# ACOUSTIC WAVE MEASUREMENTS IN REACTOR-GRADE CONCRETES

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## SUMMARY

In this paper, five reactor grade concretes were investigated during their initial cure period to gather information which is a suitable data base for interpreting the results of confirmatory reactor safety research programs.

In particular, the concretes studied were the concrete proposed for the Clinch River Breeder Reactor (CRBR), which is a limestone mix with flyash, and two other limestone-aggregate mixes and two basaltic-aggregate mixes. The curing process in these concretes was followed with strength tests and with acoustic-wave velocity measurements. The choice of the latter technique was based on the successful programs of several investigators who used acoustic waves to follow the curing process in concrete and this information was also required for instrumentation techniques that are proposed for accident simulation studies.

The technique used to measure the sound velocities of concrete is a modified version of the pulse transmission technique introduced by Mattaboni and which conforms to ASTM Standard C597-71 for the measurement of the sound velocity in concrete. This technique uses an electronic technique to measure the transit time of an acoustic wave through a sample and, thus, its acoustic velocity.

The results of the CRBR concrete program illustrate that the water retension stabilizes after 10 days of cure with a net loss of 0.4 percent; the addition of flyash to the mix stabilizes it and slows down the initial curing process from 33 to 90 days; the addition of the admixtures to the mix reduces its sound velocity from 5.74 km/s to 5.64 km/s and its strength from 51.6 MPa (7590 psi) to 42.1 MPa (6190 psi); and the sound velocity in this concrete stabilized after 75 days of cure.

The data from the other varieties of concretes have the same pattern as the CRBR concrete. Namely, during the first ten days of cure, the acoustic velocity (strength) increased rapidly. After that period, the curing process proceeded at a slower, uniform rate. Quasi-equilibrium (approaching a full cure) was reached between 60 and 90 days. At 90 days, the compressive strength was 33.9 MPa (4980 psi) for the fine-basaltic-aggregate concrete mix, 31.7 MPa (4660 psi) for the coarse-basaltic-aggregate mix, 29.7 MPa (4370 psi) for the fine-limestone-aggregate mix, and 29.1 MPa (4280 psi) for the coarse-limestone-aggregate mix. The reduction in strength between these mixes and the CRBR concrete is simply a matter of different constituents and different constituent ratios. All four of these concretes had attained acoustic wave velocities of 4.53 km/s or greater by the end of the 90 day cure.

## 1. Introduction

The design and safety analysis of nuclear reactor power plants depend heavily on the properties of concrete, one of the main structural materials in the plant. For most design applications, the structural response of the concrete is sufficiently well understood that designs can be determined by ordinary stress analysis with well established material properties. However, when one considers the experimental programs that are being conducted in ~~confirmatory~~ reactor safety research which address the safety aspects of the design (as the reactions of structural concrete to a sodium spill in a LMFBR or to a hypothetical core meltdown accident in a LWR or a LMFBR), the data base that is currently available is not always sufficient. For example, some knowledge of water migration and retention characteristics of the concrete is essential for the interpretation of the results from the programs. Also, acoustic techniques for measuring interface motion in these same experiments (which are now being explored) require acoustic velocity data for the concrete [1]. In this paper, data of this nature have been summarized in the interest of contributing to the general body of concrete material property information that is available to the structural designer and safety analyst.

In this paper, five reactor grade concretes were investigated during their initial cure period to gather information which is suitable for this data base. In particular, the first concrete investigated was the concrete proposed for use in the Clinch River Breeder Reactor (CRBR) and the other four are reactor grade concretes that were formulated based on the specification for the Turkey Point Reactor [2]. Besides the usual strength tests, as a function of cure time, acoustic waves were used to investigate the curing process in these concretes. The choice of an acoustic wave investigation was made because a large number of previous authors have successfully used acoustic waves as a nondestructive technique for studying the curing process in concrete (e.g., see references [3], [4], and [5]). Also, this information is required for instrumentation techniques that are proposed for accident simulation studies [1].

Due to space limitations, the results of the work on the CRBR will be emphasized here. Additional information on the other four varieties of concrete can be obtained from reference [6].

## 2. The Materials

Three types of concrete were used in the program - CRBR concrete, which is characterized by the addition of flyash to a limestone aggregate mix, and two others without flyash. The latter two differed from each other in that one was made with limestone aggregate and the other with basaltic. Two subtypes of these last two were made, one with a "fine aggregate mix" and the other with a "coarse aggregate mix." Table I lists the weights of each constituent for a typical mix. In each case, the "aggregate mesh size" is the minimum size of a wire mesh that the aggregate will pass through.

Specimens for compressive strength tests were molded on the day of pour into cylindrical test billets that had a diameter of 152 mm and a height of 304 mm. Ultrasonic samples were sectioned from the center region of a strength test billet when they had sufficient structural strength to withstand the sectioning process.

For the CRBR concrete, several special mixes were prepared to study the effects of the various constituents on the curing process. Batch 1 was a simple mixture of cement and water with the same proportions as shown in Table 1; batch 2 was batch 1 with the addition of flyash; batch 3 was batch 2 with the addition of finely crushed aggregate (sand); batch 4 was batch 3 with the addition of the large aggregate; and batch 5 was batch 4 with admixtures (i.e., the CRBR concrete). Batches 1, 2, and 3 were molded into the size required for ultrasonic specimens. Batches 4 and 5 were sectioned from compression test billets.

Curing conditions were chosen to be somewhat different for the various types of concrete. All specimens of the CRBR concrete were stored at room temperature (~ 20° C) and 100 percent relative humidity. The four other varieties were coated with wax and then sealed in plastic bags. In all cases, the specimens were removed from their containers only for testing and were always returned to them as quickly as possible.

## 3. Acoustic Technique

The technique used to measure the sound velocities in the samples of concrete (at room temperature) is a modified version of the pulse transmission technique introduced by Mattaboni [7], which conforms to ASTM Standard C597-71 [8]. Fig. 1 is a block diagram of the apparatus. A sinusoidal wave from the variable frequency oscillator is passed through the pulse shaper unit, which allows its shape to be adjusted. This shaped wave is displayed on one channel of the oscilloscope and is used to drive the binary divider. The divider generates a system trigger at some submultiple of the timing frequency. The repetition rate is set sufficiently low to allow all internal reflections in the specimens to die out between pulses.

When triggered, the Hewlett Packard Pulse Generator (Model 214) produces a square output pulse (up to 100 v in magnitude) that follows one of two paths.* The first path, through the attenuator and directly to the oscilloscope, provides a "zero-time" reference for the second path. Following the second path, the output pulse is changed from an electrical pulse to a mechanical one by the transmitting transducer (longitudinal mode). The acoustic signal then traverses the specimen where it is monitored by the receiving transducer. The electrical signal from this transducer is then displayed on the oscilloscope. By measuring the time difference $\Delta t$ between path one (zero-time reference) and path two (with the specimen in place), the transit time of an acoustic wave through the specimen is determined and its acoustic velocity C is simply its length $\ell$ divided by this transit time $\Delta t$:

$$C = \ell/\Delta t \ . \tag{1}$$

A direct measurement of $\Delta t$ is accomplished in the following manner. The signal through path 1 is displayed on the oscilloscope (trace 1 in Fig. 2) with the output of the pulse shaper (trace 3 in Fig. 2). The internal trigger delay on the pulse generator is adjusted until the signal corresponds with one of the timing signals and then the shape of the timing signal is adjusted to match the initial shape of the output wave. The switch, S1, is changed to path 2, thus displaying the data signal (trace 2 in Fig. 2).

The frequency of the timing signal is adjusted until there is an exact multiple of cycles between the two signals (3 cycles in Fig. 2). The transit time is thus measured to be the

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*Prior to the test, the time delay in each path, without a specimen between the transducers, was adjusted (via electrical delay lines in the first path) to be within a few nanoseconds of one another.

number of cycles of the timing frequency m, divided by the timing frequency f (measured by the frequency counter); i.e.,

$$\Delta t = m/f \ , \tag{2}$$

or the velocity is given by

$$C = \frac{\ell}{\Delta t} = \frac{\ell f}{m} \ .^{*} \tag{3}$$

In normal operation, the error in matching the waves is minimized by expanding the waves over a large portion of the oscilloscope face.†

## 4. Experimental Results

The results of this program are reported in Figs. 3 through 10. All data points shown are the average of the values obtained on a minimum of two specimens, and they have been connected with straight lines in the figures for clarity.

In Fig. 3, the water retention characteristics of the CRBR concrete are shown. One notes that the concrete mixes become more and more stablized from batch 1 to batch 5. The CRBR concrete (batch 5) stablizes after 10 days of cure with a net loss of 0.4 percent by weight of water. Thus, as far as water retention is concerned, tests conducted after 10 or 20 days of cure will be roughly equivalent to test conducted after longer cure periods.

In Fig. 4, the acoustic velocity of the CRBR concrete is shown. One notes the dramatic effect of the addition of aggregate on the acoustic velocity (strength)‡ of the mix - batch 2 having a final velocity of 3.86 km/s and batch 4 and 5 having final velocities of 5.74 km/s and 5.64 km/s respectively. Another perspective to this data is obtained in Fig. 5 by plotting the velocity data points normalized to their 120 day value. In this plot, which is more indicative of the curing process, one notes that the addition of the aggregate does stabilize the curing process somewhat, but the addition of the flyash has had more influence on the curing process. Namely, it has slowed the initial cure period down from 33 days to 90 days and has made this initial curing process more uniform than the process of batch 1. The former observation could be anticipated from reference [9].

Finally, one notes that the addition of admixtures to the mix reduces its velocity (strength), Fig. 4, but does not appreciably effect the curing process, Fig. 5. This reduction in strength is also noted in the compressive strength tests reported in Fig. 6♯. At 90 days, the compressive strength of batch 5 was 42.1 MPa (6190 psi) and batch 4 was 51.6 MPa (7590 psi).

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*In Fig. 2, m = 3 and f = 0.516 MHz; thus $\Delta t = 5.81$ µs and, for a length $\ell$ of 26.44 mm, the wave velocity = 4.55 km/s.

†The sweep speed in Fig. 2 is much slower than normal for the purpose of illustration.

‡The compressive strength of the concrete is directly related to the acoustic velocity [4, 6].

♯The error bars on the compressive strength are ± 1 standard deviation.

The data for the other types of concrete are reported in Figs. 7 to 10. One notes the same type of behavior for these mixes as that observed in the CRBR concrete. Namely, during the first ten days of cure, the acoustic velocity (strength) increased rapidly. Between 10 and 60 to 90 days after pour, the curing process proceeded at a slower, uniform rate. Then between 60 and 90 days, the specimens reached quasi-equilibrium (approaching a full cure) as noted by the stable velocities. At 90 days, the compressive strength was 33.9 MPa (4980 psi) for the fine-basaltic concrete, 31.7 MPa (4660 psi) for the coarse-basaltic, 29.7 MPa (4370 psi) for the fine-limestone and 29.1 MPa (4280 psi) for the coarse-limestone. All had attained acoustic wave velocities of 4.53 km/s or greater by the end of the 90 day cure period.

## References

[1] SUTHERLAND, H. J., CARLSON, G. A., and KENT, L. A., "Acoustic Diagnostic Techniques for Post-Accident Heat Removal Experiments," Proceedings of the International Meeting on Fast Reactor Safety and Related Physics, Chicago, Ill., (Oct 1976).

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[5] SHAN, S. P., CHANDRA, S., "Mechanical Behavior of Concrete Examined by Ultrasonic Measurements," J. of Materials, 5 (3), 550-563 (Sept 1970).

[6] SUTHERLAND, H. J., KENT, L. A., Acoustic Wave Velocity Measurements in Curing Reaction Grade Concrete, Sandia Report SAND76-0416 (Sept 1976).

[7] MATTABONI, P., SCHREIBER, E., "Method of Pulse Transmission Measurements for Determining Sound Velocities," J. Geophys. Res., 72, 5160-5163 (1965).

[8] "Standard Method of Test for Pulse Velocity Through Concrete," 1974 Annual Book of ASTM Standards, 14 (C597-71), 343-346 (1974).

[9] MATHER, B., et. al., "Guide for Use of Admixtures in Concrete," ACI Journal (No. 68-56), 646-676 (Sept 1971).

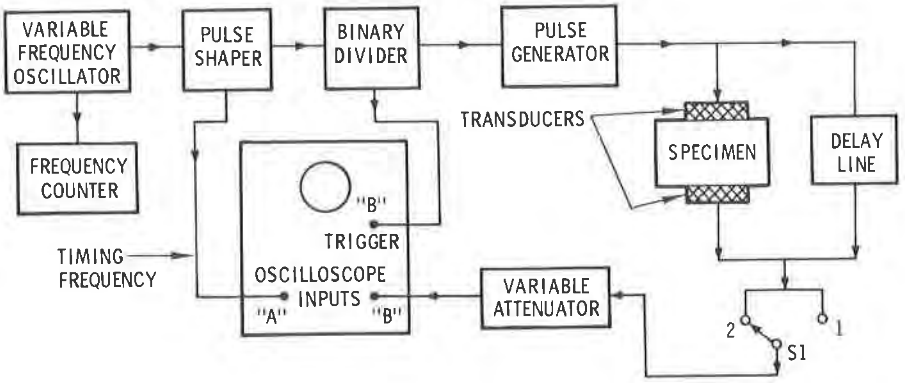
Table 1 - Concrete Mix Ratios

| Concrete | Cement (N) | Water (N) | Flyash (N) | Sand (N) | Aggregate (N) | | | AEA (N) | WRA (N) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 25.4mm | 19.0mm | 9.5mm | | |
| CRBR | 418* | 265 | 71 | 1156 | None | 1601 | None | 0.68 | 0.72 |
| Fine Basaltic | 418 | 182 | None | 770 | None | None | 596 | 0.21 | 0.28 |
| Coarse Basaltic | 418 | 200 | None | 1023 | 912 | None | None | 0.21 | 0.28 |
| Fine Limestone | 418 | 182 | None | 890 | None | None | 712 | 0.21 | None |
| Coarse Limestone | 418 | 187 | None | 912 | 832 | None | 414 | 0.21 | None |

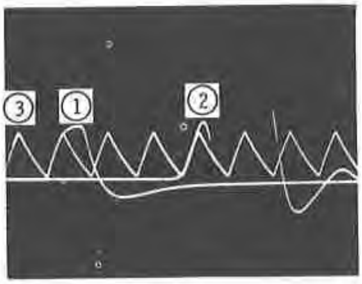
* One Sack of Cement = 418 N

** AEA - Air Entraining Agent

*** WRA - Water Reducing Agent, Plastiment, Concrete Densifier



1. Ultrasonic Apparatus

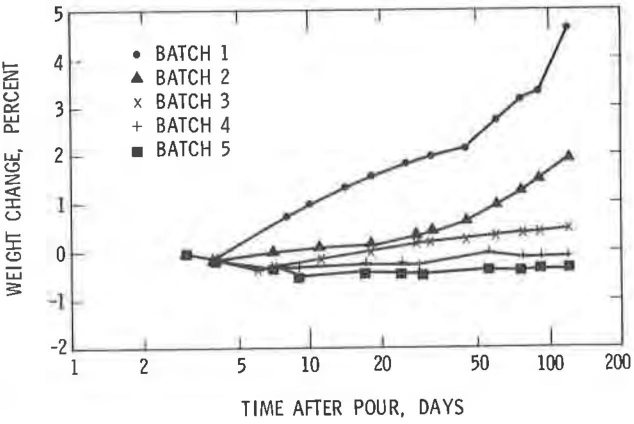


① ZERO-TIME REFERENCE SIGNAL

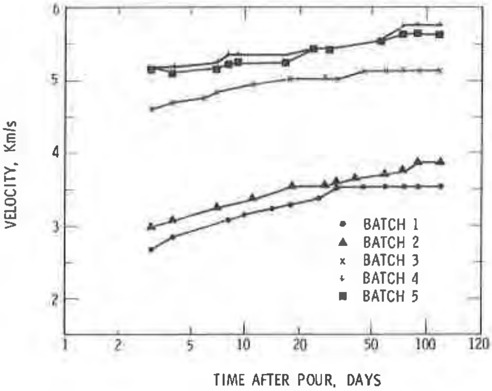
② DATA SIGNAL

③ TIMING SIGNAL

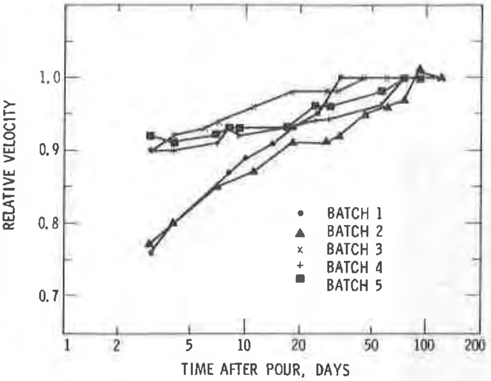
2. Typical Ultrasonic Data Frame



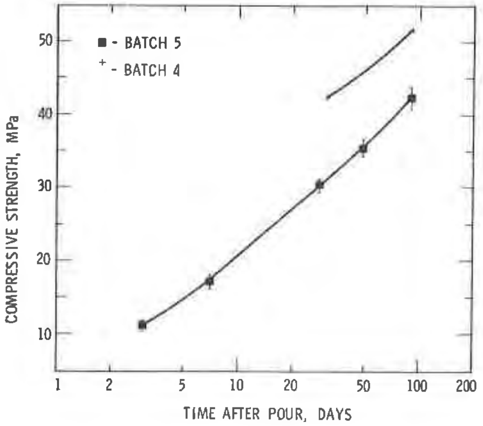
3. Water Retension in CRBR Concrete



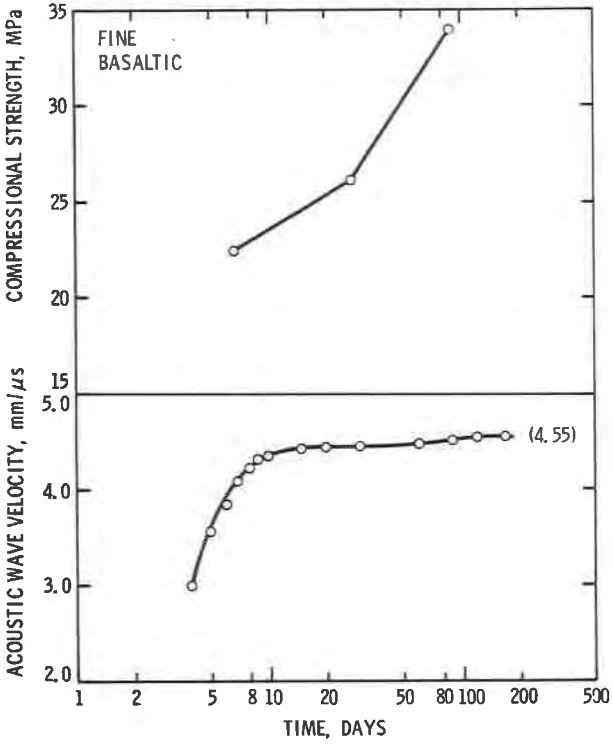
4. Acoustic Velocity in CRBR Concrete



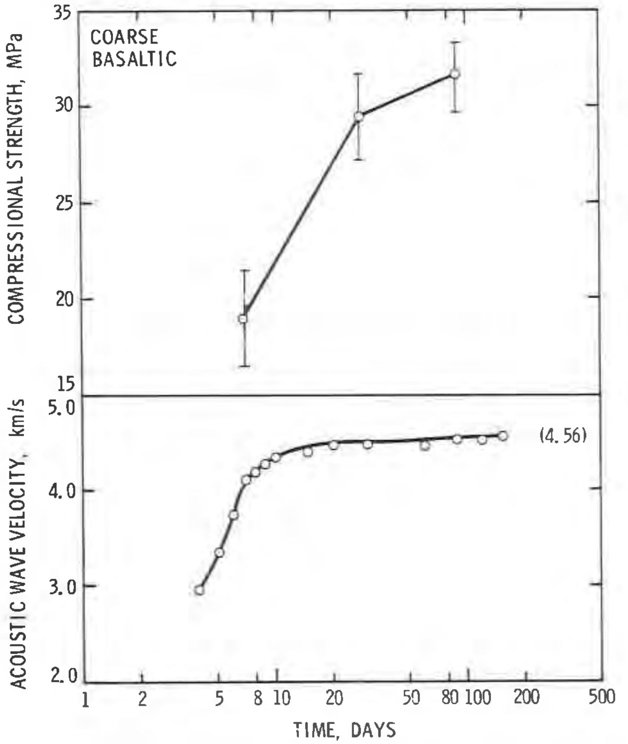
5. Normalized Acoustic Velocity in CRBR Concrete



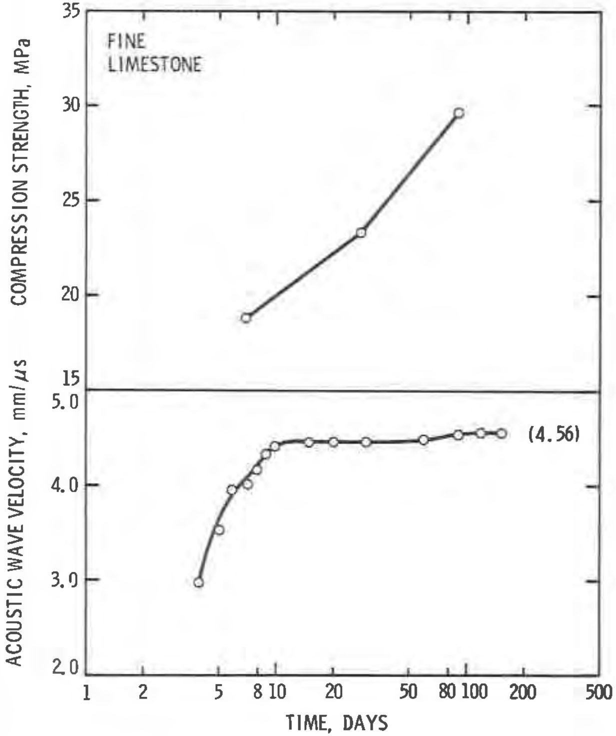
6. Compressive Strength of CRBR Concrete



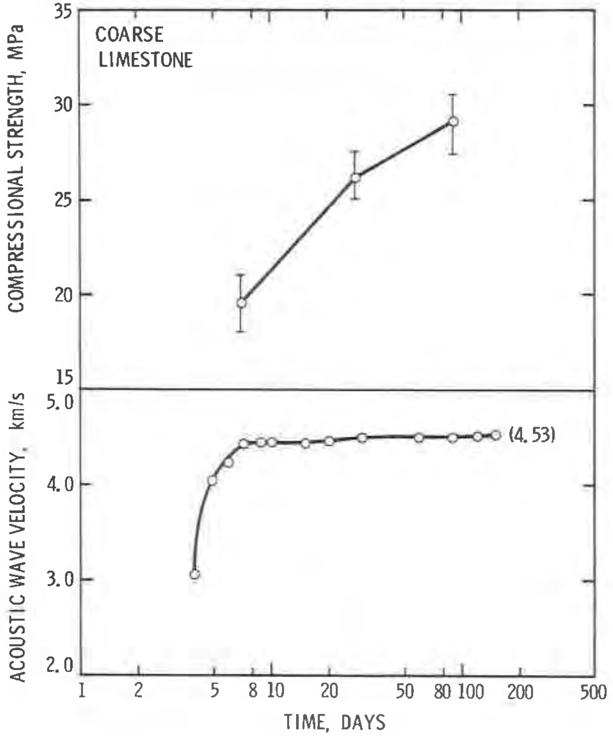
7. **Summary of Data For Fine - Basaltic Concrete**



8. **Summary of Data For Coarse - Basaltic Concrete**



9. Summary of Data For Fine - Limestone Concrete



10. Summary of Data For Coarse - Limestone Concrete