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## WORKSHOP ON NEW TECHNOLOGIES FOR NDT OF ROADS AND BRIDGES

### IMPACT-ECHO AND IMPULSE RESPONSE TESTING
### Dr. Allen G. Davis, CTL Skokie Illinois

## 1. STRESS WAVE THEORY

Several nondestructive test methods based on stress wave propagation can be used for nondestructive testing of concrete structures. This technical note deals with two such methods: Impact-Echo (I-E) and Impulse Response (IR). The following section describes the principles of stress wave propagation through concrete.

Stress waves occur when pressure or deformation is applied suddenly, such as by impact, to the surface of a solid. The disturbance propagates through the solid in a similar way to that of sound traveling through air. The speed of stress wave propagation in an elastic solid is a function of the modulus of elasticity, $E$; Poisson's ratio, ?; the density, ? and the geometry of the solid. This dependence between the properties of a solid and monitoring of the resultant stress wave propagation behavior allows information to be gathered about the properties of the solid.

When pressure is applied suddenly at a point on the surface of a solid half-space, the disturbance propagates through the solid as three different waves:
   ?? P-wave, often called the compression, dilatational or longitudinal wave,
   ?? S-wave, often referred to as the shear or transverse wave,
   ?? R-wave, named after Rayleigh, also called a surface wave.
Both the P-wave and the S-wave propagate into the solid along hemispherical wave fronts. The P-wave is the propagation of normal stress, and particle motion is parallel to the propagation direction. The S-wave is associated with shear stress, and particle motion is perpendicular to the propagation direction. The R-wave travels away from the disturbance along the surface (Figure 1).

In an isotropic, elastic solid, the P-wave speed, $C_p$, is related to the Young's modulus of elasticity, $E$; Poisson's ratio, ?; and the density, ?, as follows:

$$C_p = ? [( E (1 - ?) ) / ( ? ( 1 + ? ) ( 1 - 2? ) )] \tag{1}$$

The S-wave propagates at a slower speed, $C_s$, given by

$$C_s = ? ( G / ? ) \tag{2}$$

where $G$ is the shear modulus of elasticity.

A useful parameter is the ratio of the S-wave speed to the P-wave speed:

$$C_s / C_p = ? ( ( 1 - 2? ) / 2( 1 - ? ) ) \tag{3}$$

For a Poisson's ratio of 0.2, which is typical of concrete, this ratio = 0.61. The ratio of the R-wave speed, $C_r$ to the S-wave speed may be approximated by the following formula:

$$C_r / C_s = ( 0.87 + 1.12? ) / ( 1 + ? )$$
$$\tag{4}$$

For Poisson's ratio between 0.15 and 0.25, the R-wave travels at from 90 to 92 percent of the S-wave speed.

Equation (1) represents the P-wave speed in an infinite solid. In the case of bounded solids, the wave speed is affected also by the geometry of the solid. For wave propagation along the axis of a slender rod (such as a pile), the wave speed is independent of Poisson's ratio, and is given by the following:

$$C_b = ? ( E / ? ) \tag{5}$$

where $C_b$ is the bar wave speed. For Poisson's ratio between 0.15 and 0.25, the bar wave speed in a slender rod is from 3 to 9 percent slower than the P-wave speed in a large solid.

When a stress wave traveling through *material 1* is incident on the interface with a dissimilar *material 2*, a portion of the incident wave is reflected. The amplitude of the reflected wave is a function of the angle of incidence and is a maximum when the angle is 90 deg (normal incidence). For normal incidence, the reflection coefficient, $R$ is given by the following:

$$R = ( Z_2 - Z_1 ) / ( Z_2 + Z_1 ) \tag{6}$$

where $Z_1$ = specific acoustic impedance of *material 1*,
$Z_2$ = specific acoustic impedance of *material 2*.

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The specific acoustic impedance is the product of the wave speed and density of the material. The following are approximate Z-values for some materials:

| Material | Specific acoustic impedance (kg / m²s) |
|---|---|
| Air | 0.4 |
| Water | $1.5 \times 10^6$ |
| Soil | $0.3$ to $4 \times 10^6$ |
| Concrete | $7$ to $10 \times 10^6$ |
| Limestone | $7$ to $19 \times 10^6$ |
| Granite | $15$ to $17 \times 10^6$ |
| Steel | $47 \times 10^6$ |

Thus, for a stress wave that encounters an air interface as it travels through concrete, the absolute value of reflection coefficient is nearly 1.0, and there is almost total reflection at the interface. This is why NDT methods based on stress wave propagation have proven to be successful for locating defects within concrete.

## 2. IMPACT-ECHO METHOD

The stress waves generated by an impact at a point on a solid surface are not focused; the waves propagate into a test object in all directions, and reflections may arrive from many directions. Beginning in the mid 1980's, the impact-echo technique was developed for the testing of concrete structures (Sansalone and Carino, 1986). Applications of the impact-echo method include determining the thickness and detecting flaws in plate-like structures such as slabs and overlaid bridge decks, detecting flaws in beams, columns and hollow cylindrical structures, and assessing the quality of bond in overlays (Sansalone and Streett, 1997; Sansalone, 1997).

### 2.1. Principle

The principle of the impact-echo technique is illustrated in Fig. 2. A transient stress pulse is introduced into a test object by mechanical impact on the surface. The P- and S-waves produced by this pulse propagate into the object along hemispherical wave fronts. In addition, a surface wave travels along the surface away from the impact point. The waves are reflected by internal surfaces or external boundaries. The arrival of these reflected waves, or echoes, at the surface where the impact was generated produces displacements that are measured by a receiving transducer and recorded using a data acquisition system. Interpretation of wave-forms in the time domain has been successful in seismic-echo applications involving long slender structures such as piles and drilled shafts. In such cases, there is sufficient time between the generation of the stress pulse and the reception of the wave reflected from the bottom surface, or from an inclusion or other flaw, so that the arrival time of the reflected wave is generally easy to determine even if long duration impacts produced by hammers are used.

For relatively thin structures such as slabs and walls, time domain analysis is feasible if short duration impacts are used, but it is time-consuming and can be difficult depending on the geometry of the structure. The preferred approach, which is much quicker and simpler, is frequency analysis of displacement, velocity or acceleration wave-forms. The underlying principle of frequency analysis is that the stress pulse generated by the impact undergoes multiple reflections between the test surface and the reflecting surface (flaw or boundaries). The frequency of arrival of the reflected pulse at the receiver depends upon the wave speed and the distance between the test surface and the reflecting surface. For the case of the boundary reflections in a plate-like structure, this frequency is called the *thickness frequency*, and it varies as the inverse of the member thickness.

In frequency analysis, the time domain signal is transformed into the frequency domain using the fast Fourier transform (FFT) technique. The result is an *amplitude spectrum* that indicates the amplitude of the various frequency components in the wave-forms. The frequency corresponding to the arrival of the multiple reflections of the initial stress pulse, i.e. the thickness frequency, is indicated by a peak in the amplitude spectrum. For a plate-like structure, the approximate relationship between the distance, D to the reflecting surface, the P-wave speed $C_p$ and the thickness frequency, $f$ is as follows:

$$D = C_p / 2f \qquad\qquad (7)$$

As an example, Fig. 2 shows the amplitude spectrum from an impact-echo test of a 0.5 m concrete slab. The peak at 3.42 kHz corresponds to the thickness frequency of the solid slab and a velocity of 3,420 m/s is calculated. Fig. 3 shows the amplitude spectrum for a test over a void within the same slab. The peak has shifted to a frequency of 7.32 kHz, indicating that the reflections are occurring from an interface within the slab. The ration 3.42/7.32 = 0.46 indicates that the interface is at approximately the middle of the slab with a calculated depth of 0.23 m.

In using the impact-echo method to determine the locations of flaws within a slab or other plate-like structure, tests can be performed at regularly spaced points on the surface. Spectra obtained from such a series of tests can be analyzed with the aid of computer software that can identify those test points corresponding to the presence of flaws, and can plot a cross-sectional view along the test line.

Frequency analysis of signals obtained from impact-echo tests on bar-like structures such as reinforced concrete beams and columns, bridge piers, etc., is more complicated than the case of slab-like structures. The presence of side boundaries gives rise to transverse modes of vibration of the cross section. Thus, prior to attempting to interpret test results, the characteristic frequencies associated with the transverse modes of vibration of a solid structure have to be determined. These frequencies depend upon the shape and dimensions of the cross section (Sansalone, 1997).

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## 2.2 Instrumentation

An impact-echo system is composed of three components: an impact source; a receiving transducer; and a data-acquisition system that is used to capture the output of the transducer, store the digitized wave-forms and perform signal analysis.

The selection of the impact source is a critical aspect of a successful impact-echo system. The impact duration determines the frequency content of the stress pulse generated by the impact, and determines the minimum flaw depth that can be measured. As the impact duration is shortened, higher frequency components are generated. As an example, in the evaluation of piles, hammers are used that produce energetic impacts with relatively long contact times (greater than 1 ms) suitable for testing long, slender structures. Impact sources with shorter duration (typically 20 to 80 ?s) such as spring-loaded spherically-tipped impactors have been used for detecting flaws in structures less than 1 m thick.

In evaluation of piles, geophones (velocity transducers) or accelerometers have been used as the receiving transducer. For impact-echo testing of slabs, walls, beams and columns, a broad-band conically-tipped piezoelectric transducer that responds to surface displacement has been used as the receiver (Sansalone and Carino, 1986). Small accelerometers have also been used as the receiver. In this case, additional signal processing is carried out in the frequency domain to obtain the appropriate amplitude spectrum. Such accelerometers must have resonant frequencies well above the anticipated thickness frequencies to be measured.

## 3. IMPULSE RESPONSE METHOD

The Impulse Response (IR) test method is used extensively in the evaluation of machined metallic components in the aircraft industry. Its application to concrete structures diagnostics is less well known, and the method has received far less publicity than the more recently developed Impact-Echo method described previously.

The IR method (also referred to in earlier literature as the Transient Dynamic Response method) is a direct development of the Forced Vibration method developed in France in the 1960's for the evaluation of the integrity of concrete drilled shafts (Davis and Dunn, 1974). The theory of dynamic mobility developed at that time has been extended to include the following applications:

?? voiding beneath concrete slabs in highways, spillways and floors (Pederson and Senkowski, 1986; Davis and Hertlein, 1987; Reddy, 1992),

?? delamination of concrete around steel reinforcement in concrete slabs, walls and large structures such as dams, chimney stacks and silos (Davis and Hertlein, 1995),

?? low density concrete (honeycombing) and cracking in concrete structural elements (Davis and Hertlein, 1995; Davis *et al*, 1997),

?? the depth and severity of alkali-silica reaction in drilled shafts used as pylon foundations (Davis and Kennedy, 1998),

?? debonding of asphalt and concrete overlays and patches from concrete substrates (Davis and Hertlein, 1990; Davis *et al*, 1996),

?? the degree of stress transfer through load transfer systems across joints in concrete slabs (Davis and Hertlein, 1987).

### 3.1 Principle

The IR method uses a low-strain hammer impact to send a stress wave through the tested element. The test compressive stress from the impact is approximately 100 times that used in the I-E test. This greater stress input means that plate-like structures respond to the IR impact in a bending mode over a very much lower frequency range (0-1 kHz for plate structures), as opposed to the reflective mode of the I-E test.

Both the time records for the hammer force and the transducer velocity response are processed in the field computer using the FFT algorithm, and the resulting velocity spectrum is divided by the force spectrum to obtain a transfer function, referred to as the *Mobility* of the element under test, in units of m/s/N. The response graph of Mobility plotted against frequency (usually over the 1 Hz to 1 kHz range) contains information on the condition and the integrity of the concrete in the tested elements, as well as the support conditions to the elements. The following parameters are obtained from the Mobility response curve:

?? *Dynamic Stiffness* $K_d$: The slope of the linear portion of the Mobility plot from 1 Hz to approximately 50 Hz defines the compliance, or dynamic flexibility, of the area around the test point for a normalized force input. The inverse of the compliance is the dynamic stiffness of the structural element at the test point. This can be expressed as:

$K_d$ $f$ [ concrete quality, element thickness, element support condition ]

?? *Average Mobility, N:* At frequency values > ~50 Hz, the measured mobility value oscillates around a mean value, $N$, which is mainly a function of the test element thickness and elastic properties. For example, a reduction on the thickness of a plate element will result in an increase in the mean value of mobility over the 50 Hz to 1 kHz range. In a two-layer system such as an overlaid concrete pavement, when total debonding of the upper layer is present, the mean mobility represents the thickness of the upper, debonded layer alone, and the slab becomes more mobile.

?? *Damping:* The test element's response to the impact-generated elastic wave will be damped by the element's intrinsic rigidity (body damping). Any cracking or honeycombing in the concrete under test will reduce damping and hence the stability of the mobility plot over the 50 Hz to 1 kHz range.

?? *Peak/Mean Mobility Ratio:* When debonding or delamination is present within a structural element, or when there is loss of support below a concrete slab on grade, the behavior of the upper layer controls the IR response. In addition to the increase in $N$, the dynamic stiffness, $K_d$ is greatly reduced, and the peak value of mobility below ~50 Hz ( $M_p$ ) becomes appreciably higher than the mean mobility, $N$. An increasing ratio of $M_p/N$ is an indicator of the presence and degree of either debonding within the element or voiding/loss of support beneath a slab on grade.

Examples of Mobility spectra from concrete highway slabs are shown in Figures 3-6.

A recent approach to the measurement of the impulse response of concrete pavements has been developed at the University of Texas at El Paso (Reddy, 1992; Nazarian *et al*, 1993). This method uses the flexibility spectrum from the impulse response, which is the displacement/force transfer function. For this approach, the pavement slab is modeled as a flexible slab on an elastic foundation, and the impact is assumed to be a half sine wave. A modeled displacement-time response of the slab is shown in Figure 7, and the flexibility-frequency response is given in Figure 8. The parameters which affect this flexibility response are:

?? slab thickness, h,
?? slab elastic modulus, E,
?? Modulus of Subgrade Reaction of the soil,
?? Slab dimensions and shape,
?? point of impact on the slab.

A curve is fitted to the Flexibility spectrum (Figure 9), which can then be analyzed to provide the subgrade shear modulus, G and the damping ratio, ?. These parameters together with the dynamic stiffness, $K_d$ from the Mobility plot allow the analysis of the quality of the slab and its support.

## 3.2 Instrumentation

The impactor is usually a 1 kg sledge hammer with a built-in load cell in the hammer head. The maximum compressive stress at the impact point in concrete is directly related to the elastic properties of the hammer tip. Typical stress levels range from 5 MPa for hard rubber tips to more than 50 MPa for aluminum tips with a tip diameter of 50 mm. The response to the input stress is measured with a velocity transducer (geophone) or with an accelerometer. The geophone is usually preferred because of its stability when compared with the accelerometer over the 1-50 Hz frequency range, as well as its robust performance in practice. Both the hammer and the transducer are linked to a portable field computer for data acquisition and processing.

Automated devices have been developed for high-speed concrete pavement testing by Testconsult CEBTP (France) in 1987, with three hammer-geophone units mounted on a trailer cross-beam. The trailer was stopped at the test point on the concrete slab, and the hammers were operated in sequence. Up to 5,000 measurements could be made in one day (Davis and Hertlein, 1987). This equipment is no longer in service. A prototype unit with both Impulse Response and Spectral Analysis of Surface Waves (SASW) incorporated has been developed at University of Texas at El Paso, and is presently undergoing trials at the Department of Transportation, Florida.

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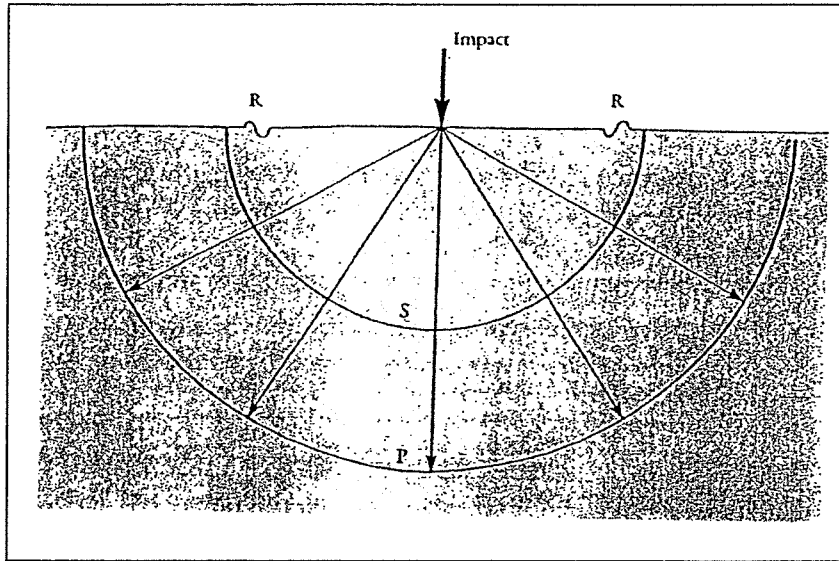
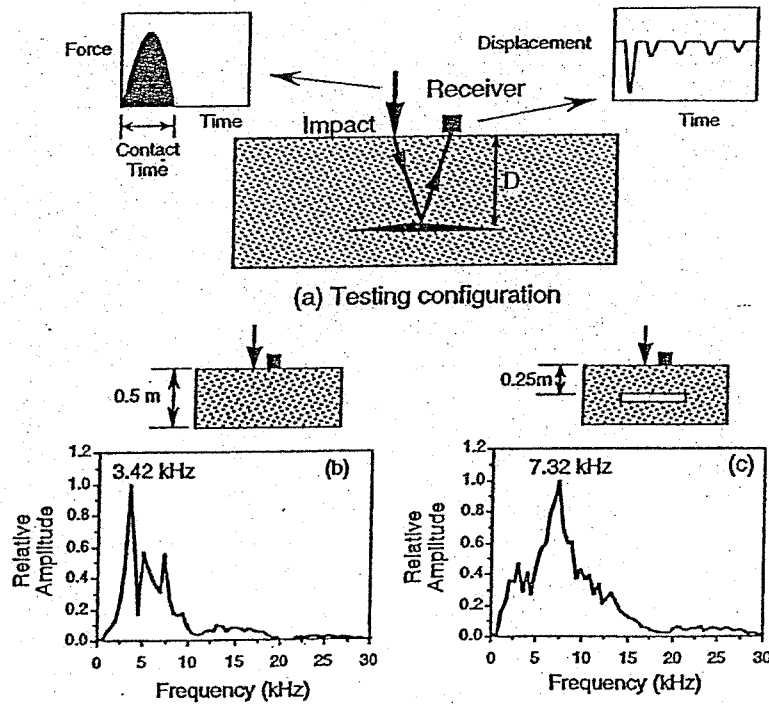**Figure 1. Stress Waves caused by impact on half-space**



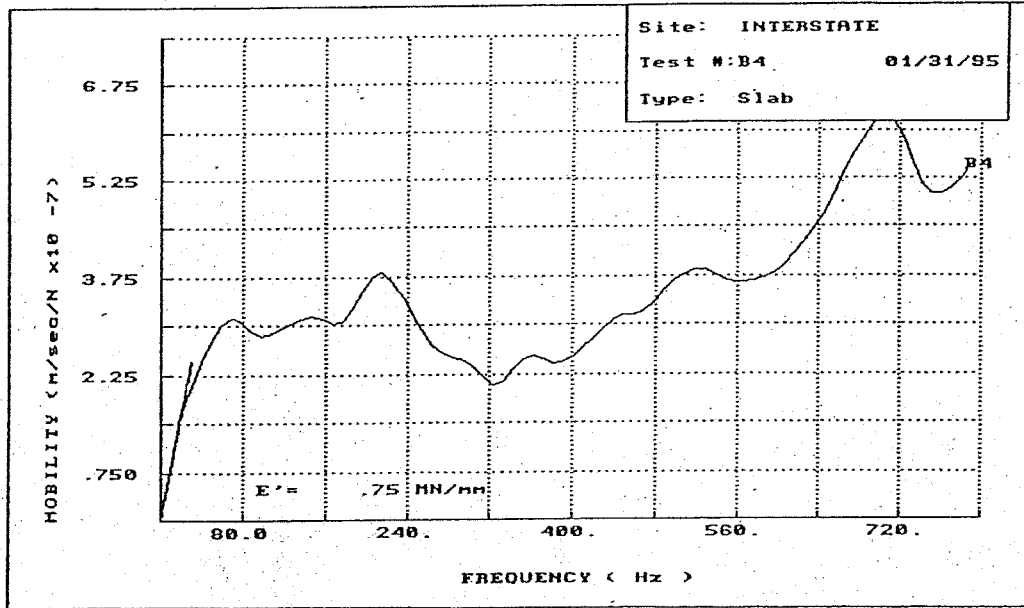**Figure 2. Impact-Echo tests on 0.5 m-thick slab**

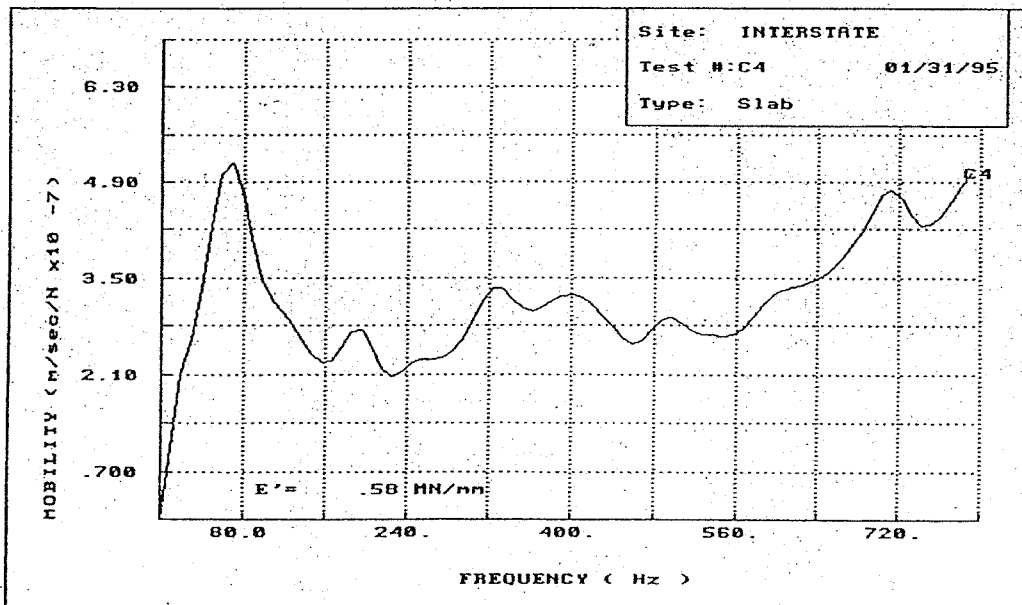**Figure 3. IR test response from sound slab/overlay interface**



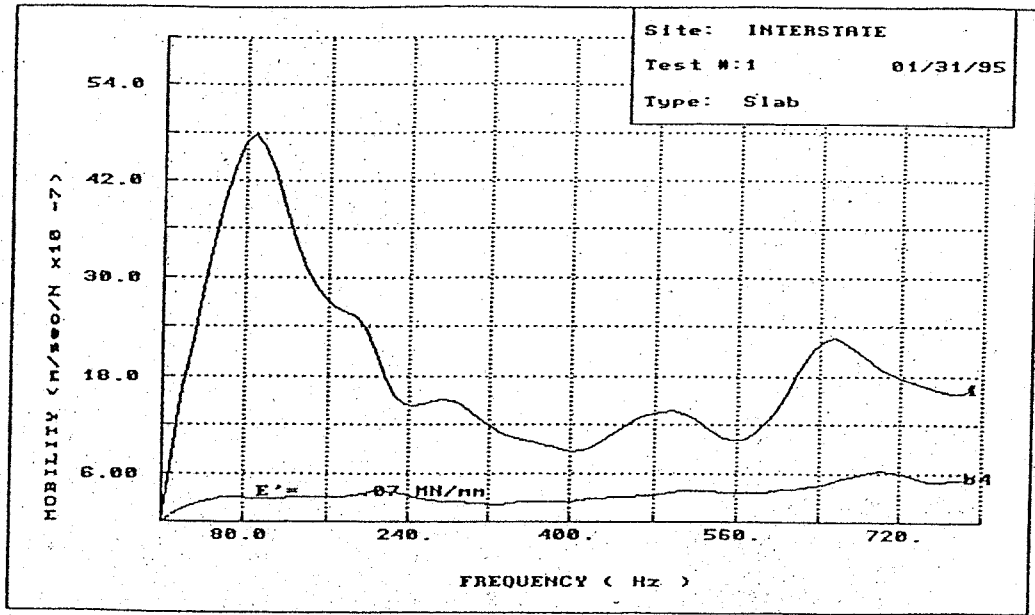**Figure 4. IR test response from incipient overlay debond**
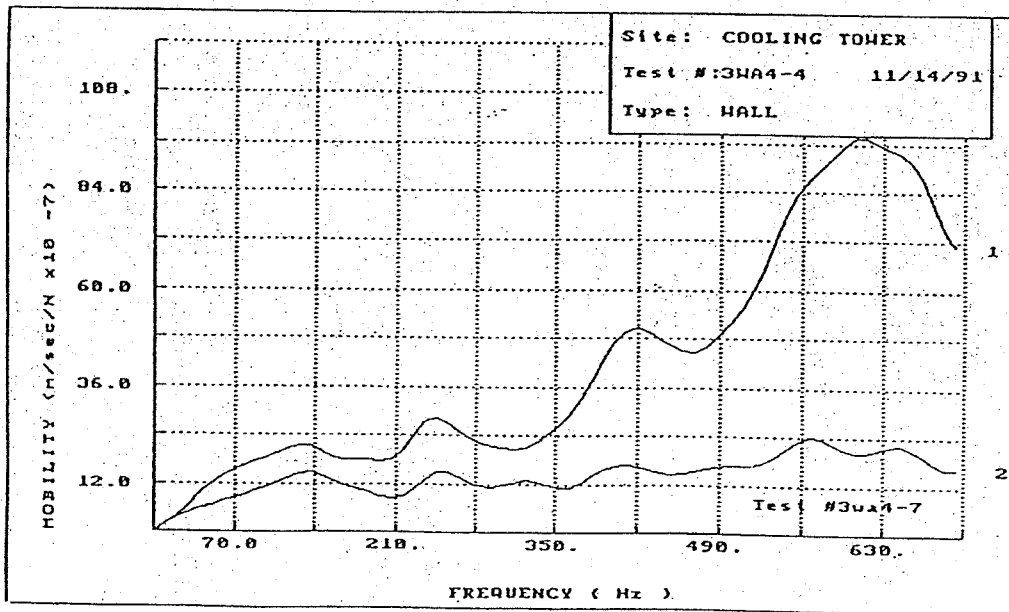
**Figure 5. IR test response from debonded area**

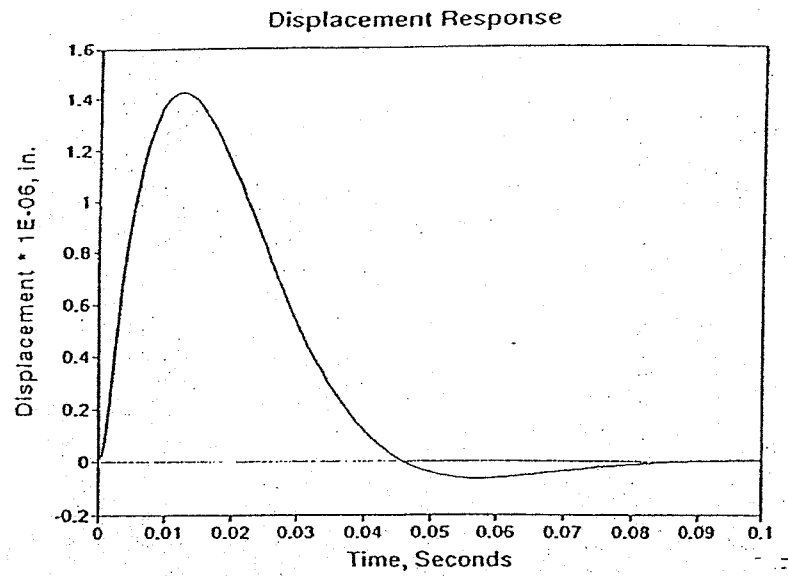**Figure 6. IR test response from honeycombed concrete**
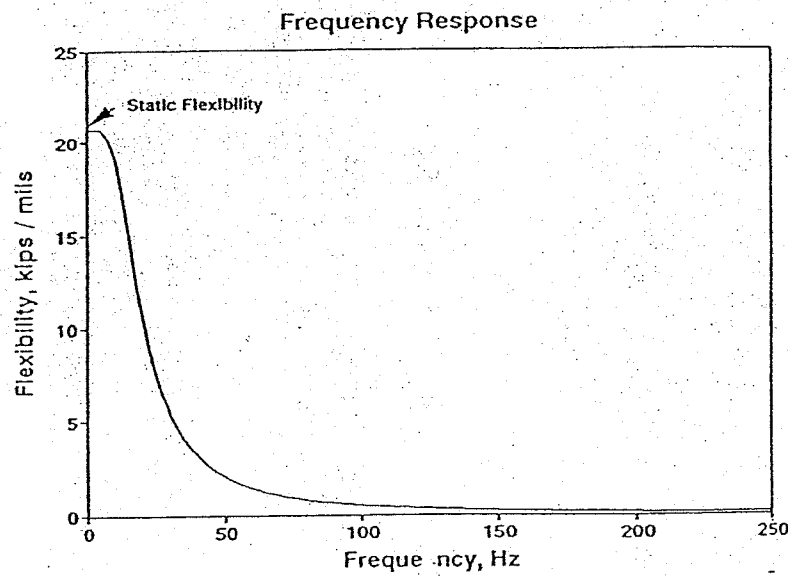
**Figure 7. IR modeled displacement-time response**
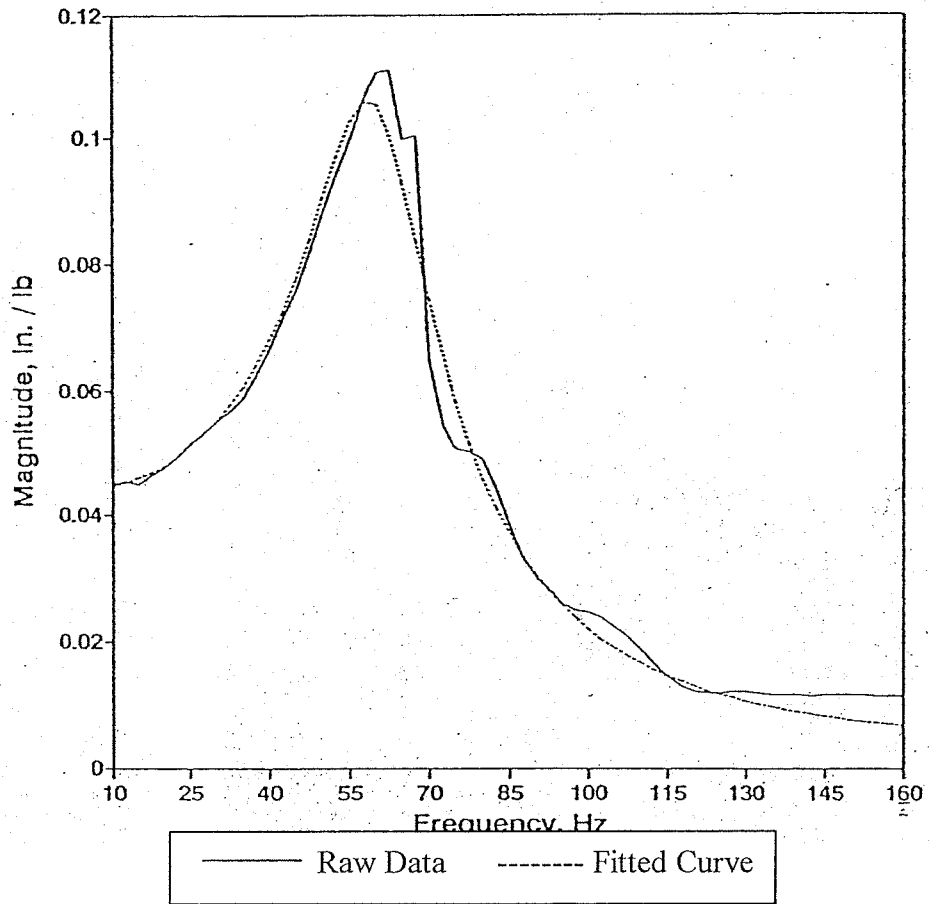
**Figure 8. IR modeled flexibility-frequency response**

**Figure 9. IR Flexibility Spectrum - curve fit**