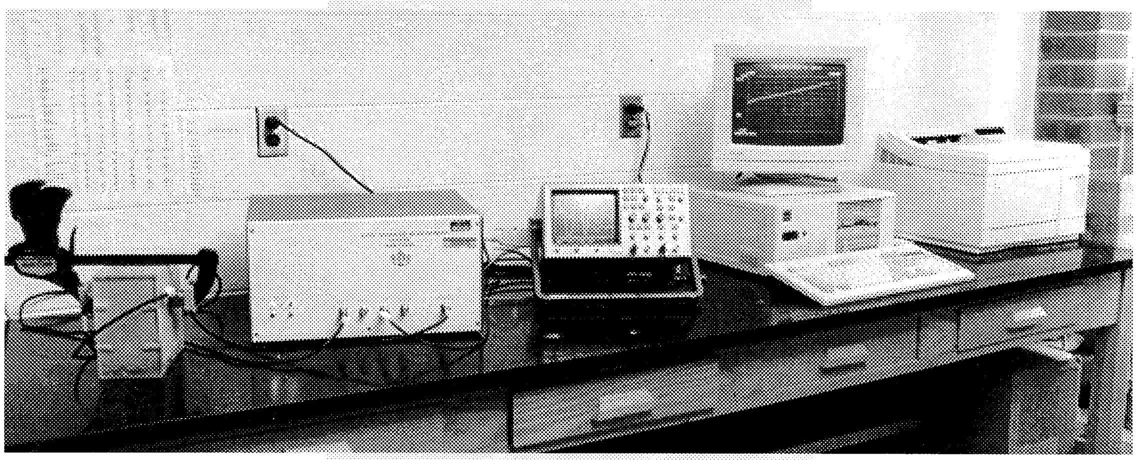
FINAL REPORT

INITIAL LABORATORY STUDIES OF THE NONDESTRUCTIVE EVALUATION OF CONCRETE CONSOLIDATION USING A PULSED ULTRASONIC INTERFEROMETER



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16. Abstract

The objectives of this study were (1) to study the feasibility of using a pulsed, swept-frequency ultrasonic interferometer in the nondestructive evaluation of the degree of concrete consolidation and (2) to find a correlation between the degree of consolidation and the ultrasonic velocity calculated from the phase slope. The system developed incorporated a pulsed ultrasonic interferometer, an oscilloscope, and a PC for automatic data logging and processing. Typical results from the ultrasonic monitoring of consolidation in fresh concrete at an early age are presented, and a correlation between the degree of consolidation and the ultrasonic velocity calculated from the phase slope is shown.

The system developed was able to make ultrasonic velocity, amplitude, waveform, and frequency measurements on plastic and hardened concrete. The results suggest that void size may affect ultrasonic travel in a manner that can be differentiated by the equipment. Variations in paste development that affect the measurement of velocity abate about 12 hr after mixing. Thereafter, the system can be an accurate approach for the nondestructive evaluation of the degree of concrete consolidation. The authors recommend additional study to further refine the capabilities of the system.

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INTRODUCTION

During mixing and placing, air becomes entrapped in plastic concrete. The removal of this entrapped air is necessary in concrete construction and is usually accomplished by the use of mechanical vibrators to consolidate the concrete. If the entrapped air is not removed, the result will be a porous concrete with low strength and durability.[1]

Generally, concrete is considered well consolidated when the entrapped air content in the hardened concrete is 1.5 percent or less.[2] The density of concrete is directly related to its air content and thus can be used to evaluate consolidation. However, this evaluation is complicated because many concretes contain intentionally entrained air voids to provide protection from freezing and thawing deterioration. Entrained air voids can be distinguished microscopically from entrapped air voids by their size (<1 mm) and regular shape (spherical). Although acceptable variations in the entrained air content and other mix proportions can confound the evaluation of concrete consolidation, density provides a reasonable foundation for assessing consolidation.

Nuclear density gauges can be used to monitor the densification of in-place concrete, and hence the degree of consolidation.[3,4] Although Ozyildirim[5] evaluated this method and found it to be ineffective, others reported success and recommended its use.[1] The use of fiber optic devices to measure acoustic acceleration and characterize the air void system has also been investigated for monitoring the consolidation process in fresh concrete, but practical applications have not been reported.[6,7]

Commonly accepted ultrasonic velocity measurement techniques, such as impulse-echo, cannot be used to characterize concrete properties because multiple-transit echoes are either not

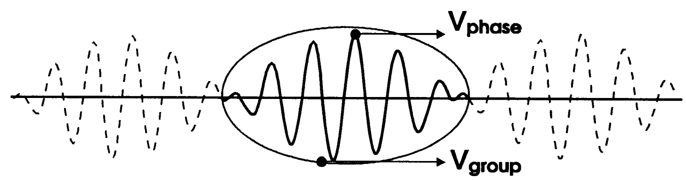


FIGURE 1. PHASE AND GROUP VELOCITIES

observable or severely distorted because of the large propagation losses. Currently, concrete group velocity data in the kilohertz frequency region are typically obtained using through-transmission (pulse velocity) or resonance (impact-echo) methods.[8,9] (The group velocity is the travel speed of the entire pulse of component phases as illustrated in Figure 1.) However, the use of these two methods cannot provide enough resolution to detect and quantify the degree of concrete consolidation.

Current ASTM standards for evaluating the consolidation of concrete include microscopic analysis and gravimetric methods using hardened concrete. These methods require the removal of samples from the structure or pavement for testing and are thus destructive and time-consuming. Nuclear gauges can be used to determine the density of in-place concrete but cannot resolve differences caused by variations in the entrained and entrapped air contents in all cases. Therefore, there is a need for a rapid, accurate, and nondestructive method to detect and quantify the degree of consolidation especially while the concrete is still plastic.

Ultrasonic measurements using a pulsed ultrasonic interferometer appear to be especially useful for evaluating consolidation characteristics with higher accuracy and resolution and may provide a means to distinguish between low densities caused by high levels of entrained air and those caused by poor consolidation. The advantages of the interferometer compared to the instruments frequently used to measure pulse velocity are:

- higher accuracy by measuring the velocity independently from the preset threshold by determining the slope of the phase versus frequency curve for a gated received signal

- higher resolution of small changes in air content by measuring the phase velocity (the rate of travel of a point of constant phase in the pulse [Figure 1]), amplitude, frequency, and waveforms of the ultrasonic signal

- higher sensitivity by using transducers with a frequency 5 to 10 times higher than the commonly used 54 kHz transducers

- higher penetration of the ultrasound in fresh concrete by using a voltage output 4 to 5 times higher than the routinely used 500 V output

Despite its promise in determining concrete consolidation, the use of an ultrasonic interferometer has not been systematically evaluated because suitable equipment has not been available. This study was conducted to evaluate its use using a newly developed system.

PURPOSE AND SCOPE

The purpose of this study was to conduct a nondestructive laboratory investigation of concrete samples with different degrees of consolidation using a pulsed swept-frequency ultrasonic interferometer to determine the feasibility of using this method to determine the degree of concrete consolidation. In addition, the authors sought to find a correlation between the degree of consolidation and the ultrasonic velocity calculated from the phase slope.

METHODS

This investigation examined concrete samples with different degrees of consolidation using a pulsed swept-frequency ultrasonic interferometer. Absolute and relative velocity, amplitude, frequency, and waveforms were measured. In addition, the velocity calculated from the corrected phase slope was correlated with the results from the microscopic analysis of the specimens.

Preparation of Test Specimens

Concrete specimens were cast from three low-slump (0 to 75 mm) paving concrete mixtures: one non–air entrained and two air entrained. The proportions of portland cement, fine aggregate, coarse aggregate, and water were held constant for the three mixtures; only the dosage of air-entraining admixture was varied. The mixture proportions are shown in Table 1.

TABLE 1. MIXTURE PROPORTIONS

Ingredient	Mix 1	Mix 2	Mix 3
Portland cement (kg/m^3)	335	335	335
Coarse aggregate (kg/m^3)	1,112	1,112	1,112
Fine aggregate (kg/m^3)	742	742	742
Water (kg/m^3)	152	152	152
Air-entraining admixture (ml/kg)	0	0.8	2.2

The concrete batches were mixed in accordance with ASTM C192-90a (Making and Curing Concrete Test Specimens in the Laboratory). The unit weight of the fresh concrete was determined in accordance with ASTM C138-92 (Unit Weight, Yield and Air Content [Gravimetric] of Concrete), and its air content was determined in accordance with ASTM C231-91b (Air Content of Freshly Mixed Concrete by the Pressure Method). In the initial tests on hardened concrete, rectangular prisms 100 x 100 x 350 mm were molded for ultrasonic testing. In molding the specimens, two levels of compactive effort were used in an attempt to produce specimens with different degrees of consolidation. In the first, hand consolidated (H), the concrete was placed in the molds and compacted with no more than 10 hammer taps of an effort similar to that used to close the voids left by rodding a standard concrete specimen. In the second, vibrated (V), the concrete was consolidated in the molds for approximately 10 sec on a vibrating table. The specimens for ultrasonic testing were moist cured for 28 days.

In a subsequent series of tests, the ultrasonic properties of concrete were monitored during the hardening process. The specimens were cast in 100 x 150 x 150 mm Plexiglas molds with holes machined on two opposite faces for the mounting of transducers. The mixtures were tested used the same mixture designs used for the hardened specimens except that an accelerating admixture was used. Hand-consolidated and vibrated specimens were fabricated as described, and monitoring began shortly after molding.

Air Content Determination

After completion of the ultrasonic testing, the specimens were sawed to obtain a cross section at a point where the ultrasonic measurement was made. This cross-sectional surface was finely lapped to produce a smooth surface for microscopic analysis. The air content of the specimen was determined by the linear traverse method in accordance with ASTM C457 (Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete). In this method, the lengths of the traverse lines that intersect the void space (chords) on the surface of the specimen are summed. The apparatus used was capable of grouping the chord length of individual void intersections based on a predetermined size range, thus providing information on the void chord length distribution.

The densities of the specimens were determined gravimetrically by measuring the mass of the saturated specimen first in air and then immersed in water. Subsequently, 100 x 100 x 100 mm cubes were sawed from each specimen and tested for compressive strength.

Ultrasonic Instrumentation and Monitoring Setup

Absolute and relative ultrasonic data were obtained from across each specimen using the phase-sensitive technique.[10] An advanced pulsed-interferometer measurement system (RITEC

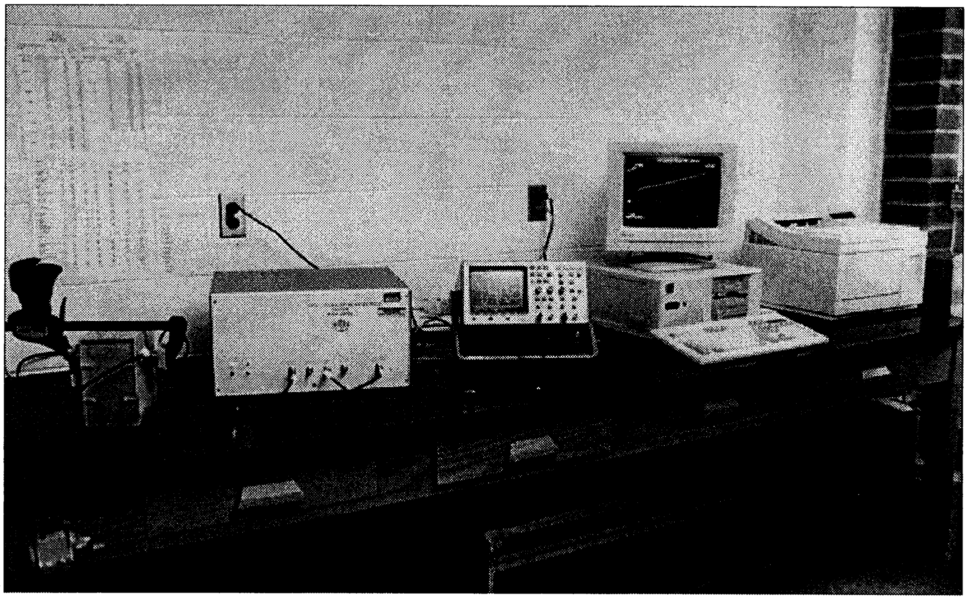


FIGURE 2. ULTRASONIC LABORATORY SETUP

RAM 10000), based on a phase-sensitive detection method, was used. The system uses a gated, phase-sensitive receiver to measure the phase of a probing ultrasonic signal as a function of frequency in the range of 50 to 20 MHz at high power (10 KW). The system allows both pulse-echo and through transmission measurements. Amplitude and phase analysis software was used to analyze the test results. The source code was provided, which allowed the authors to modify the programs for their own needs. A detailed description of the system's hardware and software is given in the Appendix.

The ultrasonic measurements were performed using the laboratory setup shown in Figure 2. A block diagram of the setup is shown in Figure 3. Acoustic contact during curing was maintained by means of springs incorporated in the bar clamps (quick-grips), which held the transducers in place. Direct contact, 250 and 500 kHz longitudinal wave transducers, both manufactured by ULTRAN Lab, were used. Cylindrical delay lines fabricated from Plexiglas were placed between the transducer and the concrete to protect the transducer surface from damage, which could have resulted from direct contact with the rough concrete surface. Thick petroleum jelly was used to provide a coupling between the delay lines and the concrete surface. In this study, 250 and 500 kHz transducers were used rather than the 54 kHz transducer used in concrete field testing to improve the sensitivity to and resolution of small changes in air content.

The first ultrasonic arrival through the concrete was successfully separated from the multiple reflections within the delay lines. The ultrasonic measurements involved measuring the

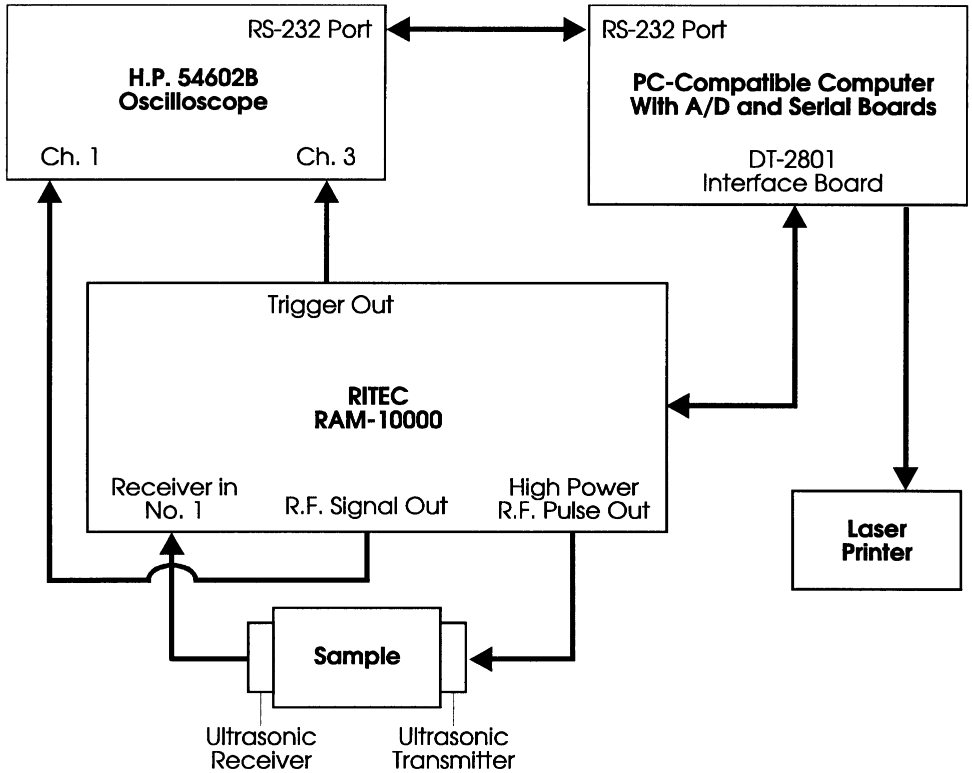


FIGURE 3. BLOCK DIAGRAM OF SETUP

transit time, amplitude, frequency, and waveform of an ultrasonic pulse between a transmitting and receiving transducer. The transit time and measured path length (the distance between the transducers) were used to calculate the ultrasonic velocity in the specimen. The velocity is given by the equation

$$\text{Velocity} = \text{Path length/Transit time.}$$

The path length was nominally 100 mm. Usually, to calculate the velocity, the transit time is determined by measuring the time separating the leading edges of the transmitted and received signals when the received signal first crossed a preset threshold (Figure 4A). Too high a preset threshold in the instrument will result in a transit time that is too high for the signal first crossing the threshold and a velocity that is too low, due to cycle skipping for waveforms of the type seen in fresh concrete.[11] Sayers and Dahlin suggested obtaining the transit time manually from the digitized waveform in mortar samples.[11] This approach cannot be applied to fresh concrete in very early stages because the amplitude of the received signal is too low and the noise is too high.

The RITEC instrument solves these problems and measures the velocity automatically after determining the slope of the phase versus frequency curve for a gated received signal. The

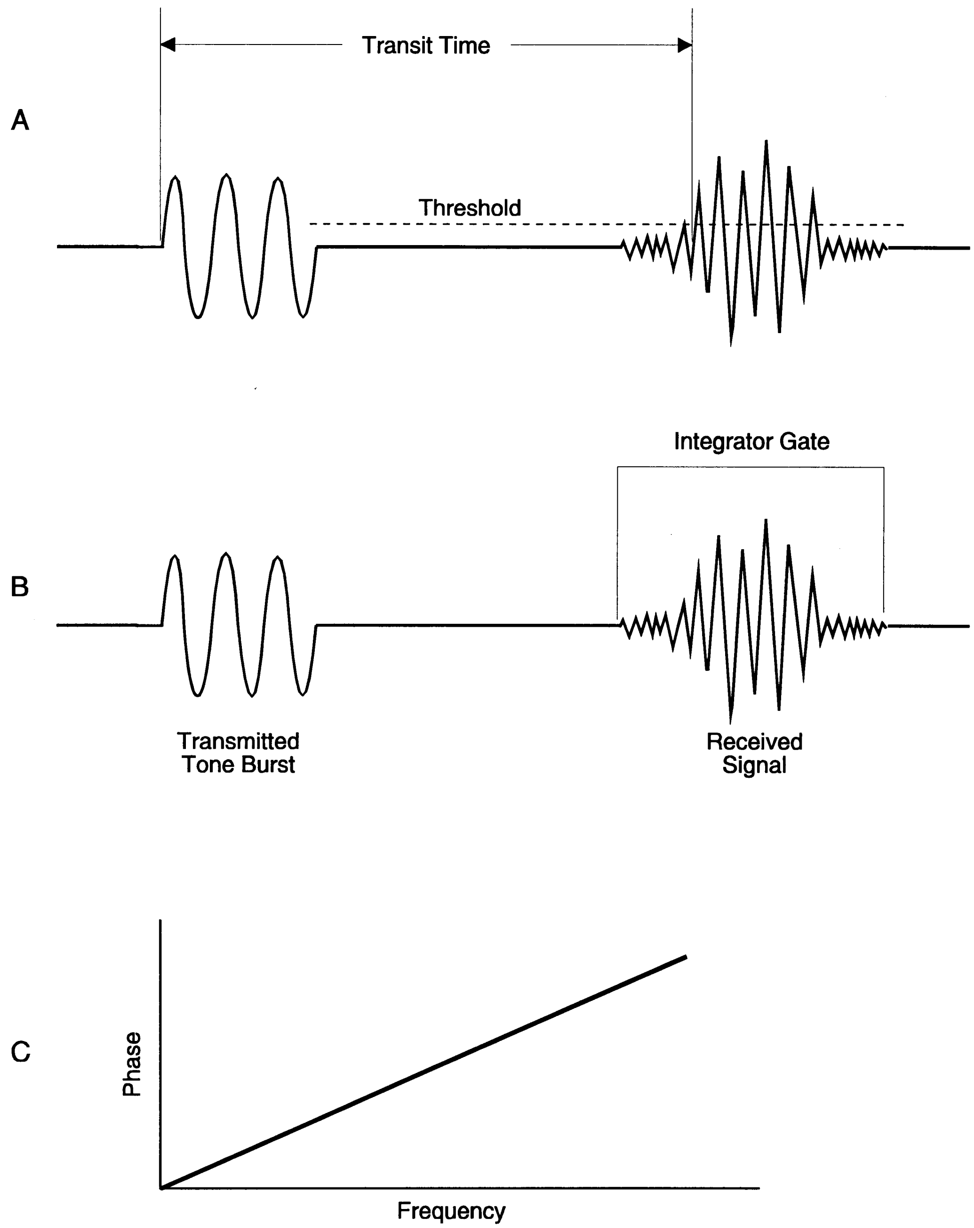


FIGURE 4. TRANSIT TIME MEASUREMENTS

position and width of the integrator gating signal are shown in Figure 4B. The total time of arrival, including delays through the electronics and acoustic elements as well as the acoustic transit time in the sample associated with the velocity, can be determined from the equation:

$$\text{Transit time} = \text{Change in the phase}/2\pi \text{ Frequency change.}$$

The computer constructs the curve of the equation, which is shown in Figure 4C, and calculates the slope and hence the velocity.

RESULTS AND DISCUSSION

The results of the unit weight and air content tests for the fresh concrete are shown in Table 2 along with the air content, density, compressive strength, velocity, and amplitude measurements of the corresponding hardened concrete. The differences between the various measures of air content in the fresh and hardened concrete based on unit weight, the pressure method (ASTM C231), and the linear traverse method (ASTM C457) are rather typical. However, although the desired differences in air content among the three concrete mixtures were achieved, the linear traverse results indicated that the differences between the air content of the hand-consolidated and vibrated specimens were negligible. This is illustrated by the distribution of void chords shown in Figure 5. Apparently, the differences in compactive effort used in producing the hand-consolidated and vibrated specimens were not sufficient to induce the desired differences in consolidation. In future attempts to simulate poorly consolidated concrete, the concrete should rest for 30 to 45 min after mixing to allow slump loss or stiffening. In compacting the specimens, fewer hammer taps may be required, or perhaps taps may be omitted altogether, depending on the consistency of the concrete. Figure 5 also depicts the difference in void chord distribution between non–air-entrained and air-entrained concrete. Non–air-entrained concretes have no void chords less than 250 μ, whereas air-entrained concretes have a large population of void chords less than 125 μ. Photomicrographs of polished surfaces of specimens showing these differences are presented in Figure 6.

The density and strength of the specimens were determined after the ultrasonic measurements. In Figures 7 and 8, strength is plotted against air content (ASTM C457) and density. The general trend was as expected, with strength showing a positive correlation with density and a negative correlation with air content. However, between the hand-consolidated and vibrated specimens, the density relationships were contrary to what was expected based on the strength and air content data, with higher densities associated with lower strengths and higher air contents. This is attributed to the small sample size and the fact that the actual differences in measured density were small.

In Figures 9 and 10, velocity is plotted against strength and air content (ASTM C457), and, again, the general trends were as expected. In Figure 9, the hand-consolidated and vibrated plots of strength against velocity follow roughly linear trends with slightly different slopes. In Figure 10, however, hand-consolidated and vibrated air content versus velocity plots follow the same trend, either curvilinear or two linear segments with a change in slope. Interestingly, the inflection occurs at the point where the numerous smaller voids in air-entrained concrete begin to influence the physical character of the concrete. In this case, the smaller air-entrained voids had a much larger effect on velocity, resulting in a dramatic decrease in its value. A possible

TABLE 2. TEST RESULTS ON FRESH AND HARDENED CONCRETE

Sample	Unit Wt. (kg/m³)	Unit Wt. (Air %)[a]	C231 (Air %)	C457 (Air %) Total	C457 (Air %) <1 mm	C457 (Air %) >1 mm	SSD[b] Density	Strength (MPa)	Velocity (m/s)	Amplitude (mV)
HC-1H	1843	1.6	1.8	3.05	1.70	1.35	2.47	56.2	4734	487.5
HC-1V	[c]		[c]	3.18	1.83	1.35	2.48	44.2	4720	485.5
HC-2H	1737	7.3	5.6	8.26	6.77	1.49	2.36	40.7	4620	485.4
HC-2V	[c]		[c]	9.05	7.17	1.88	2.40	37.7	4565	484.1
HC-3H	1639	12.5	9.0	12.59	11.03	1.58	2.26	26.1	4276	483.4
HC-3V			[c]	13,93	12.12	1.81	2.27	24.5	4098	481.3

[a]Calculated from unit weight.
[b]Specimen in saturated surface dry condition.
[c]Only one test for each batch; consolidation by standard method.

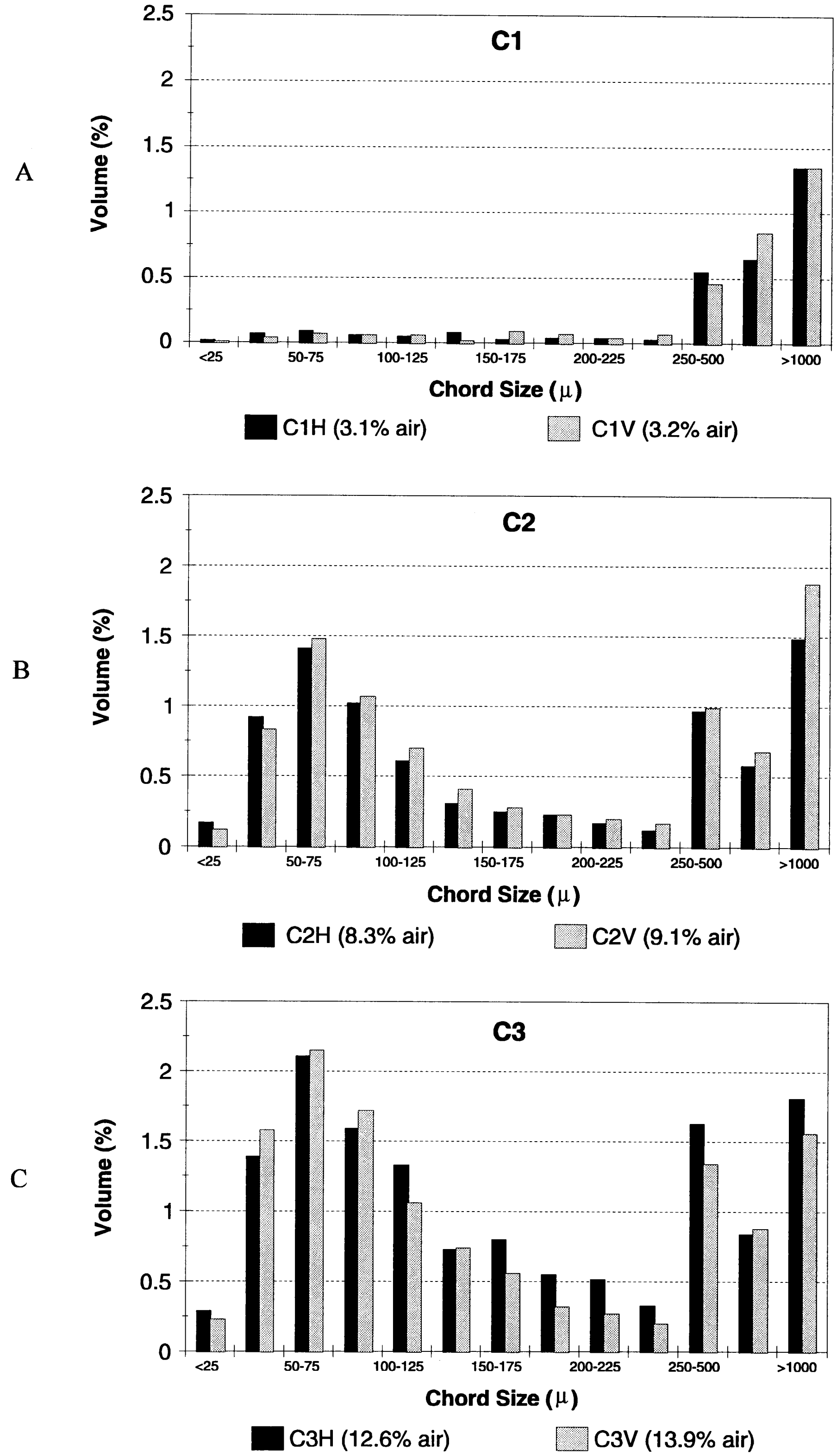
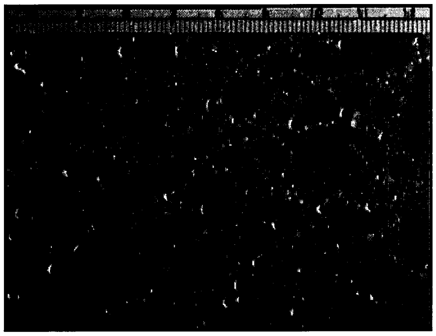
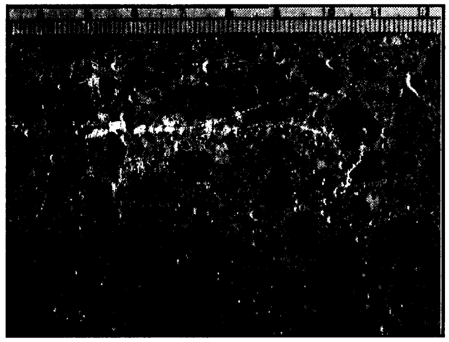


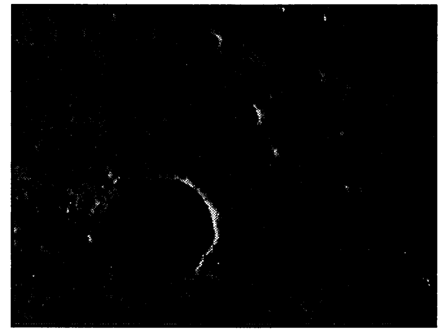
FIGURE 5. VOID CHORD DISTRIBUTION BY SIZE



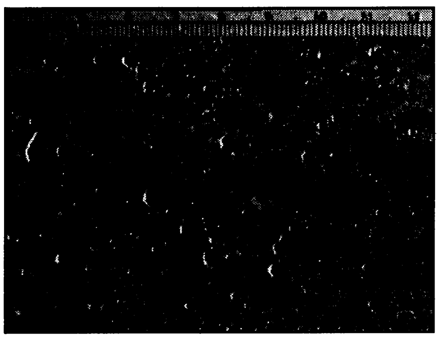
C1U



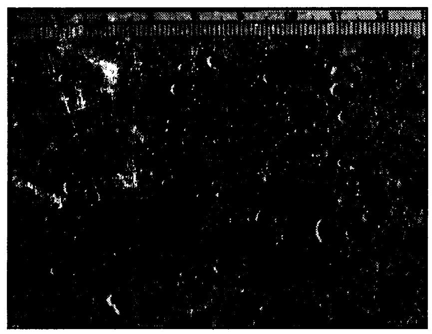
C1V



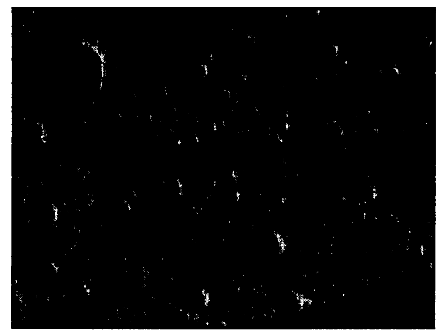
C1V 25X



C2U



C2V



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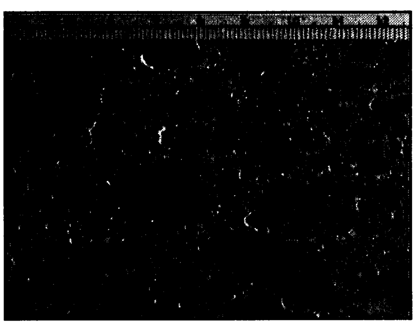
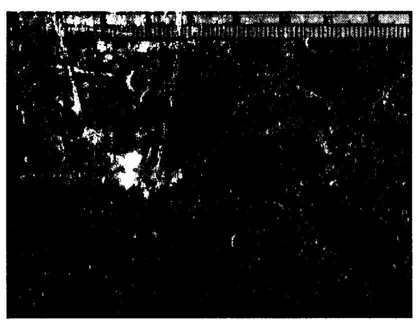
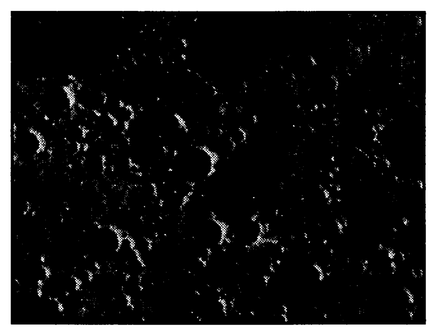


C3U



C3V



C3V 25X

FIGURE 6. PHOTOMICROGRAPHS OF POLISHED SLABS OF SPECIMENS

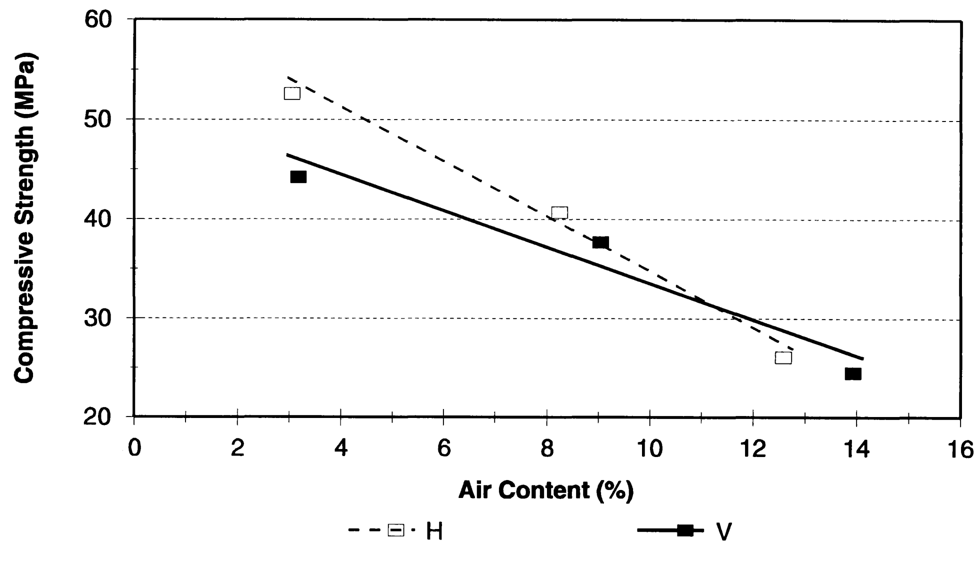


FIGURE 7. STRENGTH VERSUS AIR CONTENT

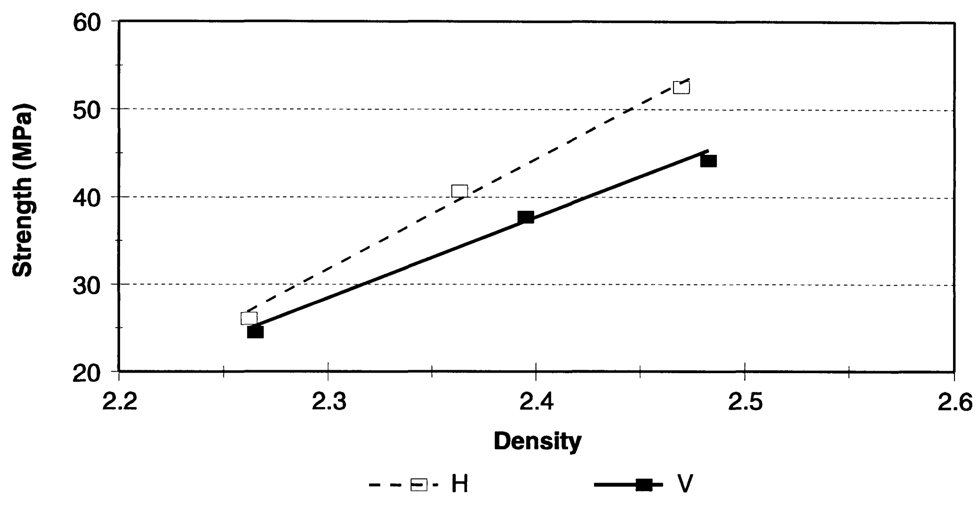


FIGURE 8. STRENGTH VERSUS DENSITY

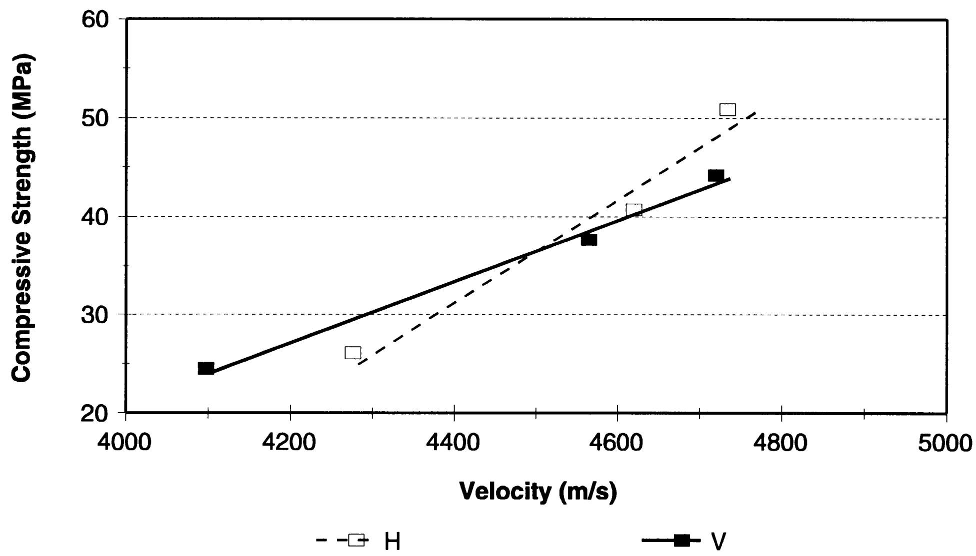


FIGURE 9. STRENGTH VERSUS VELOCITY

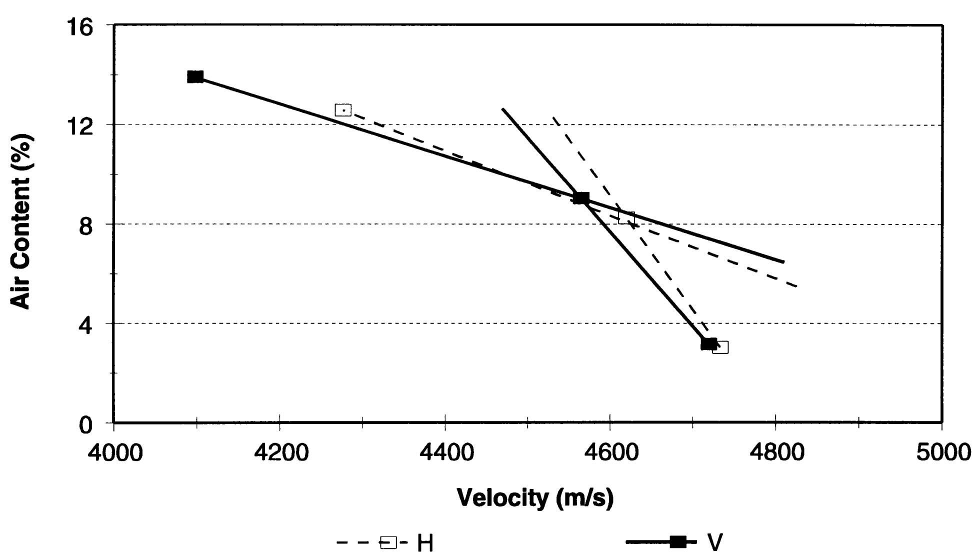


FIGURE 10. AIR CONTENT VERSUS VELOCITY

explanation is that the presence of the numerous small voids causes an increase in the path length the pulse must travel.

The signal waveforms received through the hardened concrete were recorded, and examples are shown in Figure 11. Recently developed software that provides signal qualification, pattern recognition, and detailed wavelet analysis of the waveforms will greatly enhance the interpretation of the ultrasonic properties measured. These analyses will be performed as a part of future efforts to resolve differences in the void structure of concrete.

Ultrasonic measurements as early as 10 min after mixing are possible with 250 kHz transducers, a high-voltage pulse output of 2200 V, and 80 dB gain. The reliable starting time for ultrasonic measurements depends on temperature, the presence of accelerating and retarding admixtures, cement type and content, and the water-cement ratio, all factors that affect the rate at which the hydration reactions of the system occur and, consequently, the setting time of the concrete. The heterogeneous nature of concrete produces a large signal scatter and attenuation, which is exaggerated when the concrete is fresh.[12] For the pulse amplitude and transit time to be measured accurately, hydration must have proceeded sufficiently for the paste to develop into a semi-viscous/plastic state so that a sufficient strength of signal reaches the receiving transducer.

The amplitude of the largest positive peak at first decreases versus time at a very early stage. Approximately 2 to 3 hr after mixing, the signal amplitude begins to increase steadily. The amplitude behavior versus time for fresh vibrated concrete with 3 percent total air content (1.3 percent entrapped) is shown in Figure 12 (250 kHz transducer). The relative peak-to-peak amplitude changes for different periods of time after mixing are shown in Figure 13. A large signal scatter shortly after mixing and the later slope change are possibly the result of hydration reactions of the system that affect its physical state. For the same sample, the rate of change of velocity (dv/dt) at very early ages reached the maximum approximately 2 hr after mixing. A plot of dv/dt versus time is shown in Figure 14. Casson et al.[12] considered these two maxima, amplitude and dv/dt, as an indication that the hydration reaction had reached its maximum rate. These maxima appeared to occur about 2 to 3 hr after mixing at a velocity below 2,000 m/s, regardless of air content, in the samples studied.

At early ages, high-frequency waves were propagated through the fresh concrete. The frequency of the signal decreased very rapidly and reached the minimum between 5 and 10 hr after mixing. A steady frequency increase occurred thereafter. A plot of frequency versus time for fresh concrete with 12 percent total air content (1.5 percent entrapped) is shown in Figure 15. In a similar study, Sayers and Dahlin showed the effect of entrapped air on fast Fourier spectra during the propagation of ultrasound through hydrating cement pastes at early ages.[11] They pointed out that the fresh cement paste behaved as a high-pass filter over the frequency range employed. However, because differences in entrapped air content among specimens were not obtainable, in this study no potential relationships between the frequency and amount of entrapped air in fresh concrete could be identified.

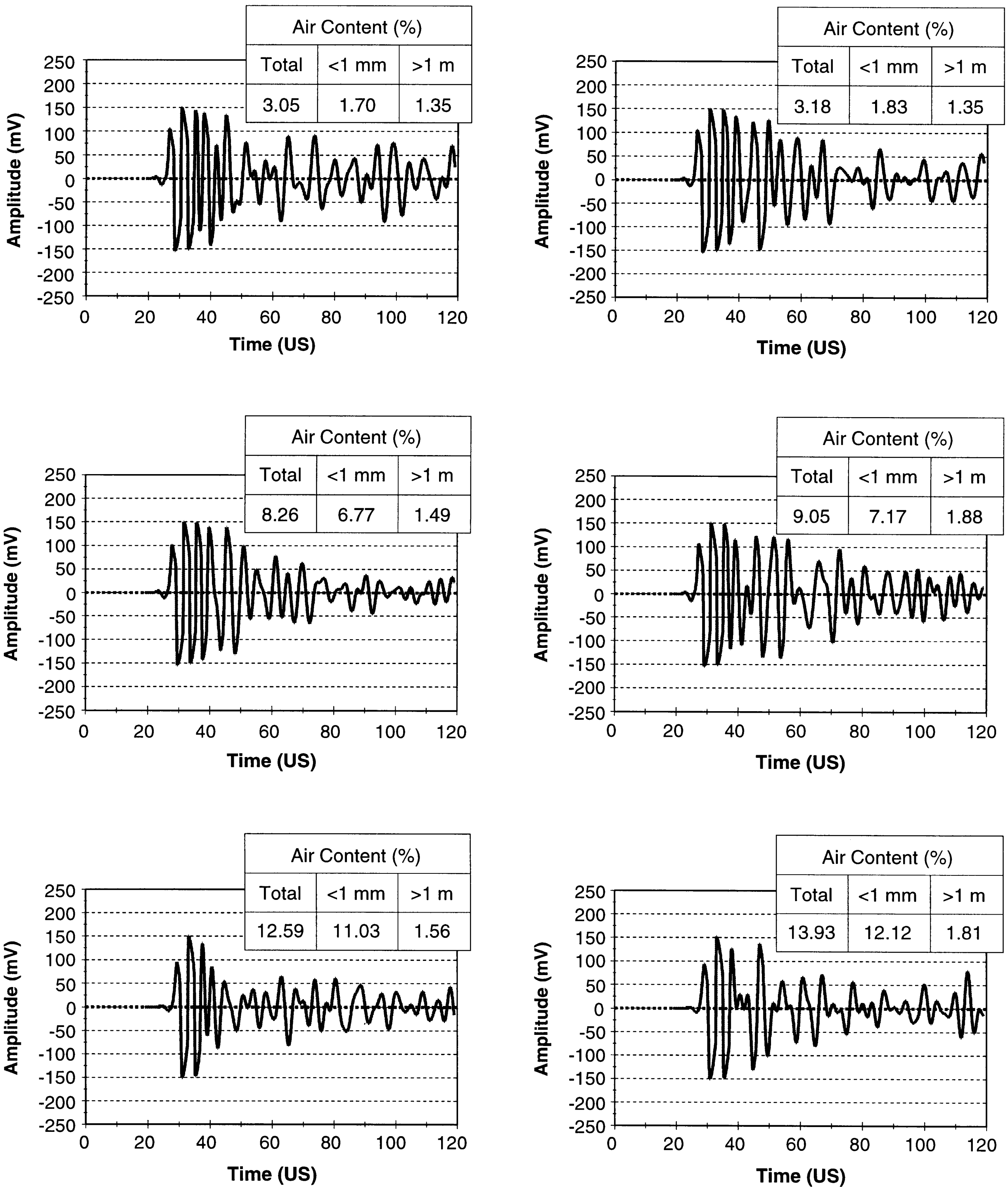


FIGURE 11. WAVEFORMS IN HARDENED VIBRATED AND HAND CONSOLIDATED CONCRETES

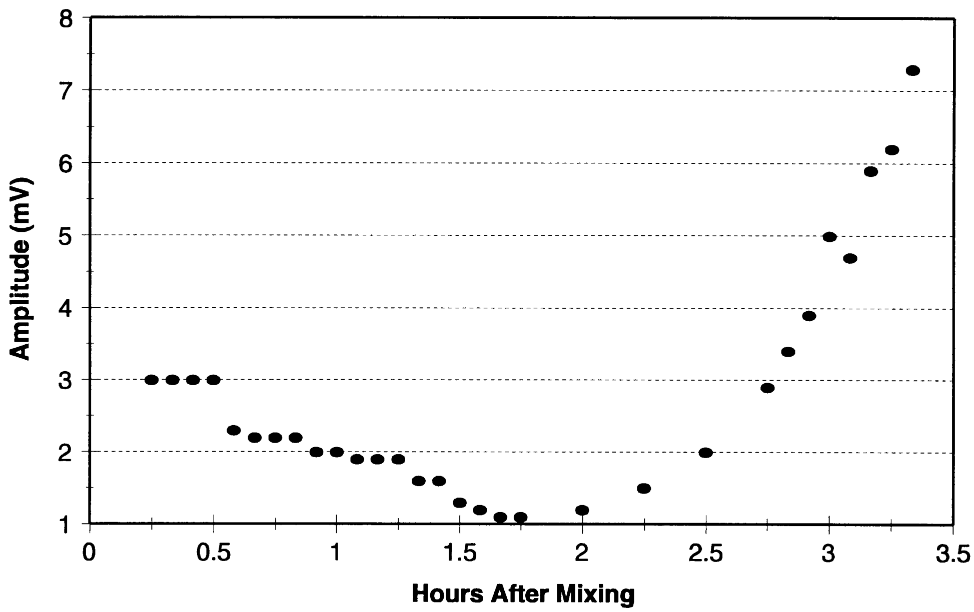


FIGURE 12. AMPLITUDE VERSUS TIME FOR FRESH CONCRETE WITH 3% AIR CONTENT (1.3% ENTRAPPED)

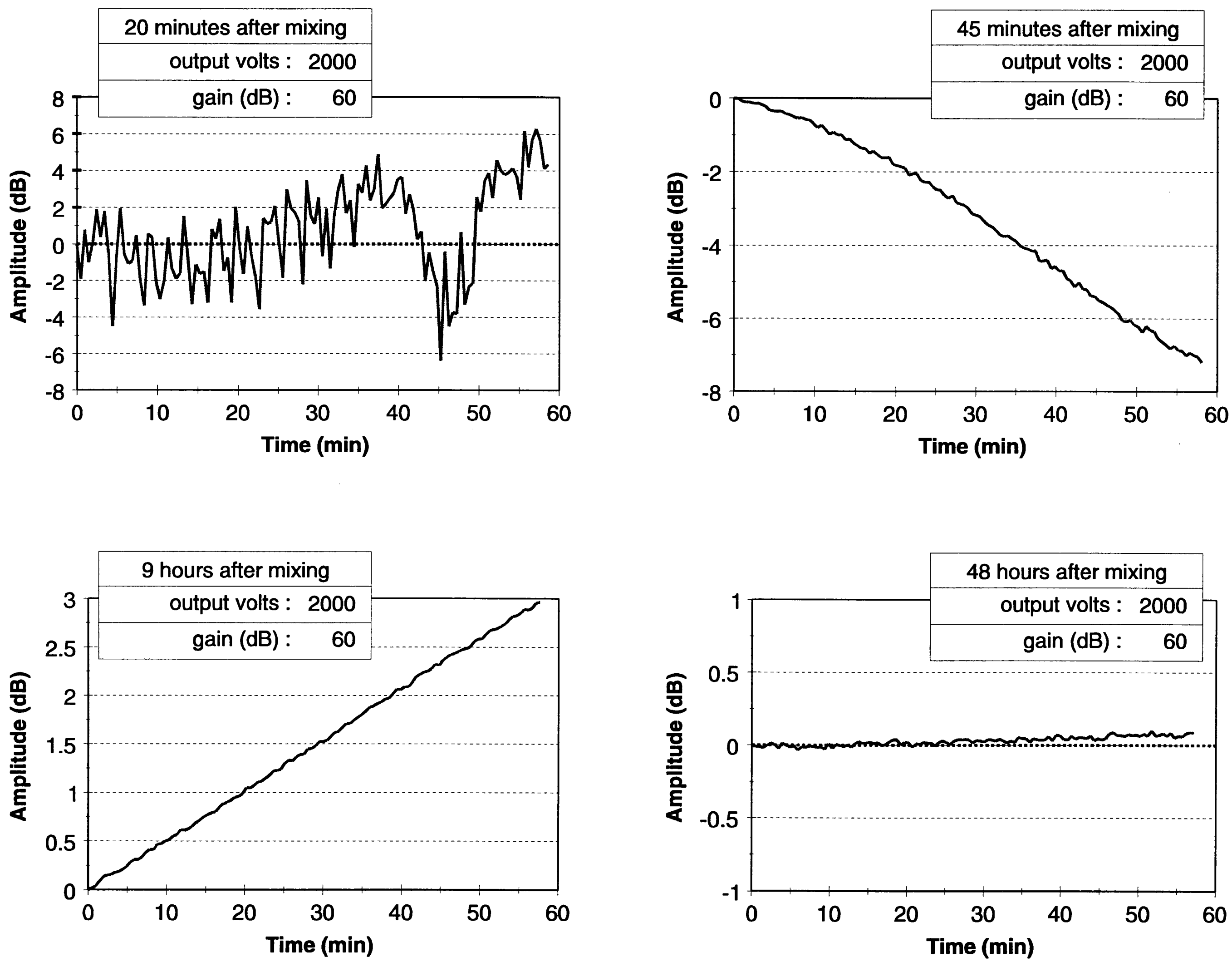


FIGURE 13. RELATIVE AMPLITUDE VERSUS TIME FOR VIBRATED CONCRETE SAMPLE

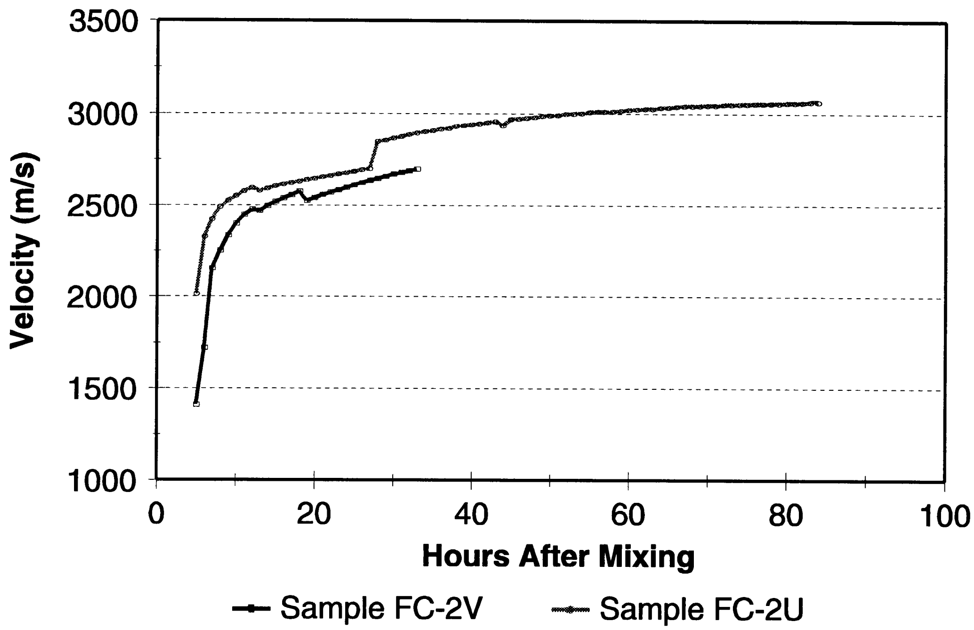


FIGURE 14. RATE OF CHANGE OF VELOCITY VERSUS TIME AFTER MIXING FOR VIBRATED CONCRETE WITH 3% AIR (1.3% ENTRAPMENT)

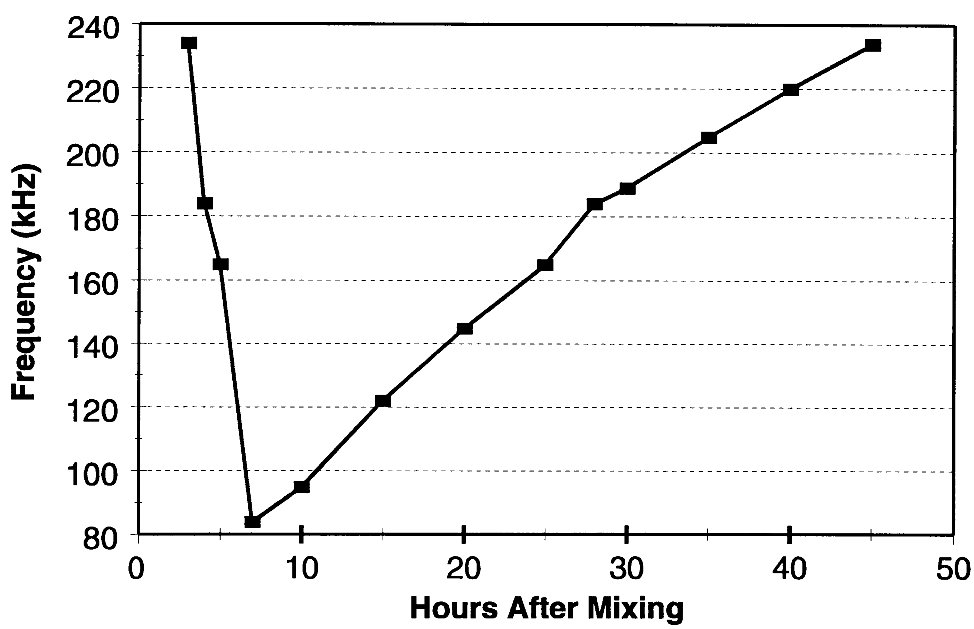


FIGURE 15. FREQUENCY VERSUS TIME AFTER MIXING FOR HYDRATING CONCRETE WITH 12% AIR (1.5% ENTRAPMENT)

No attempt has been made to perform a detailed analysis of the measured signal waveforms in fresh concrete. Figure 16 shows that there are significant differences between waveforms in early stages in fresh concrete. Further study is recommended.

In Figures 17 through 20, pulse velocity is plotted versus time at early stages after mixing for various specimens. In these figures, FC-1H denotes fresh concrete, mixture 1, hand consolidated, and other sample labels follow the same convention. The depicted results indicated that velocity measurements are sensitive to air changes in early stages. As would be expected because of the low total air content in the non–air-entrained samples FC-1H and FC-1V, much higher velocities were measured in these samples than in samples FC-2H, FC-2V, and FC-3V. The initial velocity of about 1,000 to 2,000 m/s at 3 to 5 hr after mixing increased rapidly up to 3,000 to 3,500 m/s at about 30 to 40 hr after mixing and increased more slowly thereafter.

Figures 19 and 20 show the less than 10 percent difference detected between the velocities of hand-consolidated and vibrated specimens from mixtures 1 and 2. The differences between the entrapped air in these samples were not large enough to produce measurable differences in velocity.

At early ages, the range of velocity measurements for individual specimens is quite high. A measure of this range, known as the variation range, was calculated using the equation:

$$\text{Variation range} = (\text{Vel}_{max} - \text{Vel}_{min}) \times 100/\text{Vel}_{ave}\ (\%).$$

Figure 21 presents the variation range for different samples up to 672 hr after mixing. Each point in Figure 21 represents the variation range of velocity measurements made at five different locations on the specimen. These results showed that after 9 to 10 hr after mixing, within specimen variations resulting from paste development cease to affect velocity measurements significantly and reliable measurements can be made.

CONCLUSIONS

The system developed for this project was capable of measuring ultrasonic velocity, amplitude, waveform, and frequency in plastic and hardened concrete. Software was developed that automated the measurement of these parameters, thus permitting constant monitoring of concrete during the hydration process.

Although attempts to produce specimens with different amounts of entrapped air were unsuccessful in the limited study undertaken, the results suggest that void size may affect ultrasonic travel in a manner that can be differentiated by the equipment. Tests on hardening concrete indicate that significant changes in the physical properties of the concrete during the

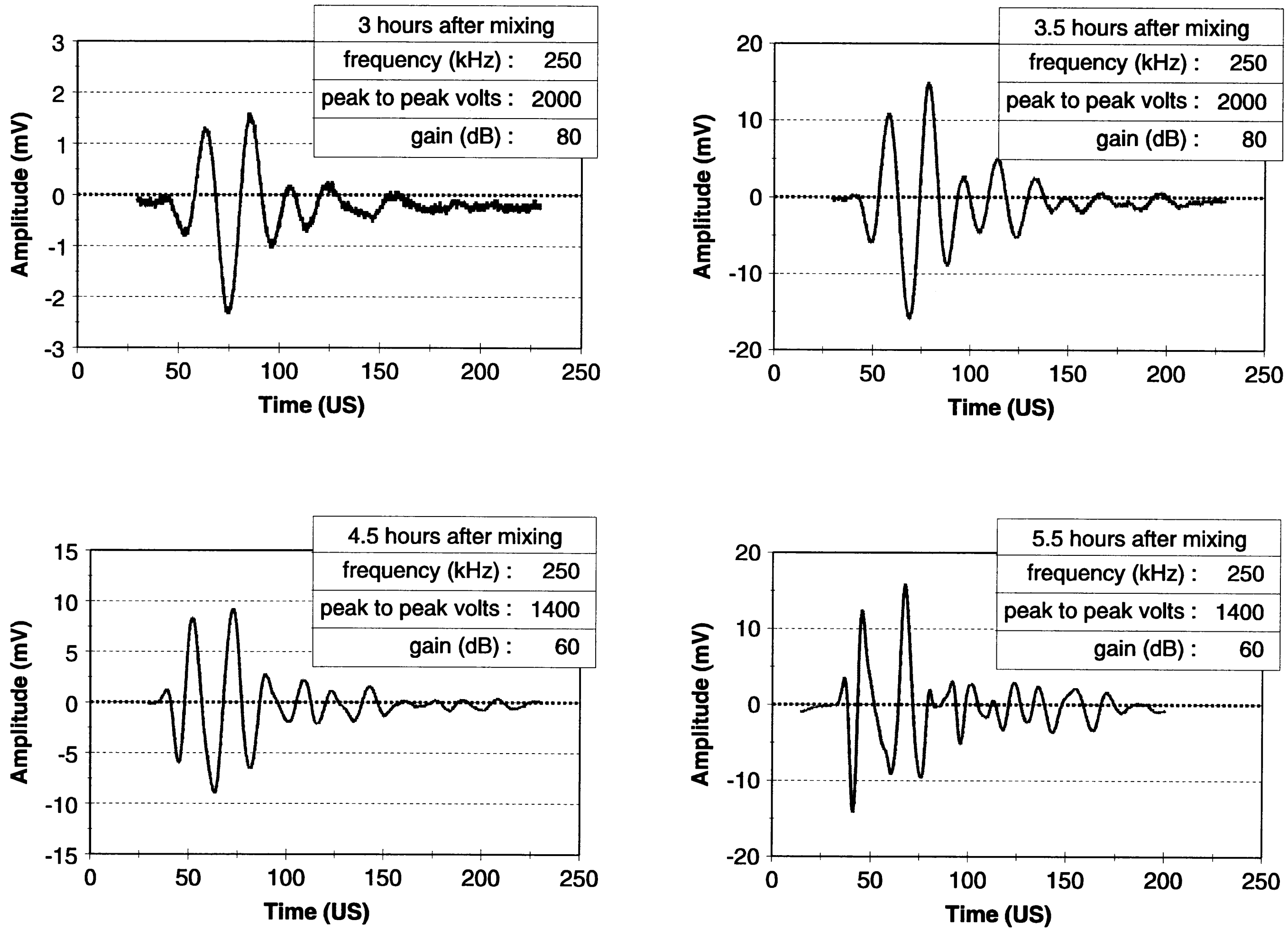


FIGURE 16. WAVEFORMS IN A HAND CONSOLIDATED CONCRETE SAMPLE AFTER MIXING

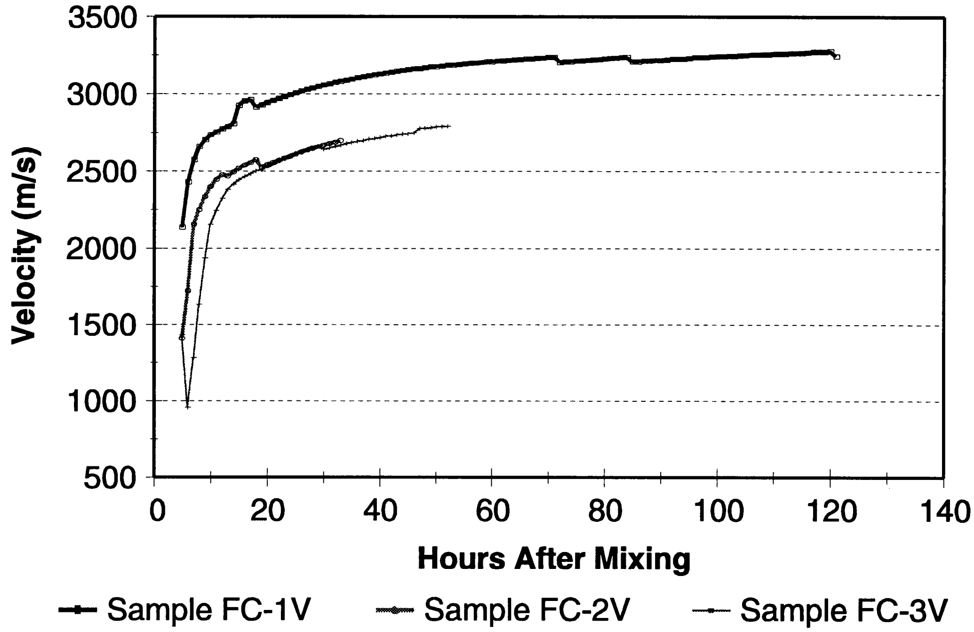


FIGURE 17. VELOCITY VERSUS TIME FOR VIBRATED CONCRETE AFTER MIXING

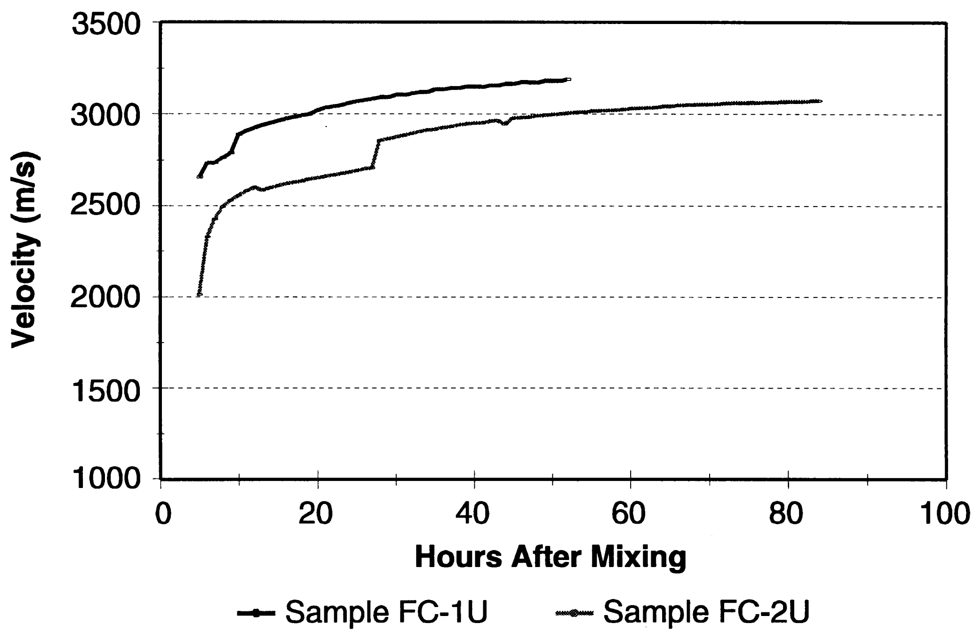


FIGURE 18. VELOCITY VERSUS TIME FOR HAND CONSOLIDATED CONCRETE AFTER MIXING

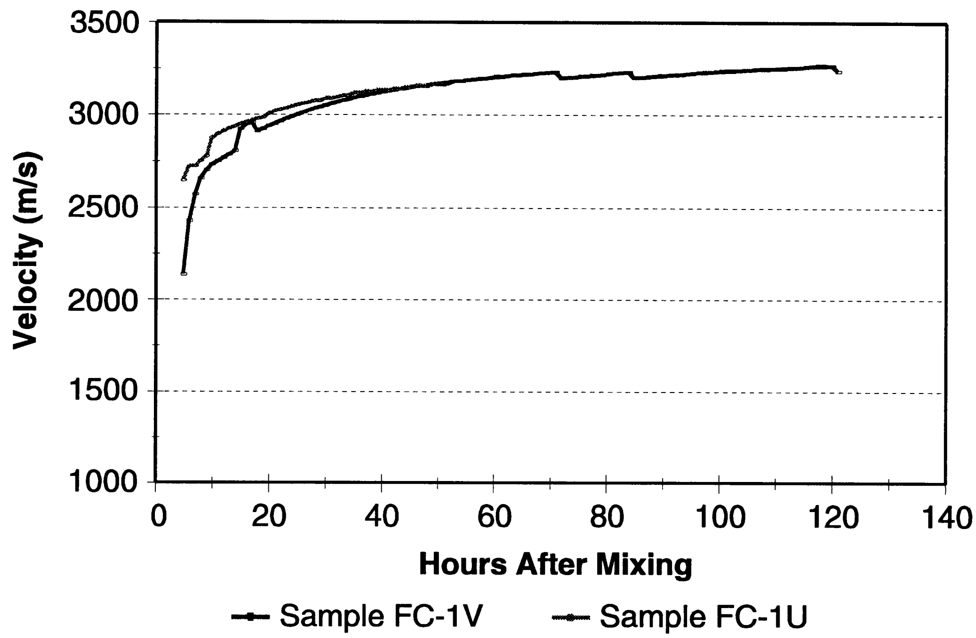


FIGURE 19. VELOCITY VERSUS TIME FOR VIBRATED AND HAND CONSOLIDATED CONCRETE WITH 3% AIR (1.3% ENTRAPPED)

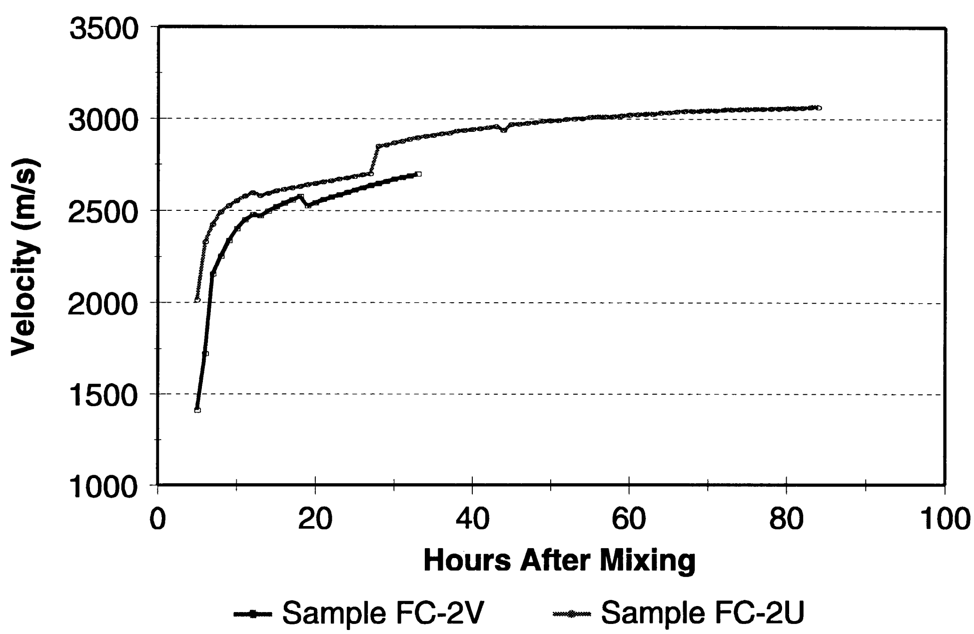


FIGURE 20. VELOCITY VERSUS TIME FOR HAND CONSOLIDATED CONCRETE WITH 8% AIR (1.5% ENTRAPPED) AND VIBRATED CONCRETE WITH 9% AIR (1.9% ENTRAPPED)

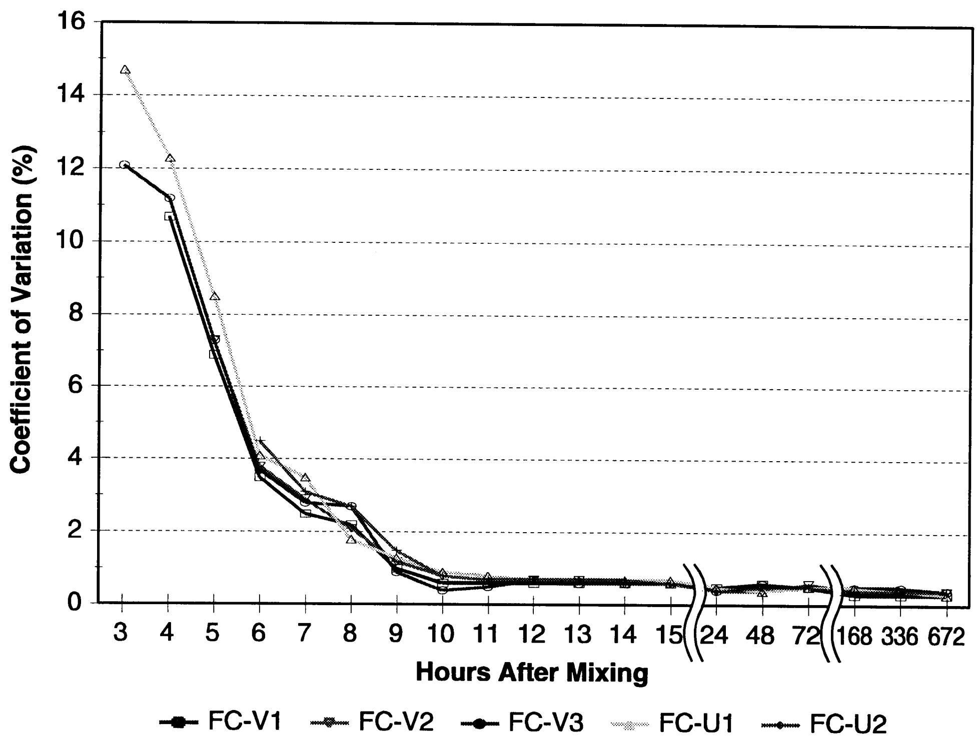


FIGURE 21. COEFFICIENT OF VARIATION VERSUS TIME FOR FIVE CONCRETE SAMPLES

setting process may be detectable by minima or maxima noted in amplitude, frequency, and velocity (dv/dt) measurements. In the tested samples, these changes occured at an age of 2 to 3 hr in the case of amplitude and velocity and 5 to 10 hr in the case of frequency for concretes containing an accelerating admixture.

Variations in paste development that affect the measurement of velocity abate about 12 hr after mixing. Thereafter, ultrasonic parameter measurements using a pulsed ultrasonic interferometer can be an accurate approach for the nondestructive evaluation of the degree of consolidation.

RECOMMENDATION

This study provides a basis for ultrasonic research of fresh concrete and pulse-echo scanning and the detection of small defects in concrete structures. Additional studies should be undertaken to refine the capabilities of the ultrasonic equipment to characterize concrete consolidation and the hydration process.

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APPENDIX

DESCRIPTION OF SYSTEM HARDWARE AND SOFTWARE

The ultrasonic interferometer RAM-10000 is at the heart of the testing apparatus used in this study. It can generate a high-voltage pulse output (up to about 2,300 V, depending on frequency) and performs internal amplification on the return signal before passing the resulting waveform out of the RITEC system. All of its functions are controlled by a PC-compatible computer through a Data Translations DT-2801 interface board.

The Hewlett Packard 54602B oscilloscope is hooked up to the ultrasonic return signal through the RITEC instrument, and also to an external trigger provided by the RITEC instrument, so that it is synched to the start of each ultrasonic pulse. It is used for two functions. First, it can be used to monitor the ultrasonic return signal and perform manual measurements. Second, when controlled by the computer through its serial port, it can be used to make automatic measurements and send the results back to the computer program.

The PC controls both the RITEC instrument through the interface board and the oscilloscope through the computer's RS-232 serial port. The software used to control these instruments is written in Microsoft Professional BASIC and consists of several main programs. One program, used for making manual measurements, was written by RITEC personnel and makes use of the Data Translations libraries for controlling the RITEC equipment. It does not control the oscilloscope. The second and third programs, based on the first program and developed at the Virginia Transportation Research Council, allows automatic testing over extended periods by using the oscilloscope to monitor the delay time and frequency of the return signal and using this information to set the RITEC instrument properly.

The latest versions of all programs include RITEC.EXE, MEASURE.EXE, and GETWAVE.EXE.

- RITEC.EXE. This program is used to control the RITEC instrument interactively. All RITEC parameters are adjusted through four interactive screens: Setup I, Setup II, Absolute Measurements, and Relative Measurements. This program will take both absolute measurements (various values as a function of frequency) and relative measurements (various values as a function of time) and will make graphs of the results. It saves its setup parameters to the file LAST.SET when it exits and loads them back up when it starts again.

- MEASURE.EXE. This program is used to automate measurements over longer periods of time. It operates for a user-specified number of iterations, with each iteration first taking a measurement of amplitude, signal, and integrator outputs versus frequency and then taking a measurement of signal amplitude versus time (for a user-selectable period of time). It will use the HP oscilloscope to determine the transit time (the time between the ultrasonic pulse being sent and then being first received) and the approximate frequency of the received signal and set the RITEC parameters appropriately. It uses several external files, rather than using an interactive interface. It uses the same file LAST.SET as RITEC.EXE, simplifying the process of using both programs with the same parameters. It overrides several of these parameters, however, with parameters from an easily readable file SETUP.TXT or with values that it calculates from the oscilloscope information. When run, this program creates a file called DELAY.LOG, which stores the determined values for transit time, velocity, and frequency for each iteration.

- GETWAVE.EXE. This utility allows one to capture a waveform from the oscilloscope into a computer file for later viewing. When run, it prompts the user for a filename and then saves the waveform on channel 1 of the oscilloscope using the parameters currently set by the oscilloscope. It does store the actual voltage at each point. All of the files it stores have a .WFM extent for waveform.