on a styrene-butadiene rubber, the other on a copolymer of vinyl acetate and versatic ester. The polymer of the experimental latex consisted of a terpolymer made from butyl acrylate, methyl metacrylate and a functional monomer. A naphtalene-formaldehyd based super-plasticizer (SP) was in some cases used to improve the workability.

Table 2: The composition of the reference mortar

Component	Amount
Cement (P30)	19 096 g
Water	9 547 g
Svelvik Sand (2.4 - 4.5 mm)	18 000 g
Svelvik sand (1.0 - 2.0 mm)	18 000 g
Svelvik sand (0.5 - 1.0 mm)	9 000 g
Svelvik sand (0 - 0.5 mm)	9 000 g
Franzefoss Calcite filler	3 600 g

The mixing procedure was one minute mixing of the dry components (except fibre) followed by five minutes mixing where water, latex and fibres were added in the respective order. The mixer was then shut off for five minutes, and then a two minutes mixing periode was carried out before the fresh properties were measured and casting took place. In the mixes with too much air, a silicon based anti-foamer (AF) was added (3 % of the polymer weight) during the last minute of mixing.

2.2 Curing and test methodes

The fresh mixes were tested for slump, flow, density and air-content. Slump was tested analoguous to the Norwegian code NS 3662, but with a cone of height 120 mm, base diameter 80 mm and top diameter 40 mm. Flow was tested according to NS 3664 and measured after 0 and 15 strokes, and given as the increase (%) of the base of the cone. The density was calculated by weighting the net mass of the container (one litre) of the air-measuring device, while the air-content was measured as described in DIN 1164.

The flexural strength was measured on 40·40·160 mm³ prisms (3 parallels) and the compressive strength on the end pieces (6 parallels) according to EN 196. This was done for three different curing schemes in order to monitor the effect of moisture:

Curing scheme I = two days in the mould covered by wet burlap ("dry") and twentysix days at 50% R.H.

Curing scheme II = two days in the mould covered by wet burlap, ("dry-wet-dry") twelve days at 50% R.H., seven days submerged in water and seven days at 50% R.H.

Curing scheme III = two days in the mould covered by wet burlap, ("dry-wet") nineteen days at 50% R.H. and seven days submerged in water

The common period of two days in the mould covered by wet burlap was to ensure good cement hydration. The rest of the curing scheme I was considered to give the best result for the polymer effect according to the principle of film-formation /4/. During the first 14 days of curing scheme I the weight-loss of the prisms were monitored as a measure of retained water. Curing scheme III will determine a possible loss of mechanical properties due to wetting, while curing scheme II will show if a loss of properties is reversible. In curing scheme III the prisms were weighed before and after submerging in water as a measure of water repellency.

The fracture energy was measured on $50 \cdot 50 \cdot 550 \text{ mm}^3$ beams with an experimental set-up as shown in Figure 1. The saw cut notch in the beam was 25 mm deep and 2 mm wide. One half of the beam was clamped between steel plates with rubber inserts. The beam is tested with a upwards force on the free end. This arrangement allows a stable test with load-displacement registration until the fracture is complete. The force working on the end of the beam is registered with a separate load cell, while the displacement is measured by an inductive transducer. Both signals are recorded on an Orion data logger, and are later transferred to a computer for analysis. The area below the load-displacement curve is a measure of the total energy supplied. The energy consumed by the fracture zone is found when the increase in potential of the beam is subtracted from the total recorded energy. The fracture energy is given as the energy consumed in the fracture zone divided by the ligament area. The method is described in detail by Aassved Hansen /6/.

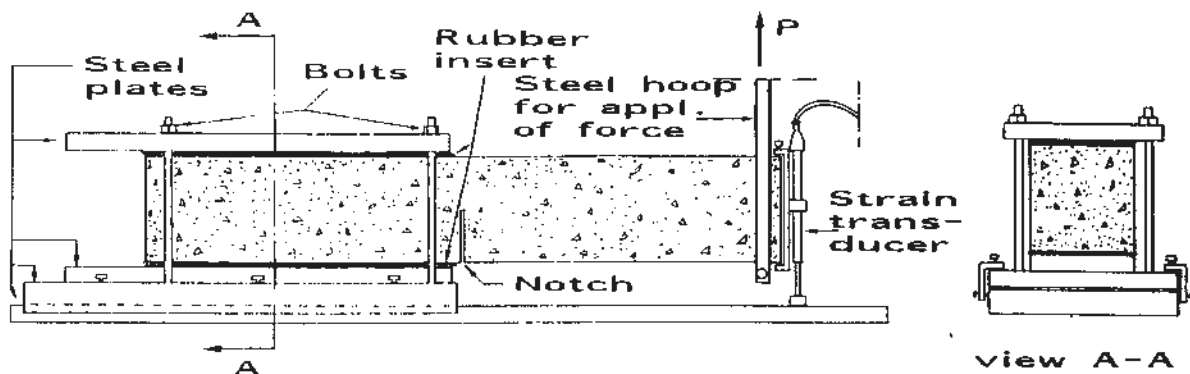


Figure 1 The experimental set-up for fracture energy measurements.

The static modulus of elasticity (E-stat) in compression was measured according to NS 3676 on cylinders of diameter 100 mm and height 280 mm cured according to scheme I. However, there was a slight deviation from the standard since the basis load was 1.25 MPa. The static E-modulus was therefore calculated from 40 % of the fracture load divided by the corresponding deformation.

The dynamic modulus of elasticity (E-dyn) was determined from natural frequency measurements on beams (50·50·550 mm³) in transversal vibrations. These beams had been cured for 25-26 days according to curing scheme I. This is a non-destructive test where the beam is placed on a 50 mm thick layer of foamed rubber (allows free vibrations) and the flexural vibration is induced by the stroke of a hammer. An accelerometer registrates the vertical movement at the end of the beam and the signal is recorded by a digital storage oscilloscope. The wave period is read and the natural frequency determined. The dynamic E-modulus was then calculated according to ASTM C 215-60 (1976), or RILEM recommendation NDT-2,3 (1984):

$$E\text{-dyn} = 0.946 \cdot T \cdot G \cdot f^2 \cdot l^3 / (b \cdot h^3) \text{ [Pa]} \quad (\text{Eq. 1})$$

where T = a correction factor depending on the beam dimensions and the Poisson's ratio (in this case T = 1.05)
G = The mass of the specimen [kg],
f = The fundamental transverse frequency [Hz],
l = length of specimen [m],
b = width of specimen [m] and
h = height of specimen [m].

The direct observations of the interface zone were studied by a JEOL T200 scanning electron microscope on the surface of the fibres in the fracture zone. The samples were coated with gold in order to lead away the electrons.

3 RESULTS

3.1 The fresh mixture

Properties describing the fresh mixture, like slump, flow and density are given in Table 3.

3.2 Mechanical properties for hardened PCC

The flexural and compressive strengths measured on the 40·40·160 mm³ prisms after the curing schemes I, II and III are revealed in Table 4, 5 and 6. The fracture energy (G_F), the compressive strength from cylinders, the static E-modulus (E-stat) and the dynamic E-modulus (E-dyn) are listed in Table 7.

Table 3 : Some properties describing the fresh mixtures.

Code	Fibres (vol%)	Polymer type	SP (%)	AF (%)	Slump (cm)	Flow ¹ (%)	Flow ² (%)	Air (vol%)	Density (g/cm ³)
CTR00	0	None	0	0	4.7	60	180	6.6	2.200
CTR05	0.5	None	.25	0	2.5	20	160	7.6	2.180
CTR10	1.0	None	.50	0	1.5	5	138	9.3	2.121
CTR20	2.0	None	1.0	0	0.0	0	80 ³	6.8	2.174
ACR00	0	PAE ⁵	0	0	9.0	140	250 ⁴	3.3 ⁸	2.124
ACR05L	0.5	PAE	0	3.2	4.8	40	165	8.9	2.110
AGR10L	1.0	PAE	0	3.0	2.5	10	130	7.3	2.165
AGR20L	2.0	PAE	0	3.0	0.0	0	80 ³	3.3	2.207
VAGOOL	0	PVAc ⁶	0	3.0	4.5	20	130	2.9	2.237
VAGO5L	0.5	PVAc	0	3.0	2.0	0	90	4.7	2.222
SBR00L	0	SBR ⁷	0	3.0	8.5	100	190	4.8	2.238
SBR05L	0.5	SBR	0	3.0	4.0	32	155	5.3	2.188

¹Before any strokes with the flow-table. ²After 15 strokes.

³Stiff mix, no cohesion. ⁴Maximum value.

⁵Poly(Butylacrylate/methylmethacrylate with functional monomer.

⁶Poly(vinyl acetate/versatic ester). ⁷Styrene-Butadiene rubber.

⁸Unlikely value. Calculation based on densities gives 8.60 vol%.

Table 4 : Flexural and compressive strength (MPa) of PAN-fibre reinforced cement mortars.

Code	CTR00	CTR05	CTR10	CTR20
Curing scheme I ("Dry")				
Weight (g)	551±4	552±12	532±7	558±4
Flexural	7.7±0.2	7.9±0.4	7.6±0.2 ¹	8.1±0.7
Compressive	45±1	44±1	40±1	51±1
Curing scheme II ("Dry-wet-dry")				
Weight (g)	555±12	562±4	535±2	568±8
Flexural	6.3±0.4	6.6±0.4 ¹	6.4±0.5	7.6±0.6
Compressive	49±2	46±1	44±1	57±2
Curing scheme III ("Dry-wet")				
Weight (g)	581±8	572±4	554±5	588±7
Flexural	6.4±0.6	5.9±0.2	5.8±0.1	7.5±0.2
Compressive	39±3	39±1	37±0	47±0

¹One of three parallels omitted due to very low value.

Table 5 : Flexural and compressive strength (MPa) of PAN-fibre reinforced PCC with 5% PAE-latex.

Code	ACR00	ACR05L	ACR10L	ACR20L
Curing scheme I ("Dry")				
Weight (g)	535±5	533±7	544±3	563±7
Flexural	8.5±0.3	10.1±0.2	10.3±0.3	10.4±0.5
Compressive	39±1	43±1	46±1	54±1
Curing scheme II ("Dry-wet-dry")				
Weight (g)	546±9	549±8	555±8	571±4
Flexural	6.4±0.4	7.2±0.2	7.1±0.7	8.5±0.4
Compressive	40±1	47±1	49±1	56±2
Curing scheme III ("Dry-wet")				
Weight (g)	553±2	556±1	568±1	579±4
Flexural	6.6±0.2	7.0±0.3	7.3±0.3	8.1±0.5
Compressive	35±0	40±0	37±0	47±0

Table 6 : Flexural and compressive strength (MPa) of PAN-fibre reinforced PCC with 5 % PVAc- or SBR-latex.

Code	VAC00L	VAC05L	SBR00L	SBR05L
Curing scheme I ("Dry")				
Weight (g)	566±1	560±9	567±7	557±5
Flexural	8.5±0.2	9.5±0.9	8.4±0.1	7.9±0.2
Compressive	45±0	49±1	45±0	42±1
Curing scheme II ("Dry-wet-dry")				
Weight (g)	568±4	579±9	575±6	553±4
Flexural	5.2±0.2	5.5±0.1	7.0±0.6	6.7±0.2
Compressive	45±1	48±1	47±0	46±1
Curing scheme III ("Dry-wet")				
Weight (g)	582±4	594±7	581±1	573±5
Flexural	6.8±0.5	6.6±0.3	6.6±0.1	6.4±0.3
Compressive	37±1	38±1	40±2	38±2

The retained water of all the PCC's after curing scheme I were 73±1 % of the added water as a measure of drying-out.

Table 7 : Fracture energy [N/m], cylindric compressive strength [MPa], static E-modulus [MPa] and dynamic E-modulus [MPa] for some PAN-fibre reinforced mortars cured according to scheme I.

Code	G _F	Compress.	E-stat	E-dyn
CTR00	40±9	29±0	22060± 80	26900± 300
CTR05	121±16	27±2	21000±1000	26700± 800
CTR10	168±30	27±1	19800± 400	25000±1300
CTR20	345±30	30±3	19800± 300	26800± 400
ACR00	62±5	27±1	18800± 500	23200± 400
ACR05L	167±10	-	-	24500± 500
ACR10L	294±28	-	-	25300± 400
ACR20L	365±40	-	-	26200± 200
VAC00L	59±15	-	-	26900± 800
VAC05L	125±35	-	-	26500± 200
SBR00L	61±13	-	-	27600± 400
SBR05L	163±13	-	-	25400± 100

3.3 Interface between fibre and matrix

The surface of the fibres in the fracture zone for the different PCC were studied by scanning electron microscopy. This was done in order to get an impression of the adhesion of the fibre to the matrix. Pictures of fibres from a PCC containing no latex, 5 % PAE, 5 % PVAc/VeOVA and 5 % SBR are reproduced in Figures 2, 3, 4 and 5, respectively. Note that the fibre from the PCC with 5 % PAE is completely covered by hydration products from the cement paste.

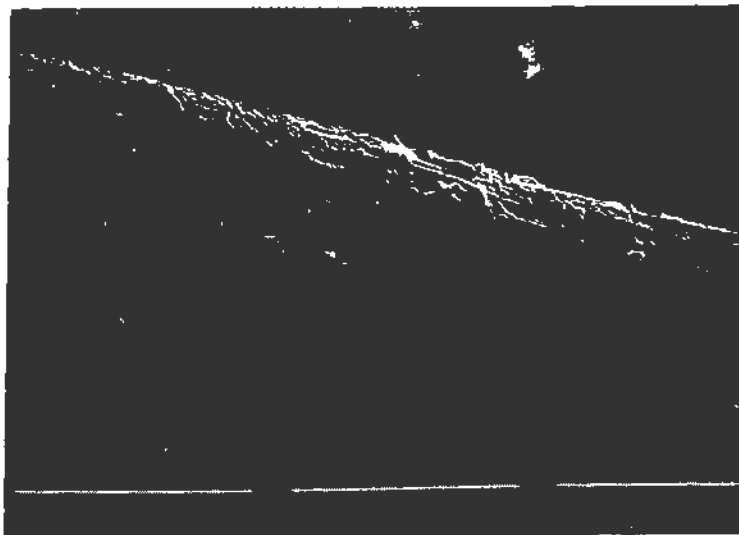


Figure 2. A fibre from a cement mortar without latex (300 x).

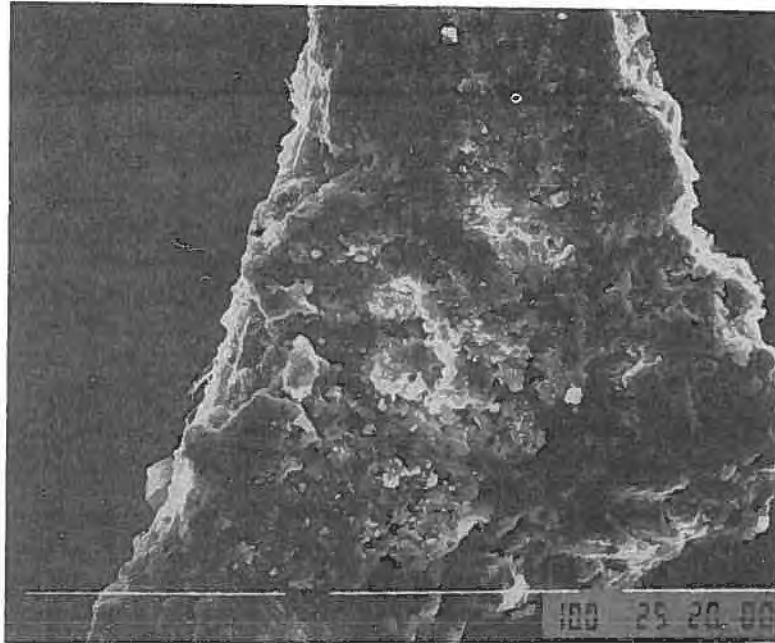


Figure 3. A PAN-fibre from the fracture zone of a PCC based on a PAE-latex with a functional monomer (350x).

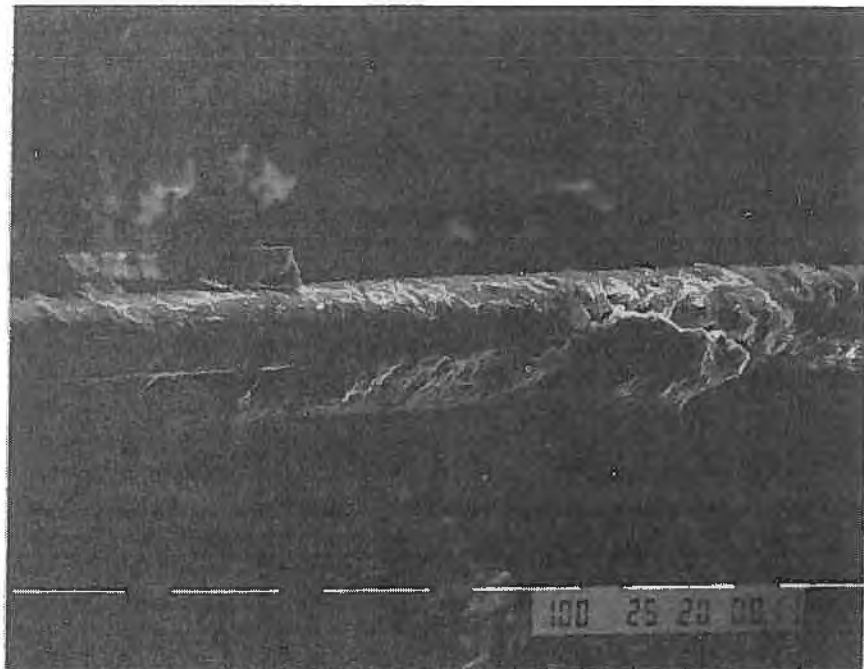


Figure 4. A PAN-fibre from the fracture zone of a PCC based on a PVAc/VeOVa-latex (150 x).

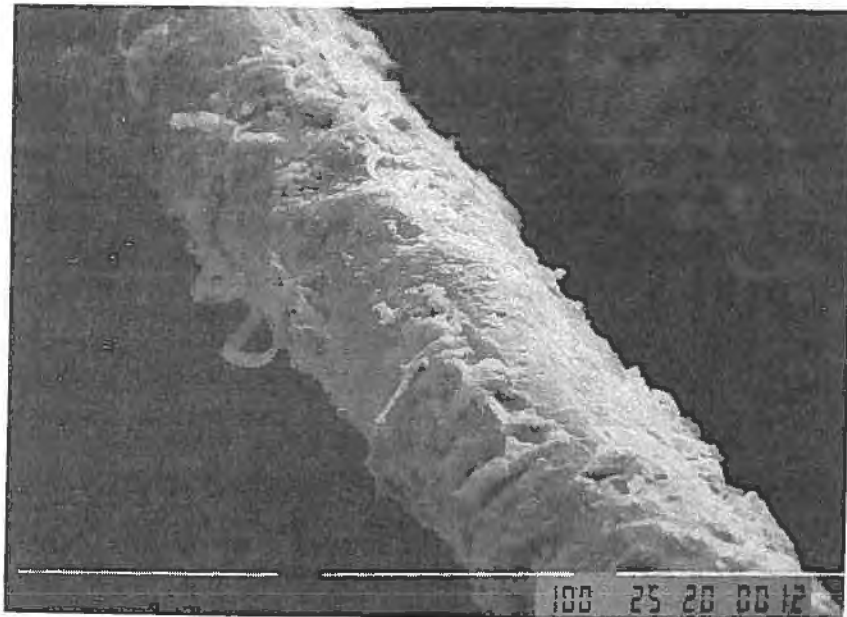


Figure 5. A PAN-fibre from the fracture zone of a PCC based on a SBR-latex (350x).

4. DISCUSSION

Hillerborg /5/ has described how fibre reinforcement do function in a matrix:

- 1) If the adhesion is too good, the fibre will act together with the matrix in such a way that the crack will go through the fibre which will be torn off. The fibres contribution to the fracture energy will then only be the energy absorbed in the fibre fracture area. This energy contribution is negligible in the case of plastic fibres. Thus, an excellent adhesion between fibre and matrix will not lead to any significant increase in the fracture energy of the composite.
- 2) If the adhesion on the other hand is suitable, the fibre will not be torn off, but will instead slide in the matrix. The fibres will then continue to transfer the load even after the crack width has become significant. Due to the consumption of energy when the fibres slide in the matrix, the fracture energy may be multiplied several times compared with the unreinforced matrix (even at small dosages of fibre).
- 3) If the adhesion is too low, the fibres will slip even at low loads. This will in turn lead to a low fracture energy.

An important factor in fibre reinforcement is thus, the relation between length and diameter. Increased length means increased adhesion. For a certain fibre in a specified matrix there will then be an optimum length. However, too long fibres are difficult to distribute in the fresh mix. Another way to increase adhesion, is by physical anchorage (shape, for instance fibrillation) or as in this case to introduce an adhesive (e.g. latex).

It is also important to note the significance of fibre dosage, since the force acting on each fibre depend on the number of fibres in the path of the crack in a fracture energy experiment, for instance.

The fracture energy for the different composites in Table 7 reveals that the addition of 5 % latex increase the adhesion of the fibre to the matrix to a suitable extent. The result being that 0.5 vol% PAN-fibre with latex is just as efficient as 1.0 vol% fibre without latex. The PVAc/VeOVA-latex has no effect compared with the PAE- and SBR-latexes. Note that these values are only measured for the "dry" curing scheme I, and that a loss in fracture energy when wet is expected as seen for the flexural strength in Tables 4 - 6. If the difference in air-content is also taken into account, the efficiency of the PAE-latex is even better. It can be seen from the prism weights in Tables 4, 5 and 6 that ACR05L contains about 2 % more air than the CTR05 and about 4 % more than VAC05L and SBR05L. Measurements of the fracture energy of the same mixtures without anti-foamer, showed that the decrease in fracture energy per % extra air is about 4-5 %.

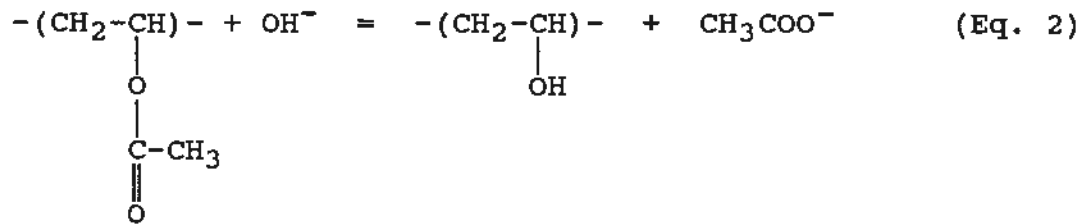
The fracture energy data in Table 7 reveal further that the value for the composite with 1.0 vol% fibre with PAE-latex is only slightly lower than the material with 2.0 vol% fibre and no latex, while the difference for 2.0 vol% fibre with or without PAE-latex is not significant. This illustrate well the preceding discussion on the adhesion of fibre to the matrix by Hillerborg /5/. At a dosage of 2 vol% the force acting on each fibre in the crack area is of such a low magnitude that the adhesion of these short PAN-fibres are suitable without a latex.

The SEM-pictures in Figures 2, 3, 4 and 5 illustrates clearly that paste residues stick to the fibre from the fracture zone when latexes are added, while the fibre from the cement mortar without latex reveals a rather smooth surface. Comparing the Figures, it appears that the PAE-latex is the most effective in this respect.

Considering the flexural strength of the reinforced cement mortars in Table 4, it seems like the fibres do not increase this property before at a dosage of 2.0 vol% and only significantly for curing scheme II and III. Note that the value after curing scheme II is lower than for I even though both are tested surface dry. The reason may be that the dry-wet-dry procedure of curing scheme II induces microcracks due to swelling and shrinkage, and since the cross-section of the beams is only $40 \cdot 40 \text{ mm}^2$, this effect becomes significant. Probably, these microcracks are

present to a lesser extent or better distributed when 2.0 vol% PAN-fibres are employed (sufficient adhesion).

If the flexural strengths are studied after the latexes have been added (Tables 5 and 6), it can be extracted from the 0.5 vol% PAN-fibre additions that the PAE-latex performs best of the three investigated latexes (especially after the air-content is considered). The poor performance of the PVAc/VeOVA-latex (worse than the controle mortar) after curing scheme II may again be explained by the swelling and shrinkage of the dry-wet-dry cyclus. In addition to the volume change of the cement paste, the swelling may be enhanced by the saponification of PVAc;



The poly(vinyl alcohol) formed during the saponification can absorb large amounts of water accompanied with swelling.

The relative flexural strength of the latex modified fibre reinforced mortars (in % of the flexural strength for the corresponding fibre reinforced cement mortars) is plotted as a function of the fiber dosage in Figure 6. The figure reveals that the new acrylic latex (ACR) gives the most enhanced flexural strength, and that there seems to be an optimal effect at a fibre dosage of 1.0 vol%. This comparison comply well with the observed results from both the fracture energy experiments and the indicative observations by SEM.

Note also that the compression strength are increased with about 10 MPa both for the cement mortars and the PCC based on PAE-latex when the PAN-fibre dosage is increased from 1.0 to 2.0 vol%. However, this is not confirmed by the compressive strength on the cylinders (Table 7, cement mortars only). This is hard to explain, but may be due to the specimen size and shape.

The tendency of the static E-modulus is to decrease with increasing fibre dosage (Table 7) and increasing air. An impression of the variations of the air-content can be obtained from Table 3 (fresh mixes) and Tables 4, 5 and 6 (prism weights after curing scheme I). The addition of 5 % PAE-latex alone lower the static E-modulus with 15 % compared with the cement mortar.

The dynamic E-modulus (Table 7) is not influenced by the fibre content, but are lowered by increasing air-content. However, the dynamic E-modulus increases with increasing fibre dosage when 5 % PAE-latex are added.

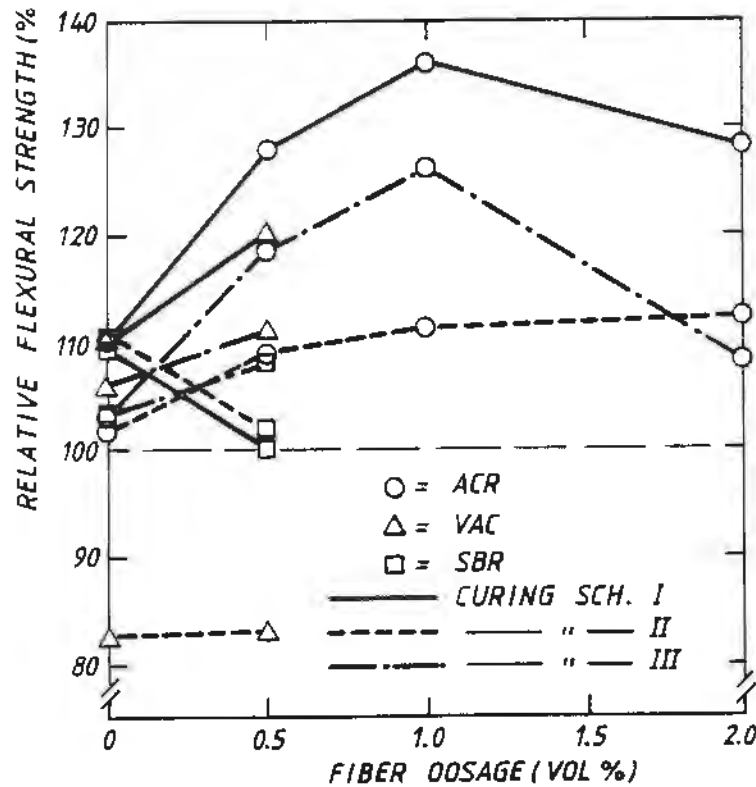


Figure 6. The flexural strength of latex modified fibre reinforced mortars relative (%) to the corresponding fibre reinforced cement mortars as a function of fibre dosage (vol%).

5. CONCLUSION

When only 5 % of a PAE-latex is added to a PAN-fibre reinforced cement mortar, only half the amount of fibres are required in order to achieve a similar gain in the fracture energy compared with an ordinary cement mortar. This is explained by an improvement of the adhesion between the fibre and the matrix as confirmed by a SEM-investigation.

The improvement of the flexural strength of the fibre reinforced mortars when latex is added, is at an optimum for a 5 % addition of PAE-latex at a 1.0 vol% fibre dosage (within the test serie). This complied well with the observations in the fracture energy experiments. Eventhough the improvement in flexural strength was lower after the curing schemes involving a one week submersion in water, the above trend was still valid.

The experimental PAE-latex performed in general better than the two commercial latexes tested (PVAc/VeOVa and SBR) in combination with the PAN-fibres.

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