ACOUSTIC EMISSION ACTIVITY IN DUCTILE FIBER REINFORCED CEMENTITIOUS COMPOSITES

G.Kalogiannakis[1], D. Van Hemelrijck[1], F. Boulpaep[1] and B. De Lhoneux[2]
[1] Vrije Universiteit Brussel, Dept of Mechanics of Materials and Constructions, Brussels, Belgium; [2] Redco NV, Kapelle-op-den-Bos, Belgium

Abstract: This study was performed in the framework of a research program focused in the development of high tenacity polypropylene (PP) fibres for the reinforcement of cementitious composites. Precedent reports have demonstrated how micromechanical modelling was used to attain significant improvements with respect to the macroscopic properties of cementitious composites. These improvements have been based on the optimized composition of the sheath of bi-component core/sheath fibers that resulted in a better interfacial frictional and chemical bonding of the fibers with the cement matrix. The principal aim of this study has been to evaluate the characteristics of AE data and correlate them with the particular fiber reinforcement. The analysis has led to the observation of clear distinct behaviour for each of the different types of fibers. Those types were namely polypropylene with variant surface coatings and polyvinyl alcohol (PVA) fibres. The results of the 'source location' data were compared to visually observed cracks during runtime with a microscope, so as to verify the supposed cracking behavior uniformity of the PP fiber composites in contrast to the localized cracking of the PVA composites. Statistical measures as the number of events and the accumulated energy of the recorded signals were to allow one to infer the underlying reinforcement.

Introduction: Cementitious composite materials have met increasing use in civil constructions during the last decade. This mainly comes as a consequence to the quality improvements regarding their macroscopic properties combined with a low cost production. One of the leading efforts in this respect has been focused to polypropylene (PP) fibres that are relatively inexpensive and worldwide available. Moreover, processing with classical melt spinning technologies adds up to make it more attractive as a raw material.

Ordinary PP fibres are extensively used for the reinforcement of concrete but their use for cementitious composites was until recently inefficient. The overall mechanical performance had to be modified in order to meet strict design requirements. To this end, understanding the mechanism of cement reinforcement with fibres was needed. On the basis of this understanding, that was gradually developed, micromechanical models [1-4] demonstrated that the macroscopic behaviour could be simulated using various micromechanical properties of the fibre-matrix system. Moreover, it was shown that the crack propagation can be unstable even though the fibre strength is relatively high and that the fractural behaviour is optimised with increasing the interfacial bonding of the fibres to the cement matrix.

According to this theoretical analysis, it was straightforward to find the origin of the inadequacy of PP fibre in interfacial bonding with cement into the properties of low surface energy (hydrophobic character) and roughness. Therefore the manufacturing that followed focused on improving these surface properties as well as the strength of the ordinary PP fibres by developing bicomponent sheath/core type of fibres, the technology of which is patented [5, 6].

The objective of this study was to establish the AE characteristics for the different types of reinforcement so as to enable the correlation with the micromechanical properties. One could therefore derive the composition and acquire further insight in the fractural behaviour of the structure. There was a clear indication of the change of the AE activity as the different types of fibres were applied in the composite.

Preparation of Samples-Experimental procedure: The composite plates were manufactured by Redco NV in their pilot bicomponent spinning plant. They consisted of various types of PP fibers in terms of sheath composition as well as PVA fibers reinforced cement matrix. The weight content of the fibers for all the plates is 1.7%. The different codenames denote the particular composition and surface processing of the fiber used. PVA corresponds to PVA fibers, and all the others are differently processed PP fibers.

The plates were numbered and afterwards cut in 3 specimens named alphabetically. In the relevant nomenclature, the name of a sample is consisted of the number of the plate, then the code and finally the letter denoting the particular part of the plate.

After the preliminary tests, it was decided to use end taps which were glued on the edges inserted in the grips so as to avoid stress concentration and for the partial elimination of strong noise sources originated from the same area. The dimensions of the cross-section of each of the specimens were measured so as to calculate the macroscopic stress levels developed.

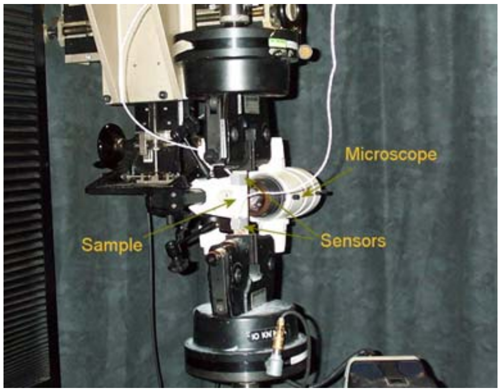

Fig. 1. Experimental Setup.

The specimens were subjected in a tensile test with a constant displacement rate equal to 0.3 mm/min. This displacement rate was selected among others after the initial tests in order to optimize the duration of the test. The experimental setup is depicted in figure 1. Two sensors were used to monitor the acoustic emission activity. Unfortunately the size of the specimens did not allow the use of guard sensors, which act as filters rejecting noise originated at the grips. Thus, post processing was needed to perform this filtering. Such signals are few and are characterized by abnormally long duration and high energy. A microscope was also set up so as to enable monitoring the onset of cracking and its evolution.

Results-Discussion: The fractural behaviour of the composite material is characteristic for the reinforcing fiber type. The material degradation initiates always with fracture of the brittle matrix. Crack propagation leads to stress concentration around the fibers, which starts pulling them out as the interfacial shear strength is not adequately high. The fibers are also subjected to higher tensile stresses as the matrix is broken. So long as the crack closing stress from fiber bridging does not exceed a certain limit a new crack might initiate elsewhere. Otherwise, further crack propagation entails so high tensile stresses for the fibers that the latter start breaking.

PVA composites develop generally one crack, which propagates and becomes fatal (fig 2a). The PVA fibers of PVA are comparatively quite brittle and exhibit high strength. In contrast, for PP-A and PP-B specimens, several cracks are developed around one or more significant cracks due to the redistribution of stresses. These cracks accumulate, evolve and cause eventually failure (fig. 2b). Pictures that were taken with the microscope demonstrate the different behaviour. One of the aims of the study was to find a parameter related to AE activity which would enable to predict at the initial loading stage the final failure behaviour.

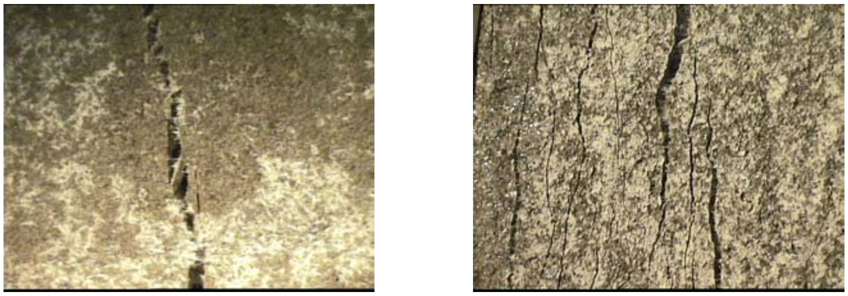
(a) (b)

Fig. 2. Typical fracture of cementitious composites with (a) PVA and (b) PP fibers.

Before proceeding in the analysis of the characteristics of the AE activity for each of the composite types, an issue should be addressed that is related with the location of the damage. As it is known, the waveform of the signal that is recorded is dependent on the distance of the source from the sensor as well as the type of the sensor. The latter problem is merely tackled using the broadband sensors but the former one remains. Placing the sensors very often results in altering the local stiffness. Moreover, the variability in the geometrical characteristics of the specimen cross-section generates various possible damage initialization areas. Finally, stress concentration at the end of the grips is possible even though end-tabs are used. All of these remarks are valuable arguments to explain the frequent fracture of the specimens under the sensor. In several cases the cross-sectional area was unluckily found to be smaller under the sensor; and there isn't any flexibility in their placement. Under these conditions, it is rather difficult to perform in depth material characterization. Some signals might even not be recorded because of combination of source position (near the grips) and certain parameters of the data acquisition. Therefore, in what follows, the analysis will be confined in a rough description of statistical measures and their subsequent evaluation.

There exists quite large discrepancy in the AE activity for each of the composites. Besides the testing procedure, this discrepancy is certainly also originated from the manufacturing procedure. Nevertheless, there is a behavioral tendency observed. Such a tendency is demonstrated in all the aspects of the recorded signals. For instance, the peak signal duration is shorter and the peak signal energy is lower for the PP fiber reinforced composites. In as much as these signals are emitted near the end, they can be associated with the mechanics of the fibers. This is because damage has progressed so that the cracks are open and there is only fiber bridging that keeps the specimen together. These fibers are pulled out and, in the final stages stress concentrations can be high enough to cause breakage. The elastic energy released triggers those peaks in the signals. It is logical that these, that is, the high energy signals in the end, are also the cause of the much higher total energy released and recorded for the PVA composites.

The AE activity increases rapidly to reach a peak after a certain elongation for each of the composites. The maximum load is not remarkably different for the various cases but the maximum strain is. So, PVA fiber composites seem to be much more brittle and their degradation is accelerated after a critical elongation point. On the other hand PP-A polypropylene composites present a slightly smoother behaviour with smaller peaks (less hits) in the AE activity and their stiffness degradation has longer duration. PP-B composites have also fast degradation like PVA, but their fracture length is equivalent or even longer than PP-A. All of the composites present a rather similar behaviour at the initial stages with damage remaining in low levels, usually barely visible. A slightly better performance might be attributed to PVA composites. Some of the characteristics are summarized in Table 1 so as to enable easier conclusions.

Table 1. AE activity characteristics for various cementitious composites

Material	*Duration*	*Energy*	*Hits*	*Events*	*Σenergy*	*Hits Vs Time*	*Ult. Load (N)*
PVA							
1b	800	80	34774	12114	794552	4000 - 200s	900
2a	800	60	21793	6071	277851	4500 - 300s	900
2b	750	60	29381	9333	395952	5000 - 300s	900
2c	800	80	25170	6666	504455		900
3a	750	80	22524	6687	367387	4000 - 250s	900
3b	800	60	23841	6408	338275	4000 - 200s	1000
3c	800	60	22252	7746	383697	2500 - 200s	800
Average	785	68	25676	7860	437453		900
Std	24	11	4776	2175	171677		57
PP-A							
2a	500	20	14611	5550	77565	1000 - 300s	900
2b	550	35	20984	7227	156333	2000 - 300s	-
2c	500	40	27310	7844	244218	3500 - 400s	-
1b	500	30	27888	8808	139237	3000 - 500s	900
3a	600	70	23176	8025	382519	2000 - 400s	1000
3b	500	30	15522	5722	133030	3000 - 300s	950
3c	650	50	26656	9480	318652	2000 - 400s	800
Average	542	39	22306	7522	207365		910
Std	60	16.4	5520	1475	111086		74
PP-B							
2a	600	40	28866	10589	248662	5000 - 900s	800
2b	500	40	28683	6899	185805	5000 - 500s	900
2c	500	50	23575	6873	191269	2500 - 400s	700
3a	500	40	22958	3996	159171	3000 - 700s	800
3b	500	60	32076	7973	267231	4000 - 600s	900
3c	500	40	26854	8683	188404	4000 - 300s	950
Average	516	45	27168	7502	206757		842
Std	40	8.4	3464	2199	41697		91

The investigation involved also finding a parameter that would enable the prediction of the fractural behavior. To this end, the data were exported and processed comparatively for the very early part of the experiment (until 800N was achieved). During this initial part load increases rapidly following the displacement rate to reach a value where it is flattened more or less. The number of hits during this early part is very small compared to the total number as the AE activity peaks near the end. Several investigations were performed in order to examine any repeatability in the results.

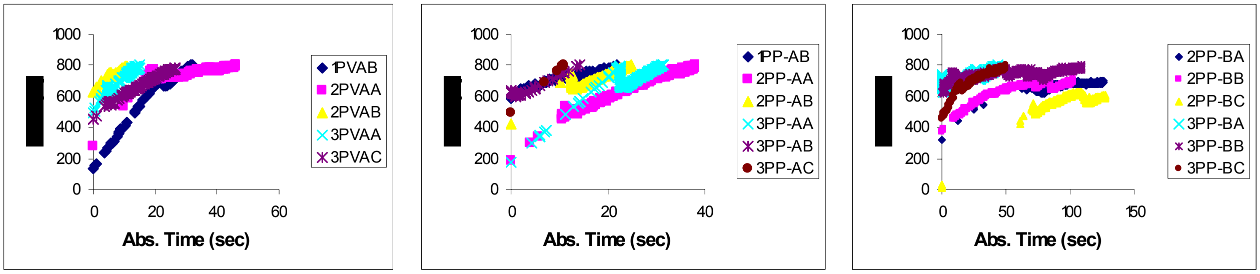

Fig 7. Load Vs Time for the different material types.

The first of the investigations involved the load as a function of absolute time. *Absolute time* runs from the moment the first hit arrives. This way it is possible to correlate the AE activity with the stiffness of the material. The longer the duration in absolute time until 800N is reached the longer the displacement and therefore the lower the stiffness. The starting point of each graph also shows an indication for the loading level AE activity starts. The graphs in Figure 7 show the variation for the different material types.

It is clear that for each material there is large discrepancy in the initiation of AE activity, that is, the minimum load emission starts. The PP-B is less stiff than the other two materials proven by the fact that much more time is needed to arrive to the endpoint. Furthermore, many more hits are produced. So, this could be a criterion to distinguish PP-B behaviour from the start.

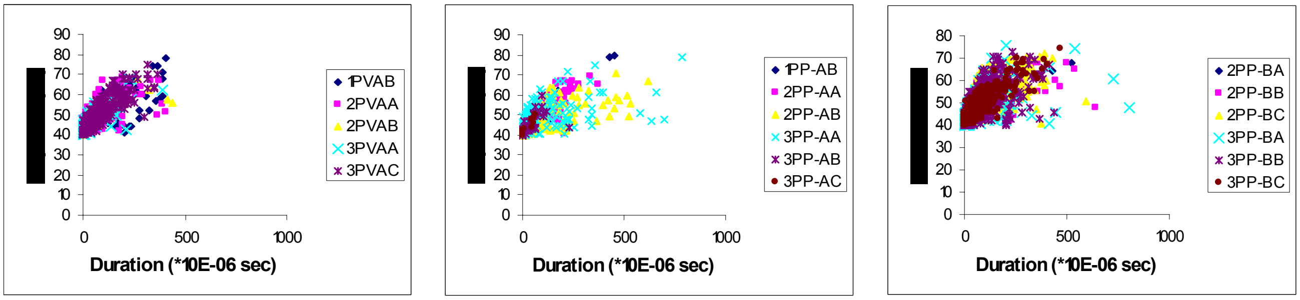

Fig.8 Amplitude Vs Duration for the different materials.

Next investigation involved the amplitude versus duration correlation. As aforementioned in the previous section there is a distinction between the different types in terms of maximum duration of signals observed and at that point they were assumed to be associated with the fibers breakage. If such phenomena take place also at this early stage then they could be used to distinguish the different materials. As depicted in Figures 8 and 9 some indication is provided in certain cases. It should be stressed that the data on the graphs are filtered. Large duration signals of one or two hits at certain points were considered originating from the grips. As a further distinctive characteristic they seem to present long rise time, especially at the closest sensor.

Finally nominal stress was plotted versus duration to examine if longer duration signals are produced only at high level loading. It would be rather indicative that for PVA long duration signals are generated near 4Mpa while for the other materials there is quite some discrepancy. For PP-A moreover, there are well distributed cases without a peak.

The last investigation was on the average values of the initial part, which are shown in Table 2. A difference can be observed on the average of the number of counts as well as on the average duration for the different types. In particular the number of counts in AE signals for PVA is higher even though the maximum duration is lower. Moreover the recorded energy for PVA seems to be higher, maybe associated with the early breakage of fibers.

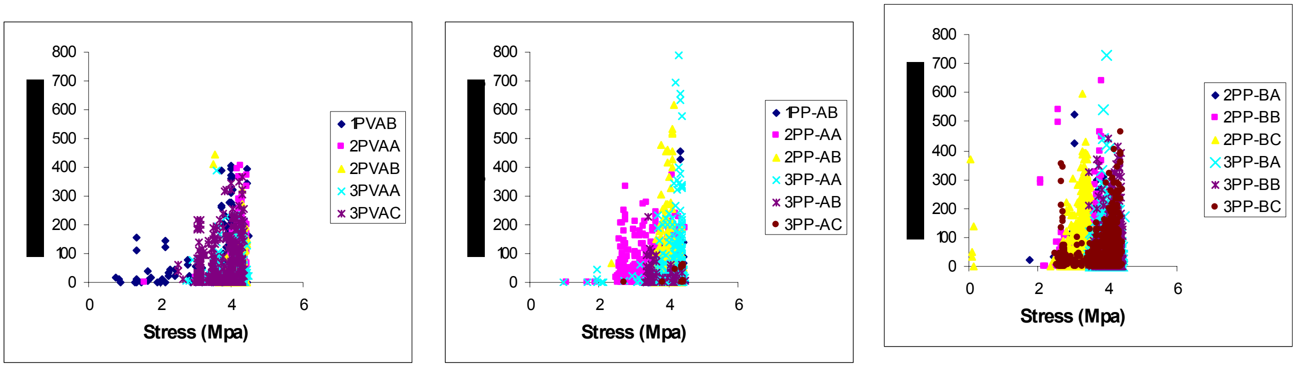

Fig. 10. Stress versus Duration for the different materials.

Table 2. Average values of the AE characteristics at the early loading stage.

Material Type	Average Values						
	Stress (Mpa)	Rise (sec)	Counts	Energy	Duration	Amplitude	Abs Energy
1PVAB	3.68	12.53	9.50	0.83	63.14	47.13	425.70
2PVAA	4.17	12.23	9.21	0.50	56.94	46.60	119.54
2PVAB	4.12	14.36	11.12	0.67	63.20	46.97	163.72
3PVAA	3.87	10.29	8.97	0.58	56.30	47.30	176.63
3PVAC	3.66	11.27	12.79	1.15	68.59	48.88	439.38
1PP-AB	4.03	7.75	5.80	0.51	36.25	45.42	637.72
2PP-AA	3.49	11.38	10.54	0.64	56.96	47.02	181.11
2PP-AB	3.97	18.28	8.78	0.57	72.84	46.02	143.79
3PP-AA	4.05	15.92	7.72	0.55	67.03	46.86	223.36
3PP-AB	3.68	10.41	5.86	0.13	35.84	44.88	31.25
3PP-AC	4.17	10.30	4.40	0.00	27.90	44.30	18.02
2PP-BA	3.69	11.19	7.30	0.33	46.95	45.48	80.14
2PP-BB	3.59	9.79	7.02	0.33	45.34	45.57	
2PP-BC	3.19	9.32	9.23	0.70	53.29	47.77	225.36
3PP-BA	3.94	8.90	6.56	0.38	43.69	45.92	169.49
3PP-BB	4.14	9.39	7.22	0.40	43.75	46.26	131.37
3PP-BC	3.84	10.14	8.37	0.58	50.66	46.26	191.99

Conclusions: It is a fact that there is potential in the research of the AE activity of the cementitious composites that were studied even though the number of experiments that was performed was not adequately large to draw definite conclusions. An adequate number of experiments are needed in order to:

1. Perform a good statistical analysis
2. Optimize the experimental set up (geometry, displacement rate, pressure of grips, end tabs e.t.c.).

There are, though, positive indications about the distinctive behavior of the different types at the initial and the final stage in their life. Parameters like the duration or number of counts seem to offer a criterion for recognizing the fractural behavior. Comparative graphs and average values enhance this to a further degree. Moreover, statistical features like number of hits or total energy recorded can also be used to distinguish the different behaviors.

References:

[1] Li V.C., Wang Y., Backer S. 1991, "A micromechanical model of tension softening and bridging toughening of short random fibre reinforced brittle matrix composites", *J.Mech.Phys.Solids*, **39**(5), p. 607-625

[2] Lin Z., Kanda T. and Li V.C. 1999. "On interface property characterisation and performance of fibre reinforced cementitious composites", *J.Concr.Sci.Eng. RILEM* vol.1, p.173-184

[3] Katz A. and Li V.C 1996. "A special technique for determining the bond strength of carbon fibres in cement matrix pull-out tests" *J. Mater. Sci. Lett.* 15, p.1821-1823

[4] Kim P., Wu H.C., Lin Z., Li V.C., de Lhoneux B. and Akers S.A.S. 1999. "Micromechanics-based durability study of cellulose cement in flexure", *Cem. Concr. Res.*29, p.201-208

[5] Vidts D. and de Lhoneux B, 1999. "Shaped Fibre-Cement products and reinforcing fibres", *Pat. WO* 99/19268

[6] Vidts D. and de Lhoneux B. 2000. "Produits faconnes en fibre-cement it fibres de renforcement pour de tels produits et procede de traitement de telles fibres. *Pat. EP* 1 044 939 A1