Copyright © 2010 Tech Science Press SL, vol.3, no.2, pp.111-125, 2010

Ultrasonic Characterization of Damage in Concrete

Manu Santhanam[1]

Abstract: Ultrasonic non-destructive evaluation is an essential component of condition assessment of concrete. Conventionally, the use of ultrasonics is limited to the study of velocity of sound through concrete. The velocity is qualitatively linked to the condition of the concrete in service. However, sophistication in signal processing has led to the development of better ultrasonic techniques that can give some quantitative estimates of the damage. This paper describes the use of the transmitted ultrasonic energy to estimate the level of damage in concrete under uniaxial compression. The experimental set up was designed to collect ultrasonic signals between transducers at opposite ends of a concrete cube that was loaded in compression. A specially designed software program allowed real time analysis of the signal – including calculation of transmitted energy, obtaining FFT, etc. The methodology adopted in the study was able to differentiate the behaviour of ordinary and high strength concrete in compression.

1 Introduction

Numerous methods are available for condition surveys of concrete structures, which are being exposed to aggressive environments during service. With the improvement of NDT methods, on-site determination of properties is becoming quicker and easier. Appropriate analyses using the results from these methods can be used to predict the remaining service life of concrete. Such analyses can also help in deciding whether the structure needs repair or even complete replacement.

Ultrasonic test methods are often employed for concrete studies, the most common of these being the ultrasonic pulse velocity method [Malhotra and Carino (2004)]. The general-purpose set-up of this test involves the measurement of the time of flight of a pulse through an object of a certain thickness. The pulse velocity is then calculated and related to the stiffness (dynamic modulus of elasticity) of the object. Since the pulse is sent through the body of the object, this set-up is also called a 'through-transmission' set up. This set-up provides the most reliable results,

[1] Department of Civil Engineering, IIT Madras, Chennai

although one drawback is that it requires access to the structure from two opposite sides, which necessitates the use of cores if access to both sides of the structure is not available.

With experimental modification [Malhotra and Carino (2004)] and using sensitive transducers, the pulse velocity (UPV) technique can be used for one-sided measurements. However, the use of this technique to quantify any changes in properties along the depth needs to be studied in detail, with sufficient data for calibration. The various set-ups using UPV and the use of one-sided pulse velocity measurement (indirect) has been depicted in Fig. 1. The transmitting transducer is kept in a fixed position, while the receiving transducer is positioned at various linear distances. A plot is drawn between the time taken by the pulse and the transducer spacing. The point where the slope of the plot changes represents a difference in the layer properties. When the change in properties along the depth is gradual, as in the case of sulfate attack, the one-sided method will not be able to pick up the change in slope clearly. Even so, the determination of the pulse velocity of the slab is possible from the plot. With increasing damage to the structure, the pulse velocity would decrease.

Concrete under uniaxial compression undergoes a series of successive damages. In the early stages, microcracks appear around the aggregates. These then localise and start spreading into the mortar. A network of cracks is formed close to the ultimate load, and the concrete fails when a critical, unstable crack length is achieved. In service, concrete members in compression are designed to take loads well below their ultimate capacities. However, due to design errors and unexpected loading situations, there are possibilities of initiating a significant degree of cracking in the concrete. Quantification of the degree of damage caused by this cracking helps in the selection of appropriate measures for repair and rehabilitation. Thus, accurate evaluation of the type, amount, and extent of cracking, entails the need for reliable non-destructive methods. The ultrasonic method has been applied successfully in the past to gauge the quality of concrete in service.

Traditionally, the velocity of the ultrasonic pulse is measured as an indicator of the degree of damage in concrete, and there is extensive use of ultrasonic pulse velocity equipments for field studies of concrete structures. However, research has shown that the velocity itself does not present a complete picture of the damage of concrete. Other ultrasonic parameters such as the amplitude of the signal and its frequency dependence are also equally, if not more, important.

Knab et al. [Knab, Blessing and Clifton (1983)] performed laboratory studies to quantify the capability of ultrasonic through-transmission methods to detect cracks in concrete. Pulse velocity and amplitude of the ultrasonic signal were analysed in directions perpendicular and parallel to the crack plane. The results indicated that

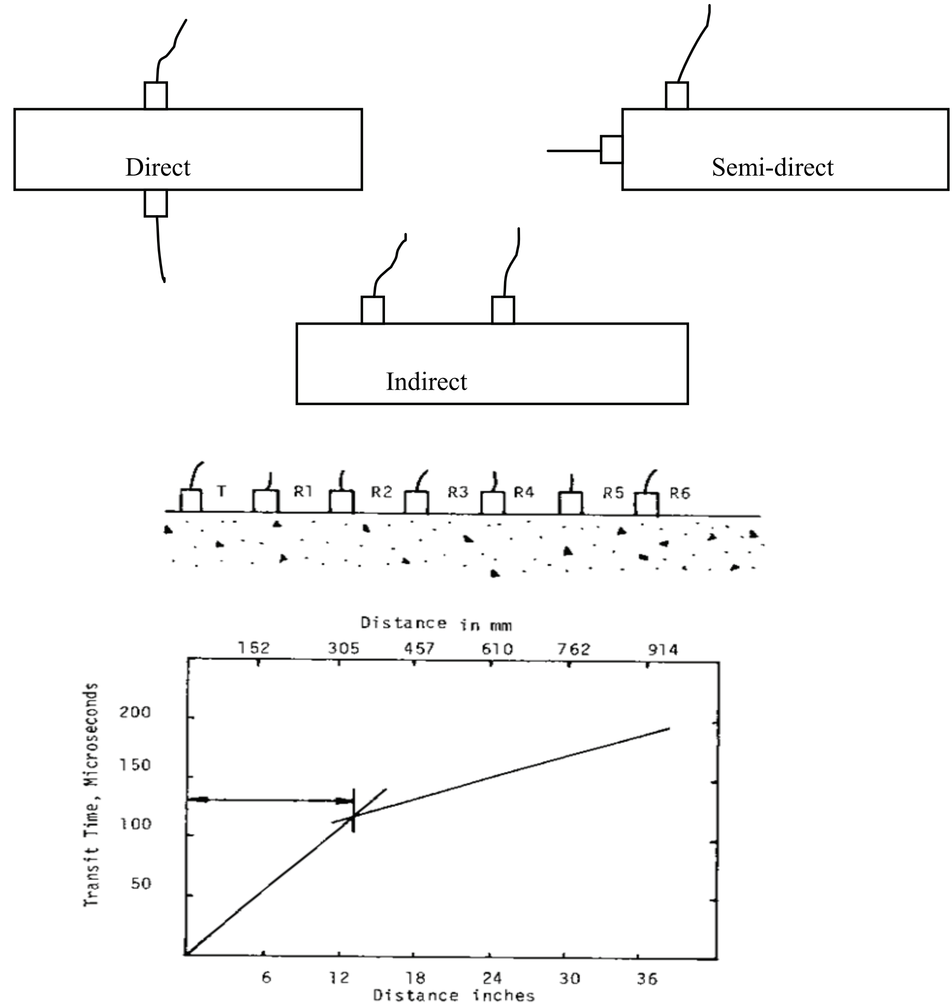

Figure 1: Use of one-sided pulse velocity (indirect) test to quantify depth of degradation [Malhotra, Carino (2004)]

both velocity and amplitude gave useful information about the extent of cracking, but the velocity appeared to be a more sensitive parameter. Suaris and Fernando [Suaris and Fernando (1987)] effectively demonstrated that the ultrasonic pulse attenuation (or the decrease in the amplitude of the ultrasonic signal) was a better and more sensitive indicator than the pulse velocity, of the degree of damage in concrete induced by cyclic loading. Tharmaratnam and Tan [Tharmaratnam and Tan (1990)] studied the use of ultrasonic pulse attenuation as a non destructive testing parameter to evaluate the quality of the material. 50 kHz piezoelectric transducers were pulsed using commercially available ultrasonic equipment coupled with a digital storage oscilloscope. The attenuation of ultrasonic pulse was found to be well correlated with the compressive strength of the mortar (for the same length).

Popovics et al. [Popovics, Rose and Popovics (1990)] studied the behavior of ultrasonic pulses in concrete, and found that the pulse velocity was independent of the stresses in concrete up to 70% of the ultimate stress. Berthaud [Berthaud (1991)] investigated the possible correlations between the mechanical and acoustical consequences of damage in concrete and concluded that the microcracks that exist even in an undamaged concrete may close under an appropriate load so that an acoustical anisotropy is induced by the stress. Also, the propagating microcracks are responsible for the observed mechanical damage.

A landmark study on the study of cracking and degradation of elastic properties in axial compression using the analysis of ultrasonic compressional and shear waves was performed by Nogueira and Willam [Nogueira and Willam (2001)]. The study indicated that the decay of peak to peak amplitude with increasing levels of stress was a useful parameter to assess the scale of damage. The study also included a comparison of concrete with mortar and paste. While the peak to peak amplitude showed some increase at low stress levels for the longitudinal waves (attributed to closure of shrinkage cracks), there was consistent decay at all stress levels for the transverse waves. The increase of the amplitude at low stress levels was most significant for the cement paste. Qasrawi and Marie [Qasrawi and Marie (2003)] used the change in the ultrasonic pulse velocity as a measure for the damage of concrete in compression. In their study, the pulse velocity was seen to decay abruptly beyond 85% of the ultimate load. The technique was used to successfully estimate the crack widths at different load levels (assuming cracks were water-filled).

The energy of a signal is proportional to the square of the amplitude. Thus, signal analysis can also indicate the acoustic energy transmitted through concrete. As damage in concrete increase at higher load levels, the presence of growing cracks will contribute to the attenuation of this energy. Estimation of the transmitted energy can then be used as an indicator of damage.

This paper reports the results of investigations carried out at IIT Madras in the past years [Ashok Kumar and Santhanam (2009); Srujan (2009)], which deal with ultrasonic investigation of damage in concrete subjected to uniaxial compression. Most of these studies were performed on two types of concrete, one with a quasi-ductile nature (NSC – normal strength concrete) and the other brittle (HSC – high strength concrete).

2 Materials used and mixture proportions

Ordinary Portland cement (Grade 53) conforming to IS 12269 and locally available aggregates were used for all the mixtures. Sand of fineness modulus 2.6 and specific gravity 2.63, and coarse aggregate of maximum size 10 mm and specific gravity 2.81 were used. Additionally, for the high strength concrete mixture, silica fume (specific gravity 2.2) and a polycarboxylate-based superplasticizer were used.

Ultrasonic studies were conducted on concrete cubical specimens subjected to loading at different levels to understand the nature of cracking in concrete. Two different types of concrete were cast - one mixture of normal strength concrete (NSC) with a target strength of 20 MPa and the other mixture of high strength concrete (HSC) with a target strength of 70 MPa, with an aim of comparing the nature of cracking. The mixture proportions are given in Tab. 1. The actual compressive strengths at 28 days (average of three cubes) were 21 MPa for NSC, and 72 MPa for HSC.

Table 1: Mixture proportions

Constituents	Proportions	
	Normal Concrete (NSC)	High Strength Concrete (HSC)
Cement (kg/m^3)	300	418
Water (kg/m^3)	180	158
Coarse aggregate (kg/m^3)	792	792
Fine aggregate (kg/m^3)	1112	1033
Silica Fume (kg/m^3)	-	32
Superplasticizer (polycarboxylate based) (% by weight of cement)	-	1
Water-cement ratio	0.6	0.35

3 Testing methodology

Initially, tests were conducted using a commercially available ultrasonic pulse velocity (UPV) equipment and the transit time of the pulse through the concrete specimens was measured. This method is viable to determine the quality of concrete but not the extent of damage. To understand the extent of damage, an analysis of the ultrasonic signals through concrete is necessary. Apart from the wave velocity the signal can reveal other information which can be used to quantify the extent of damage. To accomplish this task of collecting the ultrasonic signals a digital oscilloscope was coupled with a computer and the signals were processed using LabView 8.5 software.

Cubes of 150 mm were chosen, as the size of the specimen should be at least twice the wavelength of the ultrasonic waves in concrete, to avoid edge effects and multiple reflections. Four cubes of each mixture were studied using each frequency. Each cube was removed from water at the specified age and then wiped with a clean damp cloth to obtain a saturated surface dry condition. As per ASTM C 597, the two opposite surfaces were prepared by application of lubricating grease at the centre of the surface for ultrasonic testing. The cube was then placed in a compressive testing machine. A small load was applied to keep the cube in position. The transducers were then placed over the center of the opposite faces, and fixed in position using a C-clamp as shown in the Fig. 2. The C-clamp was used to maintain a constant pressure throughout the test. A 2 cm thick rubber sheet was placed between the transducer and clamp to avoid erroneous values due to the clamp The specimen was loaded at the rate of 20 kN/min, to record minute changes in time of flight readings continuously while loading was done.

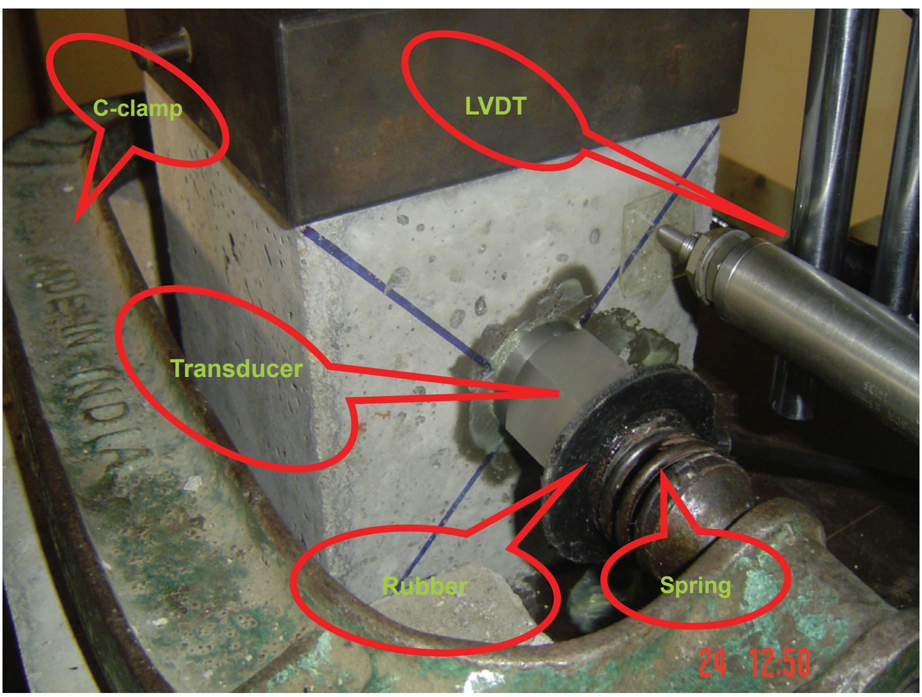

Figure 2: Experimental setup for ultrasonic measurements

The experimental set up was modified to obtain the complete information from the transmitted ultrasonic signals. The modified set up is schematically described in Fig. 3. A digital oscilloscope (NI-SCOPE USB Oscilloscope) was included to collect and digitize the signals. The UPV machine gave an output analog signal, which was sent as an input to the digital oscilloscope that converted the analog signal into a digital input to the computer. The digitized signal was analyzed by software (developed specifically for this application, on the NI LabView platform) and displayed on the monitor as the A-scan (Fig. 4), as well as stored for further analysis.

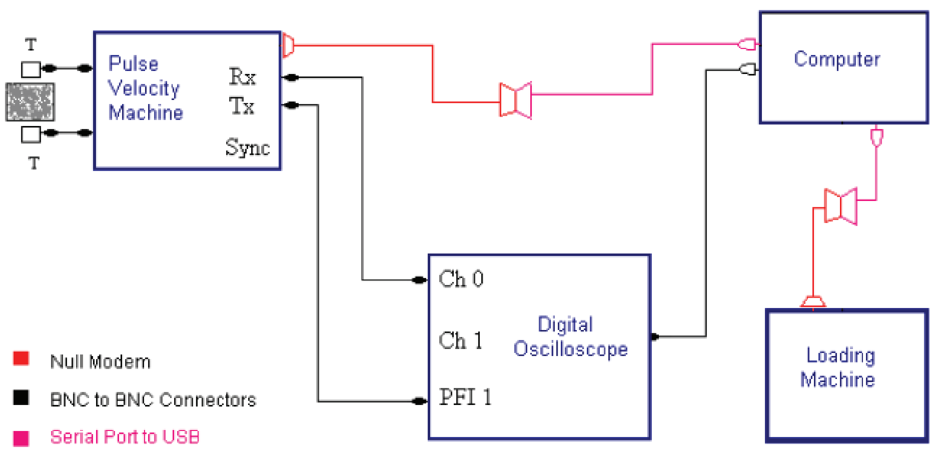

Figure 3: Experimental set up for obtaining A-scan

Signal received from the oscilloscope has noise embedded in it. This effect of noise on the actual signal data has to be minimized and this is done using signal processing techniques. For this purpose, various filters can be used. Linear digital filters perform very well when the spectra of the signal and noise do not significantly overlap. For example, a low pass filter with a cutoff frequency of 100 Hz generally works well for attenuating noise frequencies greater than 100 Hz. However, if high level noise frequencies were to span the frequency range from 50–100 Hz, attempting to remove them using a 50 Hz low-pass filter would attenuate some of the components of the signal as well as the noise. High amplitude noise corruption within the frequency band of the signal may completely obscure the signal. Thus, conventional filtering schemes fail when the signal and noise frequency spectra

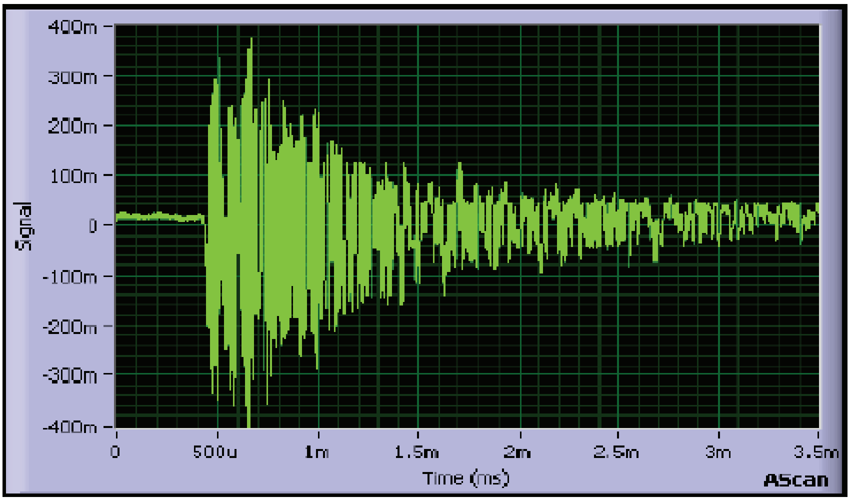

Figure 4: Snapshot of A-scan

significantly overlap. Signal averaging is a digital technique for separating a repetitive signal from noise without introducing signal distortion. In this study signal averaging method was used along with filters.

The A Scan which is micro scaled is the representation of the pulse amplitude as it travels through the concrete specimen. It gives information about various reflections and hence the attenuation that the signal undergoes due to the presence of various heterogeneous boundaries, like cracks. Thus, it indicates the extent of damage in concrete. In this study a unique proposition has been made – the Normalized Energy Curve. The Amplitude vs. Time curve can be used to analyze the time taken for total energy dissipation inside the concrete. This energy curve is obtained as shown in Fig. 5.

The flowchart in Fig. 5 was executed as a LabVIEW program and software was written to get the Normalized Energy Curve. Normalization was performed with respect to mean of the peak 5% to 10% values in the energy curve. Normalization was done to eliminate the effect of factors like amount of coupling pressure applied on the transducers, which affects the energy curve. Irrespective of the type of coupling provided, if the amount of coupling provided is constant throughout the experiment, then the normalized energy curve can be correlated to the damage in concrete. A snapshot of the normalized energy curve is presented in Fig. 6.

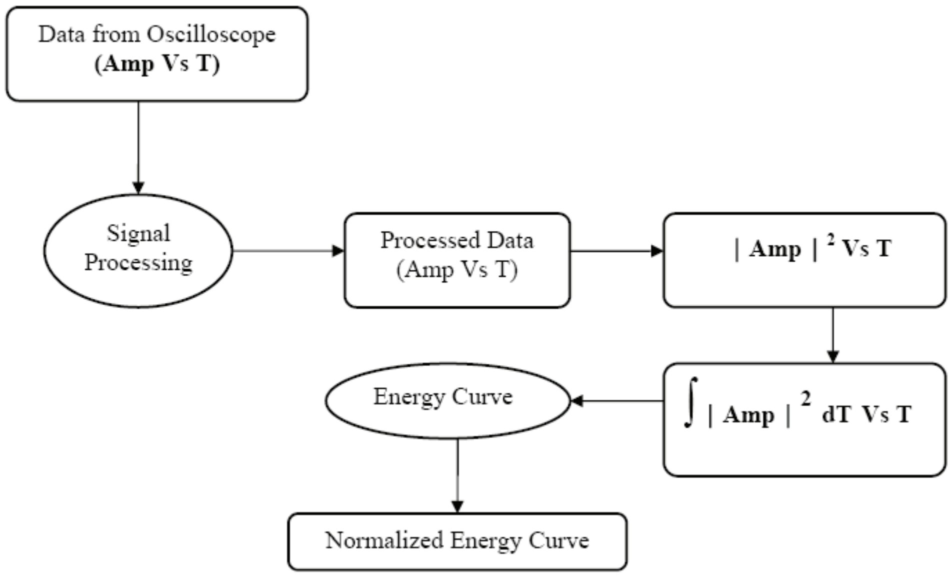

Figure 5: Block diagram for formation of Normalized Energy Curves

4 Results

4.1 Variation of pulse velocity with load level

The results of the variation of the velocity of the pulse, expressed as a fraction of the velocity in the undamaged condition, are presented in Fig. 7. As expected, the normal strength concrete, which is more ductile as compared to the high strength concrete, shows reduction in velocity at as early as 30 – 40% of the ultimate load. However, appreciable drop in velocity does not occur until the load level crosses 70% of the ultimate load. Thus, pulse velocity alone, if used as an indicator of the damage, may not really show a severely damaged condition, while in reality, a large degree of damage is expected at such load levels. In the case of high strength concrete, the drop in velocity only occurs beyond 60% of ultimate load, and becomes critical only at 90% of the ultimate load.

4.2 Variation of amplitude with load level

A plot of the A-scan observed for NSC (zoomed to get a clear picture) is shown in Fig. 8. There is a clear reduction in the amplitude of the pulse with increase in the magnitude of loading. Further, the onset of pulse is also delayed, indicating a drop

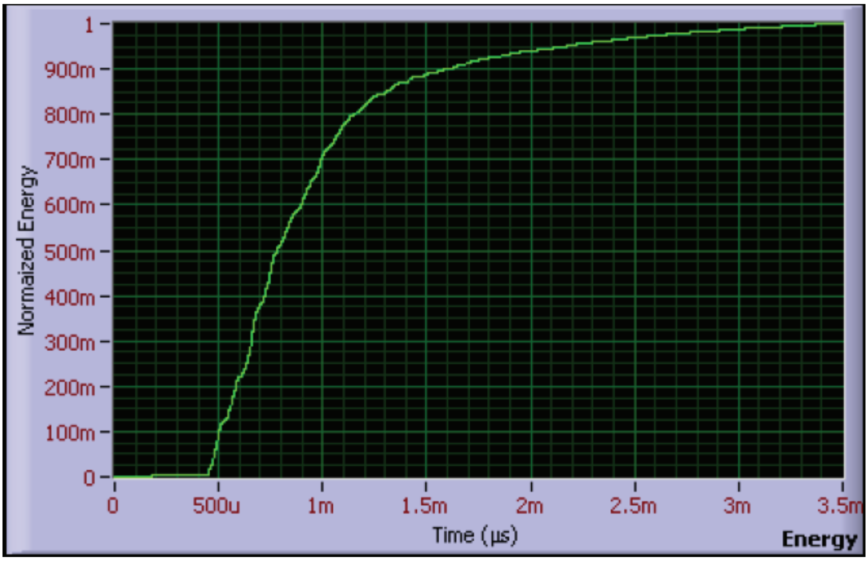

Figure 6: Normalized energy curve

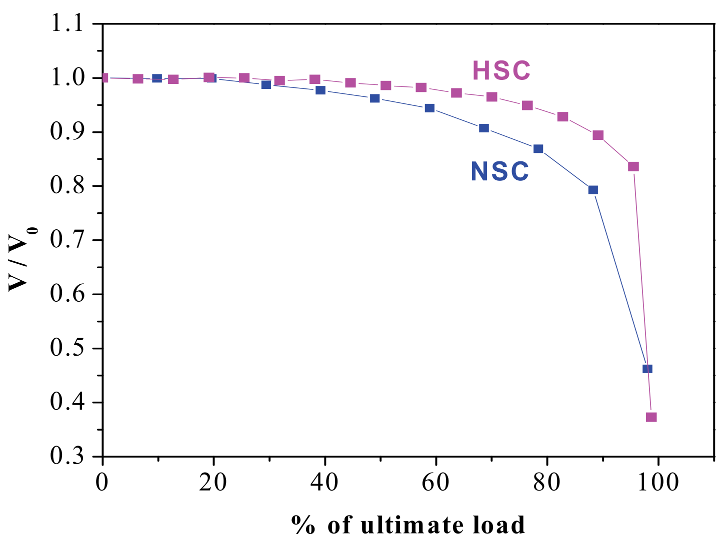

Figure 7: Variation of the pulse velocity with the load level

in velocity. The amplitude of the pulse was measured on the first peak for each curve. The variation of the amplitude with the loading level is presented in Fig. 9.

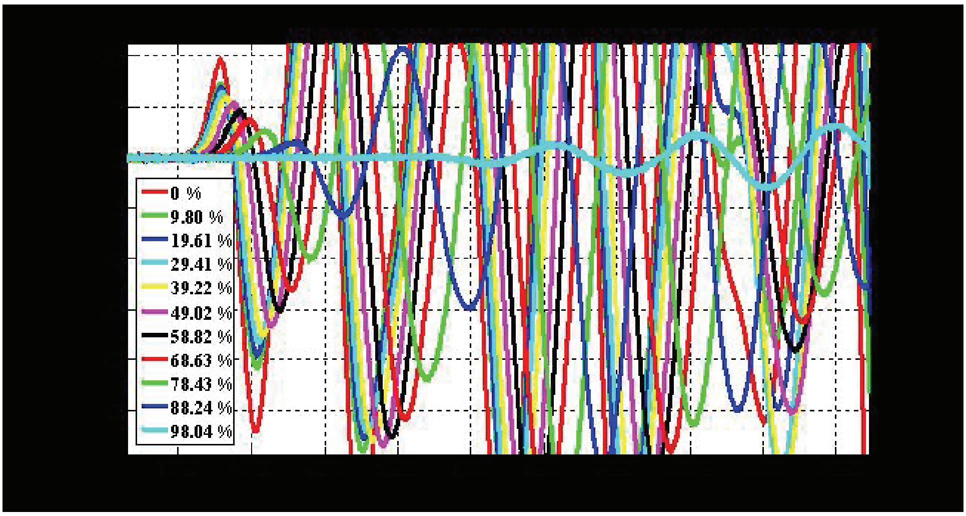

Figure 8: Ultrasonic signals collected at different load levels

The results in Fig. 9 indicate that amplitude is possibly a better indicator of damage compared to velocity. A steady drop in amplitude is seen after reaching 40% of the ultimate load for the NSC specimen, which is consistent with the available theoretical knowledge about normal strength concrete. On the other hand, the drop in amplitude for the HSC specimen starts only after reaching 60 – 70% of the ultimate load. This drop is steep, and that is expected since failure in HSC tends to pass through the aggregate.

Figure 10 depicts the variation in relative velocity and relative amplitude of pulses through the concrete at different strain levels (strains were calculated based on LVDT measurements during compression testing). The crack lengths measured at various levels through optical microscopy (detailed methodology explained elsewhere [Ashok Kumar and Santhanam (2009)]) are also presented in the same figure. Here, the strain is normalized with respect to the respective peak strains for NSC and HSC. This is because peak strains are different for both types of concrete as they are of different grades. For NSC, at the same level of strain, relative velocity starts decreasing approximately at the same time as the crack length abruptly in-

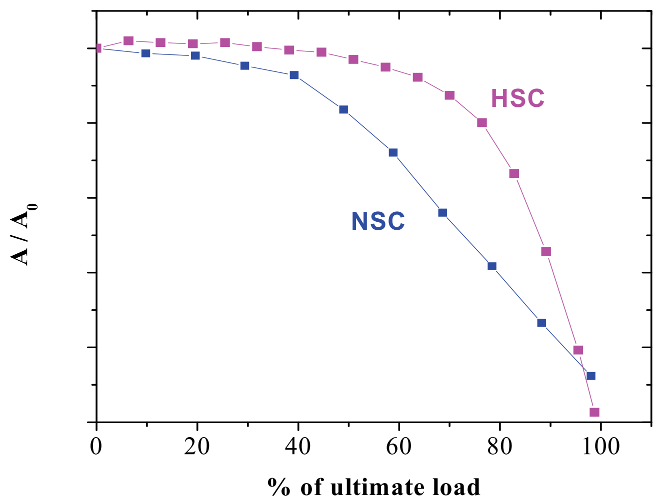

Figure 9: Variation of pulse amplitude with the load level

creases (strain level of 0.4 – Fig. 10). In HSC, the crack length grows uniformly with increasing strain, while the change in relative velocity is negligible in the early stages. However, at later stages, the relative velocity decreases rapidly as the crack grows. Overall, it can be noticed from this plot that the crack growth is not very well reflected by the changes in relative velocity. On the other hand, the amplitude drop is able to better represent the increase in crack length at all levels of strain in both the types of concrete. This result indicates that ultrasonic pulse velocity alone is not sufficient to characterize damage. The actual ultrasonic signal can give valuable information pertaining to the signal amplitude (and energy), as well as frequency dependence (which was discussed in the previous section).

4.3 Use of energy transmission

The normalized energy curves for NSC and HSC are presented in Fig. 11 and 12 respectively. As seen in the amplitude results, the reduction in energy transmitted is gradual in the case of NSC, while for HSC, there is a sudden reduction in the transmitted energy at high load levels.

5 Conclusions

Ultrasonic testing of concrete under uniaxial compression was described in this paper. Conventional ultrasonic methods for concrete primarily deal with the analysis of the velocity. However, tests conducted at IIT Madras and elsewhere have shown

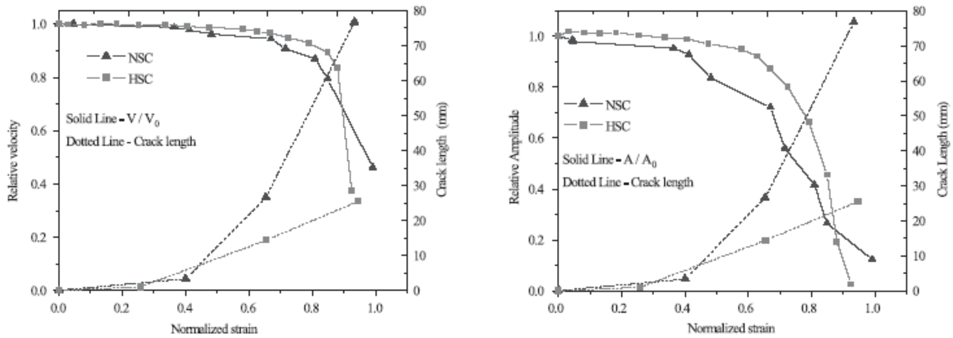

Figure 10: Variation of ultrasonic parameters (velocity and amplitude) and crack length [9] with strain levels in concrete under uniaxial compression

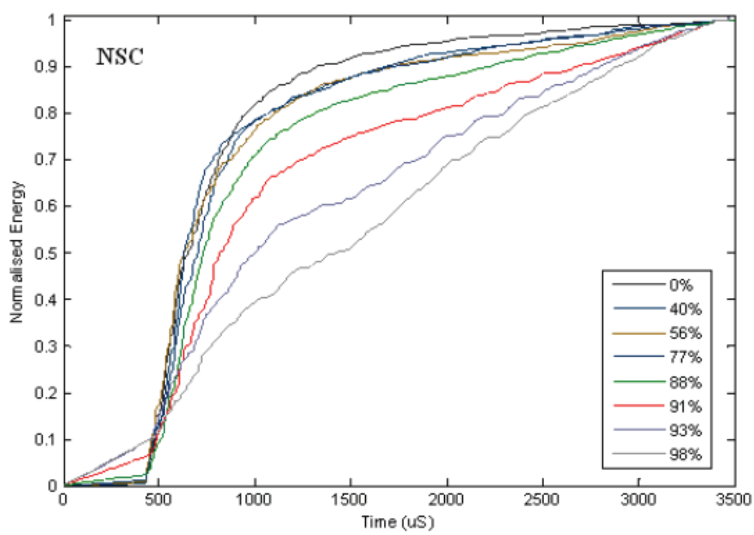

Figure 11: Normalized energy curves at different load levels for NSC

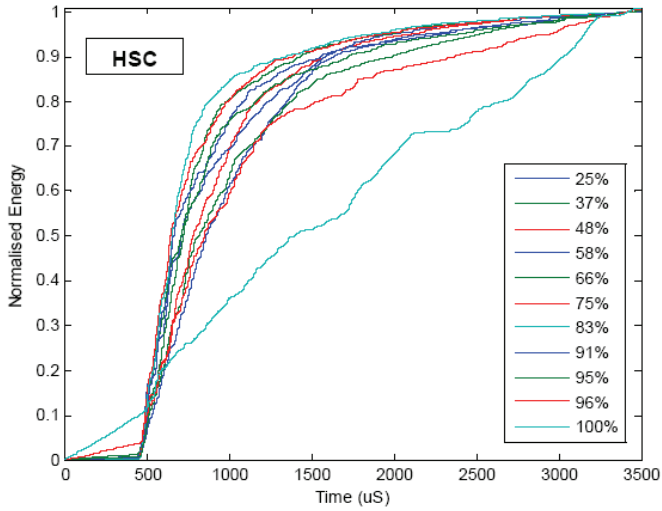

Figure 12: Normalized energy curves at different load levels for HSC

clearly that velocity need not be the best indicator of damage. The analysis of the entire ultrasonic signal, rather than just the time of flight, can give useful details that can help in characterizing the extent of damage. In this study, the amplitude of the ultrasonic transmitted pulse, as well as the transmitted energy, were able to present a clearer picture of the damage in concrete subjected to uniaxial compression, as compared to the pulse velocity value. The next step would be to use a similar ultrasonic set up for a field application.

References

Ashok Kumar, S.; Santhanam, M. (2009): Damage of concrete in uniaxial compression – an evaluation using ultrasonic method and optical microscopy, *Journal of Structural Engineering, SERC, Chennai,* vol. 36, no. 1, pp. 22–28.

ASTM C597, Standard Test Method for Ultrasonic Pulse Velocity Through Concrete, *ASTM, Pennsylvania, USA*.

Berthaud, Y. (1991): Damage measurements in concrete via an ultrasonic technique; Part I - Experiment, *Cem Con Res* vol. 21, no. 1, pp. 73-82.

IS12269, Specification for Ordinary Portland Cement – Grade 53, *Bureau of Indian Standards, New Delhi*.

Knab, L. I.; Blessing, G. V.; Clifton, J. R. (1983): Laboratory evaluation of ultrasonics for crack detection in concrete, *ACI Mat J* vol. 80, no. 3, pp. 17-26.

Malhotra, V. M.; Carino, N. (2004): Handbook of Nondestructive Testing of Concrete, *CRC Press, Pennsylvania, USA*.

Nogueira, C. L.; Willam, K. (2001): Ultrasonic testing of damage in concrete under uniaxial compression, *ACI Mat J* vol. 98, no. 3, pp. 265 – 275.

Popovics, S.; Rose, J. L.; Popovics, J. S. (1990): The behaviour of ultrasonic pulses in concrete, *Cem Concr Res* vol. 20, no. 2, pp. 259-270.

Qasrawi, H. Y.; Marie, I. A. (2003): The use of USPV to anticipate failure in concrete under compression, *Cem Concr Res* vol. 33, no. 12, pp. 2017-2021.

Srujan, Y. (2009): Ultrasonic Assessment of Damage in Concrete, *B. Tech Project Report, IIT Madras*.

Suaris, W.; Fernando, V. (1987): Ultrasonic pulse attenuation as a measure of damage growth during cyclic loading of concrete, *ACI Mat J* vol. 84, no. 3, pp. 185- 193.

Tharmaratnam, K.; Tan, B. S. (1990): Attenuation of ultrasonic pulse in cement mortar, *Cem Concr Res* vol. 20, no. 3, pp. 335-345.