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EXPERIMENTAL ANALYSIS OF THE SIZE EFFECT IN QUASI-FRAGILE MATERIALS

Leandro Ferreira Friedrich

Luis Kostascki

Vicente Bergamini Puglia

Édiblu Silva Cezar

Mylena Barcellos

Applied Mechanics Group, Post Graduate Program in Engineering, Federal University of Pampa, Alegrete, RS, Brazil.
leandroffriedrich@gmail.com, luiskostascki@gmail.com, vicentebergamini@gmail.com, ediblucesar@gmail.com, mylenabsilva@gmail.com

Ignacio Iturrioz

Angélica Bordin Colpo

Department of Mechanical Engineering, Federal University of Rio Grande do Sul, Porto Alegre, RS, Brazil.
ignacio.iturrioz@ufrgs.br, angelicacolpo@gmail.com

Abstract. *The scale effect is a phenomenon characterized by the change in structural behavior when dimensional variations occur, as stress, strain and fatigue resistance of the material, for example. When the material by nature does not show significant signs of strain, the problem is even more complex. Therefore, the study of phenomena in quasi-fragile materials, that are incapable of presenting purely plastic deformations, is still an open topic. A methodology widely used for the monitoring of structures and that has been applied to evaluate the scale effect is the acoustic emission technique, used to obtain information about how and where the structure cracks. Therefore, the aim of this work is to capture the scale effect in quasi-brittle materials mainly using the acoustic emission technique but also observing the mechanical behavior of the material. Three sample sizes made of expanded polystyrene are tested in a three point flexural test. The results are presented in terms of the global stress-strain curves of the material as well as the analysis of the amplitude distribution and the number of acoustic emission events captured for each different sample size. The obtained experimental results were in great agreement with the known fractal theory and clearly showed a size effect.*

Keywords: *quasi-brittle materials, size effect, acoustic emission*

1. INTRODUCTION

In the mid-80s, the interest of scale effect in quasi-fragile materials began and had a considerable evolution in the following years, becoming an important topic in conferences of fracture mechanics. The problem of size effect has crucial importance in this kind of material, characterized by its disordered microstructure, where the damage localization phenomenon and a significant fracture process zone, leads to the damage process (Colpo *et al.* 2016). The experimental tests which could predict the material structural behavior are limited by specimens sizes and laboratory physical space. Furthermore, performed tests in a small size structures doesn't represent the behavior of the large structures and therefore, the scale effect in the materials mechanical properties remains as great interest in structures design. Researches (Carpinteri, 1986, Carpinteri and Chiaia, 1995, Bazant and Chen, 1997) have been carried out to continue to prove and improve the estimation of the transition of the behavior of the structure in relation to its size. Within the main approaches to study the effect of scale is the Size Effect Law (SEL) by Bazant (1984) and the Multi Fractal Scaling Law (MFSL) by Carpinteri and Chiaia (1997) and Carpinteri *et al.* (2007). Different methodologies are proposed taking into account this phenomenon but nowadays a way to deal with it is far from a consensus.

On the other hand, the Acoustical Emission (AE) techniques give us new information about the structures in the damage process that complement the information obtained with the traditional ways. The AE technique has become a recognized nondestructive test (NDT) to detect and locate failures in mechanical structures. The leakage detection in oil-ducts is an AE application example; in Grosse and Othsu (2008) are presented others several aspects related to AE applications.

In the present paper, AE techniques were applied on expanded polystyrene samples to capture the influence of the size effect in the results when the bodies are subject a three point bending tests. The stress-strain relation also used to prove the changes with samples dimensions.

2. ACOUSTIC EMISSION TECHNIQUE

When an atom or molecule is moved from its equilibrium position by a force, internal stresses act to restore the particles to their original positions. Due to the interatomic forces between adjacent particles of material, the displacement of a point induces displacements at the neighboring points, thus propagating an elastic wave (ASM 1989). The amplitude, mode of vibration and velocity of the waves differ in solids and gases precisely because of the differences in the mean distance between the particles in each of these cases. The development of technologies allowed to capture the waves and use them to analyze the mechanical behavior of the material when subjected to loading, this technique is known as the acoustic emission (AE).

The AE technique is considered a non-destructive test (Grosse *et al.*, 2008), since the tests are generally performed during the operation or loading of the structure. With this, the AE technique can be very useful in the early detection of failures and cracks, preventing the structure from completely failing. Besides that the acoustic emission captures elastic waves generated by the nucleation and by the growth of some defect in the structure, being itself the source that generates the signals, without the need for an external emitter (artificial emission). Therefore, this technique is considered a passive non-destructive test.

Signals of AE of materials commonly used in construction (concrete, wood, metals, stones and composites) are generally of low amplitudes and high frequencies, according to Carpinteri *et al.* (2009) typically in the kHz and MHz band, where sensors, which in turn are subject to ambient noise. For this, it is necessary to apply methods of signal amplification and filtering of this noise.

Identifying AE events, Figure 1, is certainly the most critical phase of this kind of analysis. Each event is characterized mainly by its maximum amplitude, but also by other parameters as duration, arrival time, rise time, rise angle (RA), energy among others. To perform the processing it is necessary to define a threshold, in which after this magnitude is achieved the signal is considered an AE event, as seen in Figure 1. The count is the number of peaks above the considered threshold. The number of the count divided by the duration is called the average frequency (AF) of the event and it is also an important acoustic parameter.

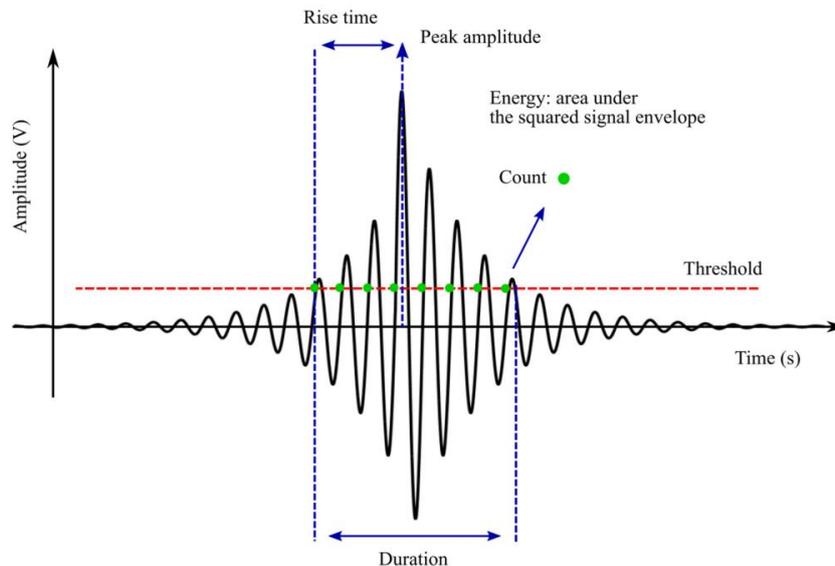


Figure 1. Common acoustic emission event features. M. Shateri *et al.* 2017.

Using the AE technique it is possible to evaluate the development of structural damage from the statistical analysis of the amplitude distribution of EA signals that emerges from the growing microcracks. This study began with geophysics, in which it expresses the magnitude (m) equal to the logarithm of the amplitude of the AE event, Equation 1.

$$m = \log A \tag{1}$$

where A is the amplitude. According to the Gutenberg-Richter (GR) law (Richter, 1958), which describes the statistical distribution of the AE amplitude signal, we have:

$$N(^3 A) = aA^{-b} \quad (2)$$

The relation (2) is used in the context of the structural problems by Shiotani *et al.* (1994), Carpinteri *et al.* (2009) where N is the number of AE signals with amplitude A , a is a constant and the b exponent is known as the b -value. For AE focus is the b -value coefficient, which characterizes the relative frequency of low amplitude events in comparison with high amplitude events. A small b -value indicates that there are few events of large amplitudes and a large b -value would indicate otherwise.

2.1 Relation between size effect and EA events

While testing the materials undergoing brittle failure, the b -value is found to be around 1.5 in the initial stages. It then decreases with increasing stress level to ≈ 1.0 and even less as the material approaches failure. The statistical analysis of b -values is closely correlated with the fractal dimension D of the damaged domain and can be write as $D=2b$ [Shcherbakov *et al.* 2003]. When $D=3.0$ ($b=1.5$) the energy release takes place through small defects evenly distributed throughout the volume and for $D=2.0$ ($b=1.0$) mean the energy release takes place on a fracture surface, that is, cracks that leading to the separation of the structural specimen, Carpinteri *et al.* (2012).

As show in, it is possible to link the energy release during the damage process (W) with the number of the acoustic emission events produced (N) and the fractal dimension where the energy dissipation ($V^{D/3}$) happens. For this reason, it is possible to write the following Equation,

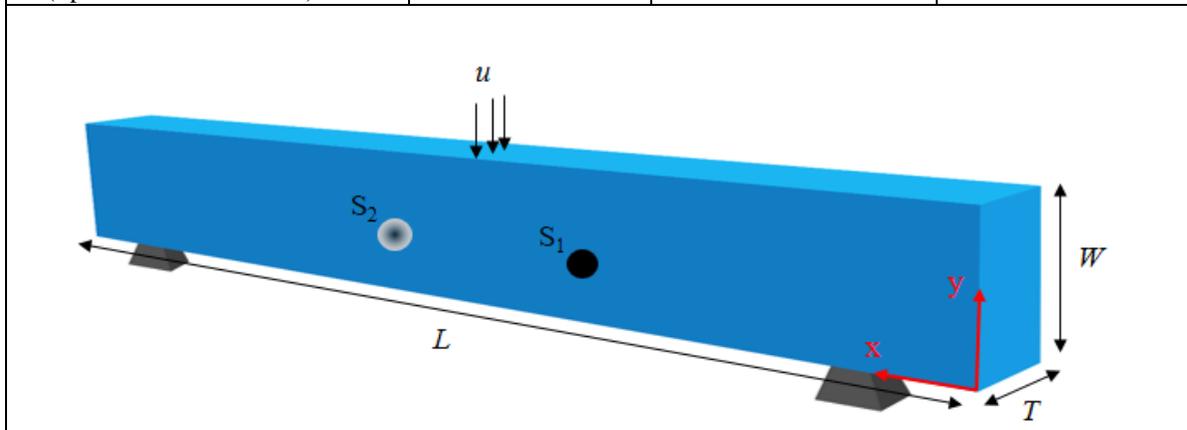
$$W : N : V^{D/3} \quad (3)$$

3. TEST DESCRIPTION

In the experimental tests, three beams with different sizes, as presented in Figure 2a, are submitted to three point test configuration as presented in Figure 2. For each configuration, four tests were performed. The same strain rate was maintained for all the tests, see Table 1 for speeds applied. In Table 1 are also presented the dimension of the three specimens. The three beams have dimensions proportional among each other, whose scale factor is approximately 2.0 on all dimensions. The tests are performed by applying of prescribed displacements, whose values grow monotonically up to the rupture.

Table 1. Speed of the test requirements and dimensions of the specimens.

Dimensions	Small	Medium	Large
L (Length - mm)	200	400	800
W (Width - mm)	24	48	96
T (Thickness - mm)	16	32	64
S ₁ (Sensor 1 xy position - mm)	80, 10	180, 18	340, 30
S ₂ (Sensor 2 xy position - mm)	120, 10	220, 18	460, 30
V (Speed of test - mm/min)	3.5	7.0	14



To measure the structural size effect through AE testing on each specimen, two AE sensors (S_1 and S_2) are installed. The Data acquisition was made by mean of a signal amplifier and microcomputer with Software PHOTON+ (Brüel & Kjaer) controlling and recording the amplitude data and time generated. The rate acquisition was made to 10.24 kHz. The specimens are instrumented with two PCB Piezotronics model 352C03 with a frequency of up to 10 kHz, positioned as indicated in Figure 2b and Table 1. One sensor (S_1) was positioned on the front face of the sample and while, (S_2) on the back face. Still during the tests, the load force measurement is carried out using a load cell.



Figure 2. a) The three models used during the test, b) Sensors position on the medium sample.

4. RESULTS AND DISCUSSION

In Figure 3, it is presented the experimental results for the three specimens tested in terms of global stress vs. strain. Dashed lines are the curves obtained from the acoustic emission tests for each size. It is possible to observe that in the small and medium samples there is a considerable variation in relation to the behavior of the curves. The large sample, on the other hand, presents little change. In general, it is perceived that the results are sensitive to sample size and some inherent defects of the material may cause such variation that are minimized when the sample size is large.

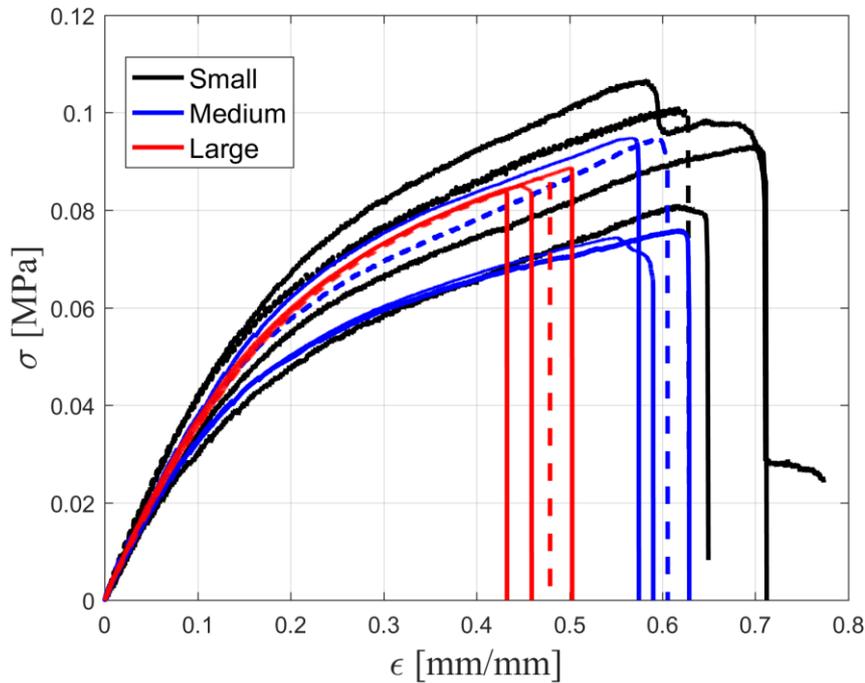


Figure 3. Experimental results: stress vs. strain curve.

Figure 4 shows the results in terms of the ultimate stress and strain (mean value, standard deviation and regression line) for the three specimens. In Figure 4b, it is possible to perceive that the material presents a more ductile behavior when the size of the specimen is smaller, that is, the mean value of the ultimate strain of the material decreases as the size of the specimen increases. This effect was not observed so clearly in the ultimate stress, Figure 3a, due to the variation of the curves of the small and medium samples. The phenomenon recorded by the ultimate strains characterizes the occurrence of the scale effect.

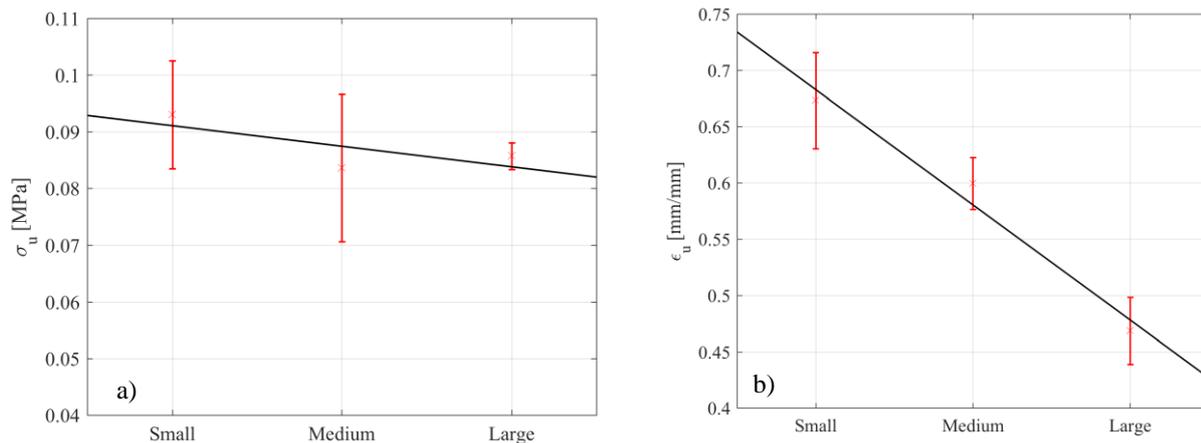


Figure 4. Mean value and standard deviation of the ultimate a) stress and b) strain for the three specimens.

4.1 Acoustic emission results

On the Small sample, only 10 acoustic emission events were recorded, which prejudice a better analysis, however, on the Medium and Large samples it was possible obtained more than 100 events and both are the focus of the study. For the initial analysis, a band pass filter among 300 and 600 Hz was used to eliminate the noise. This band was defined by evaluating the frequency spectrum in a time interval that contains an EA event. In the sequence, the filter is adjusted until evidence of the event and then facilitate the events identification. Subsequently, we used a threshold equal to $4.5e-$

5 mV as the amplitude cut-off point. This value was used for both samples studied. Event identification was performed manually.

Figure 5 shows the acoustic emission signal obtained from sensor 1 of the large sample. It is possible to note that the amplitudes of the events are small compared to that of the rupture point captured at normalized time equal 1.

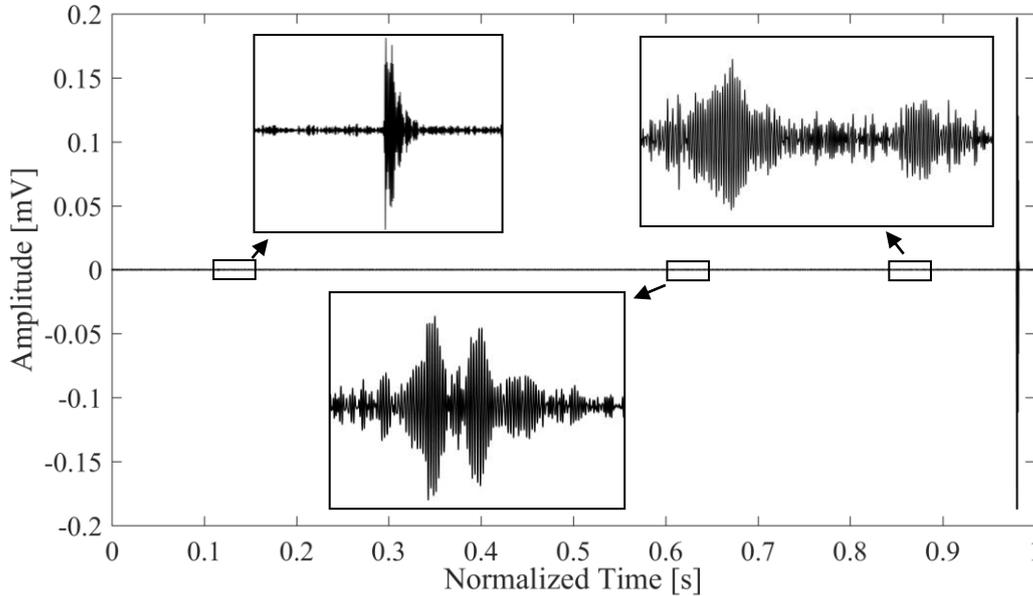


Figure 5. Signal captured by sensor 1 in large sample.

In Figure 5 some characteristic events throughout the test are shown. At the beginning tests, several mode failures I is seen, that means, were recorded tensile events, most probably an initial mechanism of damage. After that, mode II events are more frequent, and their form is quite different when compared on the mode I. On the central region, events in sequence are also seen, which may be related to rupture or debonding of small polystyrene particles. However, a deeper analysis of the average frequency (AF) and rise angle (RA) values should be performed in order to confirm the predicted citation. This method of analysis is better detailed by the Rilem Standard, presented in RILEM Technical Committee (2010). Work related to the parameters of RA and AF in different materials can be seen in Ohno and Ohtsu (2010) and Aggelis (2011).

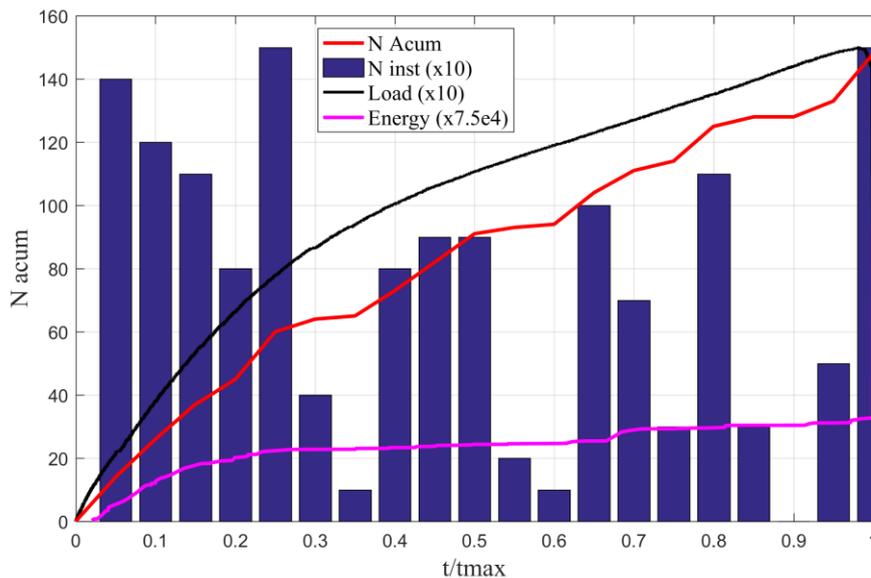


Figure 6. Analysis of the acoustic emission signal for the medium.

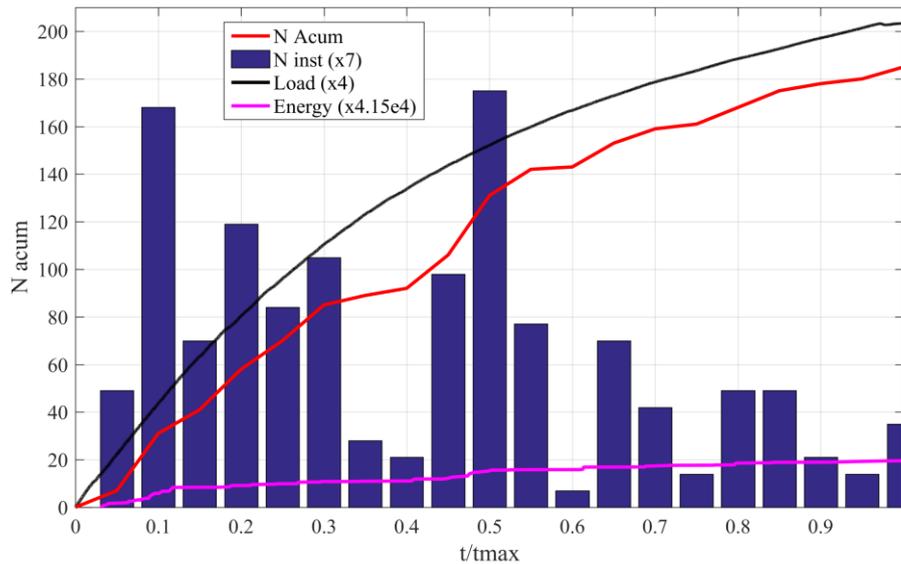


Figure 7. Analysis of the acoustic emission signal for the large sample.

In Figures 6 and 7, shows the analysis of the number of instantaneous (N_{inst}) and accumulated (N_{Acum}) events as well as the accumulated energy of the events in the time domain for the medium and large samples, respectively. In addition, the load *vs.* time is presented in the same graphic of the number of events.

Some parameters showed in this figure are increased by mean of the multiplication of a factor to a better comprehension/visualization. A large activity of events was observed in the analyzed samples. In the large sample, as it exhibits a more fragile behavior, there is not a significant register of events moments before the rupture. In both cases, the accumulated energy of the events is recorded in greater quantity in the last event, that is, an event of great magnitude in relation to the others. We can see that the number of accumulated events be directly related to the behavior of the load curve.

In Figures 8 and 9, the b -value computation for the experimental results are presented to the medium and large samples, respectively. In both cases, the b -value was computed over two intervals during the damage evolution. There aren't established criteria to determine the time intervals division. Analyzing the Figures 8 and 9 it is possible to note that the results obtained in the experimental tests follow the description of the b -value defined by Rao and Prasanna Lakshmi (2005), in which they affirm that the high b -value represents the formation and growth slowly of the new cracks, a low b -value indicates rapid and unstable growth of cracks, that can be notice in all cases with the advancement of the rupture process.

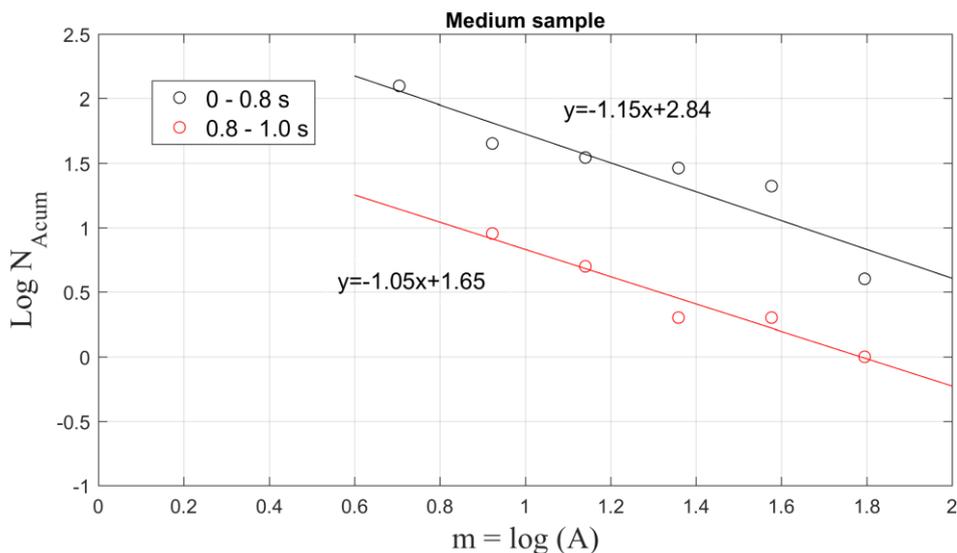


Figure 8. The b -value computation for medium sample tested.

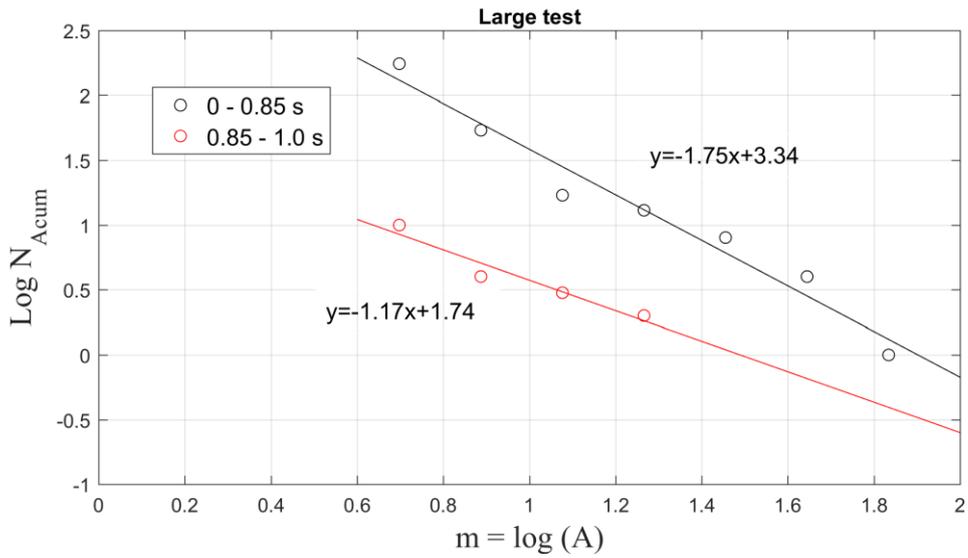


Figure 9. The b -value computation, for large sample tested.

For the two samples, the b -value shows that until the point near the rupture the energy dissipates in a 3D fractal region, once we consider $D = 2b$, then the energy is dissipated in the volume of the body. Later with the appearance of cracks, a surface is formed and the energy is directed to it, that is, 2D. This transition is an important point for the analysis of the mechanical behavior of the material and can be used as a monitoring parameter in applications.

Finally, the results that link the scale effect with the acoustic emission information (Equation 3) are presented in Figure 10. As can see thought of the angular coefficient, the correlation line indicates $D/3=0.71$, so the fractal exponent D is equal to 2.14. According to Carpinteri *et al.* (2012) the results are agree as expected and the size effect is evident.

From the practical point of view, it means that we can use a reference sample and monitor it until the rupture through the acoustic emission sensors and compare with the behavior that happens in a real structure, so that we can calculate the maximum number of events that this structure will reach (Capiniteri *et al.*, 2007; Capiniteri *et al.*, 2012). Obviously, the fundamental assumption is that the damage level observed in the reference specimen is proportional to the level reached in the entire structure before monitoring is started. We can write this in the form: $N_{max} = N_{rmax} (V/V_r)^{D/3}$, where the subscript r is the reference sample. Thus, a critical condition of the structure is possible to be obtained without the need for laboratory tests of the real structure size.

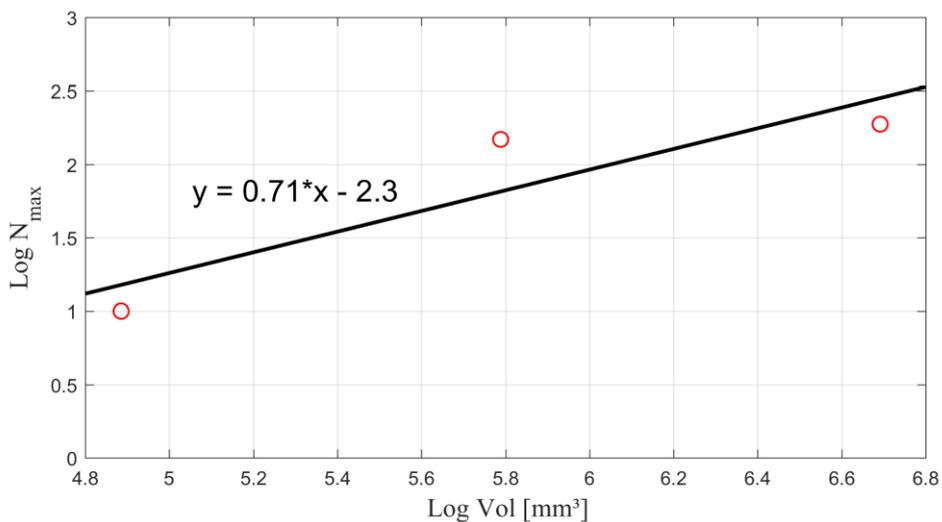


Figure 10. Maximum numbers of events vs. the specimen volume.

5. CONCLUSIONS

In this work, tests carried out on expanded polystyrene specimens loaded up to failure are analyzed. Three types of specimens with different sizes, which were subjected to three point flexural tests, were used. During the tests, the AE technique was used to display the damage process taking place in the specimens. From these analyses, the following conclusions may be drawn:

I) Using the results of the three point flexural tests, it was possible to perceive clearly the size effect in terms of the ultimate strain failure. This fact was not clear enough when we analyzed the ultimate stress of rupture, which may be associated with the intrinsic imperfections of the material.

II) The results obtained using the acoustic emission technique also proved the existence of the scale effect between the different sample sizes.

III) An initial analysis pointed to the occurrence of different types of fracture forms captured by the acoustic emission sensors, but a more meticulous analysis should be performed to prove this.

6. ACKNOWLEDGEMENTS

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