ATTENUATION MEASUREMENTS IN CONCRETE BY MEANS OF RAYLEIGH SURFACE WAVES

JONATHAN HOWELLS
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A thesis submitted in partial fulfillment of the requirements for a baccalaureate degree in Engineering Science with honors in Engineering Science

Reviewed and approved* by the following:

Cliff Lissenden
Professor in Engineering Science & Mechanics
Thesis Supervisor

Charles Bakis
Distinguished Professor in Engineering Science & Mechanics
Honors Adviser

Judith Todd
P. B. Breneman Department Head Chair
Professor, Department of Engineering Science & Mechanics

* Signatures are on file in the Schreyer Honors College and Engineering Science and Mechanics office
Abstract

A drastically high number of concrete roadways nationwide are not surviving their design life. This problem must be remedied because deteriorating concrete affects many people globally in many different ways. The impacts of concrete deterioration include but are not limited to increasing commute time to and from work, creating unsafe traveling for motorists, creating unsafe working conditions for roadway construction workers, eating away at state appropriated funds, and generating unwanted concrete remnants from replaced structures. The failure in quality is not necessarily a design flaw but more so an inability to accurately obtain and characterize freshly poured concrete’s air void system parameters. The parameters being most germane to this project are air content, spacing factor, and specific surface. In this project we investigate current applicable concrete inspection methods, design and implement an alternative inspection method employing ultrasound (Rayleigh Waves) for the purpose of obtaining accurate wave speed and attenuation measurements in hardened concrete. Hopefully, these tests will aid in characterizing air void systems, with respect to spacing and specific surface, in fresh concrete.
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Section I: The Deteriorating Concrete Problem

I.1 The Deteriorating Concrete Problem

During recent surveys, it has been estimated that 9 billion dollars is allocated annually to the construction and maintenance of concrete roadways [1]. With this large amount of money being dedicated to such a specific project category, it is expected that the results of these construction projects will be favorable. Concrete highways and other concrete transportation structures should last, at a minimum, its design lifetime. This expectation is fairly optimistic, as it has been shown through studies by the Federal Highway Administration that in excess of 34 percent of all concrete highways and related structures are in either poor or mediocre condition, it should be noted that this also takes into account structures which have exceeded their design life [1].

The leading cause of concrete deterioration is repeated exposure to the Freeze-Thaw cycle which is not necessarily confined to cold climates or northern states, although it is more prevalent in these locations. The problem lies in the unique material property of water that it expands upon freezing. Concrete, being a porous material, has an inherent void structure which allows surface water to penetrate its boundaries and fill any air gaps left from the curing process. When water occupies the majority of air gaps, approximately 91 percent of voids, the concrete slab is said to be fully saturated. Since water, in fact, expands upon freezing to a 9 percent volume increase, stress concentrations are created along the perimeter of the void [2]. If a defect exists in the cement paste of these areas, a crack will propagate. Typically, these cracks will propagate to the surface of the slab and parallel to a construction or expansion joint [2]. Once this crack reaches a critical length, it will start to propagate towards the center of
the slab. This form of failure is known as D-Cracking (Figure I.1.1) and it is the most prevalent failure mode in concrete slabs. It is at the point of central expansion that potholes form and the slab is said to have failed to the point where repair measures have to be taken to remedy the situation. After-the-fact remedies include epoxy/resin patches, concrete glue, and hydraulic cement which in theory can last up to 30 years but typically fails within 5-10 years.

Typical signs of concrete failure:

- Surface Spalling (Figure I.1.3)
- Surface Scaling (Figure I.1.2)
- Large portion of surface concrete missing
- Exposed Aggregate

It is because these patches or remedies have a high cost associated with them (roughly 1 dollar per linear foot), require many man hours, and because they pose a safety risk to motorists themselves, that an early detection system must be developed. Preferably, this system will allow for void characterization within the first few hours after placement and will provide information about spacing, size, and content.
I.2 Air Content

As previously stated, air content plays a key role in the problem of prematurely degrading concrete. It is important to distinguish different types of air voids and their respective parameters in order to determine their effects on concrete. Total air content will also be discussed due to the fact that concrete durability is related to this variable. Figure I.2.1 is a graph depicting the relation of air content to concrete durability.

![Figure I.2.1: Freeze-thaw durability factor for different levels of total air contents [1]](image)

As can be seen from the graph, a minimum of 3 percent total air is needed to achieve a sufficient level of durability, but a range from 4.5 to 8 percent is desirable.

I.2a Entrapped air

In order to achieve the desired level of total air, 1.5 percent is typically allocated for entrapped air. Entrapped air is an incidental effect from the pouring process which can be limited but not eliminated. This portion of air, large air bubbles, can reduce the strength and negatively affect the lifetime of the concrete. These bubbles in the cement paste have a diameter greater than 1 mm and are generally irregularly spaced. As
opposed to other types of air voids, entrapped air can be irregularly shaped as shown in Figure I.2. The void content of this concrete is in the middle of the specification range. The large void marked with an arrow is about 2 mm across (larger than an entrained air void). Notice the very fine voids throughout the paste.

![Figure I.2: Large irregularly shaped entrapped air voids left in the cement paste [4]](image)

**I.2b Entrained Air**

While large air voids lead to strength reduction in concrete, small evenly spaced voids actually retard the effects of freeze-thaw cycles. These bubbles are referred to as entrained air. The discovery of the effects of tiny bubbles in concrete happened accidently in New York City in the early 1930’s. At a cement grinding mill producing roadway casts for the NY DOT, bearing grease (tallow) accidently dripped into some of the cement paste. The DOT soon realized that casts from this particular mill had enhanced durability and traced the effect to the tiny bubbles left by the reaction between the oxidation of the hot tallow and the Portland cement. These discoveries lead to the advent of modern day air-entraining admixtures.
The first air-entraining admixtures (AEA) for concrete were made from salts derived from wood resin by the Hercules Company of Wilmington Delaware and marketed under the name Vinsol Resin [5]. This admixture formed microscopic bubbles ranging from 0.0001 to 0.01 inch in diameter at the end of the mixing process. As stated previously, bubbles larger than this are considered entrapped air. Early researchers realized that for maximum durability entrained air should not have spacing greater than .008 in. That is a point on the perimeter of one bubble should not be farther than .008 in from another bubble [5]. Researchers also discovered that when water froze in the entrained air bubbles, the resulting stress was not sufficient for crack propagation in the cement paste. In fact, the air bubbles actually protect a $9.843 \times 10^{-3}$ in radius of paste around the bubble by allowing ice formed in the capillary pores to expand into the adjacent pores thereby relieving the induced stress. From Figure I1.2.1 and knowing that 1.5 percent of total air is reserved for entrapped air, it can be seen that a desirable amount of entrained air should range from 4.5 to 6.5 percent [5].

Of all admixtures available for concrete, air-entraining admixtures may be the most difficult to use. Their performance is affected by temperature, mixing time, initial setting time, concrete ingredients, types of Portland cement, other admixtures, haul time, slump level, pumping, vibration, and finishing procedures [5].

Air-entraining admixtures generally fit into the following categories, all of which produce different sized bubbles and have different spacing factors. To date, Vinsol Resin is the most commonly used admixture [5]:
Section II: Inspection Methods

II.1 Conventional Inspection Methods

Due to the need for reliable concrete characterization, many detection methods have been established and implemented into industry, all of which have their advantages and disadvantages. Some, like the volumetric and pressure methods, provide information about total air content but do not distinguish between entrapped and entrained air. Others, like the Air Void Analyzer and visual inspection, do distinguish types of air voids but are either unreliable or too time consuming. In the following sections, various types of testing procedures are discussed, examining their usefulness for in field application.

II.2 Air Void Analyzer

Developed in the early 1990’s by German Instruments of Denmark, the Air Void Analyzer was heralded as the solution to all the problems faced when determining the air void structure in fresh concrete, in laboratory testing it has proved to be just that. The air void analyzer

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Figure II.2.1: AVA test set up [7]
system works on the basis of Stokes’s Law in that if air bubbles can be extracted from wet concrete paste, the bubbles will be released in order depending on size, i.e. larger bubbles will rise before smaller ones [6]. In order to secure a paste sample, a percussion drill fitted with a caged bit vibrates the concrete mix through a mesh, which removes any contamination larger than 6mm. Once the paste sample is secured in the wire cage (Figure II.2.2), a syringe is used to extract a 20 cubic centimeter volume which will be used as a representative sample of the slab in question. The sample of cement paste is then injected into a viscous and hydrophilic liquid via a riser column (Figure II.2.1). This liquid, typically glycerin, must be chosen carefully so that the bubbles are able to retain their original shape and so that they are restricted from coalescing or disintegrating into smaller bubbles. The sample and viscous liquid are then gently stirred for 30 seconds by a magnetic stirrer [7]. At this point bubbles begin to release from the paste and into the liquid, largest bubbles first. The bubbles rise through the liquid and water column, as shown in Figure II.2.3, at rates that depend on their size, which results in a separation of time when different sized bubbles reach the top of the column. The bubbles are collected by a partially submerged plate which is attached to a computer that captures change in mass of the plate as a function of time. In the beginning of the test, the size distribution of the bubbles range from a few
millimeters to a few micrometers. For each succeeding period, the size of the collecting bubbles decreases. This procedure is continued for 25 minutes or until no mass change is detected for two consecutive minutes. At this time the test is complete and the computer interprets and displays the results; including size, content, and spacing factor, in graphs and histograms [7].

Figure II.2.4: Graphical results as obtained from AVA defining size, content, and spacing of entrained air in fresh concrete. [7]

Figure II.2.5: Graph and histogram defining the distribution of entrained air in cement paste. [7]
The results that the AVA produces (Figures II.2.4-5) are readily obtained and appear to be extremely accurate, at least in comparison to the hardened concrete inspection standard of ASTM C457. A problem exists within the equipment of the AVA, as it is extremely sensitive to external factors, such as wind, vibrations, and mortar temperature, making it somewhat unreliable for onsite testing. Independent studies performed by the Federal Highway Administration and The Pennsylvania State University report that for onsite testing, the AVA is accurate approximately 53% of the time, therefore necessitating improved methods [8].

II.3 Pressure Method

The pressure method uses one of two devices: the A meter or the B meter (Figure II.3). Both of these meters rely on the relationship between pressure and volume to determine the air content of a concrete mixture. The pressure methods are not suitable for testing the air content of lightweight aggregate concrete and other porous aggregate concretes, as they would measure the air void system of the aggregates and not just the air content of the paste in the mixture. The A meter is sensitive to altitude and must be calibrated to accommodate the altitude at which it will be used, while the B meter uses the change in pressure of a known volume of air, Boyle’s Law, and is not affected by altitude variations [9].
In both of these tests, the equipment is calibrated to an initial pressure line before concrete is added. Once this is complete, three layers of concrete are placed into the mixing bowl and then sealed. Through various petcocks, water is injected into the concrete to force out all air. Water is then bled out and apparent air content is recorded on a pressure gage. This, however, is not the final data as an aggregate correction factor must be applied to account for its own air system. Now, accurate total air content is recorded [10]. The drawbacks from this testing procedure are obvious; no information about air void size, distribution, or type (entrained or entrapped) is determinable.

II.4 Volumetric Method

Possibly the most suitable onsite testing procedure, the volumetric method is relatively inexpensive, easy to perform, and viable for all types of aggregate. The American Society for Testing and Materials standard, ASTM C 173-95, describes a volumetric test method that is based on the principle that volume of air in the concrete sample, when removed by agitation can be measured using the fall in level of water over the sample [11]. The test apparatus shown here in Figure II.4 is filled in three sections, each being tamped a set number of times and then struck off flush. The upper section is then filled to the zero graduation mark on the neck of the apparatus. Once it is filled, the apparatus is inverted so that the concrete on the bottom is loosened. It is then rolled back and forth so that air bubbles in the cement paste are released. The reading on the neck gives the total air displaced during the test. The advantage of this
test over the pressure method is that it can be performed with any type of aggregate. Its main disadvantage is that excessive energy is required to agitate a sample, so for in field usage samples tend to be relatively small. This small sample may or may not accurately represent the slab being tested.

II.5 Petrography

Current visual inspection methods for concrete are rooted in the 1990’s with the introduction of the Rapid Air 457. This method is not applicable with fresh concrete but provides information about the main three parameters; specific surface, spacing factor, and air content of hardened concrete. In 2002, the advent of a Windows based operating system gave the Rapid Air 457 system two methods for inspection, the linear transverse analysis and the modified point count method. The linear transverse analysis uses a series of regularly spaced lines to intercept the sample and then sum up the distances traversed across a given component [12]. The modified point count method is based on the frequency with which areas of a given component coincide with a regular grid system of points [12]. These two testing options reduced the testing time from roughly six hours to 15-30 minutes, depending on which of the two options used, and can be performed automatically, based on color intensity, therefore avoiding human error [12].

Figure II.5.1: Rapid Air 457 test equipment [12]
The Rapid Air microscopy imaging system in Figure II.5., 1 includes a computerized control unit (PC) with a high resolution LCD color monitor, a video camera, and a microscope objective mounted on a motorized stage. Along with the hardware, user-friendly image analysis software is designed to help the operator conduct the test and process the image to determine the air void parameters [12]. White powder, such as barium sulfate, is injected into the open pores to give an enhanced resolution during the imaging process. After polishing and treating the sample, it is mounted to the moving stage of the Rapid Air system and placed under the microscope. The computer moves the stage to produce an image like that of Figure II.5.2, in accordance with ASTM C457, of the entire sample. After the scanning procedure, Rapid Air records all void structure characteristics in an Excel spreadsheet.

Figure II.5.2: Image obtained from the RapidAir after barium sulfate enhancement [12]
II.6 Ultrasound

Nondestructive ultrasonic testing techniques have been around for many decades. Though they are typically performed on metallic specimens, the use of ultrasonic NDE may be viable for use on concrete. Ultrasonic NDE involves the use of ultrasonic pulse-waves with frequencies ranging from 20 kHz to 1 GHz to penetrate into a material and detect size and location of flaws or discontinuities, typical setup in Figure II.6.1 [12][14].

Typically, an NDE setup consists of a pulser and receiver device, two transducers, and a display oscilloscope. The pulser generates high voltage electrical pulses which the transmitting transducer converts to high frequency ultrasonic energy. This energy is directed towards the sample being tested, of which it propagates through. When the energy propagates through the sample and encounters a defect, some of the ultrasonic energy is scattered or reflected back. Some of the energy, however, is transmitted forward into the receiving transducer. The receiving transducer collects the ultrasonic energy and converts it back into an electrical pulse. The converted pulse is then transmitted to the receiver and displayed on the oscilloscope. The received signal contains information about the structure (air content, void size, and other features) of the material it has traveled through and is directly related to the scattering and the distance the wave has traveled. With data analysis and signal processing, characterization of air void structures in concrete can be obtained [12].
For the purpose of reducing complexity, Rayleigh surface waves will be used in the experiments involving ultrasonic NDE. These waves, in a through transmission mode, will propagate through the concrete specimen at a depth roughly equivalent to their wavelength. Scattering defects in this area will be assumed as the worst case scenario, as it is the area of most interest (the region of initial failure), and representative of the whole sample. A modified setup of figure II.6.2 will be used to transmit and process ultrasonic signals in concrete.

![Diagram](image)

Figure II.6.2: Typical through transmission setup for ultrasonic NDE. [12]

Attenuation and wave speed measurements will be taken in concrete with and without entrained air to determine the air void system near the top surface of concrete pavement.
Section III: Equipment

III.1 Piezoelectric Broadband Transducers

The conversion of electrical impulses into mechanical vibrations and from mechanical vibrations back into electrical impulses is the basis for ultrasonic nondestructive evaluation. The element that allows this is at the heart of the transducer, which converts electrical energy to acoustic energy and vice versa. The active element is basically a piece of polarized piezoelectric material (i.e. it has a dipole moment) with electrodes attached to its opposite faces. When an electric field is applied across the material, the polarized molecules will align themselves with the electric field, resulting in induced dipoles within the molecular or crystal structure of the material. This alignment of molecules will cause the material to change dimensions. This phenomenon is known as electrostriction (Figure III.1.1). In addition, a permanently-polarized material such as quartz (SiO2) or barium titanate (BaTiO3) will produce an electric field when the material changes dimensions as a result of an imposed mechanical force. This phenomenon is known as the piezoelectric effect [13].

For testing on concrete two 500 kHz central frequency, broadband piezoelectric transducers (100-700 kHz) were used. Using broadband transducers allows us to perform frequency sweeps to compare results obtained at different excitation frequencies. Because we are concerned with transmitting energy into the concrete samples, a low central frequency of 500 kHz will allow us to transmit greater energy and penetration.
deeper into the material. A higher central frequency would provide a greater flaw resolution, but this is a secondary concern for now.

**III.2 Plexiglas Wedges and Steel Mediators**

In order to generate Rayleigh surface waves, the ultrasonic energy from the transducer must undergo an intermediate step. The energy must be converted into longitudinal waves in a Plexiglas wedge. The wedge is secured to steel mediators at an appropriate angle, which is calculated as the third critical angle. Now, at the interface between the Plexiglas and steel, longitudinal waves are converted to surface waves and are able to propagate through the concrete. The design of the Plexiglas wedges and steel mediators are shown in Figure III.2.1 and Figure III.2.2.

![Figure III.2.1: Plexiglas Wedge design [12]](image)
III.2a Snell’s Law

Because surface waves travel at a 90° incident angle with the normal to the interface, the second critical angle, $\theta$, between Plexiglas and steel can be found using Snell’s Law knowing longitudinal wave velocity of Plexiglas ($C_{L,\text{Plexiglas}}=2730$ m/sec), and the Rayleigh surface wave velocity of steel ($C_{S,\text{steel}}=2990$ m/sec).

$$\frac{C_{L,\text{Plexiglas}}}{\sin \theta} = \frac{C_{S,\text{Steel}}}{\sin 90^\circ} \quad \text{Eq.1}$$

The third critical angle, the angle need for surface wave generation, was found to be 23 degrees from the surface normal for Plexiglas and steel [12], see Figure III.2.3.

![Figure III.2.2: Steel mediator wedge design [12]](image)

![Figure III.2.3: Incident angle for Snell’s Law calculation [12]](image)
III.2b Hertzian Contact

Contact area is of concern for these experiments as it directly relates to the transmission of energy. Because of this, the contact surface must be regulated. A problem in regulation arises, because of the elasticity of concrete and steel, when the mediators come in contact with the concrete sample. The fresh concrete will deform under the pressure exerted by the weight of the mediators, effectively changing the contact area geometry and energy transmission. If this is not controlled throughout the data acquisition process, the results may be skewed.

III.3 Explorer II NDT Workstation by MATEC

The pulser and data acquisition hardware and software system used in the experimental evaluation of concrete was created by Matec Instruments. For our purposes, the settings chosen originally were held constant for all measurements. The gain was set at 40dB, sampling rate was 100 MHz, transmission mode was through transmission, and lowpass/highpass filters were selected at the extremes.

Below is a complete list of specifications for the Matec Explorer II NDT Workstation.
### ToneBurst Pulser / Receiver Specifications

<table>
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<tr>
<th>Parameter</th>
<th>Specification</th>
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<tr>
<td>Output Voltage</td>
<td>1000V peak to peak @ 5MHz</td>
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<tr>
<td>Waveform Type</td>
<td>Bipolar Gated Sinewave (toneburst)</td>
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<td>Pulse Width</td>
<td>40nS to 20µS (optional to 100µS)</td>
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<td>Power Output</td>
<td>2500W RMS into 50 Ohms</td>
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<td>Highpass Filters</td>
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<tr>
<td>Transmit/Receive Modes</td>
<td>Pulse Echo and Through Transmission</td>
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### Display Specifications

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<tr>
<td>Additional features</td>
<td>Freeze waveform; save; print</td>
</tr>
</tbody>
</table>

### Controller

- **CPU**: Pentium 233MHz
- **Storage**: 4GB Hard Drive, CD ROM, 3.5" High Density Floppy
- **Keyboard**: Mini or 101-key AT enhanced
- **Ports**: RS232 Serial and Parallel
- **Mouse**: Microsoft
- **Setup Parameter Storage**: Max. No. of Stored Setups limited only by hard disk space
- **Software**: Operating System Windows® ’95, ’98 or NT
- **Options**: Hard Travel Case Immersion Tank System, Cordura Nylon Bag Hand Scanning System

### Pulser Specifications

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<td>Output Impedence</td>
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<td>Gain</td>
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<tr>
<td>Dynamic Range</td>
<td>+63.5dB</td>
</tr>
<tr>
<td>Blanking Delay</td>
<td>0 to 200µS, Step Size 100nS</td>
</tr>
<tr>
<td>Rectification</td>
<td>None, Fullwave, +/-Halfwave</td>
</tr>
<tr>
<td>Lowpass Filters</td>
<td>.550MHz Lowpass, .850MHz Lowpass, 1.35MHz Lowpass, 2.80MHz Lowpass, 5.50MHz Lowpass, 7.00MHz Lowpass, 10.0MHz Lowpass</td>
</tr>
<tr>
<td>Highpass Filters</td>
<td>.800MHz Highpass, 2.00MHz Highpass, 4.50MHz Highpass, 7.00MHz Highpass, 10.0MHz Highpass</td>
</tr>
<tr>
<td>Transmit/Receive Modes</td>
<td>Pulse Echo and Through Transmission</td>
</tr>
</tbody>
</table>

### Quantitative Measurements

<table>
<thead>
<tr>
<th>Measurement Modes</th>
<th>Attenuation, Thickness, Velocity, Time-of-Flight, FFT Spectral Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td></td>
</tr>
<tr>
<td>Overall Dimensions</td>
<td>Length 23&quot; (584mm), Width 18&quot; (457mm), Height 8.5&quot; (210mm)</td>
</tr>
<tr>
<td>Weight</td>
<td>40 lbs (25.0kg)</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>0° to 105°F (40°C)</td>
</tr>
<tr>
<td>Data Acquisition</td>
<td></td>
</tr>
<tr>
<td>Rate</td>
<td>100MHz (realtime) ETS to 800MHz</td>
</tr>
<tr>
<td>Peak Detector Gates</td>
<td>8</td>
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<tr>
<td>Data Gates</td>
<td>8</td>
</tr>
<tr>
<td>DAC Dynamic Range</td>
<td>40dB/µS</td>
</tr>
<tr>
<td>DAC Entry</td>
<td>256 Points</td>
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</tbody>
</table>

### III.4 Early Setup and Prototype Design

The methods used for regulating contact pressure, tip spacing, suspending the mediators, and for mediator movement were changed from the initial testing period to the later period for the purpose of obtaining more accurate results. Initially, the mediators were suspended from a circular tube by means of C-clamps. The tube was supported by
leveling jacks for the purpose of adjusting the height of the mediators and also the contact pressure between the concrete and steel tips. Figure III.5.1 depicts the original setup.

Figure III.5.1: Original setup for Rayleigh wave test [12].

Inaccuracies developed because this is a crude setup and contact pressure could not be repeated on different sample areas. The effects of this factor were not known at the time of testing. Tip spacing was also a source of error, due to making one initial spacing measurement, fixing the supporting clamps and then taking numerous measurements. Also at the time of initial experimentation, the effects of contact force on the final signals were not known. Furthermore, the initial work did not consider what would be an optimal angle between mediator and concrete surface to maximize energy transfer.
During initial experimentation the angle was arbitrarily set. This angle and the close spacing of transducers, by chance, allowed for through air transmission of ultrasonic energy that had to be shielded. The prototype pictured in Figure III.5.2 was designed in order to obtain the most accurate results possible.

In this prototype, the mediators are suspended by rollers enclosed in a top and bottom rail. This allows the mediators the freedom to slide back and forth with relative ease, together or apart. The rail is attached to a cross member that is attached to a roller system. This is done so that both mediators equally feel the effects of gravity, therefore applying the same contact pressure at all testing locations. Tension springs are attached to the cross member supporting the rail at its center and at each end so that adjustments in contact pressure can be made as needed. Lastly, the angle between the mediator’s active face and the concrete was tested and the optimum angle was found. The mediators were then fixed at this angle for all testing and a bubble level was placed on the rail in order to
maintain the leveling and therefore the angle of contact. Spacing continuity was not as readily achieved. One of the mediators was fixed in place so that only the other was free to move, making it easier to measure spacing. The other tip was moved manually for each signal received and tip spacing was measured with calipers accurate to .001 in. With contact pressure, mediator angle, and mediator movement accounted for, more accurate data should be obtained.

The design of the test apparatus facilitated:

- Selection of the optimal orientation of the mediators with respect to the concrete surface.
- Control of the contact force between the mediator and concrete surface
- Accurate measurement of distance between mediator tips, as well as a means to change this distance
- Stable setup over freshly poured concrete

on a shoestring budget as all components were purchased at a local hardware store and modified for use.

**Section IV: Previous Experiments**

During the summer of 2009, experiments were performed at The Pennsylvania State University regarding the air void system of fresh concrete. The main focus of these experiments was gaining information during the curing process, primarily between 1 and 8 hours after pouring, to be used in evaluating the ultrasonic method for air void characterization. The results of these tests support ultrasonic NDE for usage in field testing of concrete. The results also determined that meaningful signals were able to propagate through wet concrete at approximately 4 hours, early enough to warrant more research.
IV.1 Frequency and Curing Time Dependence of Signal

Rayleigh waves can propagate long distances along the surface of a thick material (assumed to be a half space). Here, the term ‘thick’ is relative to the wavelength of the traveling wave [14]. The Rayleigh wave velocity equation is:

\[ \eta^6 - 8\eta^4 + 8\eta^2(3 - 2\zeta^2) + 16(\zeta^2 - 1) = 0 \]  \hspace{1cm} \text{Eq. 2}

Where \[ \eta = \frac{C_R}{C_T} \] and \[ \zeta = \frac{C_T}{C_L} = \frac{1-2\nu}{2(1-\nu)} \]  \hspace{1cm} \text{Eq. 3 & 4}

\( C_R \)= Rayleigh Surface Wave Velocity

\( C_T \)= Transverse (Shear) Wave Velocity

\( C_L \)= Longitudinal Wave Velocity

\( \nu \)= Poisson’s Ratio

Shear and Longitudinal Wave Velocities are related to material properties:

\[ C_T^2 = \frac{\mu}{\rho} \text{ and } C_L^2 = \frac{\lambda_L + 2\mu}{\rho} \]  \hspace{1cm} \text{Eq.5 & 6}

Where:

\( \rho \)= mass density

\( \mu \)= Shear Modulus

\( \lambda_L \)= Lame’s Constant

The parameter \( \eta \), which enables direct computation of the Rayleigh wave speed depends only on Poisson’s ratio, and therefore Rayleigh waves are non-dispersive (i.e., do not depend on the frequency). Thus, changes in the Rayleigh wave speed reflect changes in the material properties. Most of the energy travels within one wavelength \( \lambda = \frac{C_R}{F} \) of the surface, which ranges from 10-1.4 mm for a 1 km/s wave speed (typical for fresh concrete) and frequencies in the 100-700 kHz range [12].
Because Rayleigh wave speed is non-dispersive, we want to verify this. Through testing as described in the previous experimental method section, data was extracted and wave speeds were calculated. The results show that wave speed is in fact independent of frequency but does change with respect to curing time as shown in Figures IV.1.1 and IV.1.2.

Figure IV.1.1: Wave speed dependence on frequency and Curing time, a) Normal Mix with air, b) Normal Mix Without air [12]

Figure IV.1.2: Wave speed dependence on frequency, c) Normal Mix with air, d) Normal mix without air [12]
IV.2 Wave Speed vs Air Content

The next important feature to investigate is the effect that the air content has on wave speed as this is the focus of the experiments. Once we can distinguish how the air content effects wave speed, we can separate it out from the normal scattering events taking place. With this, attenuation based on the air structure can be determined.

Through the experimental results, depicted in Figures IV.2, we can see that there is a definite correlation between wave speed and air content. As expected, wave speed decreases as air content increases, but the graphs also show the relationship with aggregate size and wave speed. It is worthy to note that the use of larger aggregate provides less scattering interfaces which would hinder the wave speed and that the opposite is true for concrete with small aggregate pieces.

Figure IV.2: Wave speed dependence on air content for normal mix concrete, sieved concrete, and mortar: (a) 5 hr, (b) 6 hr, (c) 7 hr, (d) 24 hr after placement [12]
Section V: Current Experiments

V.1 Optimum Mediator Angle

Before acquiring data samples for wave speed and attenuation in concrete, the setup of the experimental equipment must be made as consistent as possible. This includes finding the appropriate angle between the mediator and concrete. Here, hardened concrete was used in order to accomplish this, the mediators were set in place and a sample signal was recorded. The angle was then varied in 5 degree increments, recording amplitude for each. The angle with the highest amplitude was set permanently. To ensure accuracy, this test was repeated several times. For each trial run, the mediator tip spacing was closely monitored and the area of investigation was held constant. The results obtained (Figure V.1), dictate that a 10 degree angle from the bottom face of the mediator, 37 degree angle from the active face, is optimal based on the largest amplitude signal.

Figure V.1: Amplitudes measurements take at different mediator angles.
V.2 Contact Force Effect

The next experiment was used for the determination of the effect that contact force had on signal transmission, more specifically on received amplitude. To do this, weights of different magnitudes were placed, in set increments, at the center of the cross member suspending the mediators and recorded using a standard electronic package scale. The center was used in a manner to equally distribute the forces to the two mediator tips. Weights were added to the point where the system failed and could take no more force. Figure V.2 shows a linear relationship between contact force and amplitude but the last data should not be included because that is the point of failure. This test shows that a small change in applied force does not greatly affect the amplitude of the received signal.

Figure V.2: Amplitudes measurements take with different applied forces.
V.3 Data Acquisition

With the prototype now set at a proper angle and the effects of contact pressure known, we are now able to take accurate measurements on hardened concrete. Four 2’ by 2’ samples, such as the one in Figure V.3.1, were obtained from the initial testing from summer 2009, two normal mixes with large aggregate and two with the large aggregate removed by sieve. One of each of the mixes has a high entrained air content and one with low air content (considered to be without air). The Matec Explorer II NDT Workstation was set to the specifications as described in section III.4 and data signals were taken from three areas of each sample. Within each area, three distinct distances were recorded and each was done so at three different frequencies (200 kHz, 400 kHz, and 500 kHz). Figures V.3.2- V.3.4 shows a sample of signals taken at one area.

Figure V.3.1: Areas of investigation on a sample of concrete.

Figure V.3.2: Sample signals for 400 kHz and 500 kHz at a 1 inch separation.
Figure V.3.3: Sample signals for 400 kHz and 500 kHz at a 2 inch separation.

Figure V.3.4: Sample signals for 400 kHz and 500 kHz at a 3 inch separation.
Section VI: Signal Processing

VI.1 Remove DC Bias

Once all the signals were obtained from the concrete samples, we are almost ready to make attenuation calculations. But before that can be done, we must process our waveforms in such a matter as to leave the time domain information intact while filtering out noise and other such factor which could complicate or skew our results. The first step in this process is to remove the DC Bias. The DC Bias is a result of ambient noise caught by the receiving transducer and can be removed by calculating the mean value of the entire signal and then subtracting it out. This will be useful later when calculating time of arrivals. Figure VI.1 shows the removal of the DC bias through a LabView program written for this project.

Figure VI.1: Removal of DC bias.
VI.2 Bessel Filter

The next step in signal processing is to remove, from the received signal, any contribution from outside of the excitation frequency range. In this case a Bessel bandpass filter was used in the LabView program to accomplish this task. The range that was used is from 100 kHz to 1 MHz, so anything outside of this is filtered out. The Figure VI.2 shows the signal before and after the application of the Bessel filter.

![Figure VI.2: Signal before and after the application of a Bessel filter.](image)

VI.3 Fast Fourier Transform

At this point we thought it would be wise to check the frequency content of the received signals in order to determine if the Bessel filter was removing any valuable data. The function of the piezoelectric transducer allows us to change the center excitation frequency within a range (100 kHz- 700 kHz) and we want to make sure that it is working properly. To check the frequency content of the received signal, a Fast Fourier Transform was implemented into the LabView program.
The results obtained show that the transducers were in fact working properly. Screenshots were obtained from the FFT but because they were implemented into excel and excel can only accept 32,000 data points, pictures are not displayable. For clarity, a FFT from previous works is included in Figure VI.3.

![Figure VI.3: FFT with 200 kHz excitation Frequency][12]

**VI.4 Hilbert Transform**

The final step in the signal processing program is to obtain the envelope of the waveform. We want the envelope so that we can set a threshold value, 4 dBs used in this study, for the signal and have our program record the time as soon as the signal crosses it. This point is the time of arrival and will be used in the wave speed calculations. The Hilbert transform does not give us the envelope directly but once it is found, we can take the square root of the quantity of the transform squared minus the original signal squared to obtain the envelope. Figure VI.4 depicts the envelope as obtained from Labview.
Section VII: Interpreting Data

VII.1 Attenuation Coefficient

With the envelope for each signal taken, Labview was programmed to calculate the time of arrival and also the max amplitude for each signal. With these features, the attenuation coefficient was calculated [15].

\[
\alpha(f) = -\frac{20}{d} \log_{10} \left[ \frac{A_2(f)}{A_1(f)} \right]
\]  
Eq.7

Where:

\( \alpha (f) \) = Attenuation Coefficient

\( d \) = Travel Distance Difference between Signal 2 and Signal 1

\( A_1 (f) \) = Maximum Amplitude for Signal 1

\( A_2 (f) \) = Maximum Amplitude for Signal 2

With this attenuation we are able to distinguish between geometric attenuation, a material property related to a signal spreading out as it travels through a medium, and material attenuation, which is due to absorption or scattering of ultrasonic energy. If we remove the geometric attenuation from the total attenuation, we will have the attenuation due largely to the air void system.
Figures VII.1.1 through VII.1.4 show the spread of attenuation coefficients for all samples tested. They show that attenuation is frequency dependent and that for an entire sample; there could be a wide range in attenuation values.
Figure VII.1.1: Range of attenuation coefficients for Normal Mix with air

Figure VII.1.1: Range of attenuation coefficients for Sieved Mix with air
VII.2 Wave Speed

With the time of arrivals for all the signals, we can calculate the wave speed. Wave speed measurements enable determination of elastic properties, which depend on the material composition, including porosity associated with air voids [12]. It should be noted that the difference in the time of arrival accounts for the time traveled through the mediators and therefore allows a direct calculation.

\[ V = \frac{d}{T_2 - T_1} \]  

Eq. 8

Where:

V= Wave speed through the concrete

d= the distance difference between mediator tips

T_1= the time of arrival of signal 1

T_2= the time of arrival of signal 2

Figures VII.2.1 through VII.2.4 show the wave speeds obtained from all samples.
Figure VII.2.1: Range of Wave Speeds for Normal Mix without

Figure VII.2.2: Range of Wave Speeds for Sieved Mix without air
Figure VII.2.3: Range of Wave Speeds for Normal Mix with air

Figure VII.2.4: Range of Wave Speeds for Sieved Mix with air
Section VIII: Results & Conclusions

Results: Average Attenuation Coefficient Comparison (Figure VIII.1)

The attenuation measurements are in accordance with previous studies. Theoretically, attenuation is frequency dependent and should increase with air content.

Note sample 3 is greater than expected; this is due to surface roughness defects left from previous studies.

![Graph of Normal Mix: Attenuation Coefficient Comparison](image1)

![Graph of Sieved Mix: Attenuation Coefficient Comparison](image2)

Figure VIII.1: Average Attenuation Coefficient Comparison
Results: Average Wave Speed (Figure VIII.2)

The calculated wave speed agrees with previous studies, both in magnitude and comparison. Notice sample 4 has a larger wave speed than expected; this could be due to a heavy aggregate or low air void concentration.
Conclusions:

During this project we were able to design and build a test apparatus capable of wave speed and attenuation determination for fresh concrete (4-5 hours after placement). Also, a LabView program was written and implemented for the purpose of extracting relevant features from the acquired signals. The results obtained after processing, are consistent with our expectations and surveyed literature. For this reason, an ultrasonic method for characterizing air void systems in fresh concrete warrants further investigation, as this problem affects the lives of people worldwide.
References


[5] Navsik, J., & Pistilli, M. (2004, February 1). Are we placing too much air in our concrete? Today's more effective air entraining agents are specified the same as they were 50 years ago | Concrete Construction | Find Articles at BNET. *Find Articles at BNET | News Articles, Magazine Back Issues & Reference Articles on All Topics*. Retrieved April 5, 2010, from http://findarticles.com/p/articles/mi_m0NSX/is_2_49/ai_113855231/


Academic Vita of Jonathan Howells

Name: Jonathan Howells

Address: 415 Academy St. Peckville PA, 18452

E-Mail Id: jeh325@psu.edu

Education
Major: Engineering Science
Minor(s): Engineering Mechanics, Engineering Entrepreneurship
Honors: Engineering Science

Thesis Title: **Attenuation Measurements in Concrete by Means of Rayleigh Surface Waves**
Thesis Supervisor: Dr. Cliff Lissenden

Work Experience
Date: February 2007-August 2007
Title: Mechanical Engineer Intern
Description: Responsibilities as an employee include CAD operation, engineering calculations, shop drawings, tech measures, and generating as-built documents.
Institution/Company: Highland Associates, Clarks Summit PA
Supervisor’s Name: A.J. Lello

Date: June 2004- August 2008
Title: Co-Founder
Description: Home Remedies is a small residential construction company, specializing in renovations and additions. Responsibilities include, but not limited to, rough/finish carpentry, rough/finish electric, crew management, financial accountability, and scheduling.
Institution/Company: Home Remedies, Peckville PA
Supervisor’s Name: Gene Howells

Grants Received:
- Galleta/Dreater ASHRAE Anthracite Chapter Scholarship Recipient
- Keith Grover Memorial Scholarship
- Glou/TR Senators Scholarship
- Ernest Weidhaas Scholarship
- Edward M. Frymoyer Honors Scholarship
- Brennan Trustee Scholarship
- Robert and Myrtle Virek Scholarship

Awards:
- 2007 and 2008 Penn State Worthington Scranton Merit Award Recipient
- Penn State Academic Excellence in Engineering Technology Award Recipient
- High Distinction Graduate of Architectural Engineering Technology Program
Professional Memberships:
- Tau Beta Pi National Honors Society
- Tau Alpha Pi National Honors Society
- Phi Kappa Phi National Honors Society
- ASME
- MRS
- ASHRAE

Presentations: Thesis Defense- *Attenuation Measurements in Concrete by Means of Rayleigh Surface Waves*

International Education: Global Perspective gained through extensive travel within Western Europe

Language Proficiency: English

04/10