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Predicting fracture of mortar beams under three-point bending using non-extensive statistical modeling of electric emissions

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HIGHLIGHTS

- Pressure Stimulated Currents (PSC) in cement based materials under mechanical load.
- Tsallis entropy as predictor of the expected failure.
- Study of the PSC relaxation as q-exponential in cement based materials under mechanical load.
- Evaluation of the mechanical status of cement based materials subjected to three-point bending technique.
- Non-extensive statistical physics modeling of PSC emissions during mechanical loading.

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ABSTRACT

Weak electric signals termed as “Pressure Stimulated Currents, PSC” are generated and detected while cement based materials are found under mechanical load, related to the creation of cracks and the consequent evolution of cracks’ network in the bulk of the specimen. During the experiment a set of cement mortar beams of rectangular cross-section were subjected to Three-Point Bending (3PB). For each one of the specimens an abrupt mechanical load step was applied, increased from the low load level (L_o) to a high final value (L_h), where L_h was different for each specimen and it was maintained constant for long time. The temporal behavior of the recorded PSC show that during the load increase a spike-like PSC emission was recorded and consequently a relaxation of the PSC, after reaching its final value, follows. The relaxation process of the PSC was studied using non-extensive statistical physics (NESP) based on Tsallis entropy equation. The behavior of the Tsallis q parameter was studied in relaxation PSCs in order to investigate its potential use as an index for monitoring the crack evolution process with a potential use in non-destructive laboratory testing of cement-based specimens of unknown internal damage level.

The dependence of the q-parameter on the L_h (when $L_h < 0.8L_f$), where L_f represents the 3PB strength of the specimen, shows an increase on the q value when the specimens are subjected to gradually higher bending loadings and reaches a maximum value close to 1.4 when the applied L_h becomes higher than $0.8L_f$. While the applied L_h becomes higher than $0.9L_f$ the value of the q-parameter gradually decreases. This analysis of the experimental data manifests that the value of the entropic index q obtains a characteristic decrease while reaching the ultimate strength of the specimen, and thus could be used as a forerunner of the expected failure.

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1. Introduction and theoretical ground

Numerous testing methods both destructive and non-destructive have been introduced for the evaluation of cement based materials and structures. Modern techniques mainly based on non-destructive testing have attracted the attention of scientists and engineers as they are able to provide flexibility regarding the mechanical health status of a specimen or structure in situ or in a laboratory [1]. The main goal of these methods is the definition of parameters that can be potentially used as indices for such an evaluation process.

A novel technique used for health status evaluation through the monitoring of fracture process has been introduced and is based on the detection of electric signals generated in quasi-brittle materials during the formation and growth of microcracks. When a material is subjected to external mechanical loading, transient electric phenomena appear [2–6]. Weak electric currents can be detected and measured by using an experimental technique termed as Pressure Stimulated Currents (PSC) one [5]. This technique has been already applied to marble [7–9], amphibolite [10] and cement based specimens [11–13]. The term Pressure Stimulated Currents was first used to describe the polarization or depolarization electric signals, as a result of pressure variations on solids that contain dipoles due to the existence of defects [14–19].

In previous works the PSC relaxation process was attempted to be described by an empirical equation described by two exponential decays [10,20,21]. In this work the main query that deals with the physical properties of the PSC relaxation process and the law that it follows until its relaxation back to its background level is discussed under the frame of statistical physics and specifically the Tsallis entropy.

PSCs in stressed materials are produced by microfracture creation and evolution mechanisms [2–5,22]. These mechanisms are the roots of disorder and long range interactions and thus a generalization of the Boltzmann–Gibbs (BG) statistical physics known as non-extensive statistical physics (NESP) [23–25], could be the theoretical ground for their analysis.

According to NESP, the entropy is not additive [23,25], due to the fact, that is not proportional to the number of the system's elements in contrary to the BG entropy S_{BG}. Specifically, according to Tsallis the entropy S_q defined as [23]:

$$S_q = k_B \frac{1 - \sum_{i=1}^{W} p_i^q}{q-1}, \tag{1}$$

where k_B is Boltzmann's constant, p_i is a set of probabilities, W is the total number of microscopic configurations, and q the entropic index. The entropic index q may be used to quantify the non-additivity of the studied physical system that accounts for the case of many non-independent, long-range interacting subsystems and memory effects [23–29]. In most, if not all, of the studied applications, q appears to reflect some (multi) fractality in the system [23]. It is significant to notice some indicative cases for the value of q entropic index. When $q \approx 1$, Eq. (1) leads to the classical exponential distribution and consequently it actually represents the *BG* entropy formulation, according to which:

$$S_{BG} = -k_B \sum_{i=1}^{W} p_i \ln p_i. \tag{2}$$

Focusing on the probability p_i^q of the Tsallis entropy (Eq. (1)) it becomes clear that since $0 < p_i < 1$ a bias is introduced:

a. For q values lower than 1 ($q < 1$) the corresponding p_i^q obtains higher value than p_i and
b. For q values higher than 1 ($q > 1$) the corresponding p_i^q obtains lower value than p_i.

Therefore, $q < 1$ enhances the rare events, while $q > 1$ enhances the frequent events.

Eq. (1) (as reported in Ref. [23]) introduces an invariant under permutation entropic form based on p_i^q using a simple formulation as [23]:

$$S_q = F\left(\sum_{i=1}^{w} p_i^q\right). \tag{3}$$

The simplest expression for $F(x)$ is a linear function, thus it may easily concluded that:

$$S_q = C_1 + C_2 \cdot \sum_{i=1}^{w} p_i^q. \tag{4}$$

As expected, in order for the entropy to quantify the disorder of a system it must satisfy that $C_1 + C_2 = 0$, hence Eq. (4) becomes as follows:

$$S_q = C_1 \left(1 - \sum_{i=1}^{w} p_i^q\right). \tag{5}$$

In order for the S_q to approach BG entropy $C_1 = \frac{k_B}{q-1}$ must be fulfilled.