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An Approach to Acoustic Emission Technique Applications to Evaluate Damage Mechanisms in Composite Materials

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Abstract. Acoustic Emission technique is a versatile method for characterization in materials science. It is considered to be a "passive" non-destructive method since damage can be only evaluated when de defects are being developed during the test which, at the end of the day, it is considered an advantage because failure mechanisms and damage process can be monitored and identified during the load history. When a failure mechanism is activated due to a discontinuity in the material such as crack propagation, part of the total strain energy is dissipated as an elastic waves that propagate from the damage source through the medium. Therefore, this released energy can be detected by piezoelectric sensors that perceive the emitted signal from the damage notation site by the surface dynamic movement and convert it in an electrical response. Acoustic emission signals can be correlated with the onset of damage process occurring in the tested materials and also to de diverse failure mechanisms such as matrix cracking, interface damage, fiber fracture, etc. This paper proposes to discuss our information and results on acoustic emission materials characterization undertaken on different types of materials.

1 Introduction

Acoustic emission (AE) is one of the most important non-destructive testing (NDT) method for materials and nowadays one of the most used methods for materials mechanical behaviour characterization. Mainly there are two crucial characteristic for AE in comparison of others NDT techniques: firstly, the source of the signal is always located within the investigated material/structure, secondly most NDT methods detect geometrical discontinuities, while acoustic emission senses fault movements. AE is related to an irreversible release of energy, and can be generated from sources not involving material failure including friction, cavitations and impact [1-3]. According to the ASTM Guideline of Standard Terminology for Nondestructive Examinations, acoustic emission is commonly defined "the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material, or the transient waves so generated" [2]. When elastic (transient) mechanical waves are spontaneously generated due to a discontinuity occurring in the interior of a material, an abrupt localized amount energy is released, consequently acoustic emission (AE) is emitted. Acoustic emission signals propagate to the materials surface with sufficient amplitude to be detected by special piezoelectric sensors that convert a mechanical disturbance to a voltage-time waveform. AE is a resourceful technique since it allows obtaining a vast amount of data concerning its capabilities to identity damage processes and failure mechanisms [4,5]. However, although each parameter can be useful for the comprehension of the damage progression, they are subject to be influenced by a large number of external factors sometimes difficult to distinguish from each other. This aspect is magnified in complexity when the acoustic emission technique is used on composite materials instead of classic homogeneous ones. Unlike homogeneous structural materials, composites consist of two or more phases of various forms. On the other hand, additional advantages include capabilities for maintenance of signal histories and coordination between multiple transducers that can be used, by signal wave arrival time difference, to locate the source of damage. Acoustic emissions can be detected in frequency ranges of 20 kHz to 1 MHz, and have been reported at frequencies up to 100 MHz. Lower frequencies are often associated with extraneous noise sources or resonance effects of the transducer case. Higher frequencies are excessively attenuated by polymer-matrix materials and, hence, these high-frequency parts of waves are carried to a distance no longer than a few centimetres from the source location. Nowadays, Acoustic Emission technique has been widely used as an important tool for almost any material mechanical behaviour characterization [6-11]. Some investigations carried out by Rios-Soberanis and collaborators in AE field are discussed in this document.

2 Acoustic Emission Technique Applications

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2.1 Application on fiber reinforced composites (enhancement of fiber/matrix interface)

A 20% fiber volume fraction composite material based on polymer matrix (HDPE) reinforced with sisal natural fiber (Agave fourcroydes) was manufactured for mechanical characterization and monitored with AE sensors. In order to evaluate the effect of interfacial adhesion, natural fibres surface were chemically modify with silanes and experimented under tensile test with coupled AE sensors to obtain and identify damage progression (Fig. 1). Comparisons with not treated fibers reinforced composite were also carried on.

Figure 2a shows the load-displacement for both types of fibres where is evident the enhancement of the fibres having a surface treatment with silane agent in comparison to raw fibers. Meanwhile, figures 2b and 2c present the stress-time-amplitude curves for not treated fibres and silane treated fibres respectively.

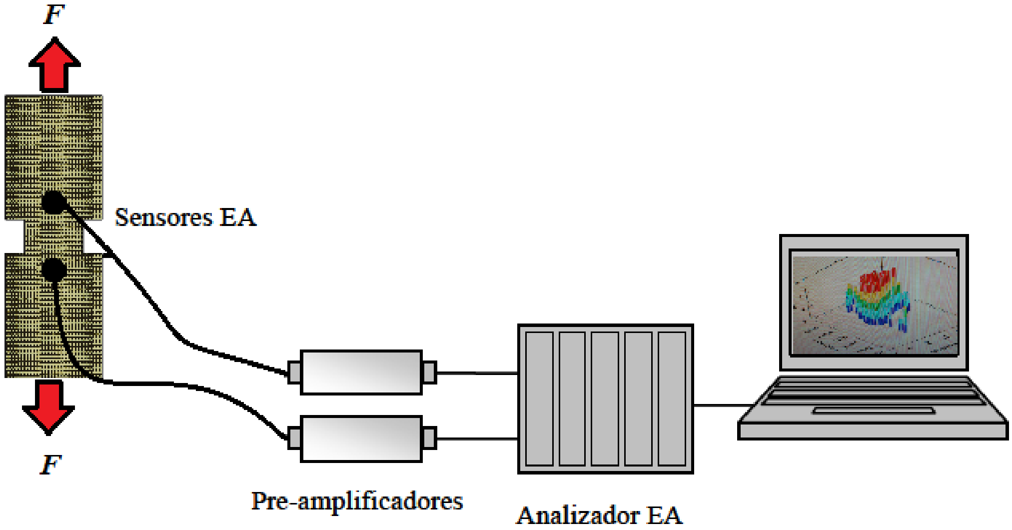


Figure 1. Schematic of tensile test mode with AE sensors attached on sample.

Acoustic Emission signals reveal that the onset of damage is higher for treated fibres since it appears at about 60 s while with not treated fibres appears at 48 s. Amplitude, intimately related to energy released in the event, was also higher in the treated ones. Damage progression, exhibited by amplitude data, indicates that higher amount of energy was released for treated fibres/HDPE samples which may be associated to a better fibre/matrix adhesion. Graphic for not treated fibres/HDPE samples shows a major amount of events detected by AE sensors related to the amplitude. This additional amount of events where originated by early interfacial damage provoking fibre/matrix pull out and friction.

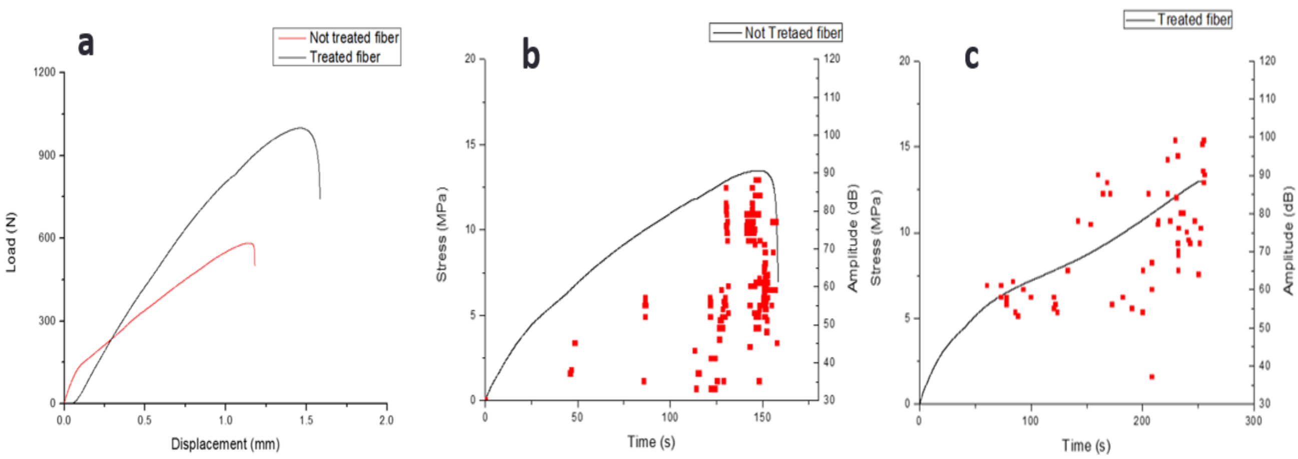
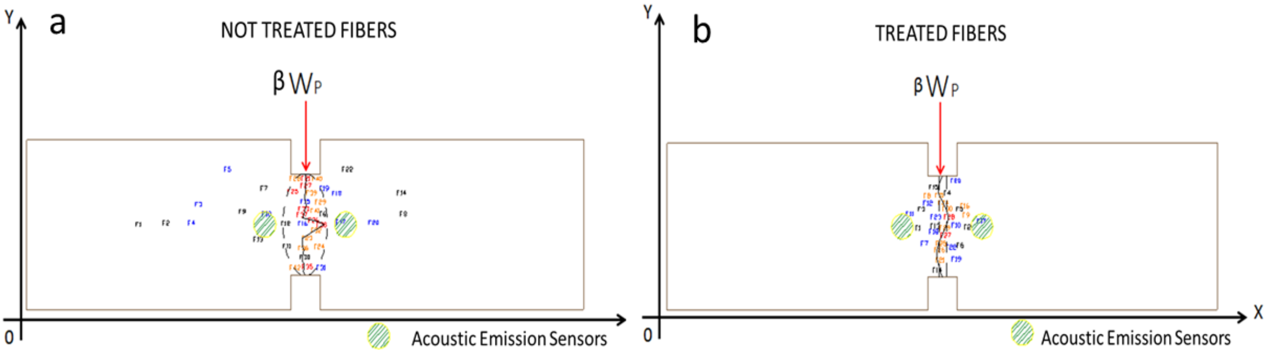


Figure 2. Mechanical behaviour curves: a) load-displacement for both types of fibres, b) Stress-time-AE amplitude for not treated fibres and c) Stress-time-AE amplitude for treated fibres.

Detected acoustic emission sources were of diverse amplitudes and duration appearing from 30 dB to 100 dB and from 5 to 30000 micro seconds respectively. Taking in account the amplitude variation and duration of AE events, some dominium were established and were correlated to the physical damage within the sample.

Composites reinforced with not treated fibres exhibited microcraking onset an a larger area along the sample. Mapping in figure 3 presents the interaction manner between fiber and matrix. Figure 3a for not treated fibers samples shows a higher amount of acoustic events while in samples with silane treated fibers (Fig, 3b) AE signals were detected with higher amplitude which is attributed to interface chemical interactions by the enhancement of the fiber/matrix adherence.



	Micro cracking onset	35-40 dB < 1000 μs
	Interfacial damage	40 -80 dB 1000 – 10000 μs
	Fiber fracture	80-100 dB 1000 – 10000 μs
	Macrocrack - Total fracture propagation	80 – 100 dB >10000 μs

Figure 3. Location of damage mechanisms: a) not treated fibre, b) treated fibres.

2.2 Application on archaeological limestone (stratus orientation effect)

Mayan archaeological limestone were drilled in order to extract cylindrical petrous samples (stone´s heart) with normalized drills (2”) based in ASTM D4543, D2938. Stone´s nucleus were obtained taking in account the anisotropy in correlation with the rock´s layers at 0° and 90° with respect to the rock position (Fig. 4). Stone cylinders were aligned with a diamond disk obtaining samples with a minimum of natural defects such as cavities, porous, etc. and then, photographs were taken to record the geometry of the running layers. Mechanical characterization was carried out in a Shimadzu universal machine under compression mode. Two AE sensors were coupled on the stones surface in order to monitor in real time the damage process to obtain information on elastic waves occurring during the test. Stone samples at 0° (geological stratum perpendicular to compression axis) and 90° (geological stratum parallel to compression axis) were tested and AE analysed. Results obtained during the experimental mechanical tests determined that archaeological stones exhibited variations in its mechanical behaviour and that it is depending on the anisotropy degree (geological layers orientation). Layer orientation effect over mechanical behaviour was also observed by Tavallai [12].

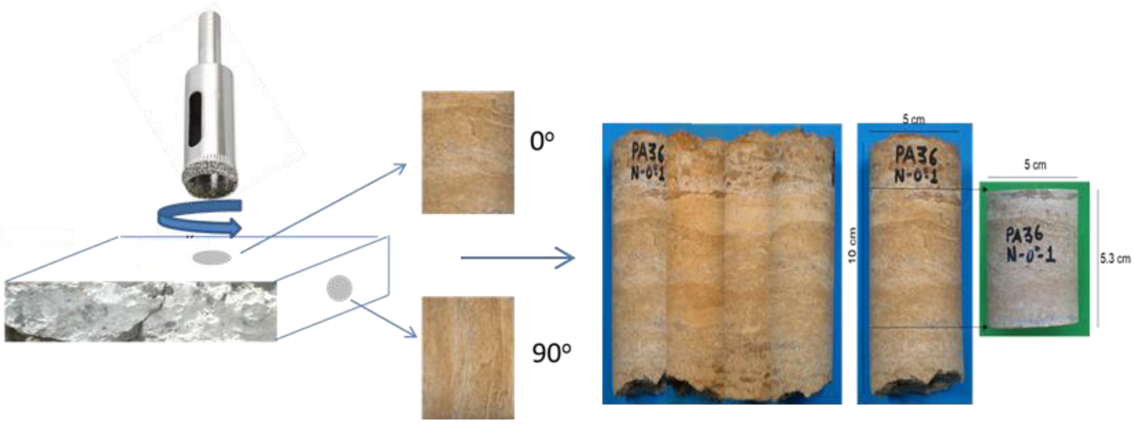


Figure 4. Stone cylinder samples at 0° and 90° and sample mapping.

Stress-time-amplitude for two archaeological stones nucleus cylinder at 0° and 90° according the geological stratus orientation are shown in figure 5. First observation on AE signal data refers to onset of damage that is early in samples at 0° when geological stratum is perpendicular to compression axis. In both samples the damage initiation is found to be between 80 to 150 s while in 90° is at about 200 s. Higher stresses originate the intensification of acoustic emission indicating significant internal failure in the stone structure. When sample is 90° with geological stratum parallel to compression axis, showed higher resistance (stress and deformation) that are supported by the latter detection of acoustic signals around 200 s. Amplitude appears to be denser since more events are occurring internally because more energy is needed to fracture de rock at this direction.

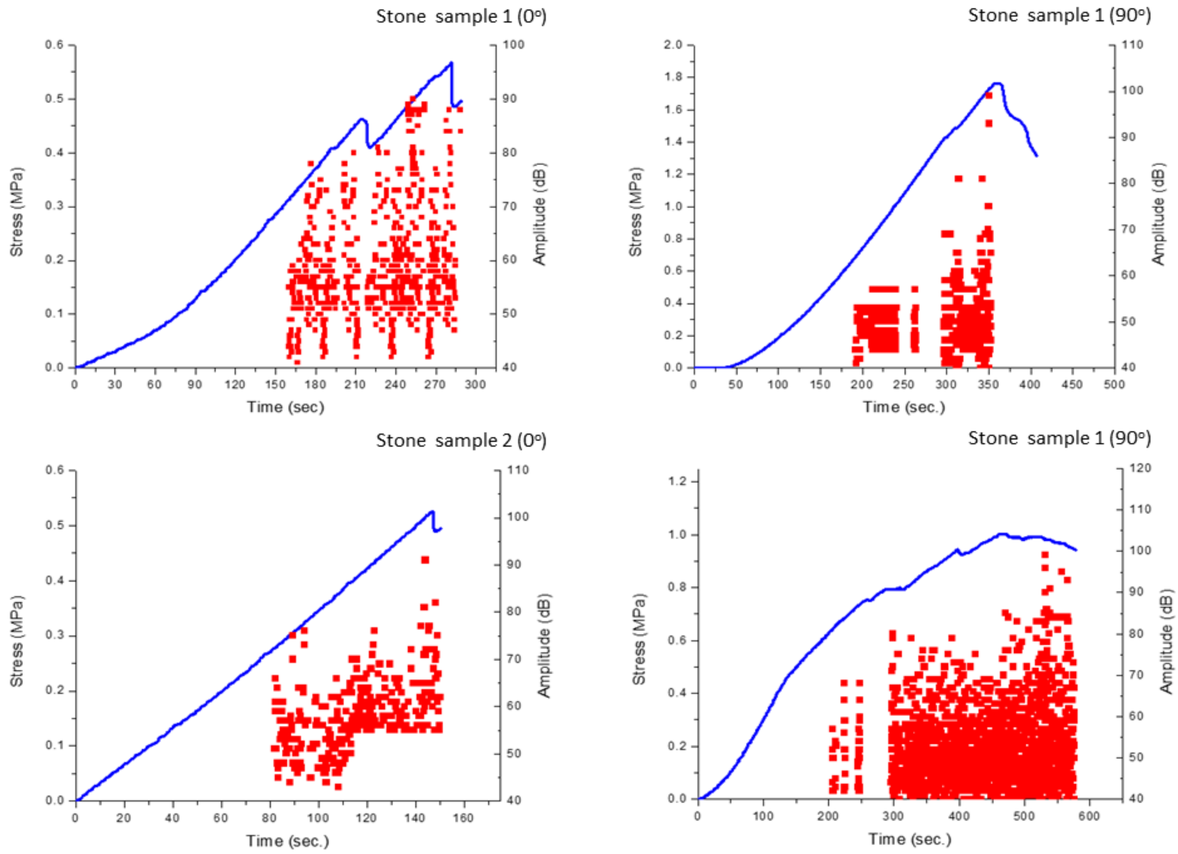


Figure 5. Stress-strain- amplitude curves for stone samples at 0° and 90°.

Figure 6 exhibit the macroscopic damage progression that is correlated to the geological stratum orientation. Acoustic Emission technique applications in archeological rocks provide information for understanding its position in antique prehispanic constructions.

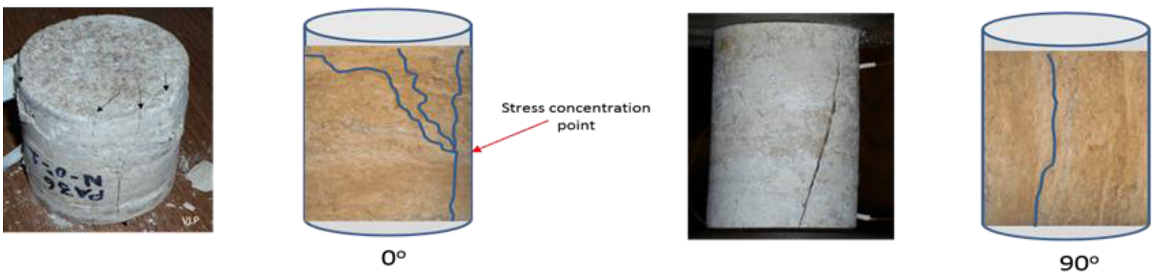


Figure 6. Failure progression found for stone samples at 0° and 90°.

2.3 Application on biomaterials (Bone cement)

The aim of this work was to identify the fracture mechanisms of acrylic bone cements containing core-shell nanoparticles during a quasistatic compression test by using the AE technique. Core-shell nanoparticles were synthesized using butyl acrylate (BA), methyl methacrylate (MMA) and styrene (St) as monomers. The nanoparticles were composed of a poly(butyl acrylate) (PBA) rubbery core and a methyl methacrylate/styrene copolymer (P(MMA-co-St)) outer glassy shell, considering that the commercial bone cement Surgical Simplex® P has this copolymer in its solid phase. Particles were prepared with different core-shell compositions (20/80, 30/70, 40/60 and 50/50) and were incorporated into the solid phase of bone cement at various percentages (5, 10 and 15 wt%). By changing the composition of feeding monomers, a series of core-shell latex particles were synthesized (20/80, 30/70, 40/60 and 50/50). Compression tests of bone cement prepared with core-shell particles were carried out in a Shimadzu AG-1000E testing machine in air at room temperature. Compressive mechanical tests were carried out on rectangular specimens at a crosshead speed of 0.5 mm/min.

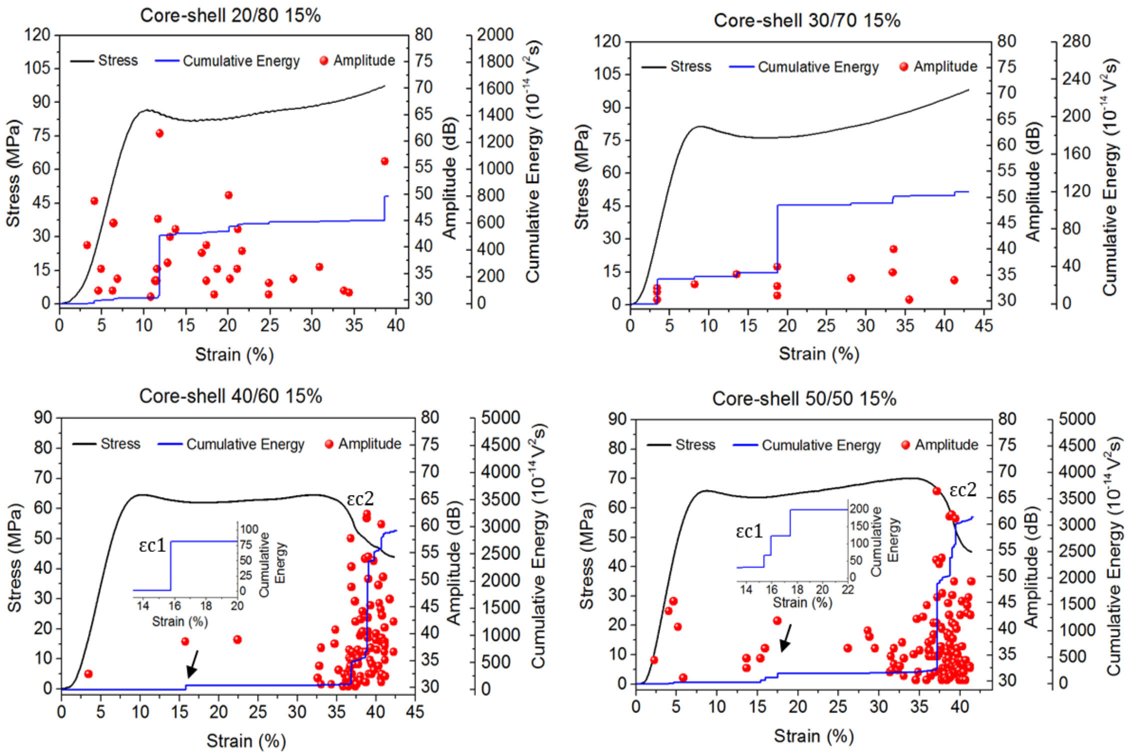


Figure 7. Stress-strain curves and AE signals analysis for bone cements containing 15 wt.% core-shell particles.

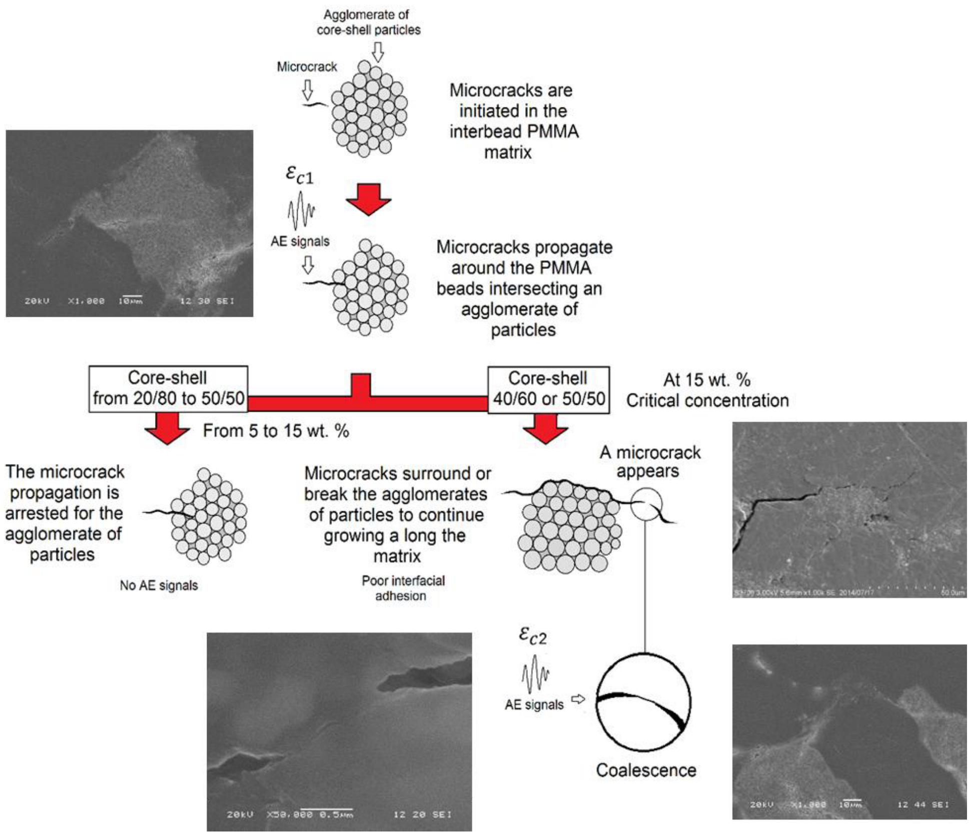


Figure 8. Schematic representation of the suggested fracture mechanism for bone cements prepared with core-shell particles during the quasistatic compression mechanical test.

Figure 7 shows the data obtained for cements containing 15 wt% of core-shell nanoparticles. As can be seen, signals related to damage initiation were recorded in these samples but at higher values of deformation (near to 15%). Based on these results, it can be mentioned that an increase of core-shell nanoparticles content delay the damage onset of cements. It can be also noted that formulations containing 15 wt% of nanoparticles displayed a second set of AE signals when the core-shell ratio increased at 40/60 and 50/50. These signals, which possess higher amplitude and energy than first ones, were detected at 40% of deformation and were associated to a significant damage in the sample. Taking all these AE results together, it is possible to postulate a possible fracture mechanism for bone cements prepared with core-shell nanoparticles during a compressive test. It is suggested that the fracture mechanism is initiated by the appearance of microcracks in the vicinity of agglomerates of core-shell nanoparticles and, during propagation, energy is emitted in the material which is detect as AE signals of high amplitude and energy (ε C1). The microcraks propagation going towards agglomerates of nanoparticles in a short-range manner intersecting them. These results are adequate until 10 wt. % of concentration because a higher percentage of these particles (15 wt%), the fracture becomes evident; this is attributed to the poor interfacial adhesion of these particles related to the lower shell thickness. The fracture mechanism of the bone cement prepared with these particles (strain $\approx$40 %) consist in a coalescence of microcracks after they surround them to continue growing up, which are presented as AE signals of high amplitude and energy (ε C2) (Figure 8).

2.4 Application on textile reinforced composites (effect of textile geometry)

Composite materials based on epoxy resin cured at ambient conditions were reinforced with two types of geotextiles in order to understand the mechanical behavior and damage development when undergo external tensile stresses. The main parameter here was to identify the influence of textiles architecture/geometry on mechanical properties and failure processes. The first geotextiles was made of polyethyleneterephthalate (PET) having a woven fiber architecture, the second one was made of polypropylene (PP) having a tape like thread along 0° and 90° axis with circular nodes creating a 45° pattern (Figure 9).

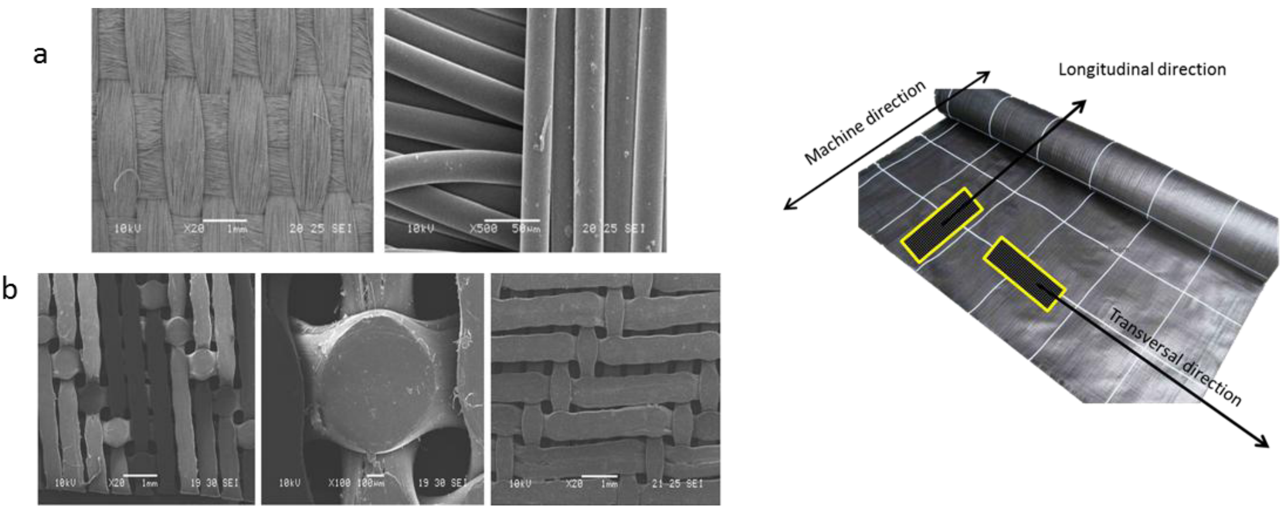


Figure 9. Geotextiles architecture: a) woven PET and b) tape like thread PP.

Epoxy samples (without reinforcement) mechanical behaviour is shown in figures 10a and 11a displaying first AE signals at about 0.5-1 % strain. Such first signals are found between 35-50 dB with release energy no higher than 10mV. These magnitudes in amplitude and energy are characteristic of structural microdamage within the material related to matrix cracking that coalesces until total fracture. When epoxy resin is reinforced with PET geotextiles, the fabric provides better mechanical properties in both sides. However higher mechanical resistance was fount when stress is applied at longitudinal direction (machine direction, 0°). Onset of damage was found to be later at longitudinal direction (1.7%) while at transversal direction (90°) damage initiated at about 0.5% (Figure 10b and c). Samples tested transversally also exhibited higher amount of damage events related to early damage initiation and the propagation of cracks starting with low amplitude fibre/matrix interface failure and continuing with matrix cracking. At higher strains fibre breakage occurs and finally totals fracture of the material releasing higher energy.

Matrix samples reinforced with PP geotextile shown no significant difference in the onset of damage when tested longitudinally or transversally. However at 0o (longitudinal) (Figure 11b), around 0.8% strain, AE signals are detected with higher energy and amplitude indicating an extensive successions of cracking initiation within the material generating an agglomeration of AE signals with amplitude between 50-80 dB. On the other hand, at 90° (transversal), it seems to be denser by the occurring of numerous damage events.

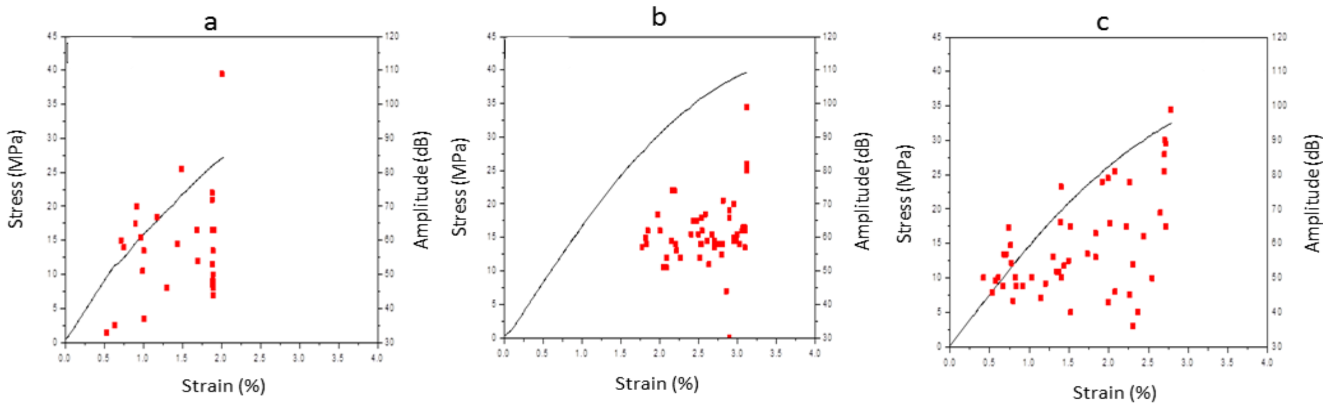


Figure 10. Stress-strain-amplitude: A) Epoxy resin, B) Epoxy/PET Longitudinal y C) Epoxy/PET Transversal with acoustic emission signal.

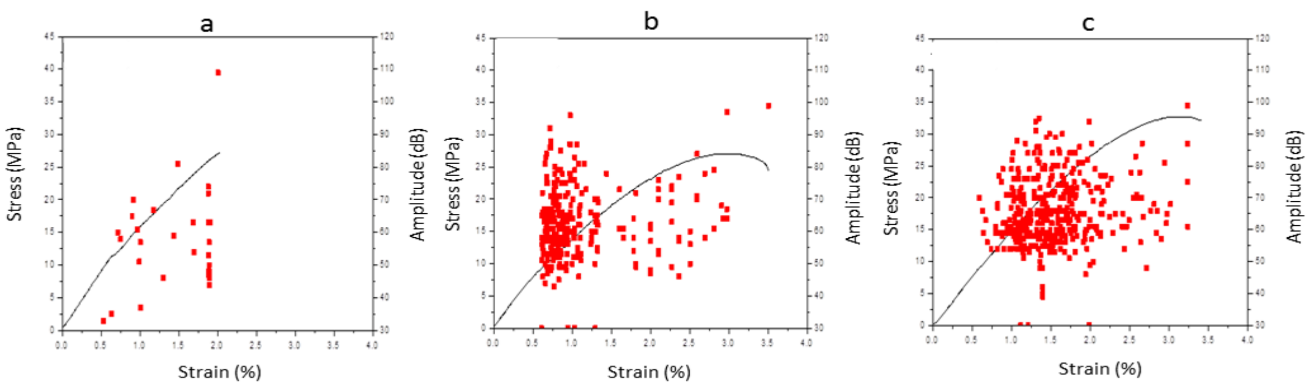


Figure 11. Stress-strain-amplitude: A) Epoxy resin, B) Epoxy/PP Longitudinal y C) Epoxy/PP Transversal with acoustic emission signal.

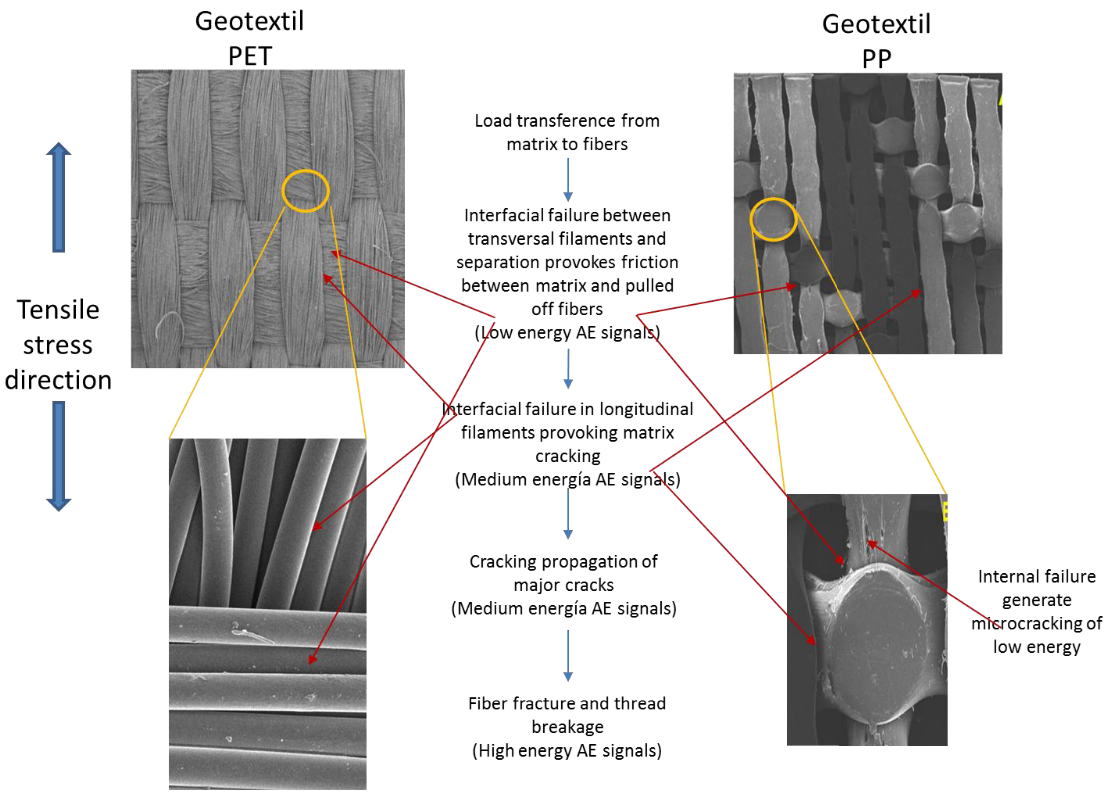


Figure 12. Damage sequence obtained by acoustic emission in both geotextiles.

Figure 12 displays the sequence damage identified by acoustic emission technique for composite materials based on epoxy resin reinforced with geotextile (PET or PP). AE was a useful method to identify damage mechanisms and to highlight the effect of textiles geometry/architecture on its mechanical properties.

Conclusions

When any material is subject to external stimulus such as load, temperature changes, impact, etc. localized sources within the structure releases energy in the form of elastic waves, which propagate to the surface and can be detected by sensors. This referred technique is Acoustic Emission, a versatile characterization procedure in Materials Science. Detection and analysis of AE signals can supply valuable information regarding the origin and importance of a discontinuity in a material. Because of the versatility of Acoustic Emission technique, it has many industrial applications (e.g. assessing structural integrity, detecting flaws, testing for leaks, or monitoring weld quality) and is used extensively as a research tool. AE data can also be easy or complex to understand but it depends on the nature of the material tested. It has been explained that different types of materials can be mechanically studied by AE and generating information in the micro structure damage and that this can be correlated to stress-strain curves in order to obtain relevant mechanisms of damage.

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