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Coupling creep and damage in concrete under high sustained loading

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ABSTRACT: In order to design reliable concrete structures subjected to high level loading during a long time, prediction of long term behaviour of concrete and coupling between creep and damage is important. An experimental investigation on the fracture properties of concrete beams submitted to three point bending tests with high levels of sustained load that deals with creep is reported. The specimens' sizes were 100×200×800mm^3 as per RILEM-FMC 50 recommendations. Quantitative acoustic emission (AE) techniques were used to monitor crack growth and deduce micro fracture mechanics in concrete beams before and after creep. The influence of creep on residual capacity, fracture energy, fracture toughness, and characteristic length of concrete has been studied. The load versus the crack mouth opening displacement relationship is linear in the ascending portion and gradually drops off after the peak value in the descending portion. The fracture energy and the characteristic length increase. The sustained loading seems to give a strengthening effect to concrete, probably because of the consolidation of the hardened cement paste. But the influence of creep on the variation of the fracture energy is not trivial. It seems that the chosen method is not fine enough to characterize the creep-damage coupling. So, the acoustic emission method has been applied to characterize the crack development during the three-point bending test. Results show a high amplitude level at the maximum load for creep specimens, which characterize a high consumed energy to nucleate the crack.

1 INTRODUCTION

Creep has important effects on the stresses and deflections of concrete structure subjected to variable stress. For low load levels, it is assumed that linear viscoelasticity takes place and the instantaneous mechanical behaviour of concrete remains elastic. However, for high load levels, this deviation is expected and nonlinear creep occurs (Mazzotti 2002, Freudenthalt 1958). In this later, concrete is submitted to the interaction between two mechanisms: creep strains and damage (microcracking) initiated by local stresses (Challamel et al. 2005, Reviron et al. 2007). Thus cracks grow and interact with the time dependent response of the bulk material (Masuero 1993) which has an impact on the safety margin and life time of many structures such as containment vessels, cooling towers or dam.

Many studies have been made in order to understand the mechanism of creep and to assess the creep behaviour of concrete. The fracture energy (G_f) is one of the important material properties for the design of large concrete structure. In the fictitious crack model proposed by Hillerborg (1985), the fracture energy, the tensile strength (f_t) and the stress-CMOD (*crack* mouth opening displacement) relationship completely describe the facture characteristics of concrete. Many investigations have been performed on the influence of concrete mixture, strength (Rao & Prasad 2002, Prasad 2001), the effect of the bond between the matrix and aggregate (Guinea et al. 2002, Tasdemir et al. 1996, Rossello et al. 2004, Rossello et al. 2006), the temperature (Menou et al. 2006), the aggregate size (Zhou et al. 1995) and the size effect on the cracking mechanism and fracture parameters of concrete. But there is a lack of results on the influence of the creep loading history. However none of these studies investigated the effects of creep on the failure mechanism including its influence on strength, stiffness, and fracture energy

In order to understand the introduction of tertiary creep, experimental observations about creep at high stress levels were studied. Therefore, we could have a sufficient basis for assessing the residual capacity and the nonlinear creep, then the safety of severely loaded structure. Softening and time dependence of fracture have to be taken into account for a realistic representation of the behaviour of concrete.

In the present paper, an experimental investigation on the fracture properties of concrete beams submitted to three point bending tests with high levels of sustained load that deals with creep is reported. Analyses are made on the specimen's response to these load condition, with particular interest in the fracture properties of the material.

The results aim first to investigate the ranges of variation of the time response due to creep damage coupled effects under constant load and secondly to evaluate the residual capacity and the characteristics of concrete after creep.

First of all, materials and the experimental methods are presented. Second of all, the creep tests and the three-point bending tests are analysed. Then, results on the fracture parameters are discussed. Finally, a study on the characterization of the crack mechanism of creep specimens by using the acoustic emission (AE) method is suggested.

2 EXPERIMENTAL PROGRAM

2.1 *Materials properties and mix proportioning*

The proportioning of the cement paste, sand and coarse aggregate were kept constant throughout the program. Specimens were made with a mix that consisted of ordinary Portland cement CPA-CEMII 42.5, crushed limestone aggregate: fine sand with a maximum size of 5 mm and a density of 2570 kg/m3 and crushed gravel of size 5 to 12.5 mm with a density of 2620 kg/m3, a super plasticizer agent (Glenium 21) and water. Table 1 shows the mix details and various quantities of constituent materials. This mixture is characterized by a water-to-cement (W/C) ratio of 0.56 and a slump of 70 mm.

Table 1. Concrete mixture proportions.

Constituents	Dosage kg/m^3
Gravel: G5/12,5mm	936.0
Sand: 0/5mm	780.0
Cement: CEMII 42.5	350.0
Eau	219.5
Superplastifiant: Glenium	1.9

2.2 *Test specimen: preparation and testing*

The fresh concrete was poured into the beam moulds. A plate vibrator was used to compact the concrete in the moulds in two layers. Then specimens were covered with a thin sheet of plastic to prevent water loss and maintained the temperature of 20°C and a relative humidity (RH) of 100%. Twenty-four hours after casting, the specimens were stripped off from the moulds and kept for curing in water for 28 days, under temperature condition of 20°C. After 28 days the specimens were taken out from the curing tanks and the central notch was formed using diamond saw cut.

The beams had the same thickness (b) of 100mm, depth (d) of 200mm and length (h) of 800mm with an effective spans (S) equal to 600mm and a notch-to-depth ratio of 0.2 ($a_0 = h/5$).

Three specimens were tested under three-point bending employing load-controlled universal testing machine as per RILEM-TMC 50 recommendations. The tests of the notched beams were conducted in a 160kN capacity servohydraulic machine under closed-loop CMOD control. The load was applied with very slow rate of loading with constant CMOD value of 0.0003mm/s, such that the peak loads occurred at about 3min.

During each test load, crosshead displacement, and CMOD were measured and recorded with a data acquisition system.

A general view of the experimental setup is provided in Figure 1. In order to measure the deflection of a central point of the beam, a laser extensometer was used. It was placed at midspan on a steel beam, which was attached at both ends and at half-height of the concrete beam. A metallic plate glued on the specimen in front of the extensometer reflected the laser beam. The deflection was measured with this setup so as not to include the effect of local deformations at the support and load points. It must be noted that with the test used both load-displacement and load-CMOD curves are very similar.

Figure 1. General view of experimental fracture test setup.

The mechanical characteristics of concrete were determined before performing the flexural creep and the residual capacity tests. The compressive strength (f_c), the tensile strength (f_t) and the dynamic elastic modulus (E_{dyn}) were measured on ϕ110x220mm^3 cylinders at 28 days. f_t was assessed through splitting tests and Edyn was determined with a Grindosonic® apparatus. All tests were carried out on three samples, and mean values of mechanical properties are given in Table 2.

Three point bending tests were realized on specimen at the age of 28 days to determine the characteristic of concrete and the maximum load so we could load the specimens in creep.

The creep tests were performed on frames with a capacity ranging from 5 to 50kN placed in a climate controlled chamber (Omar 2009). Curing conditions for all specimens were at 50% RH and controlled temperature of 20°C. The load is applied by gravity with a weight and counterweight system, which enables a fine tuning of the load and the displacement was measured at midspan.

Three-point bend creep tests were performed on notched specimens where the exchange of moisture was prevented by a double layer of self-adhesive aluminium paper. Hence basic creep was considered only and we were interested in the time dependent response of the beams. The basic creep displacement was determined by substracting the instantaneous elastic displacement from the total displacement.

The beams were loaded at 70% or at 85% of the maximum load recorded under monotonic loading in the material characterization study.

Table 2. Mechanical properties of concrete.

Properties	f_c	f_t	Edyn
	MPa	MPa	GPa
Mean values on three specimens	42.6	3.7	39

2.3 *The acoustic emission (AE) method*

The AE system comprised of an eight channel AEWin system, a general-purpose interface bus (PCI-DISP4) and a PC for data storage analysis. Four piezoelectric transducers (resonant frequency of 150 KHz) were used. Transducers were placed around the expected location of the process zone to minimize errors in the AE event localization program (RILEM TC212-ACD). They were placed on one side of the specimen with silicon in a rectangular position (12x12cm) (Fig. 2). The detected signals were amplified with a 40dB gain differential amplifier in a frequency band from 10 to 1200 KHz. In order to overcome the background noise, the signal detection threshold was set at a value of about 35 dB slightly above the previously measured background noise.

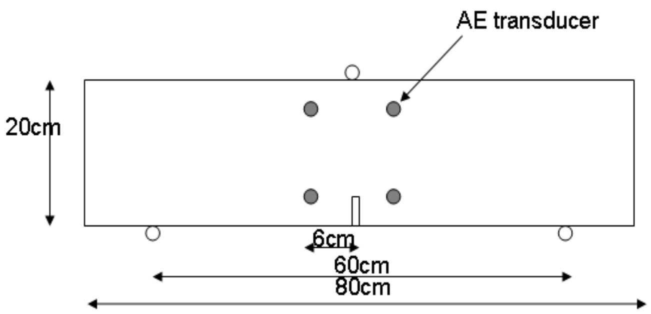

Figure 2. The specimen geometry and position of transducers.

3 TESTS RESULTS

3.1 *Creep tests*

The experimental tests show that increasing the applied load increases the basic displacement creep magnitude (Fig. 3). Creep develops very fast in the first days of loading and stabilizes after a few weeks. It is interesting to note that specimens charged at 85% of the maximum load showed a more important slope than the other specimen. Thus the basic displacement creep rate is much higher and the kinetics of creep is different under variable stress.

For specimen loaded at 85% of the maximum load, there is a deviation of the creep curve at 115 days indicating the beginning of tertiary creep. In fact, microcracking initiated due to the applied constant load begins to growth and to form a crack path (Ngab 1981, Meyers 1969, Rossi 1994, Z.Bazant, 1992). At this time we have unloaded the specimens and, in a short time after to avoid the stress relaxation and the total failure, we have realized the three points bending test.

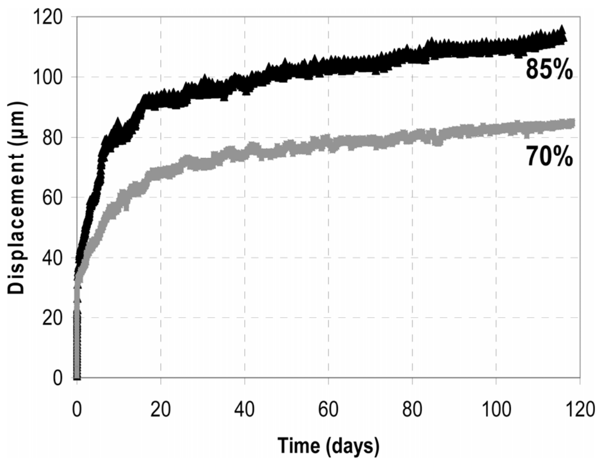

Figure 3. Deflection for different load levels.

3.2 *Softening response*

The purpose of this section is to investigate the effect of creep on the residual capacity of concrete specimens by determining the fracture energy.

After 115 days of creep loading, the beams were removed from the creep frames and then immediately subjected to three-point bending loading up to failure with a constant loading rate. In addition, aging specimens, cast at the same time as those subjected to creep and kept under the same conditions of temperature and relative humidity, were tested at the same time. For each kind of specimens two specimens have been tested.

The load-CMOD variations are linear up to about 90% of the ultimate load beyond which microcracking has started. This has been indicated by nonlinear variation up to the peak load (Fig. 4).

The difference in the softening behaviour and then the energy involved in the fracture process produced in specimens subjected to creep was smaller than those found in changing the aggregate type and size and the relative strength levels between the matrix and aggregate. However, other observations on the load-CMOD curves show different behaviour. While aging specimens (V3) present a fast decrease of load after the maximum load, the beams subjected to creep (A2, A4) show a stable portion indicating a localization of microcracks at the maximum load. In fact, the decrease in the absorption of the fracture energy for creep specimens seems to be due to the formation of a compaction zone during the creep mechanism. This compaction zone leads to a localization of the fracture process zone. In addition a stable failure at the maximum load was observed with creep beams and the postpeak response seems to be very gradual. May it is dependant of the size of the compaction zone. However the difference in the fracture energy between the specimens subjected to different loading at 70% and 85% is insignificant.

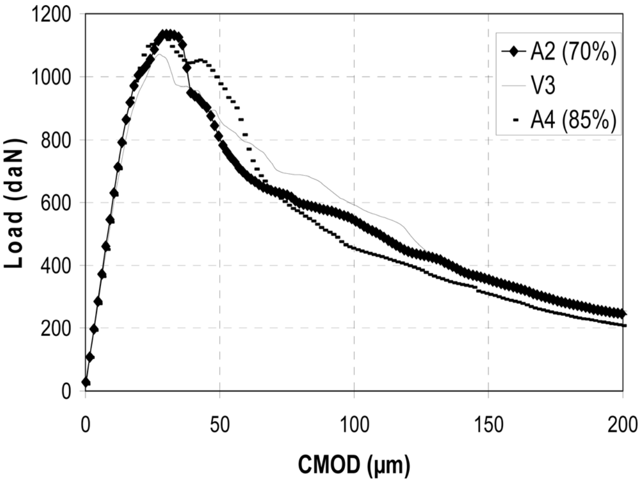

Figure 4. Graph showing the load-CMOD curves obtained before and after creep.

4 ANALYSIS OF FRACTURE PARAMETERS

4.1 *Fracture energy and fracture toughness*

The fracture energy is the energy required for creating unit area of crack surface. It is determined by means of three-point bending tests according to the RILEM recommendation. The fracture energy (G_f [N.m^{-1}]) is calculated as the work of fracture (W_F [N.m]) divided by the area of the uncracked ligament (A_{lig} [m^2]) by the following Equation:

$$G_F = \frac{W_F}{A_{lig}} = \frac{W_0 + mg\delta_0}{b\left(d - a_0\right)} \tag{3}$$

where W_0 [N.m] is the work dissipated in the area under the load-deflection curve, mg [N] the mass of the specimen between support, δ_0 [m] the maximum displacement, d [m] the depth of the beam, b [m] the width and a_0 [m] the notch depth. The fracture energy for each specimen is presented in Table 3. The creep influence is not significant and no conclusions can be done with this method.

The fracture energy does not suffice to characterize the ductility/brittleness of concrete. Brittleness of concrete or otherwise ductility is measured also by a parameter called characteristic length, l_{ch}, proposed by Hillerborg (l_{ch} = ($E.G_H$)/f_t^2). It must be indicated that l_{ch} is representative of the size of the fracture process zone, and as it decreases a more brittle behaviour appears. According to the following relation:

$$K_{IC} = \sqrt{G_F.E} \tag{4}$$

The apparent fracture toughness increases with creep (Table 3).

From the load-deflection curves, the net bending stress at maximum load, or the flexural strength (f_{net}), was also calculated following the general guidelines of the RILEM 50-FMC Committee:

$$f_{net} = \frac{6(F_{\max} + (mg/2))l}{4bh^2} \tag{5}$$

where h is the depth of the ligament region above the prenotch, l the span and F_{max} the maximum load.

It can be seen in Table 3 that when specimen were subjected to creep the flexural strength tends to increase.

Table 3. Variation of the concrete fracture characteristics.

	G_f [N.m^{-1}]	f_{net} [MPa]	l_{ch} [mm]	F_{max} [kN]	K_{IC} [x10^{5}N.m$^{3/2}$]
28days	68.03	2.45	138.80	10.75	13.97
70%	86.85	2.58	190.95	11.34	16.38
85%	84.05	2.58	184.33	11.32	16.09
Aging	75.91	2.46	160.26	10.79	15.00

The variation of the fracture properties of concrete beams induced by creep is not significant these observations. The Hillerborg method seems not fine enough to assess the influence of the creep load on the fracture of concrete. Thus quantitative acoustic emission techniques were applied to investigate microcracking and damage localization that takes place inside the specimens during the three point bending test with and without creep.

4.2 *Acoustic emission analysis*

Non-destructive and instrumental investigation methods as acoustic emission technique conducted over the last years have done much advance in the exploitation and the measurement of the evolution of negative structural phenomena, such as micro- and macro-cracking that appear in the FPZ of concrete fracture. The effect of creep on AE characteristics during the entire loading process was studied (Chen 2004).

During the three-point bending tests the correlation between AE hits and the load-CMOD (parametric1-parametric2) curves of concrete beams has been studied. Results for creep specimens are shown in Figure 5 and for aging specimens in Figure 6. Because of the large variance in absolute values of the AE parameters, only the results of one representative sample are presented. Although the differences in absolute values of the AE parameters are significant for each sensor, the graph shapes remain very similar with respect to time, for all used sensors. It was found that the occurrence of AE had a good correlation with the load-CMOD curve. Thus four stages can be observed which refer respectively to: 1) The linear prepeak region: during the initial loading stage where there was little occurrence of AE activities. Thus, micro cracks nucleate in a somewhat random pattern in the zone of the maximum tensile stress. 2) The prepeak nonlinear region: the AE activity increases indicating the formation of micro cracks bands. Thus, in this stage damage start to localize 3) The initial post peak region: when the external load exceeded the ultimate strength, the AE activity increases rapidly. This is most likely attributed to the drastic shock associated with the high surface corresponding to cracks that develop. At this point, the microcracks coalesce into an area around the location of the critical macrocraking. 4) The terminal postpeak region: during this stage the AE activity decreases and it is probably due to the existing of the fracture of the matter's bridges inside the fracture process zone.

From the comparison of creep and aging specimen, it can be observed that there existed a plateau for the aging specimen and the number of AE remain approximately constant during the post peak. While the distribution of occurring AE vector hits

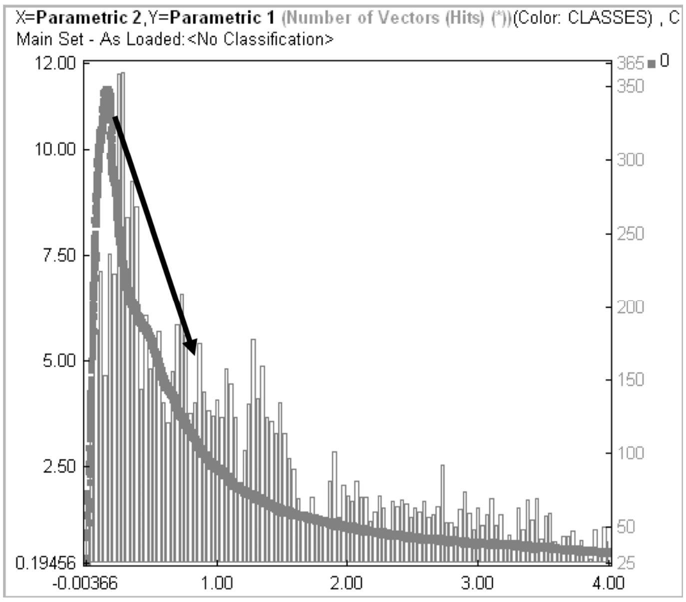

Figure 5. AE characteristic for creep beams. Correlation of load-CMOD curve with AE event rate.

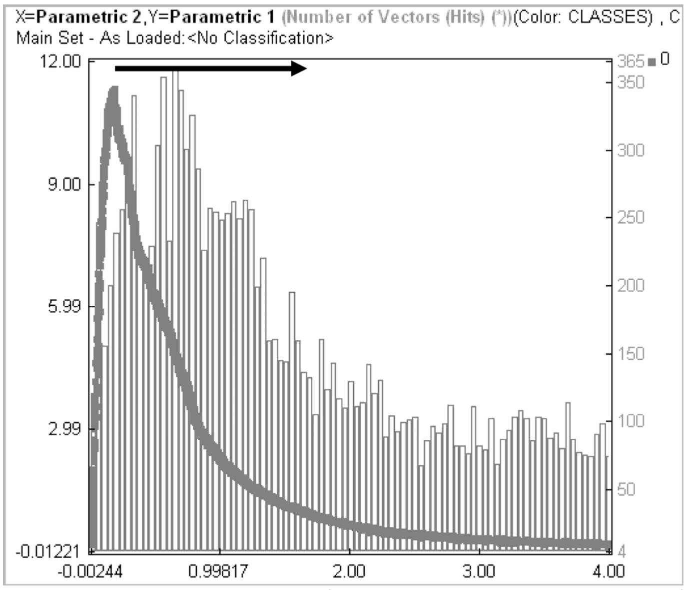

Figure 6. AE characteristic for aging beams. Correlation of load-CMOD curve with AE event rate.

for creep specimens peaked in the region of 80-90% of the maximum load in the descending branch of load-CMOD and the decrease brutally. This indicate that once the crack is initiated, the propagation will continue with less AE events and thus this may be due to the presence of microcracking and internal defect created during the creep loading.

5 DISCUSSION

According to the literature review (Hansen 1991, Carpinteri 1997) the fracture energy variation can be explained by the following mechanisms: the energy is utilized in overcoming the surface forces of concrete and in overcoming the cohesive forces due to aggregate bridging, aggregate interlocking, friction forces and other mechanisms in the fracture process zone. It is generally known that the fracture energy increases as strength increases (Zhou et al. 1995, Rao 2002). Thus the slight increase in energy may be explained by the strengthen effect due to creep. The influence of creep with this method is not clear, thus the acoustic emission technique has been applied to correlate the hit events, due to microcracking, to the fracture energy. Locally, the material has a higher tensile strength but it is more fragile. We have observed from the variation of the load-deflection curves that specimens subjected to creep have a longer tail which can be explained by two mechanisms: a more tortuous crack path has been formed by the sustained load, or the compaction zone is strength enough to prevent the crack propagation. The tortuous crack path is a consequence of the change in the concrete microstructure which can be attributed to a decrease in the matrix-aggregate bond and an increase of defects in the microstructure due to the micro-cracks development (Shah 1970, Rossi 1994) under creep. The AE results show the same tendency when analysing the local mechanisms during the three point bending test. An increase in the hit amplitude at the peak and a fast decrease in the number of AE hits were observed for creep specimens. The increase in the hit amplitude at the peak is due to a local strengthening effect in creep specimens due to the compaction. In addition, the brutal decrease of the number of AE events indicated that creep increased the brittleness of concrete beams and once the crack is initiated, the propagation will continue with less AE events in creep specimen. This may be due as explain before to the presence of microcracking and internal defect created during the creep loading.

6 CONCLUSIONS

In this study, we have analyzed the flexural behaviour of concrete subjected to creep. The fracture energy and the net bending stress at the maximum load were obtained following the general guidelines of the RILEM 50-FMC Committee. The influence of the creep on the fracture energy and on the flexural strength is not significant by applying the Hillerborg method. Quantitative AE analysis yields a wealth of information about the fracture process which helps in the understanding of microcracking and its role in the mechanical behaviour. Accordingly, we can conclude that when concrete is submitted to a sustained load, two opposing effects appear: consolidation, and consequent strengthening, and cracking, and consequent weakening. The relative magnitude of these effects will depend on the load level and its manner of application. The AE results have to be more analyzed in order to correlate each hit event to the local phenomenon (mechanical, hydrous). These descriptions will help us to characterize the fracture energy.

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REFERENCES

P.Bocca, M.Crotti, Variations in the mechanical properties and temperature of concrete subjected to cyclic loads, including high loads, *Materials and structures*, Vol.36, pp.40-45, 2003.

M.Omar, A.Loukili, G.Pijaudier-cabot, Y.Le Pape, Creep-damage coupled effects:experimental investigation on bending beams with various sizes, *Journal of materials in civil engineering*, Vol.21, N°.2, 2009.

C.Mazzotti, M.Savoia, Nonlinear creep, poisson's ration, and creep-damage interaction of concrete in compression, *ACI Materials Journal*, V.99, N°.5, 2002.

A. Hillerborg, The theoretical basis of a method to determine the fracture energy Gf of concrete, *Materials and Structures*, Vol.18, N°.106, pp.291-296, 1985.

A.Carpinteri, S.Valente, F.P.Zhou, G.Ferrara, G.Melchiorri, Tensile and flexural creep rupture tests on partially-damaged concrete specimens, *Materials and structures*, Vol.30, pp.269-276, 1997.

A.M.Freudenthalt, F.Roll, Creep and creep recovery of concrete under high compressive stress, *ACI Materials Journal*, V.54, N°.12, 1958.

A.Menou, G.Mounajed, H.Boussa, A.Pineaud, H.Carre, Residual fracture energy of cement paste, mortar and concrete subject to high temperature, *Theoretical and applied Fracture Mechanics*, Vol.45, 2006.

A.S.Ngab, F.O.Slate, A.H.Nilson, Microcracking and time-dependent strains in high strength concrete, *ACI Materials Journal*, 1981.

B.Chen, J.Liu, Experimental study on AE characteristics of three-point-bending concrete beams, Cement and Concrete Research, Vol.34, pp.391-397, 2004.

B.K.R.Prasad, G.A.Rao, R.Patnaik, Influence on the fracture energy of HPC, *Transaction, SMIRT 16*, 2001.

B.L.Meyers, F.O.Slate, Relationship between time-dependent deformation and microcracking of plain concrete, *ACI Materials Journal*, 1969.

C.Mazzotti, M.Savoia, Nonlinear creep, poisson's ration, and creep-damage interaction of concrete in compression, *ACI Materials Journal*, V.99, N°.5, 2002.

C.Rossello, M.Elices, Frature of model concrete 1.Types of fracture and crack path, *Cement and Concrete Research*, vol.34, pp.1441-1450, 2004.

C.Rossello, M.Elices, G.V.Guinea, Frature of model concrete 2.Fracture energy and characteristic length, *Cement and Concrete Research*, vol.36, pp.1345-1353, 2006.

C.Tasdemir, M.A.Tasdemir, F.D.Lydon, BI.G.Barr, Effects of silica fume and aggregate size on the brittleness of concrete, *Cement and Concrete Research*, vol.26, N°1, pp.63-68, 1996.

E.A.Hansen, Influence of sustained load on the fracture energy and the fracture zone of concrete, in *Fracture process in concrete, Rock and Ceramics*, edited by J.G.M.van Mier, J.G.Rots and A.Bakker, E&FN Spon, UK, pp.829-838, 1991.

G.A.Rao, B.K.R.Prasad, Fracture energy and softening behavior of high-strength concrete, *Cement and Concrete Research*, Vol.32, pp.247-252, 2002.

G.V.Guinea, K.El-Sayed, C.G.Rocco, M.Elices, J.Planas, The effect of the bond between the matrix and the aggregates on the cracking mechanism and fracture parameters of concrete, *Cement and Concrete Research*, Vol.32, 2002.

J.R.Masuero, G.J.Creus, Crack growth initiation in concrete like materials in the presence of creep, *Elsevier Science Publishers*, 1993.

M.Omar, A.Loukili, G.Pijaudier-cabot, Y.Le Pape, Creep-damage coupled effects:experimental investigation on bending beams with various sizes, *Journal of materials in civil engineering*, Vol.21, N°.2, 2009.

M.Omar, A.Loukili, G.Pijaudier-cabot, Y.Le Pape, Creep-damage coupled effects: experimental investigation on bending beams with various sizes, *Journal of materials in civil engineering*, 21, 2009.

N.Challamel, C.Lanos, C.Casandjian, Creep damage modeling for quasi-brittle materials, *European Journal of Mechanics A/Solids*, Vol.24, pp.593-613, 2005.

N.Reviron, F.Benboudjema, J.M.Torrenti, G.Nahas, A.Millard, Coupling between creep and cracking in tension, *Fracture Mechanics of Concrete and Concrete Structures*, 2007

P.Bocca, M.Crotti, Variations in the mechanical properties and temperature of concrete subjected to cyclic loads, including high loads, *Materials and structures*, Vol.36, pp.40-45, 2003.

P.Rossi, N.Godart, J.L.Robert, J.P.Gervais, D.Bruhat, Investigation of the basic creep of concrete by acoustic emission, *Materials and Structures*, Vol. 27, pp.510-514, 1994.

RILEM 50-FMC Recommendation, Determination of fracture energy of mortar and concrete by means of three-point bend test on notched beams, *Materials and Structures*, Vol.18, pp.285-290, 1985.

RILEM TC212-ACD Recommendation1, Acoustic Emission and related NDE Techniques for Crack Detection and Damage Evaluation in concrete.

R.L.Carrasquillo, F.O.Slate, A.H.Nilson, Microcracking and behavior of high strength concrete subject to short-term loading, *ACI Materials Journal*, 1981.

Z.P.Bazant, R.Gettu, Rate effects and load relaxation in static fracture of concrete, *ACI Materials Journal*, V.89, N°5, 1992.