Impact-Echo and Impulse Response stress wave methods:
Advantages and limitations for the evaluation of highway pavement concrete overlays.

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ABSTRACT

Concrete overlays with thickness ranging between 25 mm and 300 mm are frequently used to restore and strengthen existing concrete pavements and bridge approach slabs. Differences in the strengths and elastic moduli of the overlay and the substrate, as well as the cleanliness and roughness of the interface between the two layers affect the medium and long term performance of these structures. Debonding at the interface, excessive tensile stresses at the base of the overlay and delamination within the upper layer are commonly occurring problems. If these defects are not detected and corrected in good time, the deterioration of the overlay under the action of heavy axle loads is rapid and becomes expensive to fix. Nondestructive methods are required to identify budding problems of the type described above, by surveying overlay systems quickly and economically. Stress wave methods for flaw detection in concrete structures and foundations have shown great promise in recent years. The Impact-Echo (I-E) test has been applied successfully to many diverse concrete material problems. The Impulse Response (IR) test is proven in the detection of flaws in deep concrete foundations, as well as the location of poor support conditions beneath and delaminations within concrete slabs on grade. This paper presents a case study where both methods were used to examine a stepped concrete overlay on approach slabs to bridge decks on a heavily trafficked Interstate highway. The two test methods are briefly described, and a comparison is drawn emphasizing the advantages and disadvantages of both techniques.

Keywords: concrete pavement overlay, nondestructive testing, stress wave methods.

1. INTRODUCTION

In January 1995, the authors were able to examine the condition of reinforced concrete approach slabs by nondestructive stress wave methods at seven different bridge decks on a heavily trafficked Interstate highway in the eastern USA. The original slabs were constructed in a stepped configuration along their longitudinal direction, with slab thickness between 375 mm (15 inches) and 625 mm (25 inches), in 125 mm (5 inch) steps. The approach slabs were supported on soil fill. Each bridge approach slab is approximately 6 m (20 feet) long and 4 lanes wide, with one slab width per lane. The stepped areas had first been overlaid by asphalt, which was subsequently removed and replaced by reinforced concrete overlay, intended to be bonded to the underlying slab. These concrete overlays now exhibit cracking, delamination and spalling. It was believed that mich of the deterioration was associated with debonding of the overlaid stepped areas from the underlying approach slab.

Nondestructive methods using stress waves have been used to examine debonding of concrete layers in previous studies.[1-7] However, a comparison between the two principal practical methods available (Impact-Echo (I-E) and Impulse Response (IR)) has not been reported to date. The opportunity

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was afforded in this study to use both test methods in parallel, and to compare the relative merits of the two techniques.

2. TEST METHOD DESCRIPTIONS

2.1 Impact-Echo

The I-E technique applied to the detection of layer debonding is fully described in references 4-7. A short summary of the method and test equipment is given here.

The equipment used was the Germann Instruments DOCter system, which comprises a mechanical impactor source and an electromechanical receiving displacement transducer located in a common unit. The spherical impactor generates a broad band stress pulse, or P-wave, typically with a maximum compressive stress of from 0.5 to 0.1 MPa at the surface to a depth of 25 mm. Below that depth, the compressive stress decreases rapidly, falling to between 1e-02 and 1e-03 MPa between 150 mm and 200 mm[7]. Reflected stress waves are detected by the displacement transducer, and the time-displacement response is converted to a frequency response using a Fast Fourier Transform (FFT) algorithm.

The reflected stress wave from the base of a concrete slab supported on subgrade with a lower elastic modulus is a tension wave, as is the reflected P-wave from any debonded surface between concrete overlay and substrate. The time taken, dt, for the return wave to reach the receiving transducer is a direct function of the P-wave velocity in the concrete, c_p ; and the thickness of the tested element, H:

$$dt = 2H / c_p \tag{1}$$

The plate thickness (or depth to a debonded interface) can be determined more accurately from the displacement-frequency response curve, by locating the characteristic frequency, f, for the particular plate thickness on the response curve:

$$H = c_p / 2f \tag{2}$$

The P-wave velocity is either obtained by calibration on elements of known thickness, or by using two displacement transducers at different distances from the impactor, and measuring the Rayleigh, or surface wave velocity. Typical I-E records from this case study for debonded overlays are given in Figures 1-2. Figure 2 also has a peak at very low frequency, which is equivalent to a response from the slab in the bending mode. This feature is used in the Impulse Response test described below.

2.2 Impulse Response

The IR test [1-3] (often referred to previously as the Transient Dynamic Response, or TDR test) also uses a low strain impact to send a stress wave through the tested element. However, the impactor takes the form of a 1kg 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. This greater stress input than for the I-E test means that plate structures behave differently. At relatively low frequencies (0-1 kHz) the plate responds to the IR hammer impact in a bending mode. The response to the input stress is normally measured using a velocity transducer (geophone). This receiver is preferred because of its stability at low frequencies, and its robust performance in practice. The equipment used in this project was developed by STS Consultants, Ltd.

Both the time records for the hammer force and the geophone response are processed using the FFT algorithm, and the resulting velocity spectrum is divided by the force spectrum to obtain a transfer function, referred to as the plate Mobility. The resultant test graph of Mobility plotted against frequency over the 0-1 kHz range contains information on the condition and integrity of the concrete in the slabs, obtained from the following parameters:

- Dynamic Stiffness: The slope of the portion of the Mobility plot from 0-100 Hz defines the compliance, or flexibility of the test point for a normalized force input. The inverse of compliance is the dynamic stiffness of the slab at the test point. This can be expressed as:
  Stiffness = f [concrete quality, slab thickness, slab support conditions].
- Mobility and Damping: the slab's response to the impact-generated elastic wave will be damped by the plate's intrinsic rigidity (body damping). The mean mobility value over the 0.1-1 kHz range is directly related to the density and thickness of the plate. A reduction in plate thickness corresponds to an increase in mean mobility. When total debonding of the upper layer is present, the mean mobility reflects the thickness of the upper (debonded) layer; that is, the slab becomes more mobile. Also, any cracking or low density concrete in that upper layer will reduce the damping, and hence the response curve stability, of the mobility plot over that frequency range.
- Peak/mean Mobility ratio: when debonding is present, the upper debonded layer controls the IR result. In addition to the increase in mean mobility, the dynamic stiffness decreases greatly. The peak mobility below 0.1 kHz becomes appreciably higher than the mean mobility from 0.1-1 kHz. The ratio of this peak mobility to the mean mobility value is an indicator of the presence and the degree of debonding.

Examples of these features are given in Figures 3-5, representing test results from this case study. Figure 3 (test B4) shows a typical mobility plot for a well bonded overlay, with a relatively high stiffness and an average mobility of approximately 4e-07 m/s/N.

Figure 4 (Test C4) is a mobility plot for an overlay which is showing incipient debonding with a higher mobility peak between 0-100 Hz, a resulting lower stiffness, but a similar average mobility to test B4 in Figure 3.

Figure 5 shows a totally debonded overlay with very high initial mobility and low stiffness, and 20e-07 m/s/N average mobility. The peak/mean mobility ratio for this test point is 2.4. The plot for test B4 is superimposed on Figure 5 to demonstrate the remarkable difference between the curves for a sound overlay and a debonded layer.

3. TEST PROGRAM

3.1 Feasibility and correlation testing

Initial testing with both methods was performed on a trial section of four slabs on one bridge:

a) to demonstrate the ability of the test methods to detect debonded areas, and
b) to correlate the test results obtained with cores taken at locations exhibiting different features reported by the stress wave tests.

This proof test series was carried out during one night, with traffic diverted around the test slabs.

The concrete surface was considerably roughened by wear, and was grooved for skidding resistance. As a result, it was often difficult to guarantee a good coupling between the I-E displacement transducer and the concrete surface, and some test points had to be retested several times. The very small contact area of the I-E impactor also meant that the point of impact could not be located immediately at the crest of a concrete groove, because the impactor would crush the relatively weak surface concrete at that point. The IR test equipment with a 50 mm diameter rubber hammer tip and a 50 mm diameter geophone base adapted to the grooved surface was not as sensitive to surface variability. As a result, the IR t[illegible]g output was much faster for a given area tested.

Six cores were taken by the local Department of Transportation at selected test points, and Table 1 summarizes the correlation of the core findings with the NDT observations.

Table 1. Correlation of NDT results with cores

LOCATION	I-E Results delamination depth (mm)	IR Results Stiffness (MN/mm) & Mean Mobility	CORE SUMMARY
1	140	0.18 / 18	Delaminated at interface between two different concretes at 133 mm
2	300	0.27 / 15	Delaminated at interface between two different concretes at 290 mm
3	115	0.23 / 40	Large void in core between 75 and 125 mm from core top
4	150	0.13 / 10	Broken at interface between two different concretes at 150 mm depth
5	165	0.35 / 5	Intact core with epoxy resin layer between 140 mm and 280 mm depth
6	140	0.07 / 30	Core separated at 140 mm, with drilling water loss. Layer of loose aggregate present in hole.

A good agreement was obtained for both tests with the core observations. The dynamic stiffness for the IR test decreased with increasing severity of the overlay debonding, and the mean mobility increased with decreasing effective layer thickness. The depths to layer separations were clearly recorded by the I-E test, except for Location #5, where the depth to the intact, epoxy-bonded interface was seen.

In view of the performance of the equipment during this preliminary test series, it was decided that all subsequent testing would be done using IR equipment to locate and measure the area of potential debonded areas, followed by I-E testing to quantify the depths of the debonded interfaces.

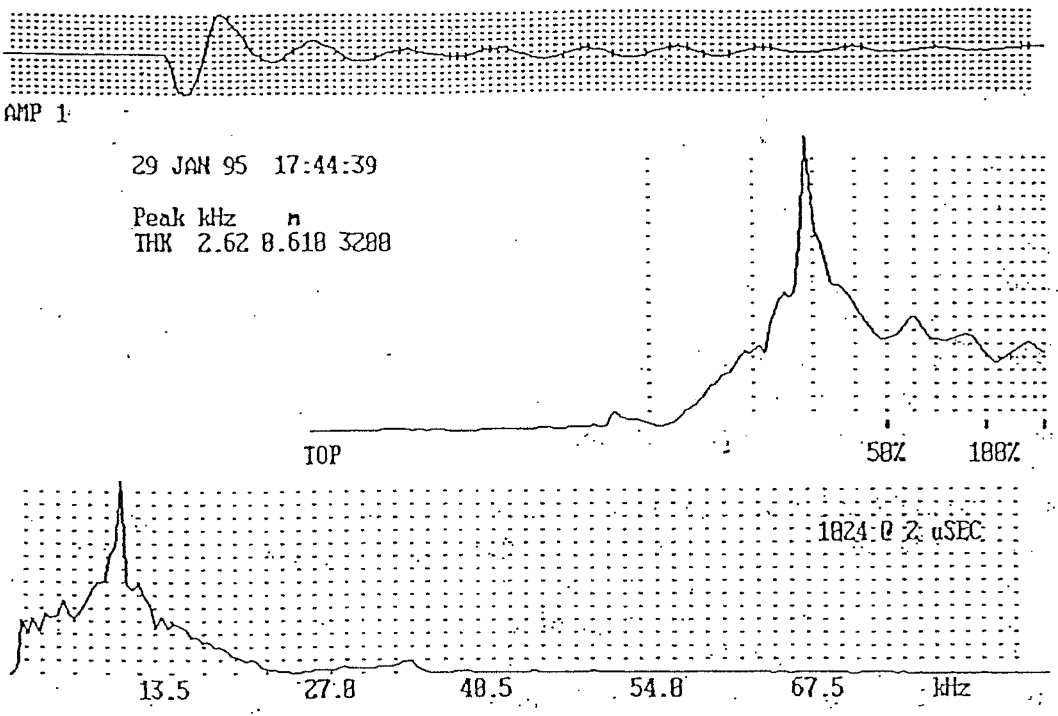

Figure 1. I-E test response from debonded overlay

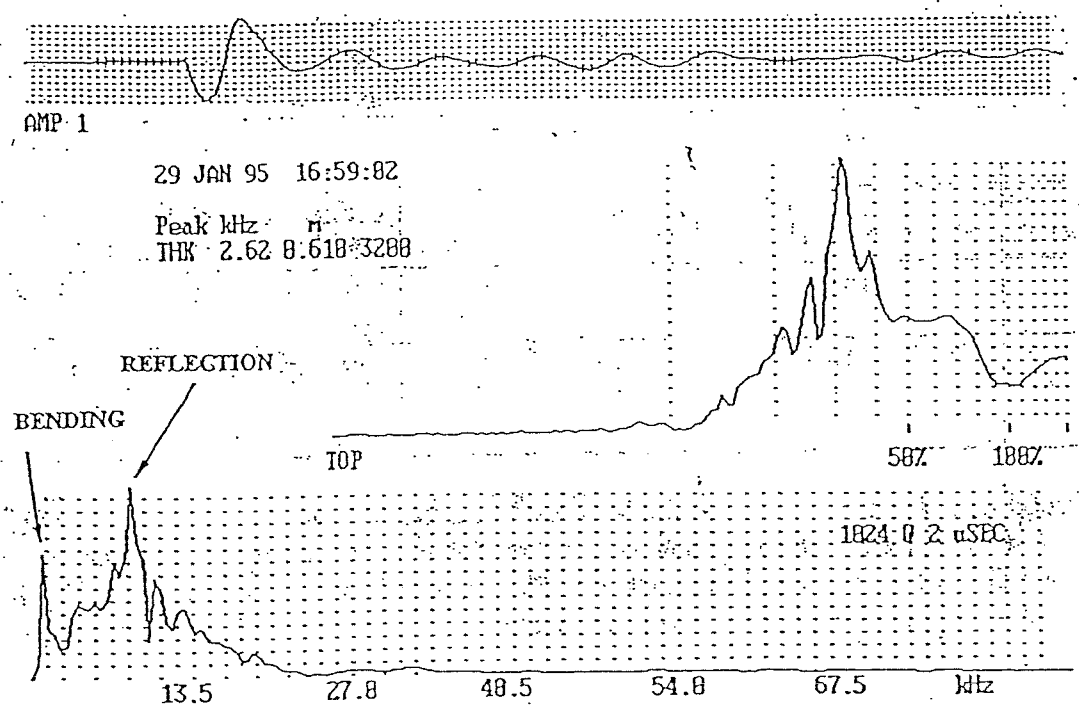

Figure 2. I-E test response with reflection and bending peaks

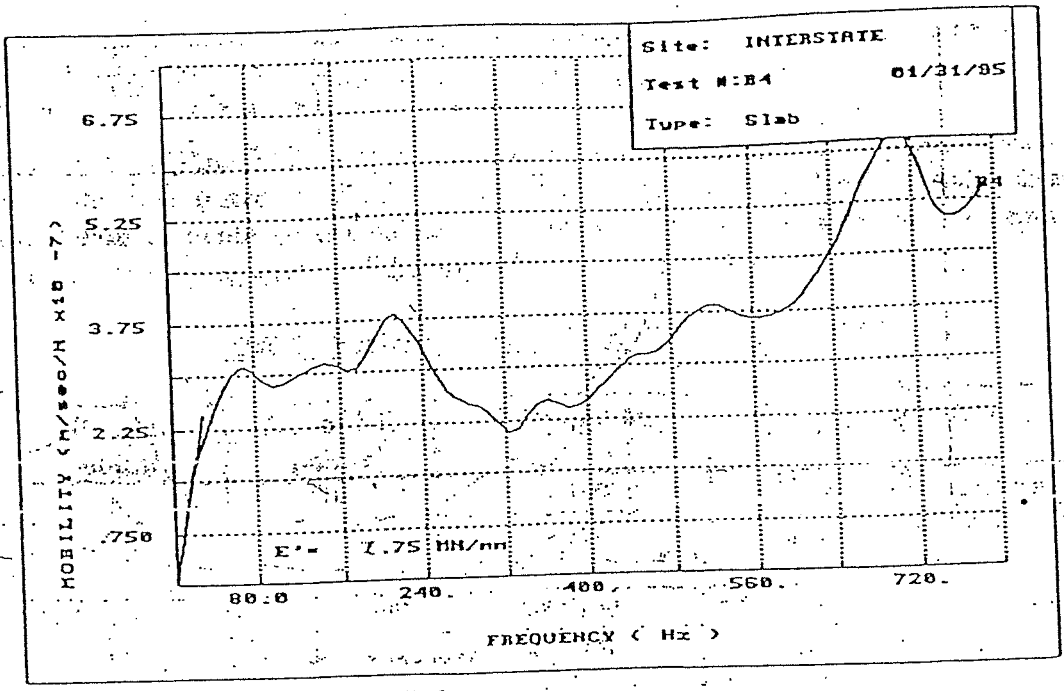

Figure 3. IR test response from sound slab/overlay interface

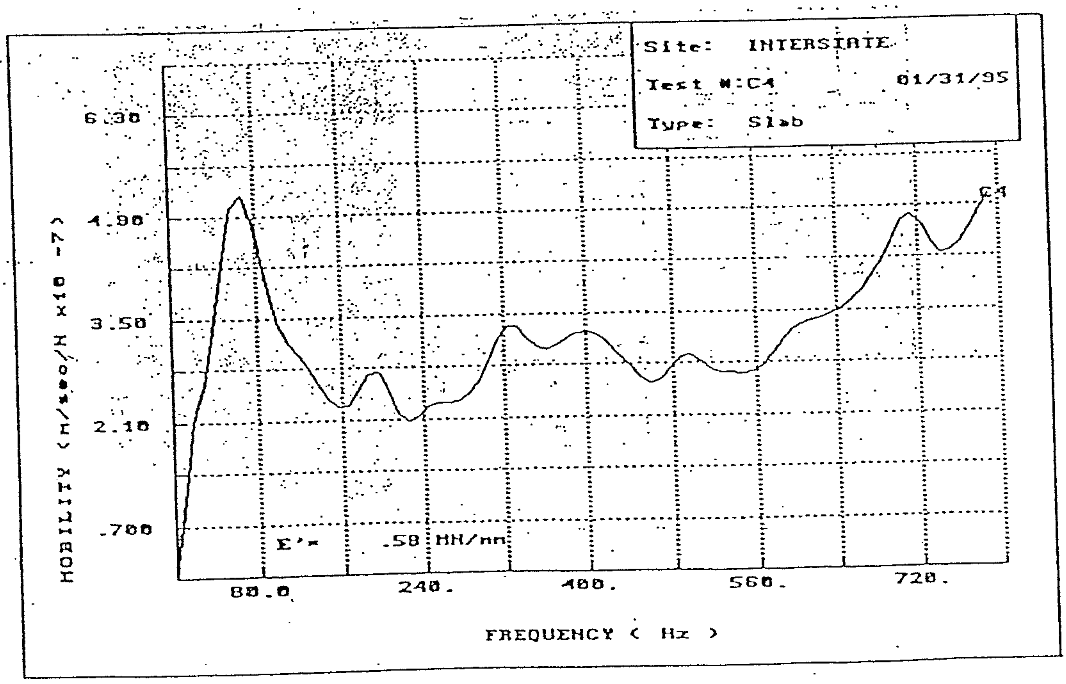

Figure 4. IR test response fron incipient overlay debond

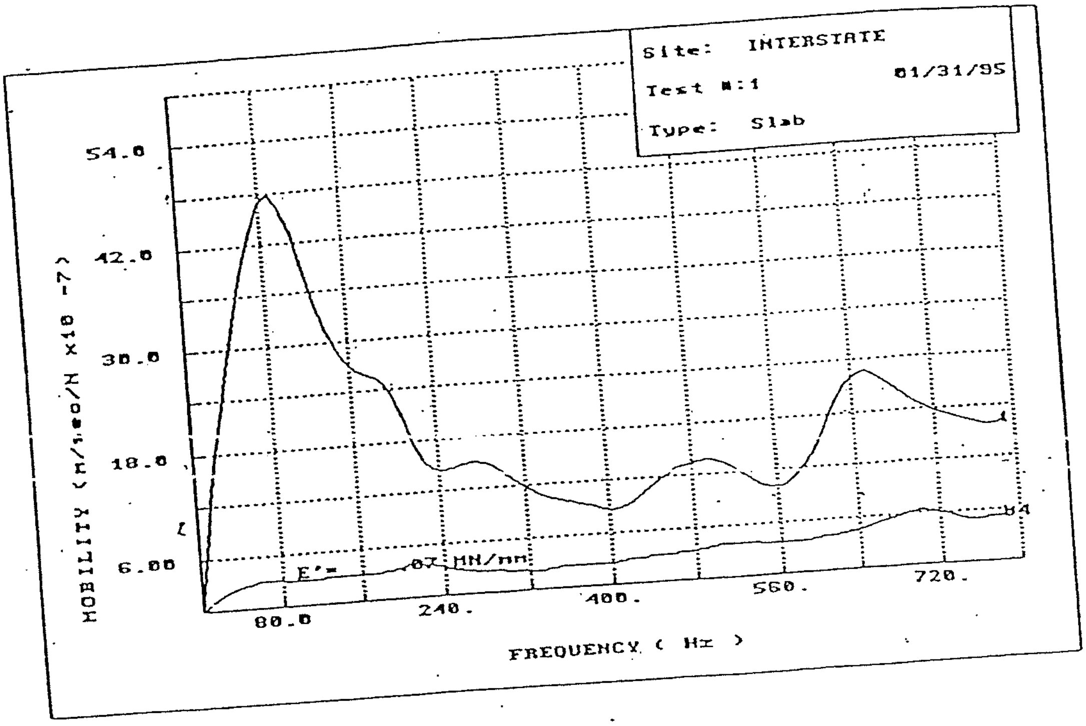

Figure 5. IR test response from debonded area

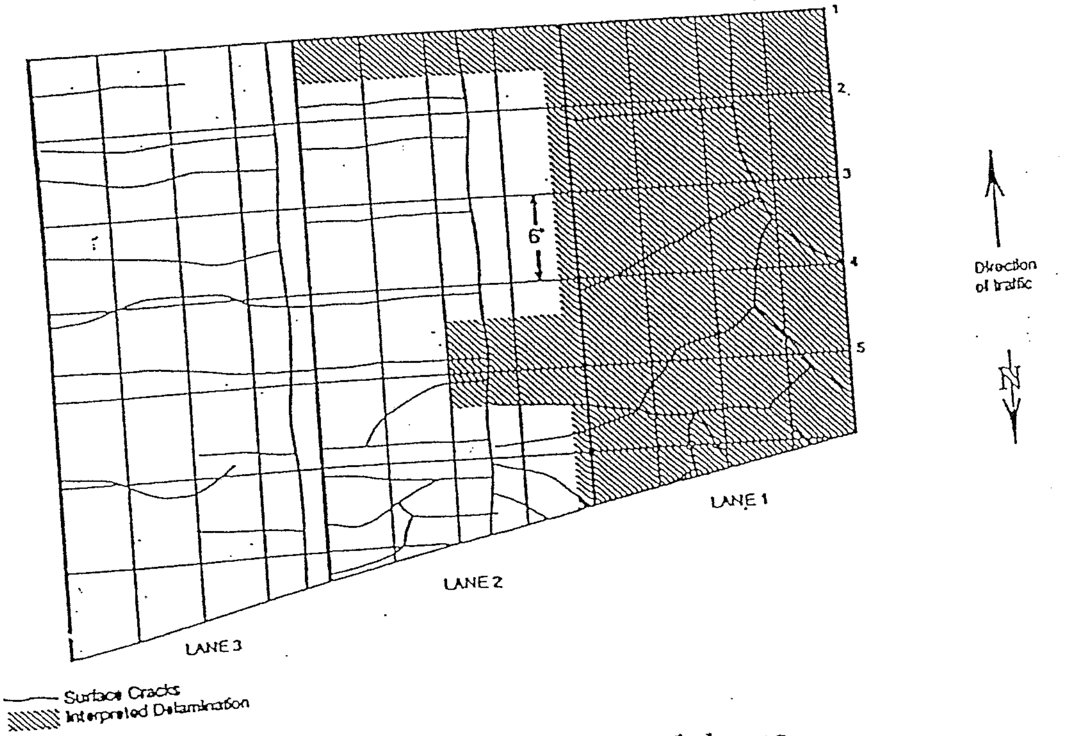

Figure 6. Mapping of debonded areas

3.2 Production Testing

The remaining approach slabs to the seven bridges were tested during the following two nights. A total of 54 slabs was tested at all bridges. The test results are summarized in Table 2, and a typical area of debonding for one bridge approach is shown schematically in Figure 6.

The results indicated that 9 slabs were debonded over their total area, 27 slabs had separations at 50% or more of the area tested, 6 slabs were less than 50% debonded, and 12 slabs showed no debonding. The measured depth of debonding generally corresponded to the recorded depth of the interface between the overlay concrete and the original slab.

Table 2. Summary of Production Test Results

Bridge No.	No. of IR points	No. of I-E points	% debonding	Comments
1	62	49	0 - 100	Testing on wheel path
2	112	127	0 - 100	Testing on wheel path & lane center
3	85	75	50 - 100	Testing on wheel path
4	114	113	44-100	Testing on wheel path and lane center
5	90	65	0-67	Testing on wheel path
6	57	57	0-100	Testing on wheel path
7	81	52	0-100	Testing on wheel path

The I-E tests were used to verify the IR test results, and to measure the depth of debonding. The percentage debonding for each slab was calculated by interpolation of the IR test results.

Table 3. Comparison of the two test methods

Test Method	Impact-Echo	Impulse Response
Advantages	• Apparatus very light and portable, battery operated • Easy data storage and data recall for analysis and reporting • Measures direct depth to reflected features • Single operator, 15-20 sec/test	• Apparatus is robust and portable • Easy data storage and data recall for analysis and reporting • Not affected by relatively rough concrete test surfaces • Fast testing (each test point covers an area of 20 square feet)
Disadvantages	• Good sensor coupling and impactor points are difficult to achieve on rough and grooved surfaces • each test measures the layer depth only immediately below the test point	• Apparatus requires electricity supply (generator) • No depth measurement to debonded surface • Requires skilled data interpretation

4. DISCUSSION

The complementary advantages of the two test methods (summarized with their disadvantages in Table 3) were combined to give a fast, certain evaluation of the state of the interface between the original concrete approach slabs and their concrete overlays. The IR test has the disadvantage of not giving the depth to the debonded layer, but does identify wider areas of delamination around each test point. The relatively rough working surface of the overlays resulted in difficult testing conditions for the I-E equipment commercially available at the time of these tests, with uncertain coupling of the displacement transducer and awkward positioning for the impactor. The authors understand that new I-E equipment is now available to overcome these problems. The high frequency, reflected signal from the I-E method gave the thickness of the reflected interface immediately below the test point, but did not give information on the state of the interface on either side of this point.

The combination of the two test methods provided an extremely cost-effective and rapid approach for the evaluation of the 54 approach slabs in less than two nights' work on the Interstate. Finding the right combination of test techniques for a specific problem is the key to success in nondestructive testing. In the authors' experience, it is unusual to find a single test method that can completely resolve the issues raised by any project.

5. REFERENCES

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