Concrete Damage Assessment with Innovative Non-Destructive Testing Techniques

Abid A. Shah

Abstract—Ultrasonic attenuation changes and acoustic emission events were used in assessment of concrete damages. 18 cubic specimens were cast with w/c of 0.40, 0.50, and 0.60, respectively. The specimens were damaged by loading under un-axial compression in several steps until failure. At each loading step the ultrasonic amplitude attenuation and acoustic emission activity were measured. It was found that ultrasonic amplitude attenuation is quite sensitive to change in damage. It increases as damage increases. Similarly acoustic emission events were observed increasing with increasing damage level.

Keywords— acoustic emission, concrete damages, compression, ultrasonic attenuation.

I. Introduction

THE inspection methods for nondestructive evaluation (NDE) of concrete structures are in great demand. For this purpose, a variety of inspection methods have been studied to provide early detection and warning for critical defects in concrete. For a quasi-brittle material like concrete, a substantial non-linearity in the shape of micro-cracking exists even before maximum stress is reached. In order to maintain the safety and performance of concrete structures, these cracks should be inspected properly for quantifying the condition of structural integrity and assessing the degree of damage and deterioration.

Attenuation is an important parameter in ultrasonic applications. It plays a major role in the non-linear response of concrete. When attenuation varies with frequency, other ultrasonic properties such as pulse velocity are also affected. A major issue, however, is that P-wave velocity is not sensitive to microstructural changes such as internal microcraks and microvoids in concrete materials. By contrast, wave amplitude is very sensitive to material microstructural changes [1]. Ultrasonic attenuation can therefore be used as a measure of the internal damage in a concrete member. Suaris and Fernando [2] employed ultrasonic pulse attenuation as a measure of damage growth. In that study ultrasonic tests were applied to the concrete cylinders progressively damaged under cyclic compressive loads. In previous research it was reported [2, 3] that attenuation increases as damage accumulates. It was also shown [4, 5] that attenuation changes as the input frequency changes. This research has shown that attenuation remains relatively constant for frequencies at or below 150 kHz for concrete without damage. Recently, Woodward et al. [6] reported that attenuation changes when power levels change for a given frequency and damage level. The current research attempted to estimate the attenuation changes in concrete using low to very high power input signals.

Concrete specimens with different w/c were evaluated both in damaged and undamaged states. Damage was induced into the concrete specimens progressively under uni-axial compression step loading. The amplitudes of the fundamental frequency at different damage and power levels, were measured and compared for damaged and undamaged conditions.

The AE technique is one of the most sensitive techniques to non-invasively monitor deformation, fatigue, and fracture of materials and it is an experimental tool well suited for monitoring fracture processes [7-11]. Acoustic emission is caused due to localized and rapid release of strain energy in a stressed material. AE is a class of phenomena whereby transient elastic waves are generated by rapid release of energy from localized sources within a material. The stress waves can be detected on the specimen surface and analyzed to deduce the magnitude and nature of the damage present in materials.

AE technique is one of the potential tools to estimate the fracture process zone. As concrete is a heterogeneous material consisting of different phases, the inelastic zone around a crack tip is termed a fracture process zone and AE has been used to observe the fracture process zone [12-15]. Concrete structures contain flaws such as pores, air voids, and shrinkage cracks even before they are mechanically loaded. These flaws cause the microcracks under the external loading, which extend to macrocracks until large fractures are formed, which cause collapse of the structure. To describe the fracture mechanism as well as fracture parameters and to locate cracks AE has been used [16-19].

Researchers have suggested the applicability of Kaiser Effect for assessing the deterioration of concrete structures [20]. It is defined as the AE activity that would start to be observed at the load level of the maximum prior load. *b*-value analysis of acoustic emission (AE) signals was used to assess the damage that occurred in reinforced concrete beams [21]. AE was used to quantify damage in generic laboratory structures for the purpose of tuning damage models [22]. Damage estimation of structural concrete from concrete samples was developed, combining acoustic emission measurements with damage mechanics [23]. Acoustic emission characteristics due to microcracking were studied in full scale prestressed concrete piles by applying AE and fundamental study on the mechanism of the piles under both

A. A. Shah is with the College of Engineering, King Saud University, P. O. Box 800, Riyadh 11421, Kingdom of Saudi Arabia.(corresponding author phone: +96614670631; fax: +96614673600; e-mail: abishah@ksu.edu.sa).

cyclic and monotonic loads [24]. Acoustic emission characteristics of three-point bending concrete beams were investigated during the entire loading period and found that relative notch depth significantly influenced AE characteristics [25].

In the present experimental study it is intended to examine the concrete deterioration under axial compression loading using ultrasonic and acoustic emission techniques. The sensitivity of ultrasonic attenuation test method in detecting cracks or defects is certainly influenced by the microstructural behavior, which in turn is influenced by the change in damage level and w/c. It is also obvious that acoustic emission events are influenced by the change in damage level and w/c. Therefore it will be appropriate to check the sensitivity of both the methods in assessing damage growth in concrete, as it will be very useful in understanding the concrete material behavior subjected to axial compression steps loading.

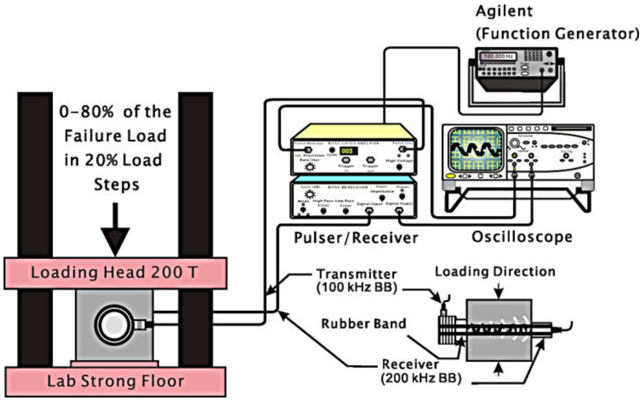
II. Experimental Program

Cubic concrete specimens 150 x 150 x 150 mm were cast using w/c of 0.40, 0.50, and 0.60. The specimens were produced with Type I Portland cement, 12 mm coarse aggregate, fine aggregate, water, a high range water reducing admixture, and air entraining agent. Three specimens at each water cement ratio were tested and the average values of three tests were plotted.

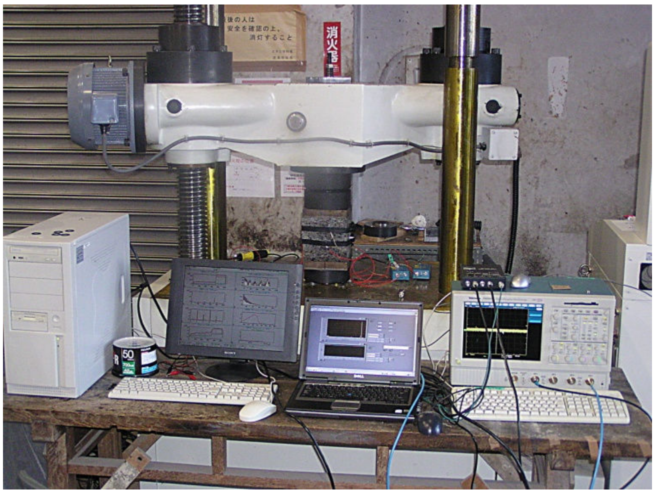
For attenuation measurements the specimens were progressively damaged by compression loading and evaluated using a high power toneburst ultrasonic unit in the through transmission mode. The ultrasonic test setup consisted of a function generator, a toneburst gated amplifier, a receiver, two contact transducers, and a PC based oscilloscope, as shown in Fig. 1 (a). Specimens were evaluated in the undamaged condition to establish a base line. Next, the specimens were loaded in compression to approximately 20 percent of their ultimate strength and ultrasonically evaluated. This procedure was repeated at load intervals of 20 percent until failure occurred. The tests were also run at five pulser output power levels corresponding to 10, 30, 50, 70 and 90 percent of the maximum possible output of 2000 V.

For acoustic emission tests, 4 sensors MISTRAS-2001 AE system was used (see Fig. 1 (b)). The sensors were of R15 type with resonance frequency of 50-200 kHz. The sensors were connected to 4 pre-amplifiers of 1220A type and were firmly fixed at the center of the cube surfaces with special wax couplant and rubber bands. AE events induced by compression loading were subsequently amplified by 45 dB at pre-amplifiers and fed in AE monitoring system. Both AE parameters and waveforms were recorded with the system.

In acoustic emission experiments evaluation of concrete specimens was performed under cyclic compression loading in several steps. At each step AE activities were recorded both during loading and unloading operations. Fig. 2 shows, the load history detail and typical trends of increase in peak amplitudes and AE events recorded by 4 AE sensors with respect to load for a tested concrete cube. As is clear from the figure, the load is approached to peak loading stage in several loading and unloading cycles.

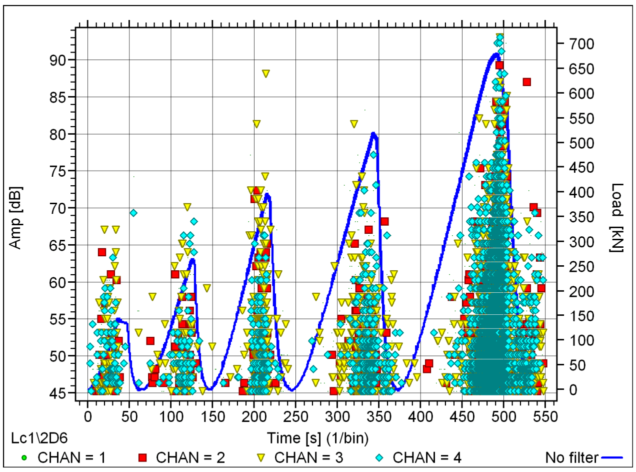


(a)

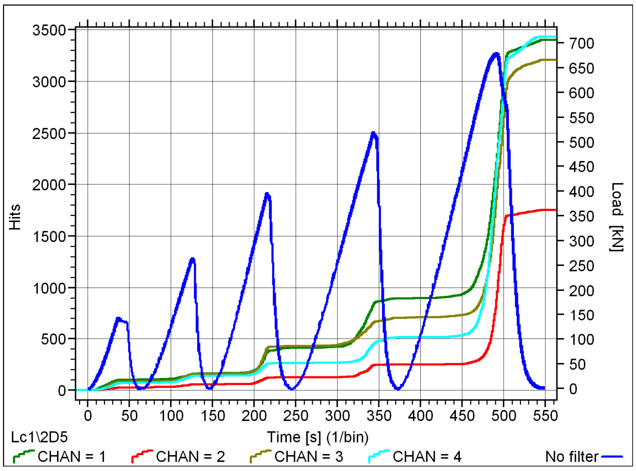


(b)

Fig. 1 Test setup (a) ultrasonic attenuation (b) acoustic emission



(a)



(b)

Fig. 2 AE monitoring (a) peak amplitude and load Vs. elapsed time (b) AE hits and load Vs. elapsed time

III. Results and Discussion

Normal service loads for a concrete structure correspond to a damage level of approximately 40 percent. Thus, our primary interest is in attenuation changes which occur above the 40 percent damage level. Fig. 3 shows the changes in the fundamental amplitude with different power levels as damage changes for specimens with a water cement ratio of 0.40. For the specimen shown in Fig. 3, large reductions occur in the fundamental amplitude for damage levels above 40 percent. For damage level of 80 percent the amplitude is reduced from the undamaged state by approximately 70 percent. Variations in input power level had only a minor effect on attenuation for these specimens.

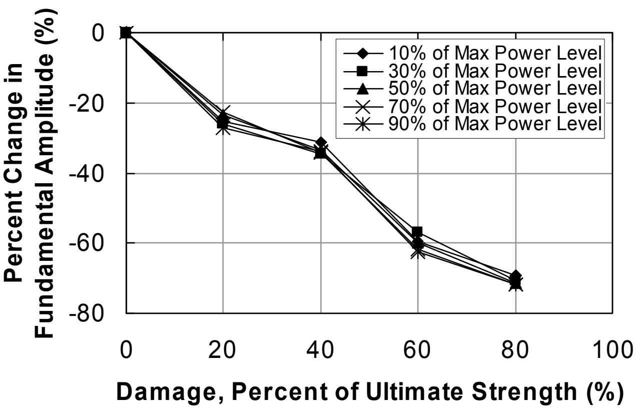


Fig. 3 Change in amplitude with power and damage levels for specimens with w/c of 0.40% (avg. of three tests)

Fig. 4 shows the same information for specimens with a water cement ratio of 0.50. The trend of increasing signal attenuation with damage is apparent in the figure. However, the reduction in signal amplitude with damage is less than that which occurred in the specimens with a water cement ratio of 0.40. Slightly higher effects of variations in power level on attenuation were observed for these specimens. Data for the 0.60 water cement ratio concrete was similar to that for the 0.40 and 0.50 water cement ratio concrete and is therefore not presented here for that reason.

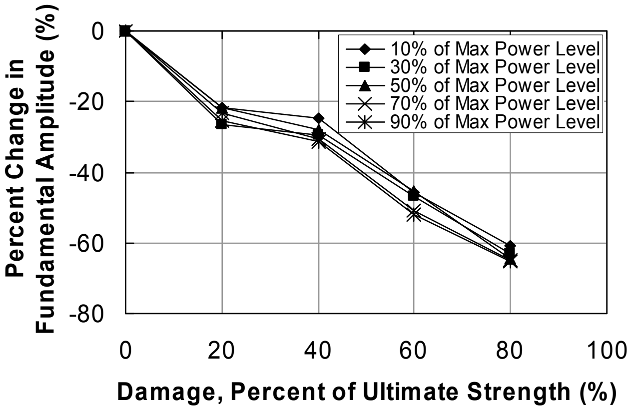


Fig. 4 Change in amplitude with power and damage levels for specimens with w/c of 0.50% (avg. of three tests)

The data shown in Figs. 3 and 4 illustrate that there was a smaller change in attenuation for high water cement ratio concrete than that which occurred for low water cement ratio concrete. This is due to the fact that high water cement ratio concrete in the undamaged state has more defects in the form of voids and porosity as well as a weaker interfacial transition zone than low water cement ratio concrete has. These defects lead to premature micro-crack formation and increased attenuation. Thus, the change in attenuation for high water cement ratio concrete was smaller from the undamaged state to the damaged state. Additionally, variations in input power had influenced the attenuation trend, which implies that attenuation measurements should be taken at several power levels.

Averaging the results for different power levels is useful to reduce the effects of variation in power. Fig. 5 shows the average percent change in the fundamental amplitude for all power levels used for all specimens.

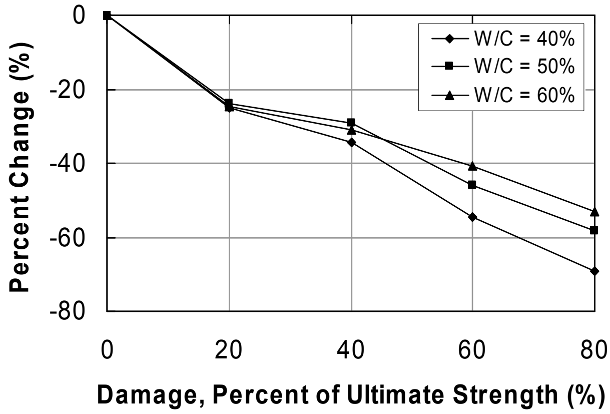


Fig. 5 Change in amplitude with power and damage levels for specimens with w/c of 0.40% (avg. of three tests)

This figure clearly shows that as damage progressed, the specimen with a water cement ratio of 0.40 experienced a greater loss in fundamental amplitude than the specimens with water cement ratios of 0.50 and 0.60, respectively. Fig. 6 shows the average results of three test specimens with w/c of 0.40 obtained using AE technique as loading changes. For the specimens tested with acoustic emission technique, AE activity increases as load increases. The AE hits rate shows the rate of total AE hits derived from all 4 channels. Moreover, during several loading and unloading cycles the data obtained was thoroughly examined for the occurrence of Kaiser Effect. None of the specimens clearly exhibited any sign of the occurrence of perfect Kaisar Effect. AE hits were actively generated during 30-40 percent of the previous maximum load even at the first cyclic loading stage. This suggests that Kaiser Effect started to break from approximately 40 percent of the first maximum cyclic loading stage and continuous AE activity was obtained not only in loading but also in unloading operation at below 40% of the previous maximum load at higher loading stages.

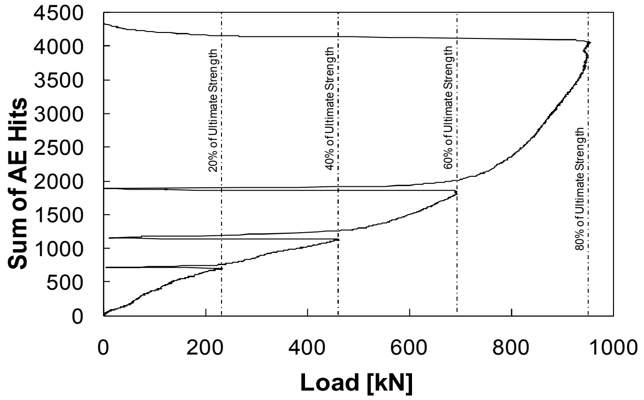


Fig. 6 AE events Vs. the load applied for w/c of 0.40

Figs. 7 and 8 show similar information for the test specimens with w/c of 0.50 and 0.60, respectively. Average results of three specimens using AE technique were plotted against the applied load.

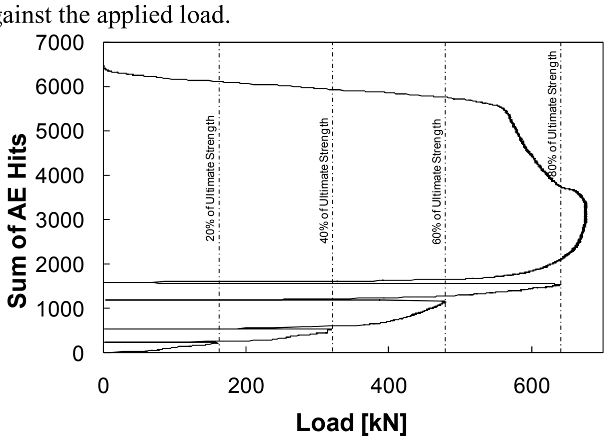


Fig. 7 AE events Vs. the load applied for w/c of 0.50

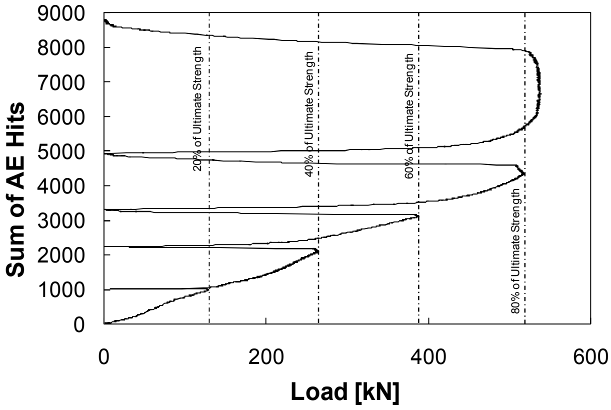


Fig. 8 AE events Vs. the load applied for w/c of 0.60

The trends of increasing AE events with damage are similar to those observed for ultrasonic attenuation. However, the increase in AE hits with damage for w/c of 0.50 and 0.60, respectively, is higher than that which occurred in the specimens with a w/c of 0.40. Again no sign of Kaiser Effect was clearly observed. For both w/c concretes AE activity at each loading stage resumes at or below 30 percent of the previous maximum applied load.

IV. Conclusion

The experimental program described here explains the utilization of ultrasonic attenuation method and acoustic emission technique in nondestructive evaluation of concrete damaged under compression loading. Cubic specimens, 150 x 150 x 150 mm, were cast with three different w/c i.e. 0.40, 0.50, and 0.60. The ultrasonic evaluation was based upon measuring the change in fundamental amplitude with increasing damage and output power level. In acoustic emission testing technique 4 sensors were used to listen to the wide range of events under various loading and unloading cycles. Each loading and unloading stage was carefully examined for Kaiser effect in order to assess the concrete deterioration. The test results analysis led to the following conclusions.

1. The acoustic emission activity and ultrasonic amplitude were found quite sensitive to change in the applied loading events and w/c.
2. AE events were found to increase significantly as damage progresses. Additionally, the increase in AE events was found higher for high w/c concrete than for low w/c concrete.
3. Attenuation was also found to increase with increase in damage. The changes in attenuation, however, were greater for low w/c concrete than for high w/c concrete.
4. Since concrete contains microcracks even under initial loading stages, none of the test specimens exhibited clear signs of the occurrence of Kaiser Effect.
5. Generally, ultrasonic parameter (wave attenuation) appears to be an easy measure of assessing concrete damages.

6. These results can be of great interest in evaluation of concrete structures.

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Abid A. Shah. This author was born on November 02, 1974 at Bannu Pakistan. He earned his B.S. degree in Civil Engineering from N.W.F.P. University of Engineering and Technology, Peshawar, Pakistan in 1996, in 2000 he received his M.S. degree in Structural Engineering from National University of Sciences and Technology, Islamabad, Pakistan, and in 2004 he got his Ph.D. degree in Structural Engineering from the University of Leipzig, Leipzig, Germany.

He worked for one and half years (2005-2006) as Senior Lecturer in Civil Engineering at the University of Botswana, Gaborone, Botswana (Southern Africa). Afterwards, he joined Tokyo Institute of Technology, Tokyo, Japan as Postdoctoral Fellow under a fellowship from Japan Society for the Promotion of Science (JSPS) in 2006. He worked there in the area of Nondestructive Evaluation of Distributed Damages in Concrete using Nonlinear Ultrasonics and Acoustic Emission Techniques. Presently, he is working as Assistant Professor, Specialty Units for Safety and Preservation of Structures, College of Engineering, King Saud University, Riyadh, Kingdom of Saudi Arabia. He is doing research in the area of Infrastructure Health and System Monitoring. He has published 24 papers in refereed journals, 14 papers in international conference, submitted 3 research reports, and delivered three invited talks. He has also published one book on the subject of Punching Shear of Flat-Plate Slab-Column Connections with Book on Demand, GmbH, Norderstedt, Germany in 2005. His current and previous research interests include Structural Health Monitoring, Rehabilitation of Concrete Structures using FRP, Nonlinear Ultrasonics and Acoustic Emission based Assessment of Damage in Concrete, and Punching Shear of Flat-Plate Slab-Column Connections.

D. Shah is registered as Professional Engineering with Pakistan Engineering Council since 2000. He is also a member of Saudi Council of Engineers (SCE).