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RESEARCH PAPER

An Experimental Study of Acoustic Emission Monitoring on Cement-based Material under Compressive and Tensile Indirect Tests

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Abstract
Acoustic emission method can monitor the solids' fracturing process during a period of time, and this method is extensively used in studying the fracturing process and inspections. In the present study, tensile splitting and uniaxial compressive tests were done on concrete sample accompanied by AE (acoustic emission) monitoring. The chart of AE parameters was analyzed and regarding that, the parameters include energy, energy cumulative values as well as amplitude values, duration, average frequency, rise angle, b-value, and improved b-value relative to the stress applied to the specimens during the loading time were investigated. Based on the results, most of the crack growth signals in tensile splitting tests were tensile crack signals, and there were fewer shear crack signals; however, in uniaxial compressive tests, there were more shear cracks. Moreover, the b and Ib-values can be used for predicting damages in large scales during the fracturing process in specimens, based on AE parameters.

Keywords: Acoustic Emission, Crack Propagation, Concrete, Crack Type Classification, Monitoring.

Introduction

Acoustic emission test is a nondestructive testing method. When a solid material is under stress, its defects create high-frequency acoustic waves. These waves are emitted in the material and could be received by AE sensors; by analyzing these waves, the defect type, its location, and its severity will be determined (Hampton, 2012). Totally, AE in concrete and rocks can be created by pores and micro cracks closure, displacement among micro cracks surfaces, micro cracks formation and propagation, intergranular displacement, and failure (Grosse & Ohtsu, 2008).

Determining the rock damage quantity by using the AE energy recorded during the uniaxial compressive test have been studied (Khazaee et al., 2015). The AE energies recorded during the uniaxial compressive test on the rock specimens ranging from weak to very strong have been analyzed by studying the changes in the b-value, the total energy recorded, and the maximum energy recorded for each test. Classifying the crack type has been investigated using a type of AE produced during the cementitious materials compressive test. The results showed that as the size of coarse aggregate in the concrete increases, the AE events related to shear crack decrease and the b-value reaches its minimum at peak loading and the AE related to shear crack extremely increases (Sagar, 2020).

The effect of induced micro cracks by temperature on the fracturing mechanism of rock specimens have been investigated. Their research results showed that considering the AE

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method, as the induced micro-cracks caused by temperature increase, the ratio of shear micro-cracks to compressive micro-cracks increases during loading (Khodayar, 2016). The effect of silica nanoparticles on the fracture mechanism and strength of cement-based materials by using AE system have been investigated (Nazeri et al., 2016). Based on their results, the concrete produced with silica nanoparticles had the most rise angle and the least average frequency compared to normal concrete. Therefore, most of the micro-cracks were tensile in normal concrete specimens and were shear in nono concrete specimens. In fact, a change of behavior was observed from tensile mode to shear mode in the specimens. The quartzite AE under compressive loading have been monitored. Based on their results, the fracturing process of a brittle rock greatly depends on the formation and propagation of crack. The total strain energy saved by the sample has been suddenly released (Prateek et al., 2016).

The AE and mechanical features of rocks in various sample sizes have been investigated (Yan et al., 2017). Their results show that the sample size scale affects the events maximum and AE amplitude. The effect of concrete sample particles size on the features of AE under uniaxial compressive loading have been investigated (Wu et al., 2017). According to the results, there is a nonlinear relation between AE and stress surface, and the AE cumulative value has been shown in nonlinear growth maximum stress as the concrete particle size increases. The fracturing and AE signal features of the sample under uniaxial loading have been analyzed (Chen et al., 2017). Based on their results, using the 3 parameters (the frequency range of maximum energy, energy percentage maximum, maximum instantaneous energy), it is possible to predict the sample failure and use it for improving the accuracy and performance of alarm systems. The fracture in sandstone under uniaxial compressive loading by using AE have been predicted (Niu et al., 2020). According to their results, macro crack leads to a quick decrease in b-value. When the specimens experience final fracture, b-value reaches minimum level. The effect of AE on the crack emission mode during Brazilian Crack have been investigated (Zhang et al., 2021). Their results indicated that the amplitude of AE signals increase accompanied by loading stress. More than 99 percent of crack signals were classified as tensile mode, and there were a few shear cracks occurring during Brazilian test. The central frequency of tensile crack was 138.58 kHz. The effect of damage in AE parameters investigated (Farhidzadeh et al., 2013; Carpinteri et al., 2013). The crack propagation in concrete using AE method analyzed experimentally (Zaki et al., 2015; Saliba et al., 2015). The crack propagation in laboratory tests, AE, and fracture mechanics investigated (Stoeckhert et al., 2015). Also the fracture and AE signals features investigated (Nikkhah et al., 2011; Rodriguez, 2016; Koumoudeli, 2018; Munoz et al., 2019; Jung et al., 2020; Thirumalaiselvi et al., 2020; Zhang et al., 2020). The energy parameters in cumulative form have been used to determine the Kaiser Effect point (Kharaghani et al., 2021). The cumulative energy with respect to time was plotted and where a significant increase in the energy parameter was considered as the Kaiser Effect location. In addition, wavelet transform have been used to process acoustic emission signals for determining Kaiser effect point (Dinmohammadpour et al., 2022).

Materials and Methods

Specimens Preparation

In order to do the tests, artificial concrete specimens were used. These specimens were provided with mix design and specific materials. The mix design for providing the artificial concrete specimen includes a combination of sand, cement, lime, and water. The mixing ratio has been based on weight: sand to cement = 3 to 1, sand to lime = 3 to 0.25. The sieve analysis was done to obtain the granulation curve of the sand used in the mix design. The graph of the particle size distribution of the used sand in the preparation of specimens is shown in Fig1.

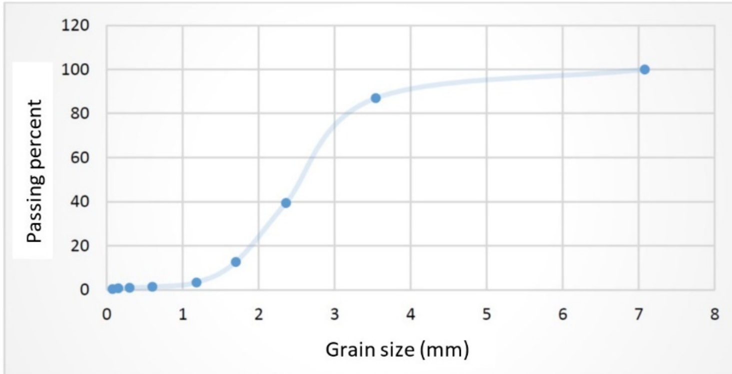

Figure 1. Particle Size Distribution of aggregate by Sieve Analysis

Moreover, the water added to this combination has been 0.25 ratio to sand and 0.75 ratio to cement. For exiting bubble and causing vibration while concreting, ASTM standards have been applied in a way that specimens were taken out of the mold and put in water tank after stirring the materials put in the mold and after the passage of 24 hours since concrete placing. Then, after 7 days since putting the concrete in the mold, the specimens were left in open air to become ready for testing. Finally, 6 cylindrical specimens (diameter = 10, height = 20) were prepared; the concrete placing stages and mix design were considered the same for all specimens. Sieve analysis was performed for gaining the sand sieve curve in the combination in a way that the total weight of the materials equals 1.5 Kg, vibration time and device screening equals 10 minutes.

Mechanical and physical properties of the specimens

Totally, 6 cylindrical specimens were built for gaining the mechanical properties of the mix design. Uniaxial compressive strength test and tensile splitting test were done on them. Also, tensile splitting and uniaxial compressive loading test were performed on 4 cylindrical specimens accompanied by AE monitoring; in the following, all the tests performed will be explained. Fig. 2 shows the tensile splitting and uniaxial compressive strength tests. The mechanical and physical properties of the specimens are given in Table 1 and Table 2, respectively.

Testing Method

For performing the tests aiming at determining the tensile and compressive strength of the cylindrical specimens, the device in the rock mechanics laboratory of Shahrood University of Technology was utilized. This device has been manufactured by Controls in Italy and has a hydraulic compressive jack capable of 3000 KN as well as the possibility of automatic measuring and recording the results by 8-channel data logger. The uniaxial compressive loading test was done on 2 cylindrical specimens, and tensile splitting test was done on 2 cylindrical specimens using the splitting method. Two AE sensors were mounted to the specimens for recording the acoustic waves emitted by specimens and for AE monitoring. In the present study, for AE monitoring, the device AMSY-6, made in Germany by Vallen, has been used. The sensor which was used, called VS900-M, is an AE piezoelectric sensor that has a frequency range of 100 to 900 KHz and its maximum frequency is 350 KHz. The software Vallen AE-Suite has been presented for accessing data and processing AE measuring data (Vallen System. 2020).

Table 1. Mechanical properties of the specimens

Specimen code	Uniaxial compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)
Pc1-u	21.80	---	21.94
Pc2-u	25.47	---	23.71
Pc3-u	26.48	---	24.18
Pc4-b	---	3.01	---
Pc5-b	---	3.39	---
Pc6-u	26.01	---	23.97
Average	24.94	3.20	23.45

Table 2. Physical properties of the specimens

Longitudinal wave velocity (m/s)	Dry Unit Weight (gr/cm^3)	Saturated Unit Weight (gr/cm^3)	Porosity (%)	Specific Weight (gr/cm^3)	Parameter
3546	2.14	2.23	1.29	2.11	value

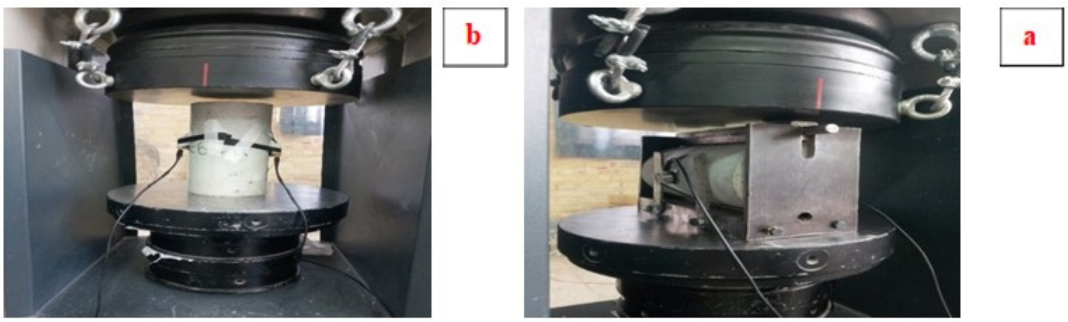

Figure 2. testing procedure, (a) tensile splitting test, (b) uniaxial compressive strength test

Results and discussions

In the present study, the parametric analysis (including count charts, energy and the cumulative values, amplitude values, duration, average frequency, rise angle, b-value, and its improved value compared to the stress applied to specimens) has been done during the loading process.

Frequency Spectrum Features of AE Signal

FFT (Fast Fourier Transform) is a spectrum analysis method for analyzing the non-constant signals; by performing FFT on AE waveform signals, the information of the frequency domain of waveform signals can be obtained. The features of the AE signal spectrum produced can determine the specimens condition and structure as well as their mechanical features. As the AE waveform changes from time domain to frequency domain, the frequency distribution norm can be gained, and the dominant frequency is defined as the frequency relate to amplitude maximum in spectrum (Zhang 2018). Having the waveform spectrum observed, it is clear that the dominant frequency of AE waveform signal is 129 KHz for uniaxial compressive tests and 126 KHz for tensile splitting tests. The signals received are mainly friction and tensile signals, as shown in figures 3 and 4.

The tensile signal is mainly a sudden signal that has high frequency and low amplitude happening normally at the early stages of the test which indicates the crack formation. The friction signals have low frequency and are divided into 3 types of amplitude: low amplitude, high amplitude, and the friction signal indicating the friction between cracks and the common contact surface.

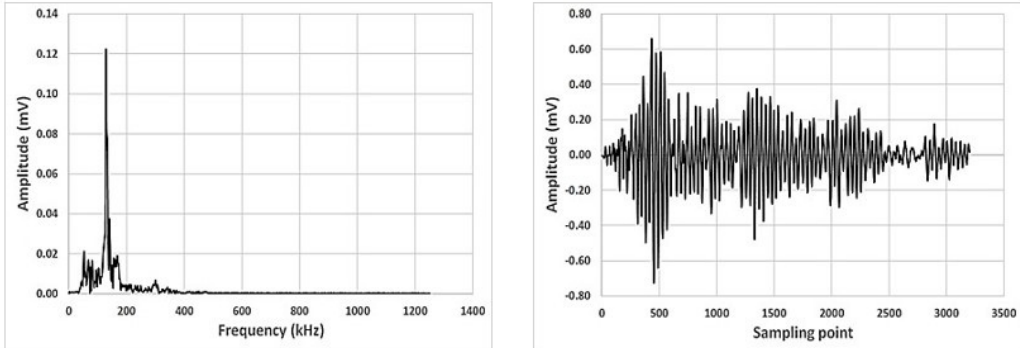

Figure 3. AE waveform and the signal frequency spectrum related to uniaxial compressive tests

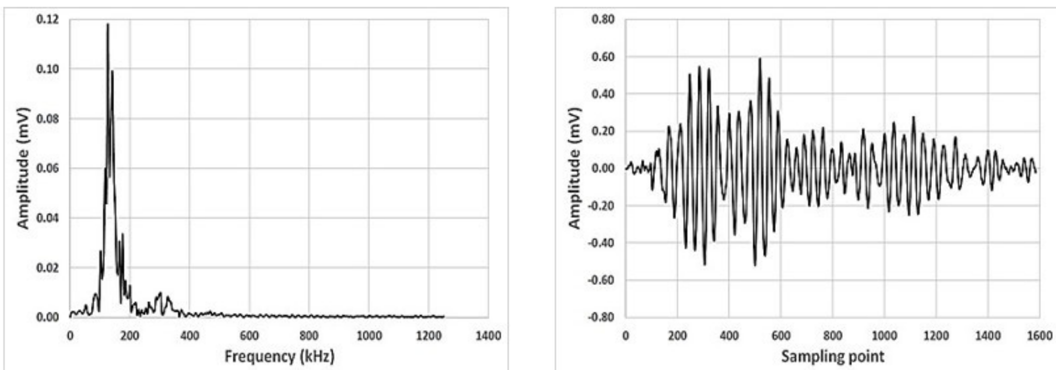

Figure 4. AE wave form and signal frequency spectrum related to tensile splitting tests

Low-amplitude low-frequency signals and average-amplitude low-frequency signals are mostly produced during the tensile splitting test along with some weak friction sounds. The high-amplitude low-frequency signals normally occur at the last moment of the test producing a loud noise, and the signal amplitude is several times bigger than low-amplitude signal (Hou et al., 2021).

AE Energy Parameter

Energy means the time-amplitude sub-chart area in an AE wave, and it is AE energy if higher than the threshold level. Fig. 5 shows the energy chart, the cumulative energy, and the stress applied during the tensile splitting and uniaxial compressive tests. There was totally less energy in the tensile splitting test specimens but it suddenly increases at the moment of the peak fracture. Unlike the uniaxial test, there was less AE before the peak fracture; however, in uniaxial test, there was plenty of AE before the peak fracture. In pc6-u and pc1-u specimens, the energy generation has gradually started from the beginning of the loading process, and the energy peak has occurred before the maximum stress due to formation of micro cracks in the sample; the early cracks and pores in the sample were compressed under uniaxial compression and energy gradually increases, but, in pc4-b and pc5-b, the fracture happens suddenly in a shorter time, and the energy suddenly increases. Various AE energy changes, AE cumulative energy, and stress were observed during loading time. AE energy change processes were basically simultaneous with AE monitoring change processes; in general, more AE energy was produced in uniaxial test. Moreover, the test time till the final fracture was less in tensile splitting test while applying stress to the sample. AE energy and the AE energy cumulative curve were similar to the changes of the stress applied to the specimens, that is, greater count with the highest energy level was related to the specimens experiencing most of the stress at the fracture moment.

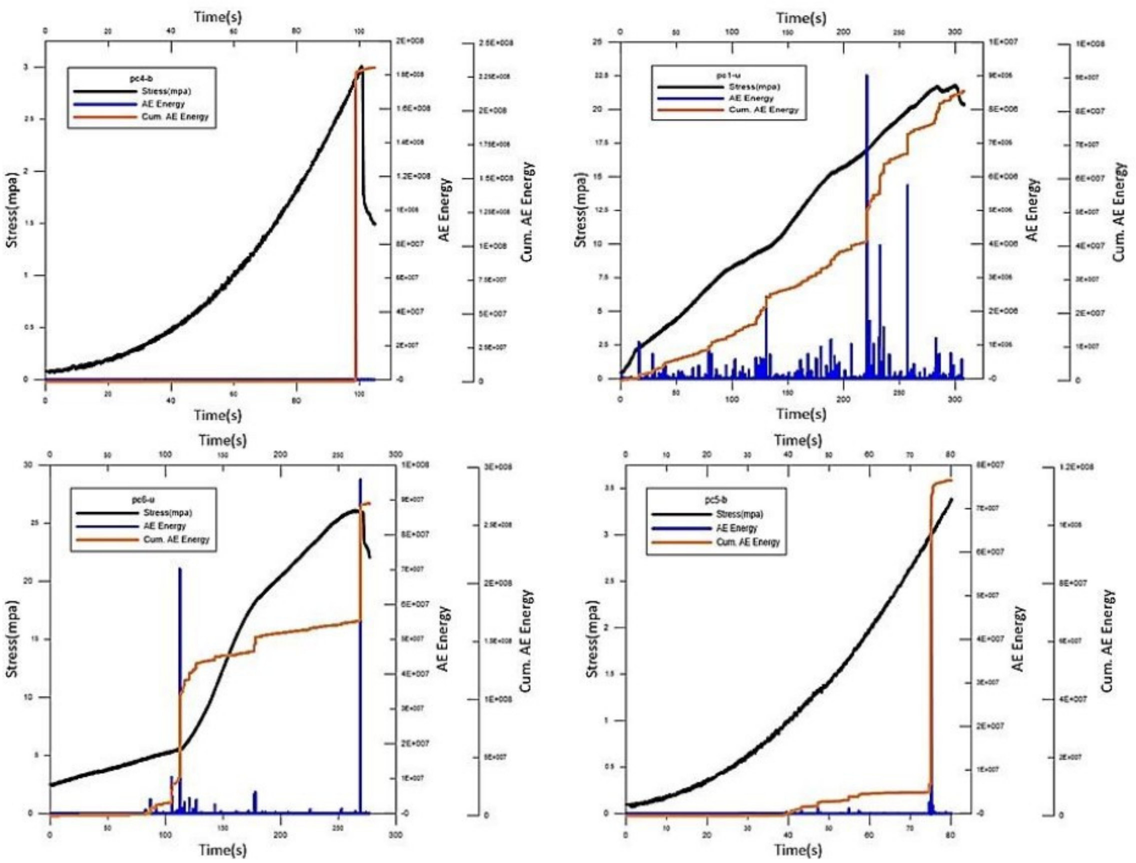

Figure 5. The chart of the changes in energy level, cumulative energy, and stress in tensile splitting (pc5-b, pc4-b) and uniaxial tests (pc6-u, pc1-u)

Cracks Classification

Assessment of the material failure process in different stages of damage along with the crack propagation mode is very important for better understanding of its mechanical behavior. To determine the cracking mode type, the parametric analysis method of acoustic emission data on rock and concrete materials is used (Prem & Murthy, 2017; Wang et al., 2017). Different crack modes emit different AE waveforms; the cracks classification can be studied by AE parameters. Also the cracks classification have been studied and analyzed the AE data by GMM (Gaussian mix modeling) (Farhidzadeh et al., 2013). Their results showed that this method can recognize the 3 stages of loading process: tensile crack formation, crack change, and shear crack formation (Sagar, 2020). The existing tensile cracks, compared to shear cracks, produce waves with low rise angle and high average frequency.

Average Frequency (AF)

AF means the ratio of the number of the counts to AE wave duration. This feature can be utilized for connecting the AE parameters to fracture mode and its analysis (Ohno & Ohtsu, 2010). Fig. 6 shows the AE parameter in a hit. AF could be calculated from equation 1; its changes chart as well as the loading stress during a period of time for tensile splitting and uniaxial compressive tests are shown in Fig. 7.

$$AF = \frac{Counts}{Duration} \quad (1)$$

AF is calculated in the 200 to 300 KHz range for uniaxial test and in the 150 to 200 KHz range for tensile splitting test. Such activities are due to formation of micro cracks in the sample because there is no apparent drop at the moment of the massive fracture. When the main fracture occurs, a sudden drop of AF happens in the sample. This sudden drop also exists in tensile splitting test but it is less than uniaxial compressive loading. AF decreases considerably after the main failure; for the specimens tested by uniaxial compressive method, this process is gradual and smoother.

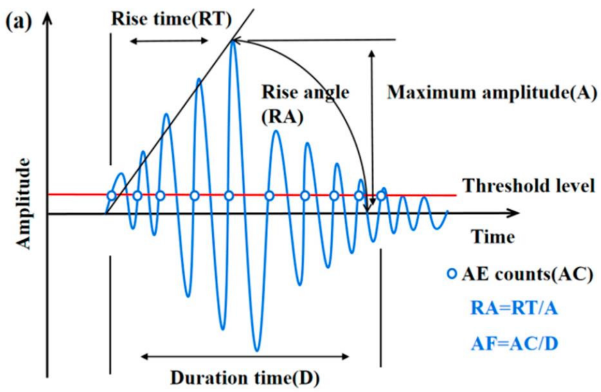

Figure 6. Typical AE waveform and AE parameter in a hit (Aggelis 2011)

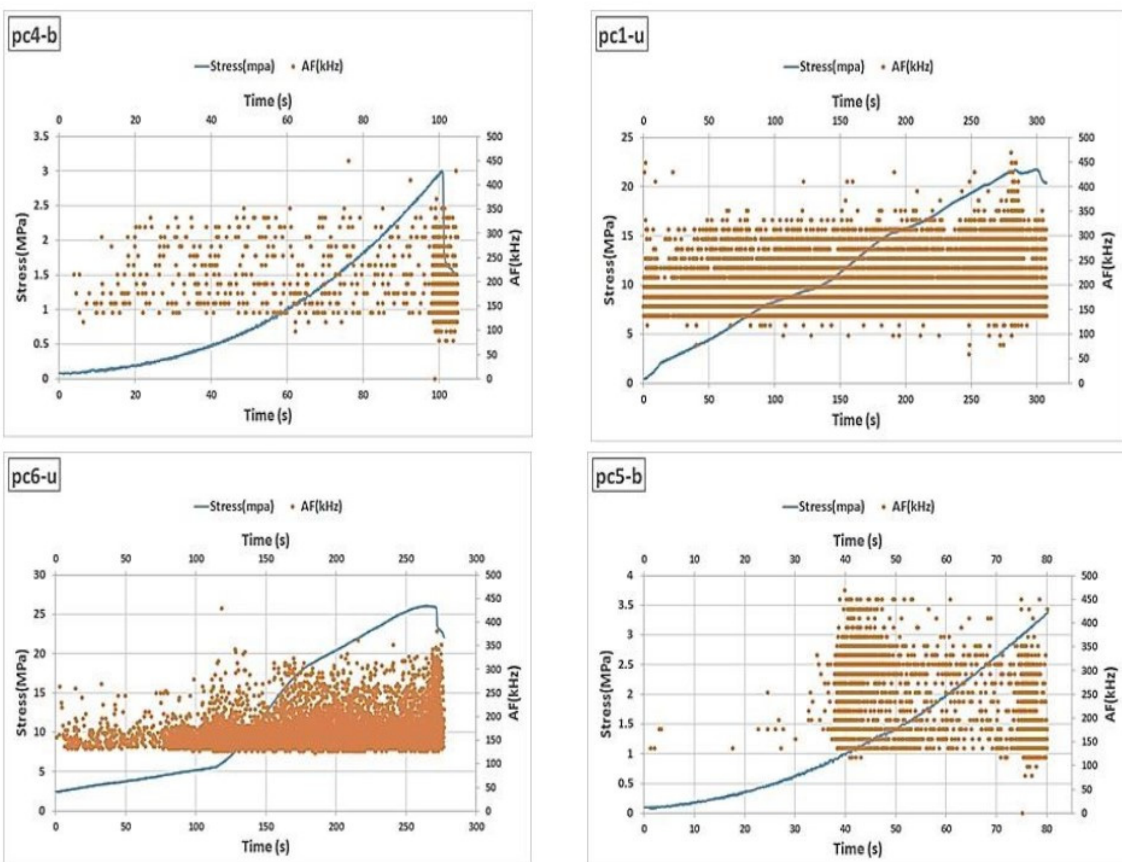

Figure 7. Chart of average frequency changes and loading stress in tensile splitting (pc5-b, pc4-b) and uniaxial (pc6-u, pc1-u) tests

As observed in Fig. 7, at the time of crack formation, AE activity is similar in both tests but, in the tensile splitting test, at the fracture moment, energy is suddenly released which leads to a sudden drop of AF. However, for the uniaxial test, the energy is released a bit down the location of sample fracture, and it is clear that the fracturing energy is gradually released.

Rise Angle (RA)

The ratio of rise time to AE wave amplitude is indicated by RA (Fig. 6). RA is calculated from equation 2 (Ohno & Ohtsu, 2010); its changes chart as well as the loading stress for tensile splitting and uniaxial tests during a period of time are shown in Fig. 8.

$$RA = \frac{Rise\ Time\,(RT)}{Amplitude\,(A)} \tag{2}$$

Based on Fig. 8, the tensile crack is determined as AE signal with high average frequency and low RA, and the shear crack is determined as AE signal with low average frequency and high RA. RA is a parameter used for describing the damage type which is stated as the ratio of wave increase time to amplitude called ms/V. Totally, RA is related to the wave form and considerably changes when the damage increases. In Fig. 8, a little decrease is observed in RA in the early stage of loading and the formation of stress applied to specimens. At the time of fracturing, RA increases for uniaxial specimens, and, as the stress increases, the RA increasing process is somehow fixed. On the other hand, the increase in RA is observable for tensile splitting specimens at the time of fracture. Totally, RA continues to increase till the end of loading and the sample fracture.

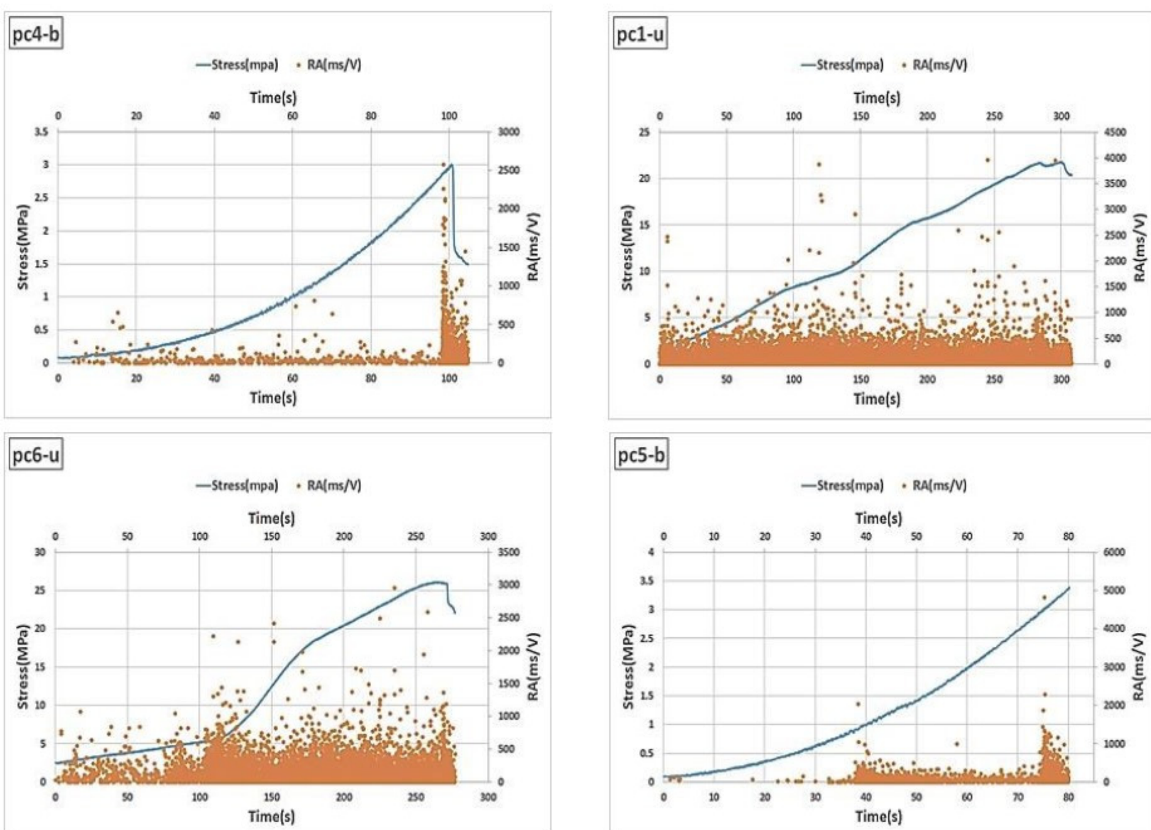

Figure 8. Chart of the changes of rise angle and loading stress in tensile splitting (pc5-b, pc4-b) and uniaxial (pc6-u, pc1-u) tests

Most of the RA changes occur before and after the fracture, and its changing process is slower for uniaxial test, but it is sudden for the tensile splitting test at the fracture time; based on Fig. 8, it is possible for AR to decrease in the first stage of fracturing (micro cracks formation) and to increase and continue increasing till the end of the second stage (macro cracks formation). In the last stage of fracturing (macro cracks opening), the decreasing process is seen again, and it, somehow, is vice versa for AF.

Cracks type classification

The cracking can be classified into two types of fracture mode namely tensile and shear cracks. The source type can be classified by tracking the characteristics of an AE signal to improve the understanding of the material cracking mode. These types of crack classifications are shown in Fig. 9. The tensile cracks exhibit a high average frequency (AF) and low Rise Angle (RA) values. In contrast, shear cracks occur close to failure corresponds to an AE signal with high RA value and low AF value (Ohno & Ohtsu. 2010; Aggelis, 2011).

As mentioned before, the shear cracks have lower average frequency and higher rise angle, compared to tensile cracks. The changes of average frequency and rise angle for the specimens are of great importance for determining the type of the signal received by the acoustic device. Fig. 10 depicts the classification of the cracks formed in tensile splitting and uniaxial tests. Based on the parameters analysis, in Fig. 10, the points above the line are classified as tensile and the points below the line as shear. In the tensile splitting test, the mode of crack propagation is tensile; most of the cracks were of this type, and there were few shear cracks. For the uniaxial test, cracks were of shear type, and tensile cracks formed in the early stages of specimens loading. Totally, AF increases but RA decreases before the fracture, and AF decreases when the main fracture occurs, and RA increases. Most of the signals of crack propagation are of tensile crack signal type in tensile splitting test, and there are less shear crack signals.

b-value Analysis

b-value indicates the strong and weak events in a way that micro crack causes numerous low-energy acoustic events which leads to high b-value cracking, however, macro crack creates low b-value. As the stress increases, micro cracks tend to coalesce; as the stress increases up to the fracture point, b-value decreases (Aggelis, 2011). In the first stages of loading up to the maximum strength of the sample, b-value increases when stress increases, it refers to the formation of micro cracks in the sample. Also, a sudden drop in b-value has been observed in the maximum stress stage which indicates the change in crack formation from micro to macro; formation of macro crack leads to a sudden decrease in b-value.

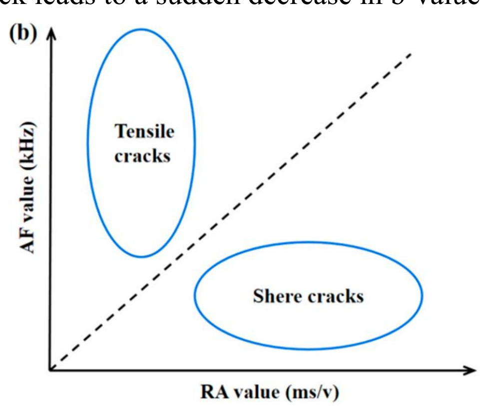

Figure 1. Crack classification (Aggelis 2011)

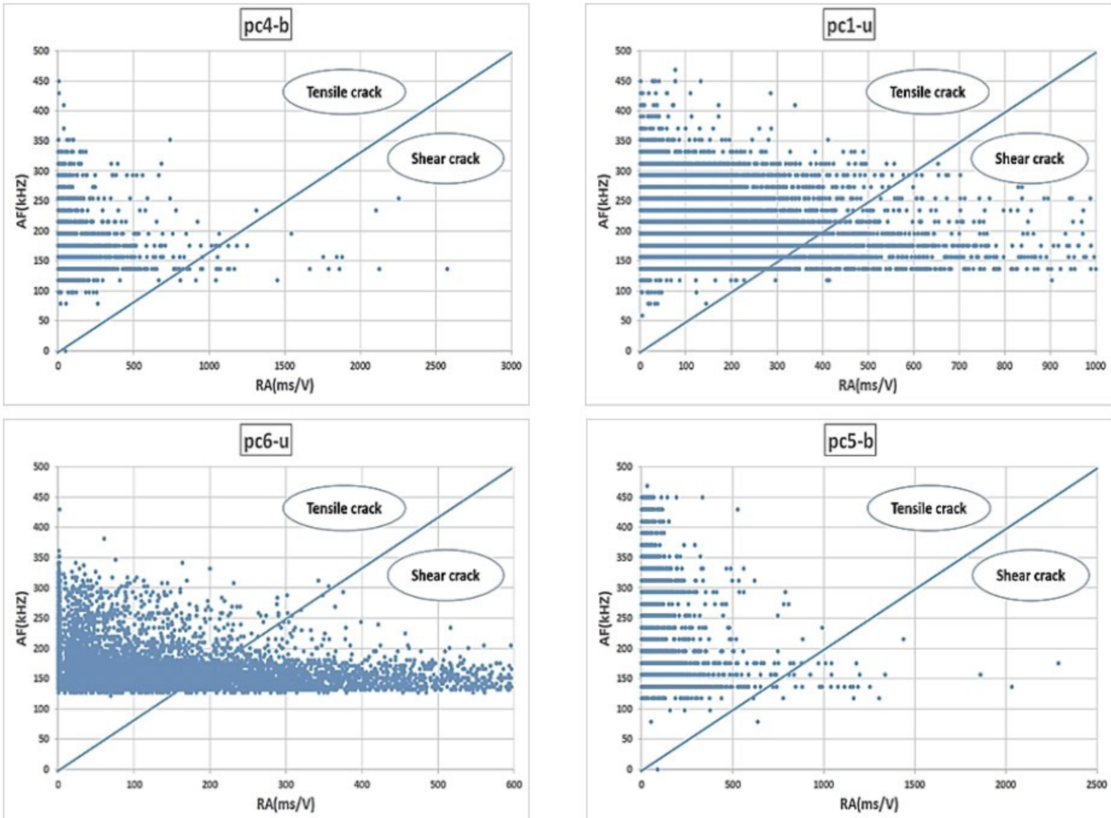

Figure 2. Cracks classification in tensile splitting (pc5-b, pc4-b) and uniaxial (pc6-u, pc1-u) tests

Therefore, b-value analysis could be done for understanding the crack formation nature (Aggelis, 2011; Thirumalaiselvi et al., 2020). Normally, b-value is extensively useful in seismology and is negatively calculated from linear-logarithmic graph between earthquake frequency and its magnitude (the number of earthquakes bigger than a specific earthquake). The Gutenberg-Richter relation for seismology is as equation 3 (Rao & Lakshmi, 2005).

$$Log_{10}(N) = a - b\,M \tag{3}$$

where a and b are the constants that depend on the tectonic condition of the range. M is the earthquake magnitude. N is the number of the earthquakes bigger than M in the range considered. b-value for AE is normally calculated from the Gutenberg-Richter relation which is between cumulative frequency and earthquake magnitude. The equation is as follows (Rao & Lakshmi, 2005):

$$Log_{10}(N) = a - b\left(\frac{A_{dB}}{20}\right) \tag{4}$$

where a and b are the constants that depend on the sample cracking condition. A_{dB} is the amplitude of signals created by events. N is the number of events with an amplitude bigger than AdB; the changes in the constants a and b are studied in the specimens intended. The b-value method has extensively been used for determining the features of the seismic waves formed during earthquake. b-value is calculated similar to the Gutenberg-Richter relation which is extremely useful in seismology. b-value has been used in analyzing the AE signal due to the similarity observed between seismic wave and AE waves. b-value plays a role in understanding the nature of crack formation and detection of macro cracks formation (Thirumalaiselvi et al., 2020). While the cracks are forming, AE events increase and cause a decrease in b-value. When the micro cracks occur in the first stage of cracking and when the macro cracks coalesce, b-value is high. Based on the previous studies, b-value less than 1.0 is in accordance with change from micro crack to macro crack (Zaki et al., 2015).

b-value measurement is performed on 50 events of the recorded AE data because, based on the reported literature, the number of the events must be between 50 and 100 (Farhidzadeh et al., 2013). In every set of amplitudes, the number of the counted AE events is calculated based on logarithm relative to the amplitude value divided by 20, then its chart is depicted. Based on the points gained, the linear fitness is depicted using the method of least squares; the slope of the fitness line shows the b-value. The time considered is the time of the last (50) event of the set. The chart of b-values for the specimens in uniaxial and tensile splitting tests is shown in Fig. 11.

The graphs in Fig. 11 are similar to Gutenberg-Richter relation; they have different slope of the origin and different y-intercept, and the equation of each line is written on them. The origin of the point is (0, 2.21) which is corresponding to the threshold level of 44 decibels considered for AE; the amplitudes less than the threshold level were not recorded. The y-intercept of the lines considered shows the number of the events that lead to AE signals; the less the y-intercept value, the less events recorded. With the help of the y-intercept of the values registered, the number of the events in the sample could be determined while the stress is increasing; for the tensile splitting test in which there is sudden failure and it occurs in a shorter range of time, there is somehow more y-intercept compared to uniaxial test, and there were more events leading to AE signals. The other point indicated by the charts is b-value which is corresponding to the line slope of each sample; in seismology, an increase in b-value indicates a decrease in the ratio of major earthquakes to minor earthquakes. When b-value increases, fewer major earthquakes happen. In tensile splitting tests, it is more in comparison with the uniaxial compressive tests; it indicates that when b-value increases, low-energy events have occurred; it could be due to micro cracks with less amplitude.

Ib-value Analysis

Ib-value is a parameter that is calculated from the data of AE amplitude distribution which includes filtering high and low AE amplitude via a selective method (Rao & Lakshmi, 2005). The distribution of AE amplitude changes during the test, therefore, the statistical values such as mean and standard deviation of every set of amplitudes were considered.

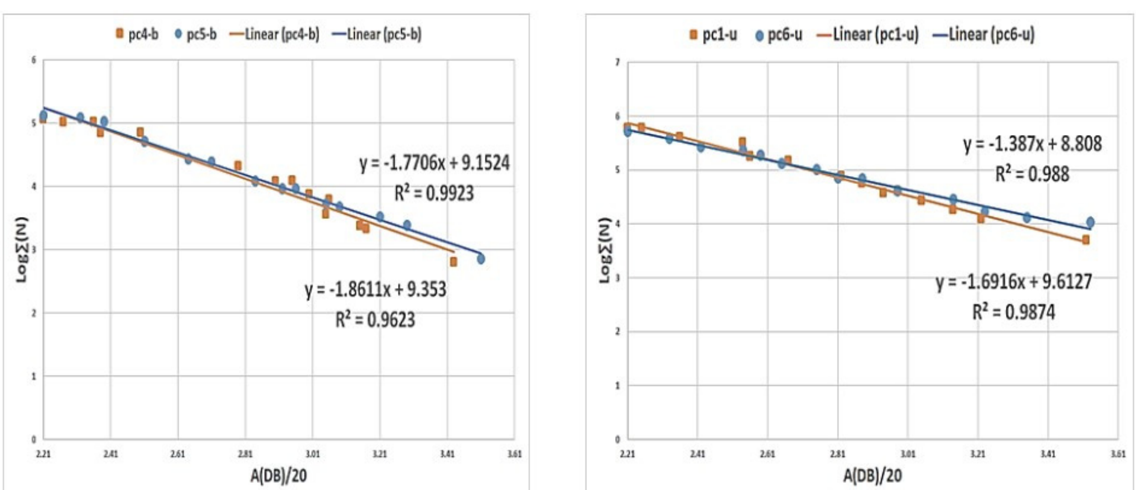

Figure 31. b-values in uniaxial (pc6-u, pc1-u) and tensile splitting (pc5-b, pc4-b) tests

The equation of the improved b-value which is utilized for evaluating the sample fracturing process have presented having considered the amplitude range (Shiotani et al., 2001); Ib-value is calculated as follows:

$$Ib = \frac{Log_{10}(N(\mu+\alpha_1\sigma)) - Log_{10}(N(\mu-\alpha_2\sigma))}{\sigma(\alpha_1+\alpha_2)} \quad (5)$$

where, μ is the amplitude distribution, σ is the standard deviation, and α1 and α2 are the constants defined by the user indicating the coefficients of high and low boundary of the amplitude (Shiotani et al., 2001).

Ib-value is a criterion for determining the crack propagation; any change in its value is related to the oscillation in the number of major and minor events in the sample i.e. the crack propagation process in various scales. Ib-value process indicates that the crack in the sample propagates suddenly or continuously. When its value constantly experiences oscillation, the ratio of major and minor AE events is preserved on the surface, and the micro cracks propagate stably in various scales. Too much oscillation in Ib-value indicates the sudden explosion of the crack propagation. And, its decrease before the damage indicates that AE events exist in larger scales, the cracks propagate faster and penetrate (Rao & Lakshmi, 2005; Aggelis et al., 2011). AE is extensively utilized in investigating the fracture mechanics which becomes possible with various analyses on the parameters. Ib-value is a numerical criterion of investigation fracture, therefore, it can act as alarm system in major structures such as tunnels, concrete bridges, and dams. The AE produced throughout the stages of the tensile splitting and uniaxial tests is analyzed by MATLAB software for calculating the improved Ib-value. In Fig. 12, the chart of the changes in Ib-value is depicted for the 4 tested specimens using MATLAB (two specimens under tensile splitting test, two specimens under uniaxial test).

Determining this parameter depends on the damage; with the help of this method, it is possible to determine the amount of the damage of the sample under loading and to show that Ib-value can lead to determination of the sample damage amount based on the acoustic events amplitude. Ib-value increases in the first stage of loading which indicates the increase in the micro crack events in specimens. When the stress increases, it increases that indicates that the ratio of micro crack events in small scale rise up drastically. Then, Ib-value varies in a small range indicating the stable progressive propagation process of micro cracks before the peak strength of the sample. At the peak strength point, Ib-value reaches maximum and then decreases and experiences a descending trend; its sudden decrease indicates major cracking events. The changes in this parameter, based on the constants defined, were about 2.5 to 4.5 for the high-boundary and low-amplitude coefficients, and the first stage (micro cracks formation in specimens) has an ascending process. This ascending process is gentler for tensile splitting test. As the stress is applied to the specimens, a momentary increase is observed in Ib-value due to the coalescence of micro cracks and formation of macro cracks. As the test goes on, one can observe that Ib-value experiences a descending process indicating crack propagation; at the fracture moment, Ib-value suddenly increases; this ascending process is done more suddenly in the tensile splitting test. Then, Ib-value experiences a descending process indicating the crack propagation.

After the beginning of loading, Ib-value is somehow high compared to the whole loading process; there are more micro cracks in the early stage, and numerous cracks form as the loading increases. The scale of the new cracks is greater than the first cracks, therefore, the ratio of major AE events gradually increases. Crack propagation approaches the sample failure, Ib-value experiences severe vibrations and reaches minimum. The great AE events exist in this process, and a great number of cracks start propagation and penetration in various scales. When the stress is maximum, Ib-value experiences severe vibrations; numerous changes in Ib-value indicate severe changes in crack propagation. When the micro crack occurs in the early stage of loading, Ib-value is high; when the macro crack beginning propagation, Ib-value is low.

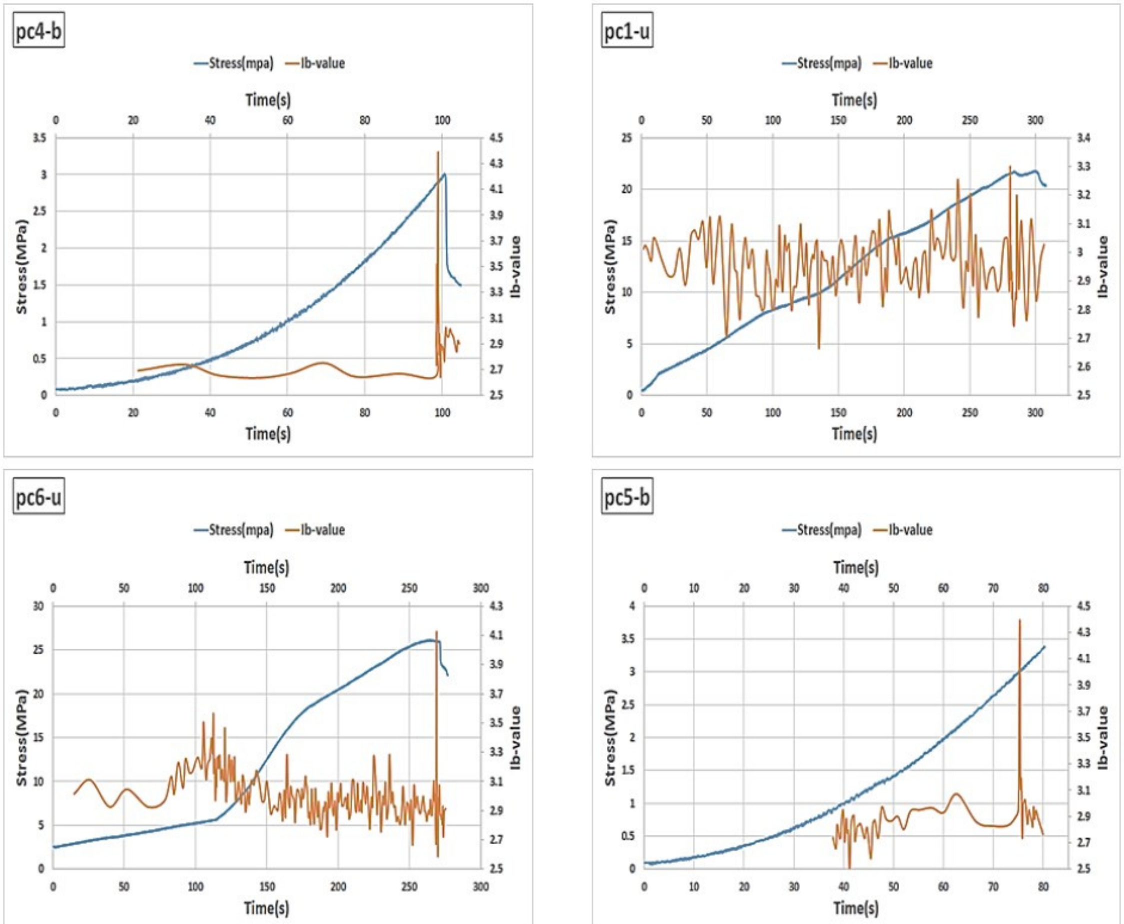

Figure 12. Ib-value changes chart and the loading stress for uniaxial test (pc6-u, pc1-u) and tensile splitting test (pc5-b, pc4-b)

This result can indicate the propagation of small shear cracks in the first loading cycle. Then, tensile macro cracks form that leads to the second cycle of loading.

Comparison of Ib-value and b-value

Ib-value and b-value were calculated using MATLAB software; in Fig. 13, the chart of their changes during a period of time is depicted along with the loading stress for tensile splitting and uniaxial tests. Macro crack releases the strain energy saved in specimens. b-value could be used for predicting macro crack in specimens.

b-value shows the ratio of high-amplitude AE signal to low-amplitude AE signal. Before the formation of macro cracks, AE events exist in specimens in small scales (micro crack), and the strain energy is continuously stored, and low-amplitude AE events are activated, and b-value is somehow high. When the macro crack occurs, the stored strain energy is released and causes the emission of high-amplitude elastic waves, and b-value decreases. Therefore, b-values can, based on AE parameters, be used for predicting the occurrence of damage in large scale during the fracture process of specimens. In the beginning stages of loading, the AE produced due to micro cracks causes an increase in b-value and Ib-value. These values, then, decrease and become fixed in the elastic transformation stage; at the end of this stage, the non-elastic volume transformation stage, a sudden fracture occurs due to the formation of numerous micro cracks in peak fracture surface, and b(Ib) values drastically decreases.

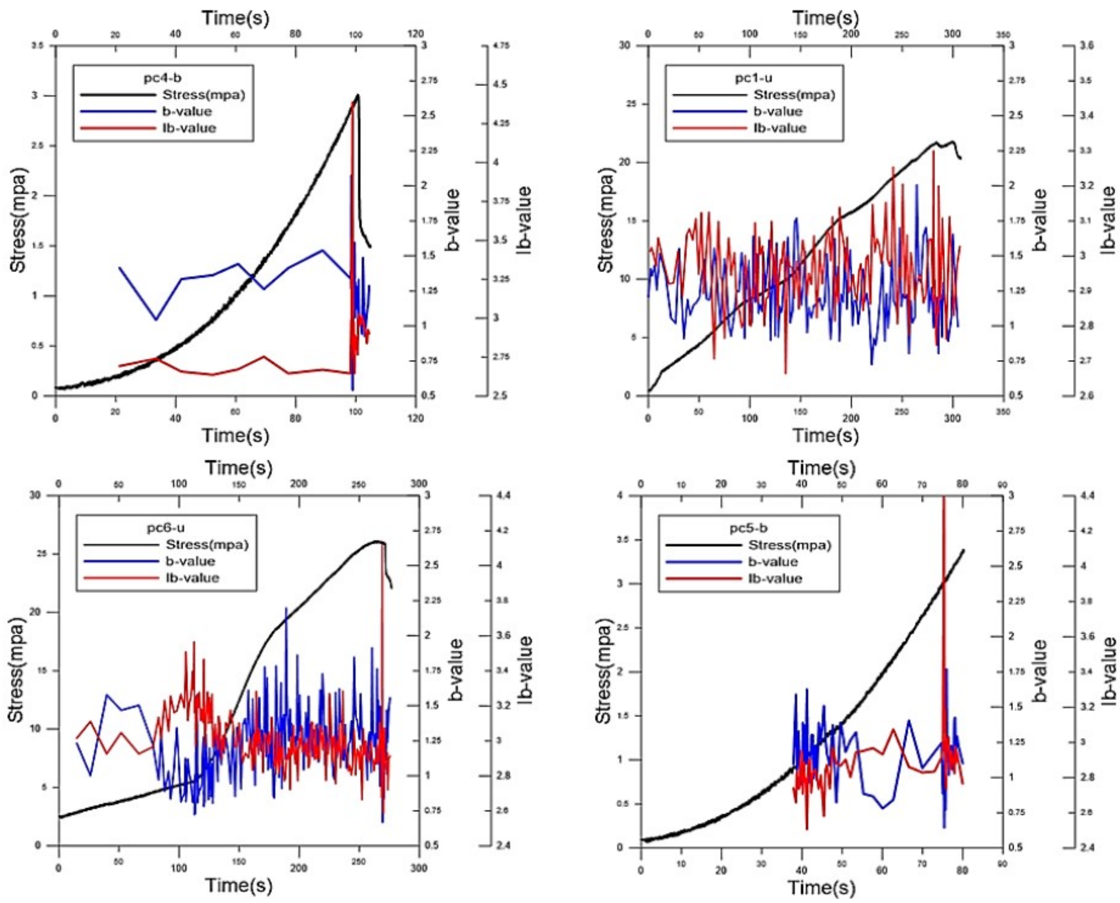

Figure 13. Chart of the changes in b-value and Ib-value and the loading stress for uniaxial (pc6-u, pc1-u) and tensile splitting (pc5-b, pc4-b) tests

As the stress increases, b(Ib)-value increases a bit which indicates going from crack formation towards new cracks propagation. The new cracks formed start an unstable propagation in terms of number and size in fracture plane of the specimens i.e. the stage in which b(Ib)-values is fixed; then, as the unstable crack starts, it causes its decrease until the time that the applied stress reaches the failure stress. b(Ib)-values decreases at the failure moment due to cracks coalescence and stress decrease. b-value is less practical for the specimens with low-amplitude AE signals formed during fracture, but the Ib-value calculated shows the process of the amplitude distribution regardless of the total amplitude distribution. For Ib-values, the AE cumulative events in the low-amplitude area do not affect the total slope because this value is calculated in a small area. Microcracks create low-amplitude AE events, while macrocracks have higher-amplitude AE. The low b-value indicates that more microcracks have appeared in specimens. While, Microcracks have less energy, but their large number causes high cumulative AE energy in the specimens. When macrocrack occurs, AE events with high amplitude and low b-value appear and the stored strain energy is released, leading to the emitted of elastic waves with high amplitude and low b (Ib)-values.

AE Amplitude Distribution versus Time Duration

The highest amplitude gained by AE is called amplitude, and the time interval between the first and the last AE wave crossing the threshold level (44 decibels) is called duration. AE amplitude distribution according to duration for the specimens in uniaxial and tensile splitting tests are shown in Fig. 14. Based on Fig. 14, AE activities for specimens under tensile splitting test in the stage before fracture (micro cracks propagation) were extremely less than the uniaxial test. It could be due to the concrete fracture behavior; because of micro cracks formation and compression of pores and early cracks in specimens under uniaxial compression, numerous AE events have occurred before the fracture. When macro crack occurs in tensile splitting tests, plenty of energy is emitted. The released energy in the tensile splitting test exists at the moment of the specimens' fracture, and the fracture suddenly occurs. The energy attracted by the specimens increases through performing the uniaxial test, but, at the same time, the maximum amplitude and AE signal energy decrease.

For the specimens pc1-u and pc6-u, under the uniaxial test, the AE events have less difference before and after the fracture indicating that, before fracturing, due to micro cracks formation, numerous AE events have occurred and energy has been gradually released. AE duration times for the specimens pc1-u and pc6-u are 0 to 7252 and 0 to 14389 microseconds, respectively. For the specimens pc4-b and pc5-b under tensile splitting test, more AE events occur after the fracture indicating that micro cracks have been formed a bit before fracturing and, at the fracture moment, the energy has been suddenly released due to macro cracks formation. The AE duration times for the specimens pc4-b and pc5-b are 0 to 8854 and 0 to 8158 microseconds, respectively. Although the frequency of the occurrence of AE in uniaxial specimens has been remarkably more, its maximum amplitude is a bit less than the tensile splitting specimens (96.5 dB versus 99.4 dB).

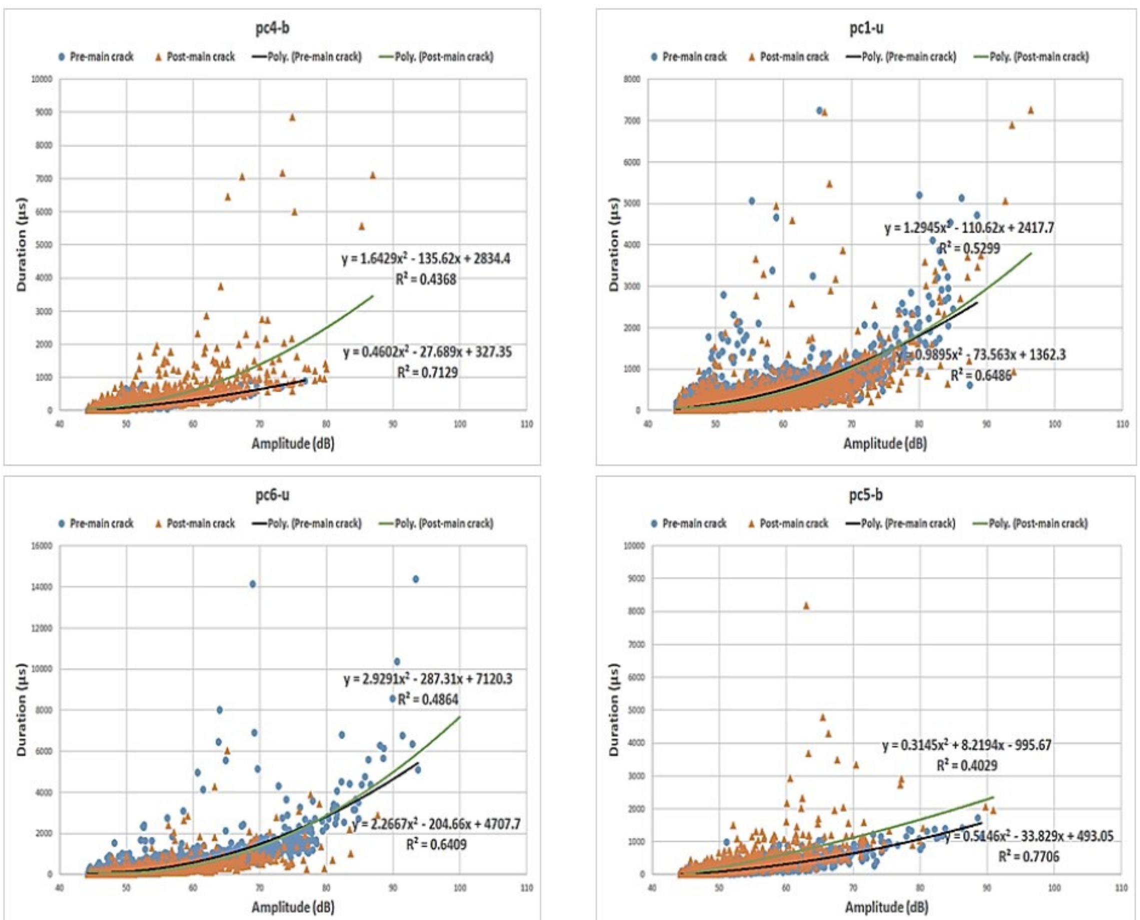

Figure 14. AE amplitude distribution versus time duration in uniaxial (pc6-u, pc1-u) and tensile splitting (pc5-b, pc4-b) tests

Conclusion

In the present study, tensile splitting and uniaxial compressive tests were performed on cement-based specimens along with AE monitoring. The AE different parameters including AE energy, energy cumulative values, amplitude, duration, average frequency, rise angle, b-value and improved b-value compared to the stress applied to specimens during the loading time were depicted and analyzed. According to the obtained results, the following conclusions are drawn:

Most of the crack propagation signals in tensile splitting tests are tensile crack signals, and there are less shear crack signals.

Low-amplitude micro cracks have mostly occurred in tensile splitting tests. b-value, according to AE parameters can be utilized for predicting damage in large scale during the fracture process in specimens. When the crack propagation approaches the sample failure, Ib-value reaches minimum. Ib-value changes indicate the severe changes in crack propagation; moreover, its sudden decrease indicates major cracking events.

AE activities for specimens under tensile splitting test (before the fracture stage i.e. micro cracks propagation) are extremely less than specimens under uniaxial compressive tests.

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