Acoustic Emission Monitoring of the Fracture Behaviour of Concrete containing various size and shape of glass aggregates

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ABSTRACT

Acoustic Emission monitoring during three-point load test on concrete blocks prepared using variety of glass aggregates indicates that the mode and nature of crack initiation and propagation is highly dependent on the composition and the type of aggregates. The mechanism of crack arresting and bridging can only be investigated using Acoustic Emission. The results obtained are encouraging and lead to increased understanding of cracking mechanism in concrete containing various types of aggregates, in particular, utilisation of waste materials to manufacture environmentally friendly concrete.

INTRODUCTION

Safe disposal of waste material is one of the major global environmental concerns. Pioneering work is being carried out in various countries to investigate the suitability of waste material such as rubber tyres, glass, polyethylene bags etc in the manufacturing of concrete. [1]
Concrete is utilised for the construction of most civil and non-civil engineering structures. However, health and safety and the integrity of a structure require a thorough understanding of the material behaviour under various conditions before being put into use.

The main basic ingredients of a concrete block are mineral cement, mineral aggregates, water and air. When these simple ingredients bond together they produce a very complex composite material. The complexity in the cement and water paste, in some cases with added additives to enhance the curing and setting properties, leads to more complexity when this paste entraps the mineral aggregates, air and water.
The interfacial bonding between the various phases is mostly responsible for the wide variation of strength in the manufactured block.

Generally aggregates are looked upon as an inert filler material and not much importance is given in regard to its influence on the properties of concrete and especially on the initiation and movement of cracks, micro-cracks and toughening mechanisms of cement based materials. Accordingly aggregates do play an important factor in determining the cost, workability and most importantly on the micro-mechanism of concrete. Therefore, no less respect should be given to aggregates than cement.

A number of toughening mechanisms take place when cracks initiate and propagate in the concrete. The location of these toughening mechanism sites is around the fracture process zone, which is the inelastic region around the crack tip. The two common toughening mechanisms are crack deflection and crack bridging. When a crack alters its position due to the presence of a strong aggregate blocking its travel path, crack deflection occurs, thus requiring more energy to

cause fracture. If the numbers of crack paths are more, the greater amount of energy is required to cause fracture in the material. When a crack passes beyond and through an obstacle (arrestor), which distributes stresses from one side of the main crack to the other, bridging occurs. This transfer of stress continues until the particle is ruptured or pullout occurs.

Although the evidence exists that the release of residual stresses/ micro-crack formation leading to permanent deformation in flexural tests, the mechanisms in action has not been observed due to the complexity of the material. [2]

Since concrete is a homogeneous material with multiphase features, its mechanical behaviour cannot be easily observed and understood. Several investigations to understand the behaviour of normal concrete under different loading conditions have been carried out using acoustic emission. [3, 4] However, very little attention has been given to the application of AE to understand the failure mechanism of concrete with different aggregates, and in particular the waste materials and optimise the quality of the manufactured blocks. Although study has been carried out with regards to increment of fracture energy with an increase in aggregate size in the form of sand, this investigation looks at the micro-behaviour of concrete in relation to toughening mechanism using waste glass and rubber in the form of the aggregates. This work also looks at the mechanism of crack bridging in concrete using AE.

The physical observation of micro-cracks, the crack arrest and the effect of crack bridging is not possible during the three point bend tests (flexural tests). With the aid of acoustic emission it is possible to monitor the micro-crack / formation during the test and follow the crack growth while the samples are under stress. Micro-cracking, de-bonding, crack-formation and crack growth are the main sources of acoustic emission signals in concrete.

This paper reports the results of AE monitoring carried out to investigate the effect of various type, size and quantity of aggregate on the fracture behaviour of concrete. A set of AE signal parameters recorded during the flexural test for different specimens are given. Additional investigation was carried out to look at the effect of expansive cement based concrete and addition of calcium carbonate to OPC under flexural test on AE activities.

MATERIALS AND METHODOLOGY

Several batches of cements based mortars (blocks of dimensions 210mm x 70mm x 70mm) were manufactured using ordinary Portland cement (OPC), an expansive cement and Calcium Carbonate ($CaCO_3$) added as an additive to OPC. In other batches a glass plate and or waste rubber / glass aggregates were added to investigate their effect on toughness and monitor crack initiation and growth.

Equal quantity of cement and aggregates were added into water. The cement to water ratio was 3 ratio 1(C: W = 3:1). The prepared paste was poured into a wooden mould and vibrated vigorously to eliminate air traps and create a homogenous mixture. A sharp blade of dimensions 20 mm x 1mm was placed on top of the casting to create a notch for monitoring the crack growth under the flexural load. After a period of initial setting of 24 hours, the casting was transferred to a moist environment for curing and post setting for a period of 28 days, (at ambient temperature and 75% of relative humidity).

Flexural / Three Point Bend Test

Three-point bend tests were carried out on the Denison Avery 7150 loading frame. A rubber pad was employed on all rollers to minimise the frictional noise and any unwanted vibration pick-ups.

The tests were carried out at a constant displacement rate of 0.25 mm/minute. The load cell amplifier output was connected to one of the parametric input of the AE system to record applied load to the block under test. The central roller was in an eccentric position with respect to the notch as shown.

The position of centre load point is significant in three-point bending test arrangement. Basically, the bending point curvature is a maximum at the centre roller position and not at the tip of the notch. The centre load offset produces two unequal moments (Force x arm length) in the specimen causing more damage and AE activity in the longer arm compared to the shorter.

The Stress σ applied to the specimen:

$$\sigma = \frac{My}{I} \qquad y = \frac{notchdepth}{2} = t/2$$

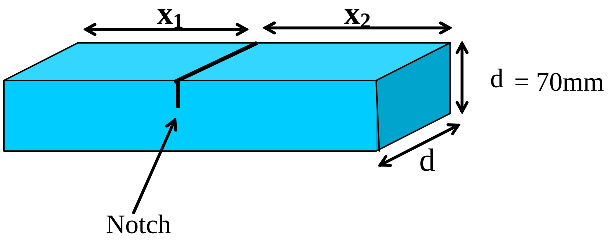
$$M = \frac{F}{2} \times \frac{x}{2} \qquad y = \frac{10mm}{2} = 5mm,$$

Therefore due to centre offset of 10mm, x_1 = 115mm, x_2 = 95mm

$$M = \frac{Fx}{4}$$

I = second moment of area m^4

$$= \frac{td^3}{12}$$



$$\sigma_1 = \frac{My}{I} = \frac{Fx}{4} \times \frac{t}{2} \times \frac{12}{td^3}$$

$$\sigma_1 = \frac{3Fx_1}{d^3} \qquad \sigma_2 = \frac{3Fx_2}{d^3}$$

The centre roller was offset near to one sensor, approximately 10mm. The offset of the central roller position changed the moment (force x distance) at the notch, causing more damage in the longer arm than the shorter. All tests had been carried out under the eccentric load condition.

ACOUSTIC EMISSION

The Vallen AMSY4 AE System was used to record the acoustic emission events produced when the block specimens were subjected to applied flexural load. On either side of the specimen, two resonant transducers of frequency 150 kHz were attached using silicon grease. The AE data was analysed using Vallen visual AE software. The signal waveforms received by the probes were recorded using the two transient recorders for frequency domain analysis.

RESULTS AND DISCUSSION

Concrete blocks manufactured with various types and sizes of aggregates were kept under humid condition for a period of 28 days. These blocks were subjected to eccentric three point bending load. The AE activity recorded during the test was evaluated to investigate the affect of composition and various aggregate had on the crack arrest initiation and growth. The signal waveforms were separately analysed using unsupervised classification.

The effect of composition on strength and AE signal parameters

Batches of concrete blocks were manufactured using three types of cement and another batch containing a glass plate and glass aggregate added to the 3 different type of cement. Flexural tests were carried out to study the effect of composition and aggregates.

Comparisons of fracture load (strength) of plain concrete samples indicate that addition of $CaCO_3$ to OPC enhances toughness of the block by relaxation of residual stress (micro cracking) under load.

Sample containing $CaCO_3$ showed an increase of 60% strength over OPC block, (load 2.82kN to 4.50kN). Similar results were obtained with blocks containing glass aggregates and a glass plate to deflect cracks and arrest crack propagation through the block respectively.

The results of the blocks containing a glass plate are shown in figure (1) a. It can be seen that the load versus time plot is less skew and become smooth when the load is transferred to the glass plate (linear region). When the crack arrested by the plate overcomes the obstacle, an energetic event occurs and the block fractures. The strength of the block containing $CaCO_3$ is higher than the OPC block. See figure (1) b.

The test results of the blocks containing a glass plate and glass aggregates are shown in figure (1) c. From the load and hits versus time history multi-plots it is apparent that the glass aggregates display inhomogeneous nature of the block. The path of cracks is more skew as a result of resistance offered by the glass aggregates. When the crack reaches the glass slide the load is transferred to the slide, the slope in the load versus time plot changes, until the crack overcomes this obstacle. The number of hits and load is higher for the blocks containing $CaCO_3$ and manufactured using the expansive cement.

The effect of crack bridging on AE signal parameters

GLASS AGGREGATE

The results of the three point bending test on concrete blocks containing various sizes of glass aggregates are shown in figure 2. The load carried by the tested blocks increases progressively with the size of glass aggregate, increasing from 2.6kN for 1mm to 3.2kN for 4mm. The hits versus time plots show that 3 and 4mm glass aggregates offer stronger resistance to the cracks and leading to high energy, high event duration pull out events (sudden load drop). The time taken from the maximum load to final fracture depends on the number of these pull out events and degree of porosity in the tested block.

A batch of expansive cement containing various sizes of glass beads was prepared. The flexural test results of a block containing 3mm diameter beads are shown in figure 2e. The smooth surface of glass bead facilitates easier crack movement leading to adverse effect on flexural strength. A comparison with OPC containing 3mm waste glass aggregates indicates a drop of 10% in strength. As shown in figure 2e, the load versus time plot is smooth indicating progressive crack development and a final sharp quick brittle fracture. The highest energetic recorded events from pull out and large size crack growth had peak amplitude within 70dB, and event duration of 1200µs.

Glass Plate and Glass Aggregates

The load versus time plot for the OPC samples (i) containing glass plate (ii) glass plate with glass aggregates is shown in figure (3). It can be seen in figure (3) a, that after a period of 110.54 seconds the crack arrested by the glass plate bridging overcomes the obstacle giving rise to few high amplitude, long event duration and short rise time events (93.8 dBs, 4000 µs and **50** µs**).**

In the case of sample containing both glass aggregates and glass plate it is evident in figure (3) b that after a period of 111 seconds, the load is transferred to the glass plate (changed slope) and the crack after propagating from the notch is completely bridged by the plate. The crack overcomes this obstacle with a sharp load drop after 156.25 seconds, producing high energy, long duration and short rise-time events. The glass aggregates then become active by deflecting the crack causing a number of major pullout events before final fracture of the block.

It is apparent from the hits versus time, amplitude versus duration and location versus amplitude multi-plots, shown in figure (3) a, b; that the extra AE activity is the result of addition of glass aggregates to the concrete block. It is conspicuous from the flexural test results of these blocks that the additional sources of AE are due to deflection of crack, arrest of crack, pullout events at glass aggregates and major pullout events at porous regions.

Rubber aggregates

The results of AE monitoring during flexural tests of concrete blocks containing various size of rubber aggregates are shown in Figure 4. The two major effects of waste rubber addition to the concrete block are: (i) Drop in strength and (ii) increase in attenuation

Increasing rubber content leads to decrease in flexural strength. This may be due to change in water cement aggregates ratio, increased porosity and poor interfacial bonding between cement paste and the rubber.

Addition of rubber in concrete alters the sound propagation characteristics, causing more scattering and absorption of the energy at rubber mortar interface. This attenuation resulted in heavily damped AE signals, highest recorded peak amplitude was in the range of 65 to 85dB and

most of these high-energy signals had event duration within 1000µs. AE waveforms recorded contained only 2 or 3 modes and were heavily damped.

Sample	Load (kN)	Max Duration (µs)	Max Peak Amplitude (dB)
100gm of waste rubber aggregates	3420	600	85.9
150gm of waste rubber aggregates	3360	590	80
200gm of waste rubber aggregates	2820	730	73.1
250gm of waste rubber aggregates	2700	998	66
OPC concrete	2820	12200	88
530gm of waste glass aggregates	3240	9500	94
530gm of waste glass aggregates (3mm)	3360	4100	93.6
530gm of waste glass aggregates (2mm)	2940	14500	93.6
sample 10 (GP + PAgg 4mm)	2640	4520	93.6
cara 2 (GP + Ca CO_3 + GAgg)	3000	7200	93.6

Load and the AE parameters

UNSUPERVISED CLASSIFICATION OF AE WAVEFORMS

AE SIGNAL WAVEFORMS

The signal waveforms recorded during flexural tests were analysed using unsupervised classification to differentiate various sources of AE and to discern the affect various additives and aggregates have on the emitted and transmitted energy through the block. One set of signal waveform data (7632 data sets) for an OPC containing 4 mm of glass aggregates was evaluated using visual class. The features were extracted automatically and grouped in 5 clusters containing a minimum of 50 members. An analysis of these clusters provide indispensable source characterisation, for example, signals grouped as cluster 1 belong to mostly high energy events namely crack jumps, pull-outs, crack increment, growth etc. as shown in figure (5). Statistical results of feature extraction, classification and clustering of this sample is shown in figure (6). It can be seen that 367 events (4.8%) belong to this category of damage in the sample. To investigate the suitability of this unsupervised classifier it was then applied to other block samples of this batch. The results obtained are summarised in histograms in figure (7). Cluster 5 is a major source of an AE event in all blocks with approximately 50% of the waveforms and cluster 4 belonging to another event with approximately 17% members. The presence of additives or aggregates in the concrete block does not appear to change the population of clusters 4 and 5.

It may be concluded that these events are from sources like micro-cracks, roller friction, and etc. characteristics of the flexural test condition.

The AE waveforms recorded for another batch of concrete samples manufactured using waste materials like rubber and glass were subjected to similar treatment. An OPC block containing 4mm waste glass aggregate was automatically clustered using

unsupervised classification and then applied on to other samples of the batch. The results of the feature extraction, classification and clustering are summarised in the histograms in figure (7).

There are obvious similarities of classification results between the two very different batches of concrete possessing different physical and mechanical properties, indicating existence of similar damaging mechanism under flexural test condition. A summary of the result of classification is as follows:

- **Feature extraction, grouping and clustering of AE signals provide valuable information about the fracture characteristic of the material.**
- **Signals grouped as cluster 1 are energetic damage events providing the number of pullouts, crack jumps and growth.**
- **Cluster 4 and 5 represents roller friction and other less energetic events characteristic of the flexural test conditions.**
- **Cluster 2 and 3 are representative signals cause by the addition of additives in the block.**

Scanning Microscopy and Ultrasound characterization of concrete

The fracture behaviour of the concrete blocks containing various aggregates using scanning microscope and ultrasound was carried out. The results, which support the AE monitoring data of flexural test, will be reported elsewhere. Some typical optical micrographs of the fractured sections are shown in figure (8).

CONCLUSION

The AE monitoring of concrete blocks under Flexural loading has shown that it has potential advantage over other techniques in understanding the toughening mechanism, strength and fracture behaviour of the material especially when the blocks were manufactured using various types of cement and different size, shape and kind of aggregates.

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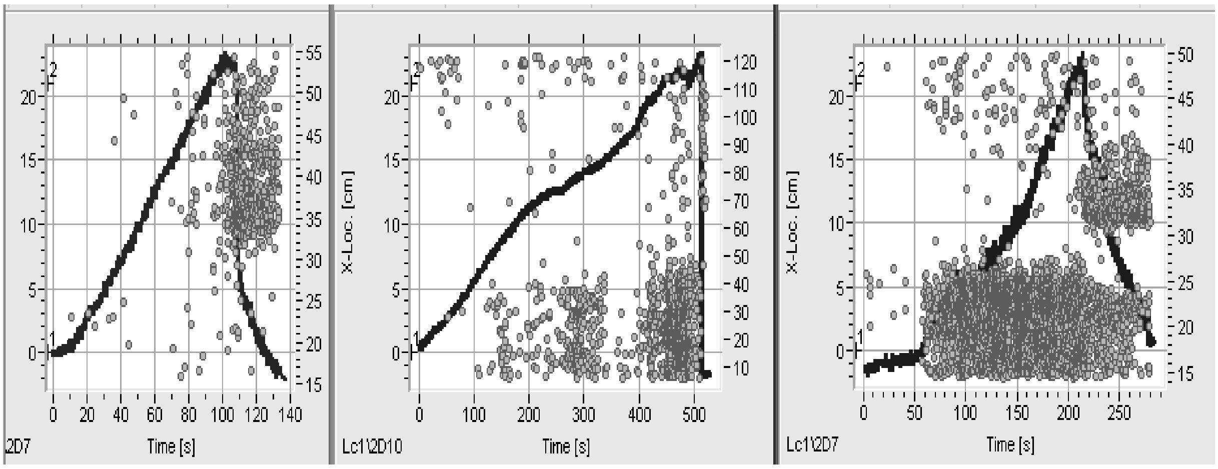
[2] H. W. Chandler, I. J. Merchant, R. J. Henderson, D. E. Macphee, A. M. Siddiqui, K. Fraser, Enhancing the toughness of cement based materials, Brittle Matrix Composites 6, Warsaw, October 2000

[3] A. M. Siddiqui, A. H. Choudhury, S. Jihan, Acoustic emission monitoring of cracks in Cement based materials, British Institute of Non-destructive Testing, Conference Proceedings, September 2002

[4] Keru Wu, Bing Chen and Wu Yao, Study of the influence of aggregate size Distribution on mechanical properties of concrete by acoustic emission Technique, Cement and Concrete Research, Volume 31, Issue 6, May 2001, Pages 919-923.



a. b. c.

Figure1 load /location ~ time plot (opc +gp, caco+gp, caco+gp+ga)

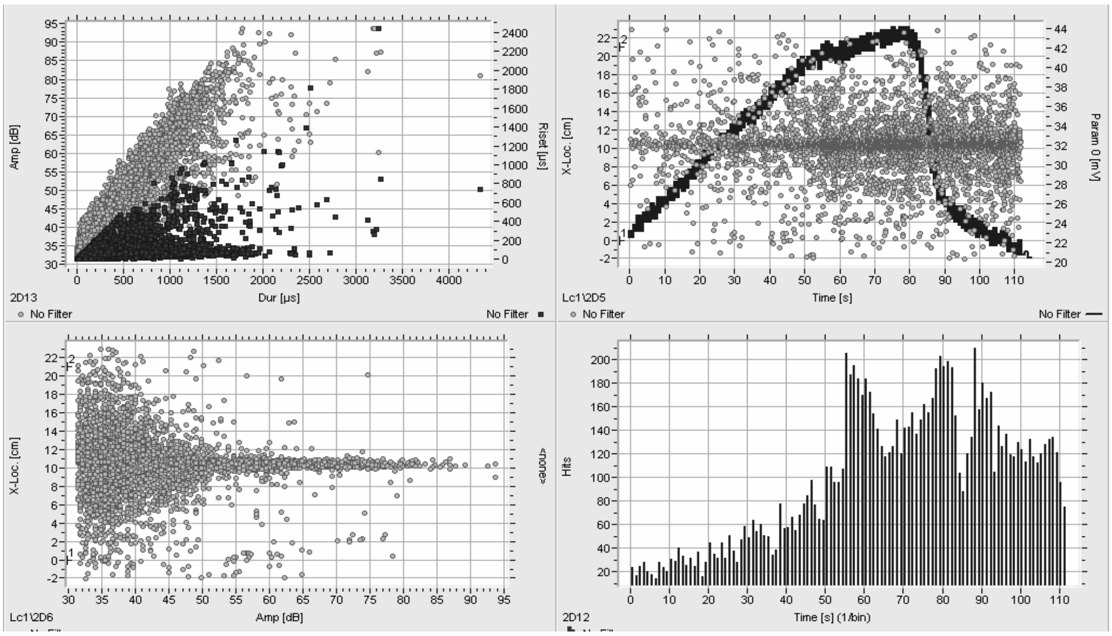


Figure (2) a: Glass aggregates 1mm

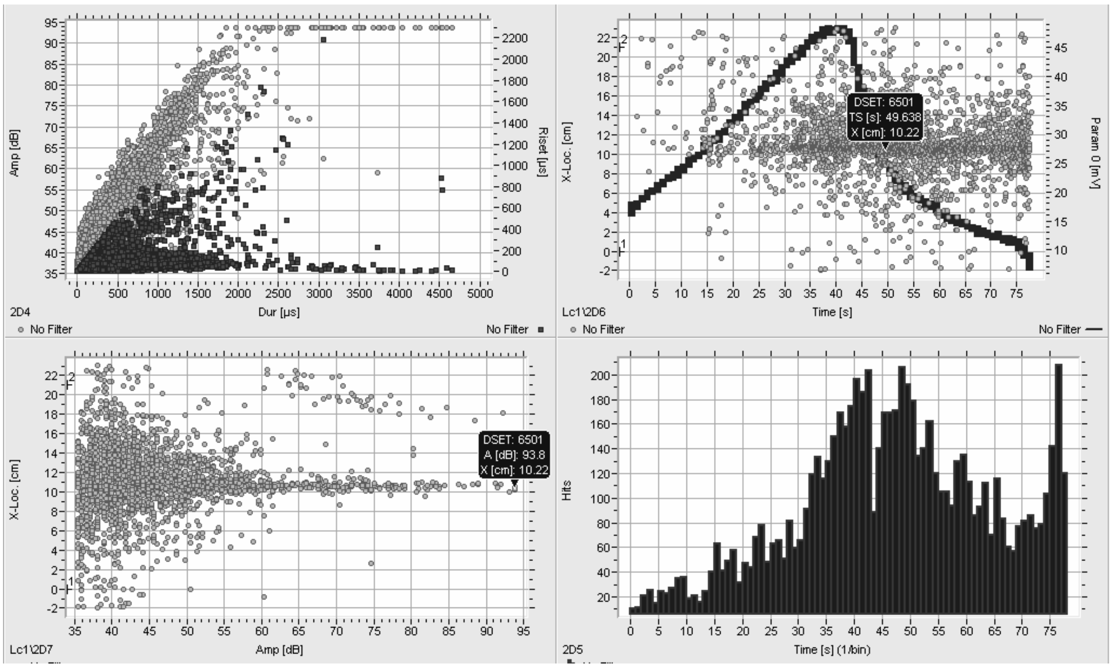


Figure (2)b. Glass aggregates 2mm

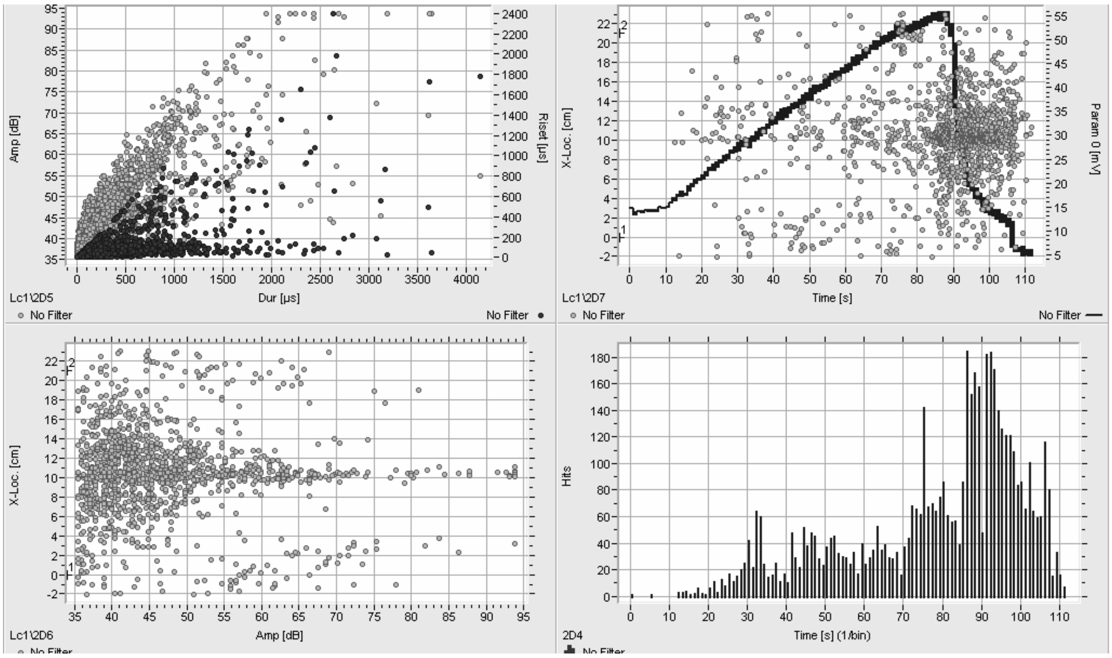


Figure (2) c: Glass aggregates 3mm

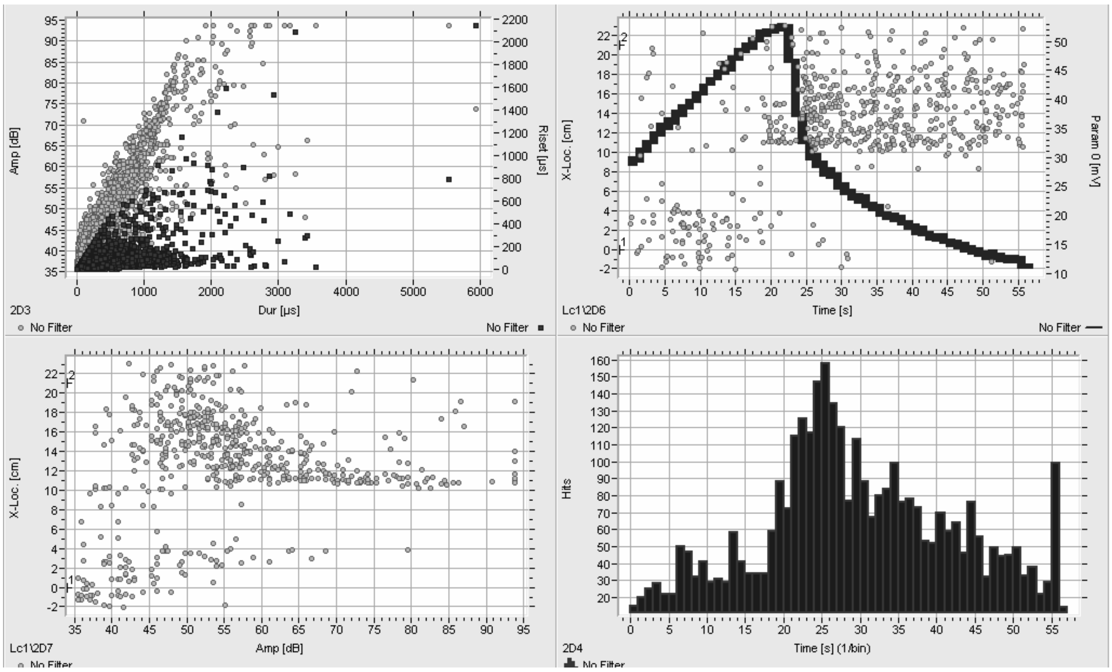


Figure (2) d: Glass aggregates 4mm

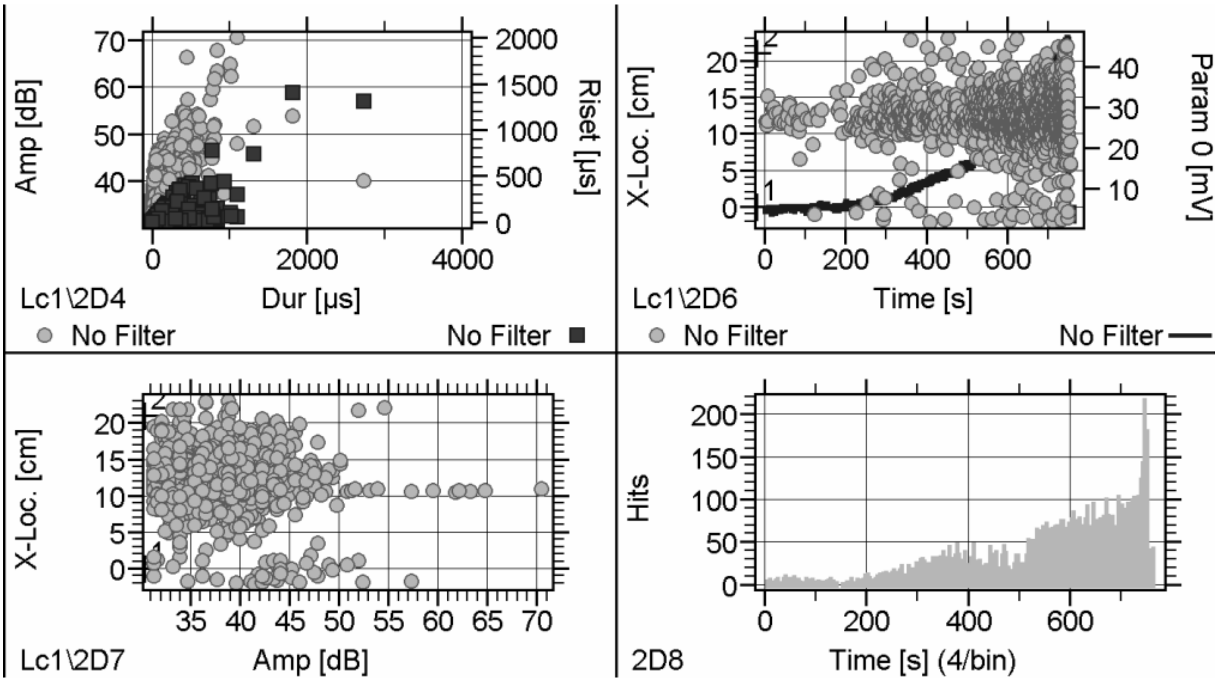


Figure (2) e: Sample Expansive cement + Glass bead 3mm

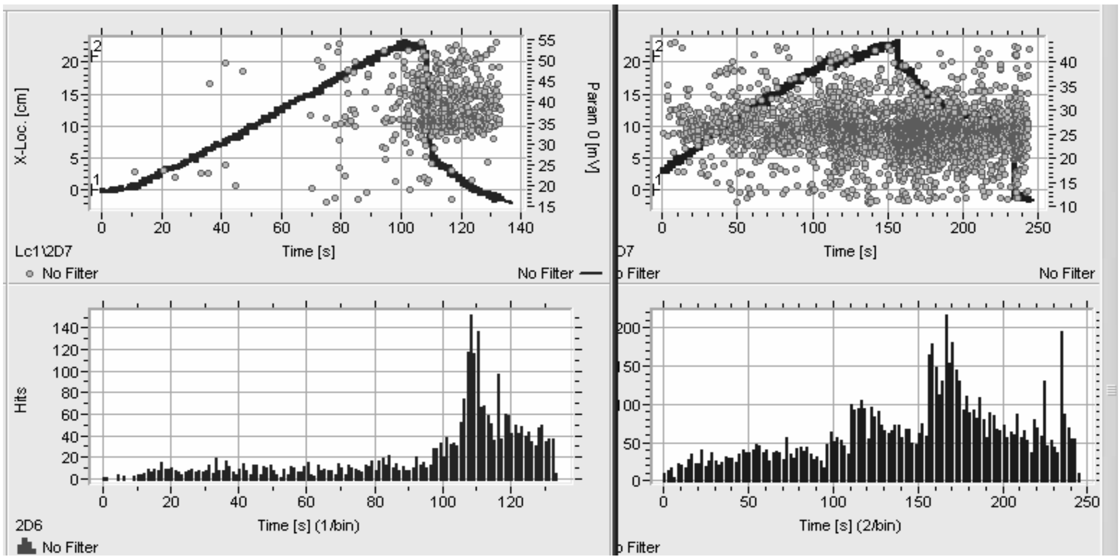


Figure (3) a: glass plate glass plates and glass aggregates

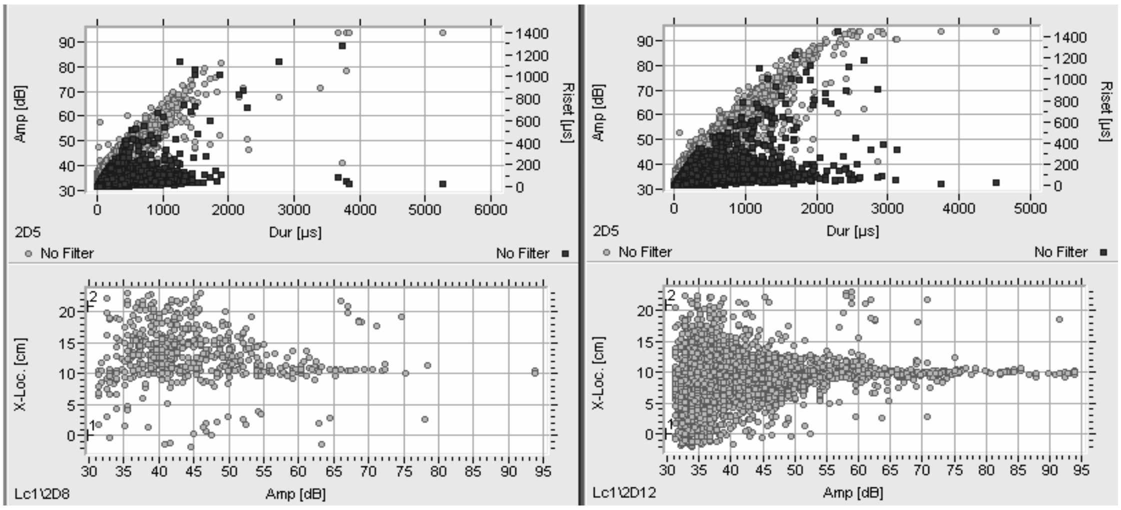


Figure (3) b: glass plate glass plates and glass aggregates

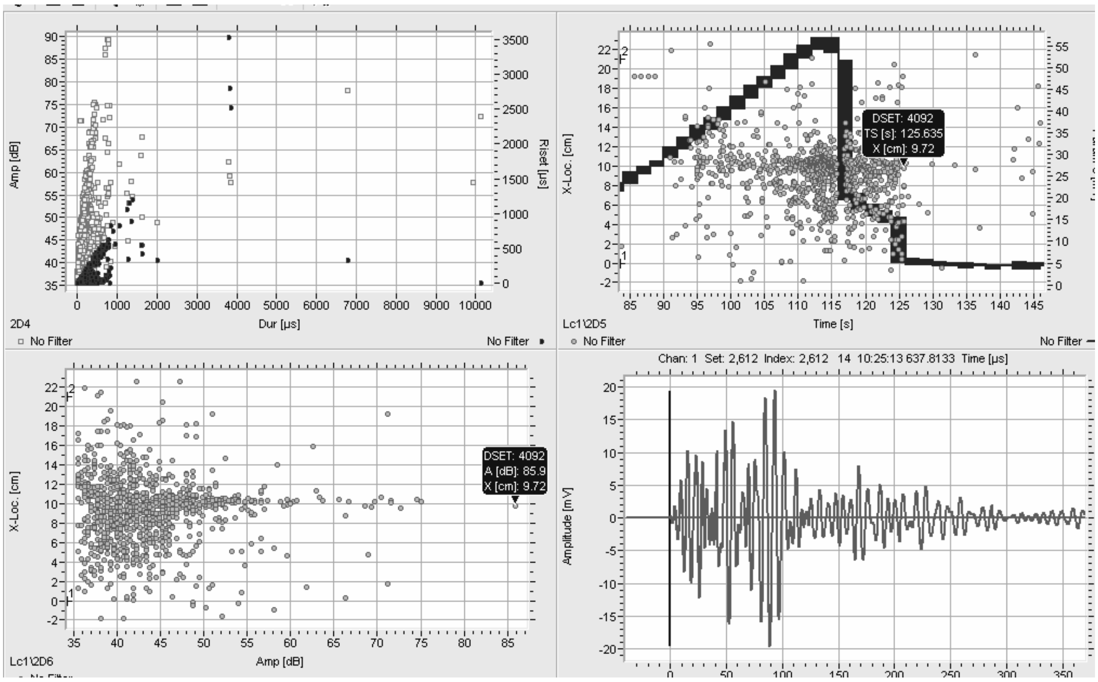


Figure (4) a. 100 gm of waste rubber aggregates

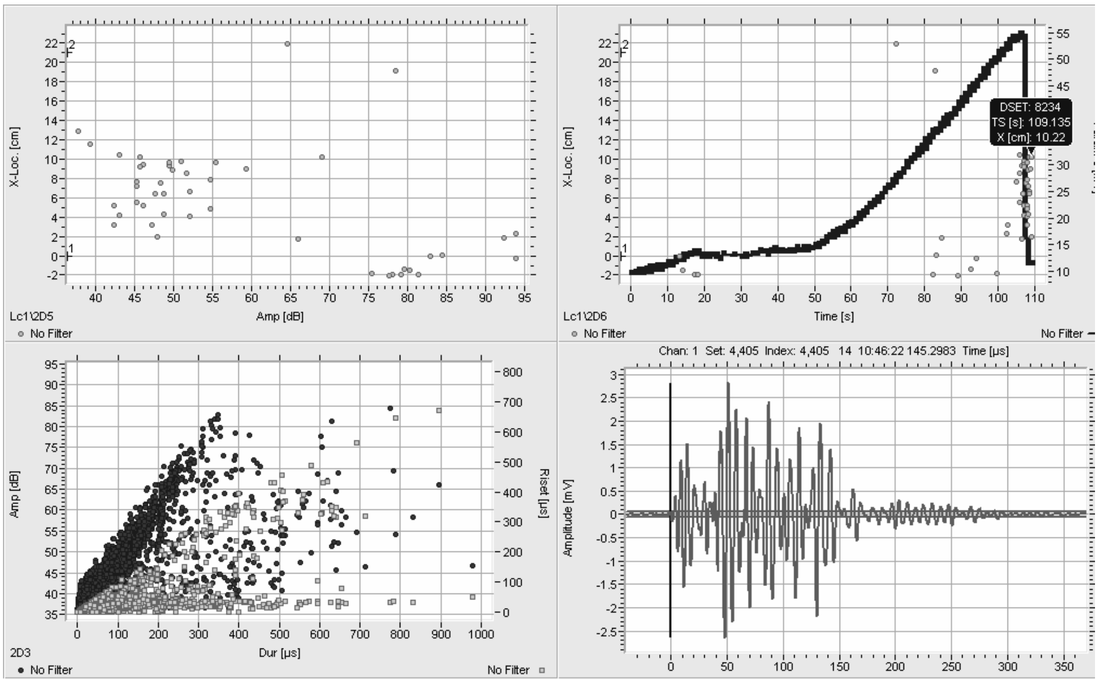


Figure (4) b. 150 gm of waste rubber aggregates

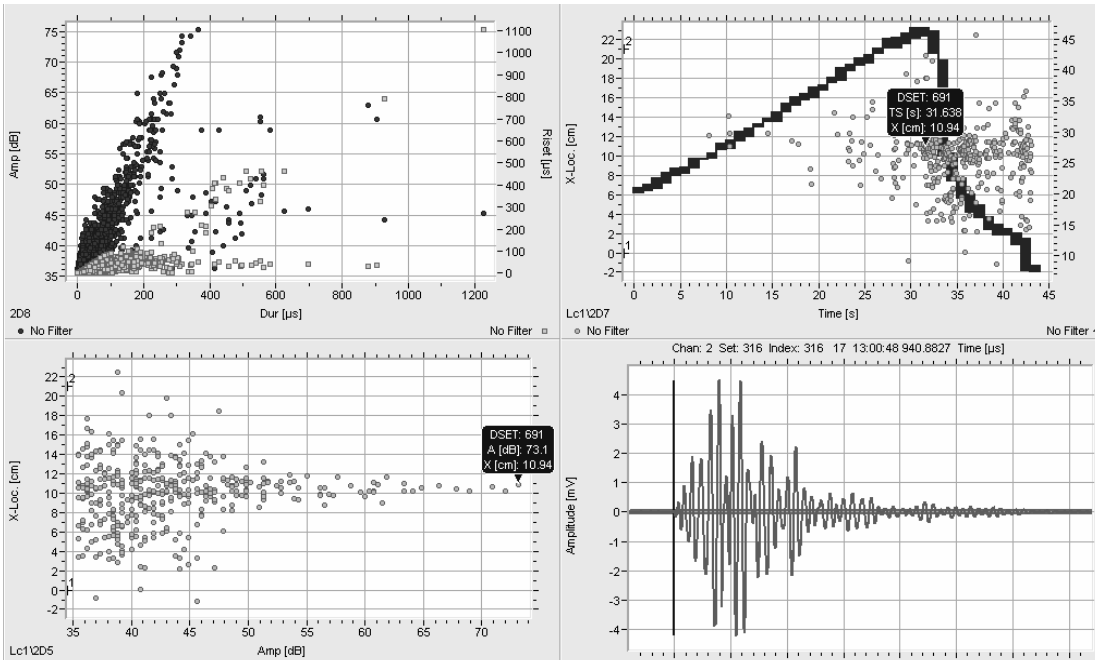


Figure (4) c. 200 gm of waste rubber aggregates

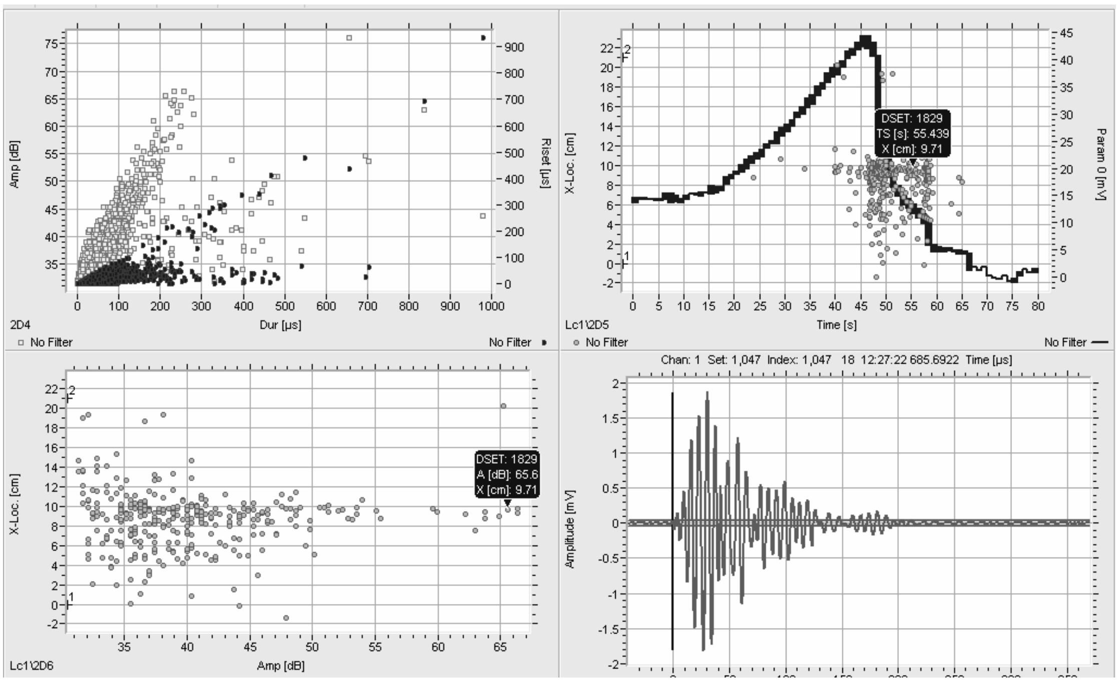


Figure (4) d. 250 gm of waste rubber aggregates

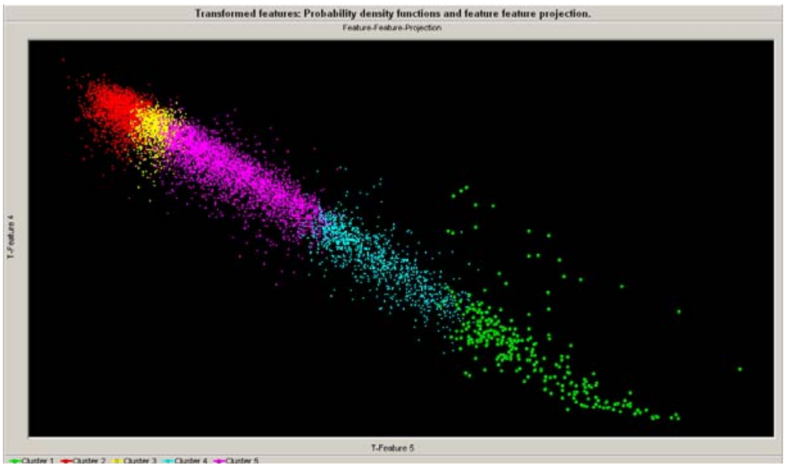
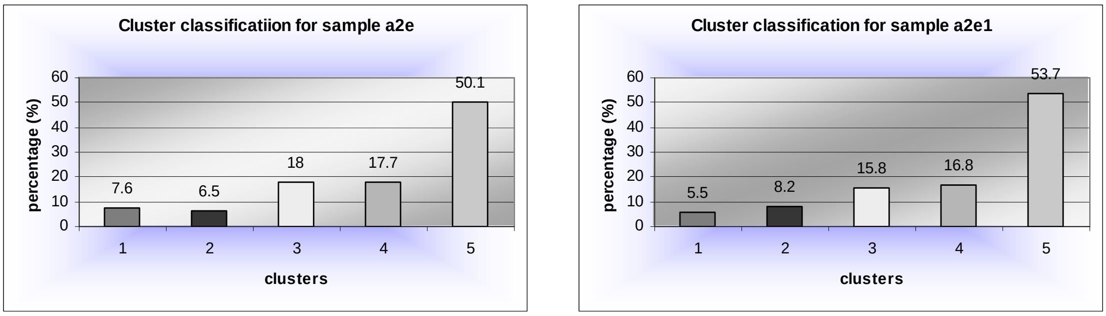
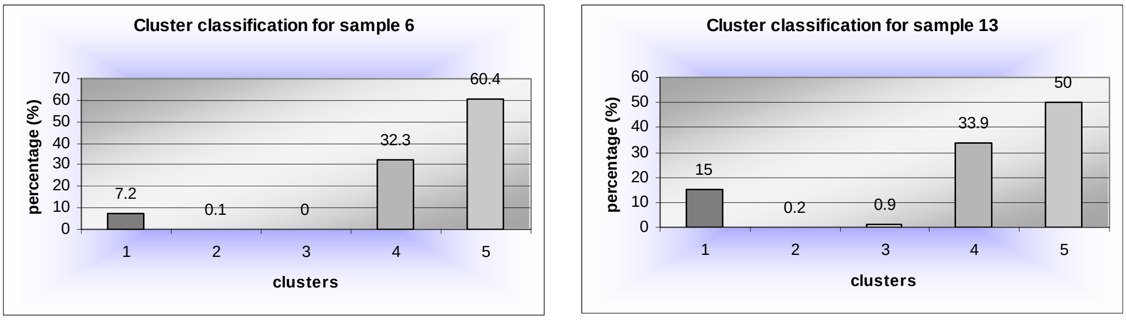


Figure 5 Feature extraction and cluster grouping



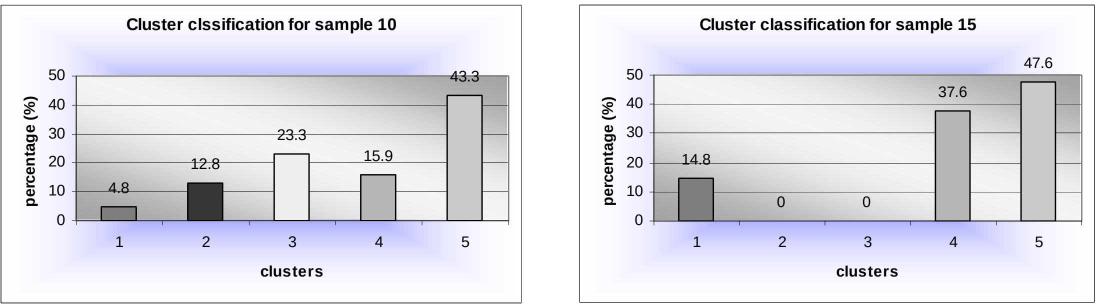
(a). sample a2e (glass slide + glass agregates)

(b). sample a2e1 (glass slide + glass agregates)



(c). sample 6 (glass slide + 3mm glass agregates)

(d). sample 13 (glass slide + 3 mm glass agregates)



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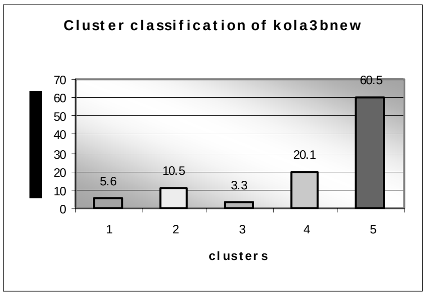
(e). sample 10 (glass plate + boken glass -- 4mm)

(f). sample 15 (1 mm glass)

Figure 6


Cluster classification of kola3bnew
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10
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70
5.6
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3.3
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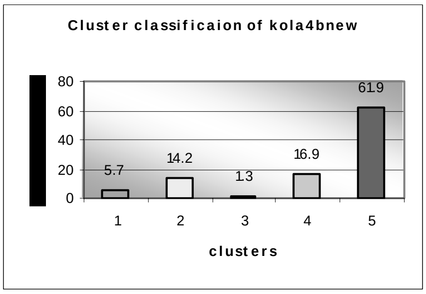
1
2
3
4
5
clusters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61.9
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3
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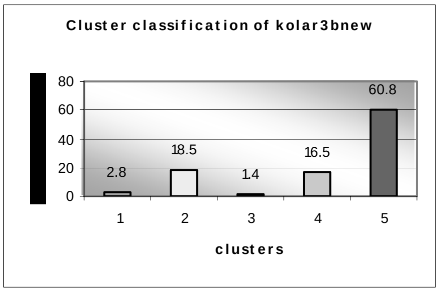
5
clusters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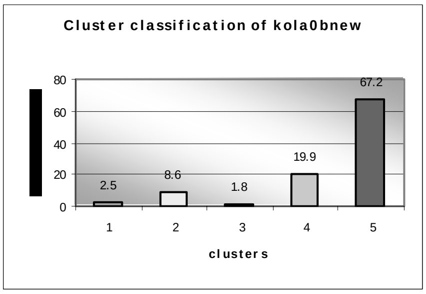
clusters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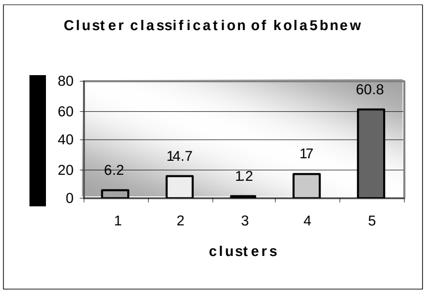
clusters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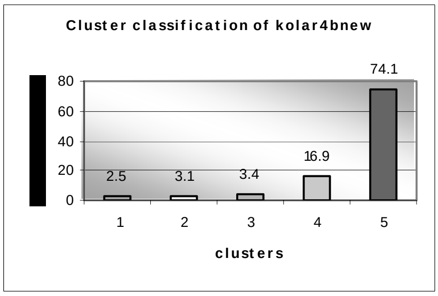
clusters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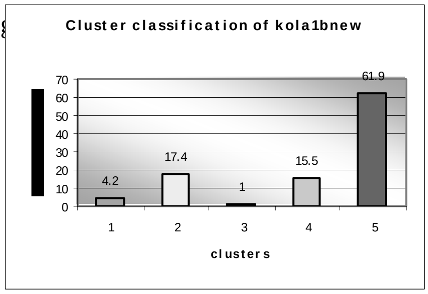
clusters

Fi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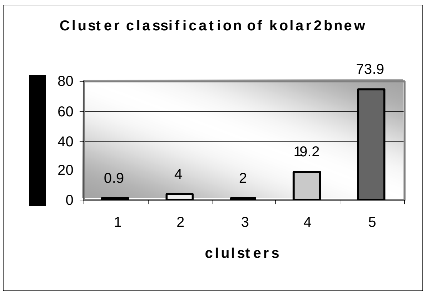
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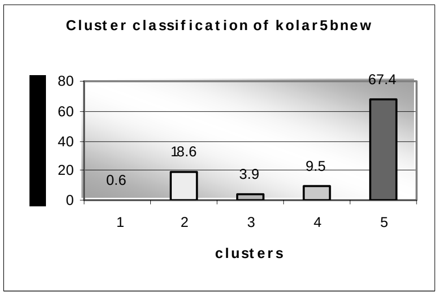
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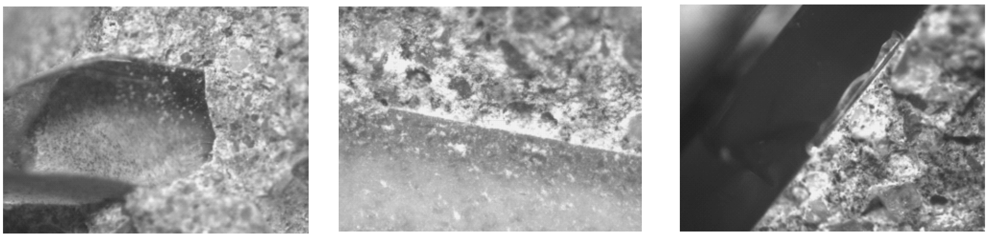
80
0.6
18.6
3.9
9.5
67.4
1
2
3
4
5
clusters

Figure 7

(a). Glass slide and glass aggregates (top view)

(b). Rubber aggregates

(c). Glass slide (slide view)



glass aggregate (pull out effect)

glass slide bonding

glass slide and rubber aggregate

Figure 8