STRUCTURAL MATERIALS TECHNOLOGY (SMT): NDE/NDT FOR HIGHWAYS AND BRIDGES 2004

Title: Verification of concrete placement in post-tensioned bridge box girders using a rapid nondestructive test method.

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Abstract:

In 2002, the authors participated in a program to evaluate concrete placement in bridge sections comprising post-tensioned box girders at an early stage in the construction of the Taiwan High-Speed Rail (THSR) project. Nondestructive, Impulse Response testing was used to locate and quantify deficiencies in the girder concrete including poor consolidation, internal voiding, and debonded repair patches. The testing also identified absence of prestressing in concrete repair areas that were made after post-tensioning. The NDT program was beneficial in assessing and quantifying. these early concrete placement difficulties, both for cast-in-place and full-span precast girder construction.

Introduction

The Taiwan High-Speed Rail (THSR) project, between Taipei in the North and Kaohsiung in the South of the island, comprises a total length of 345 km (216 miles), 70% of which is on viaducts and bridges. With the exception of a few long span steel structures, the viaducts and bridges are concrete box girders using a variety of construction techniques. These include full span precast, cast-in-place on advancing shoring, cast-in place on fixed shoring, cantilever segmental and incremental launching construction methods. The structures are designed for a life of 100 years, and accordingly had strict concrete quality assurance provisions.

Figures 1 to 3 show general views of viaduct girder construction, as well as details of one of the post-tensioning systems used. Typical concreting deficiencies appeared on some girders in the early stages of construction in both precast and cast-in-place units, primarily in three separate construction contract sections of the Project. Problem areas included incomplete consolidation of concrete, cold joints, low concrete cover over embedded reinforcement, debris present in the body of the concrete, and questionable concrete repairs (Figures 6 and 7). Incomplete consolidation of concrete resulted in areas of segregation, honeycombing, and voids. Large quantities of steel reinforcement at girder end diaphragms, plus box girder webs with either large-diameter post-tensioning ducts (in cast-in-place sections) or large numbers of prestressing strands (in precast sections), complicated concrete placement. Other factors were initial problems in using new, specially designed formwork for cast-in-place girders and refinement of concrete placement techniques.

Construction Problems

Concrete placement deficiencies became apparent immediately after stripping girder formwork, suggesting the need for some form of nondestructive testing to determine the nature and extent of internal deficiencies in the web and diaphragm concrete. Visibly apparent areas of poor concrete consolidation were patched after form removal and post-tensioning. The authors had developed an evaluation approach built around the nondestructive, Impulse Response (IR) test method to assess such problems, and they were asked by the Taiwan High Speed Rail Corporation to demonstrate the suitability of this approach in a pilot test program on selected girders on the THSR to support the owner's strict quality assurance program. This test methodology was recommended for the following reasons:

- Our experience on other similar projects had shown that the IR method can detect the nature and can quantify the severity of defects typically observed in these girders (e.g., poor concrete consolidation, internal voids, and repair patch debonding).
- The close spacing of reinforcing steel in the girders (Figure 6) ruled out other nondestructive methods
- The IR test can rapidly cover the large areas to be tested
- A trained engineer can quickly assess the test results onsite. Test results are obtained by a field computer and processed immediately.

For prestressed/post-tensioned box girders of the types found in this project, the IR test method proved successful to detect voiding and poor concrete consolidation in both original concrete and repair areas, as well as identify debonding of repair patches. In addition, the IR test provided information about the difference in stress levels between original prestressed/post-tensioned concrete and unstressed patch repairs.

The Impulse Response Test Method

The IR test was originally developed to assess the quality of deep foundation construction, where it is known more commonly as a drilled shaft integrity test (Ref. 1). The method as applied to concrete structures in general has been developed relatively recently, and is fully described in Reference 2. A low-strain impact is used to send stress waves through the tested element. The impactor is usually a 2-lb sledgehammer with a load cell built into the hammerhead. The maximum compressive stress at the impact point in concrete is directly related to the elastic properties of the hammer tip. Response to the input stress is normally measured using a velocity transducer (geophone). Both the hammer and the geophone are linked to a portable field computer that acquires and stores data. Both the time records for the hammer force and the geophone velocity response are processed in the field computer using the Fast Fourier Transform (FFT) algorithm. 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. The test graph of mobility plotted against frequency from 0 to 800 Hz contains information on the condition and the integrity of the concrete in the tested elements. Typical test outputs are given in Figure 5.

The IR method is a point test, with the hammer influencing a circle on the tested element with a radius of approximately 600 mm around the impact point. Test points are normally laid out on a grid between 450 and 600 mm, depending on the element tested (diaphragm or web). The hammer blow depth of influence on plate structures of this type is 500 to 600 mm (20 to 24 inches), which incorporates the full depth of the girder webs in most cases. The diaphragms are thicker than this zone of influence, and, consequently, only the outer 500 mm (20 inches) can be assessed with this method.

When the *mobility* of a sound concrete plate element (such as the web of a girder) is compared with that of concrete with voids or honeycombing, the latter shows increasing mobility with increasing frequency, whereas the former maintains a relatively constant mobility over the same frequency range. This IR parameter is referred to as the *mobility slope*. Figure 5 shows different values for mobility slope, and when this parameter >4, it indicates poor consolidation. The severity of internal voiding increases with increasing mobility slope. This applies to voiding within the original concrete, as well as voiding in or beneath repair patches. If repair patches are debonded or adhere poorly to the substrate, then the IR test shows an increase in a parameter referred to as the *voids ratio* (ratio of peak mobility from 0-100 Hz to the average mobility between 100 and 800 Hz). When the voids ratio exceeds 2, patch debonding is probable. At the same time, debonding reduces the *dynamic stiffness*. The *mobility* and *stiffness* of concrete with locked-in stresses (such as those created by prestressing/post-tensioning) are different from those for the same concrete with no applied stresses (such as repair patches after post-tensioning). The mobility is discernibly higher and the stiffness lower in the latter case.

One major advantage of the IR test method is the relative ease with which it allows the technician to detect anomalies. As individual tests are compared with other test results, anomalous results that indicate likely defects quickly become apparent. The use of these IR test parameters for defect detection is summarized in Table 1 below.

Table 1: IR Parameters for Defect Detection

Defect	Mobility	Stiffness	Mobility Slope	Voids Ratio
Poor consolidation/internal voiding (original and repair concrete)	*		**	
Debonded repair patches	*	**		**
Absence of prestress in repair patches	**	*		

** Strong indicator * Moderate indicator

THSR Girder Results

Figure 4 shows an IR test being performed inside a girder web, producing test results as in Figure 5. The demonstration project included IR testing on girders in three separate contract sections; two with cast-in-place and one with precast construction techniques. The contractors had made concrete patch repairs to areas with visible honeycomb surface deficiencies prior to our arrival on site and testing. Repair areas were reported to range from shallow and partial depth to full thickness of the webs.

Figures 6 and 7 are IR test contour plots adjacent to photographs of the tested areas in the plots. The high mobility values in the vicinity of the full-depth patch repair in Figure 6 indicate that the patching is not integral with the surrounding concrete, but also that no voiding remains within or around the patch (normal mobility slope values). Figure 7 confirms the presence of localized internal voiding behind a partial depth patch, indicated by high values for both mobility and mobility slope.

Conclusions

To fully evaluate the extent and possible implications of the early concreting problems noted within the box girder webs and diaphragms, and to gauge the effectiveness of repairs, nondestructive Impulse Response testing was demonstrated on selected precast and post-tensioned girders. Despite the density of reinforcing steel and the thickness of webs and diaphragms, the testing identified and quantified deficiencies such as incomplete consolidation of concrete and internal voiding, debonded repair patches, and incompletely filled repair areas. The IR method is very fast, allowing more than 300 m^2 (3,000 $ft^{2)}$ of web and diaphragm to be tested during the 3-day demonstration. This output can be easily increased to 300 – 400 m^2 per day for a 2-person testing team. The method also lends itself to rapid interpretation onsite, thereby facilitating repair decisions early during construction. The authors believe that no other nondestructive test method now available can fully address these problems.

References

1. American Concrete Institute Report ACI 228.2R-98, "Nondestructive Test Methods for Evaluation of Concrete in Structures". ACI, Farmington Hills, Michigan, 1998, 62 pp.
2. Davis, A.G., 2003. "The Nondestructive Impulse Response Test in North America: 1985-2001". NDT & E International (Elsevier Science), Vol. 36, 185-193.

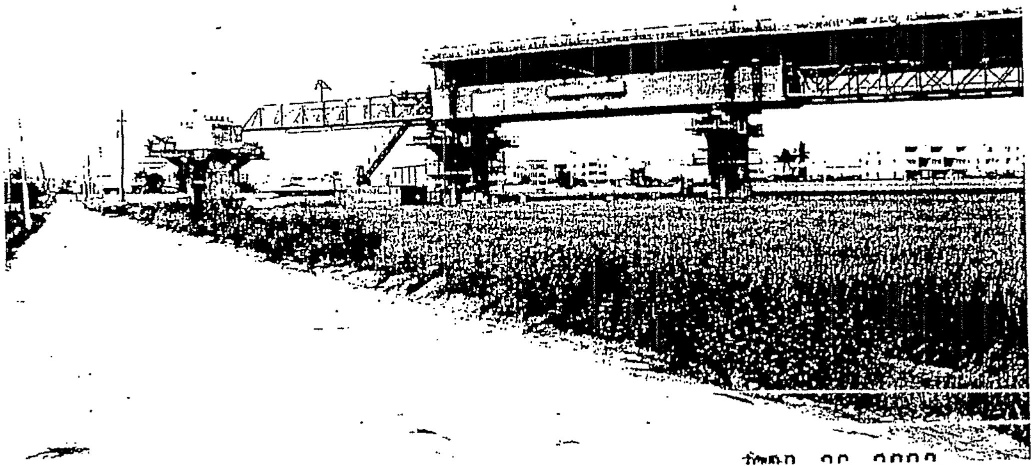


Fig. 1 Cast-in-Place Girders Under Construction

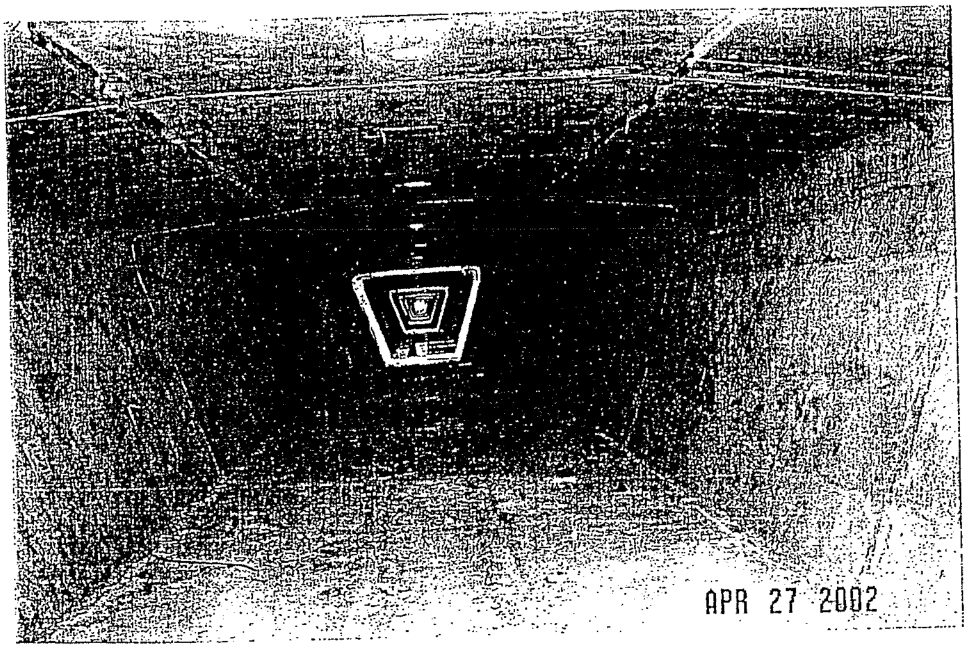


Fig. 2 Box Girder Internal View

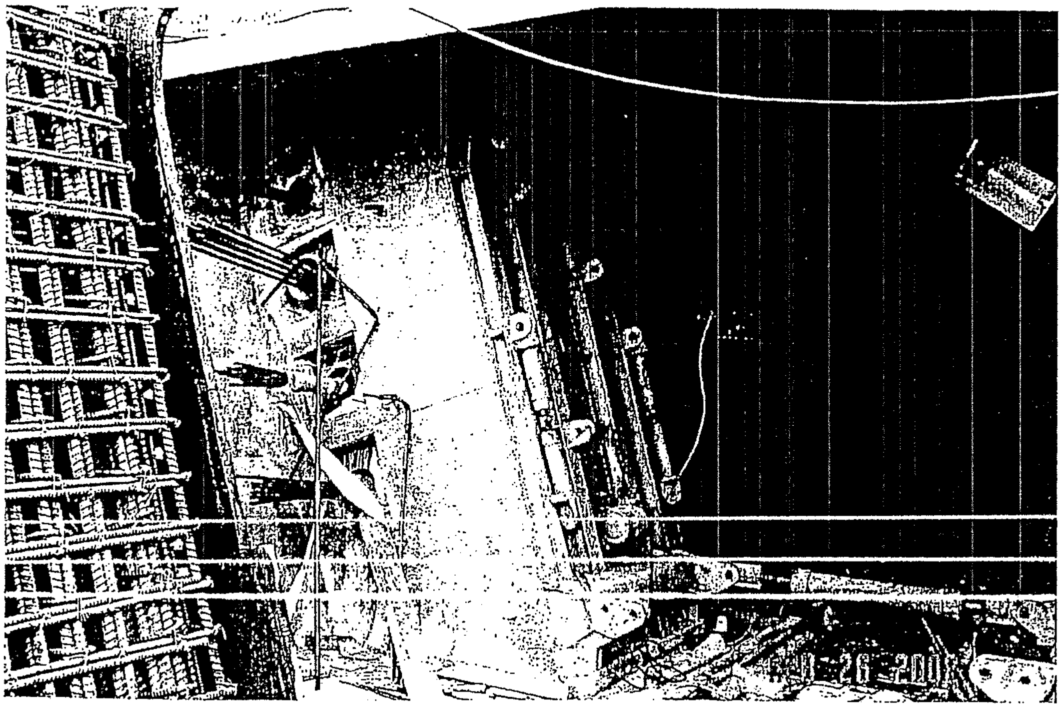


Figure 3 Post-Tensioning Details at Diaphragm

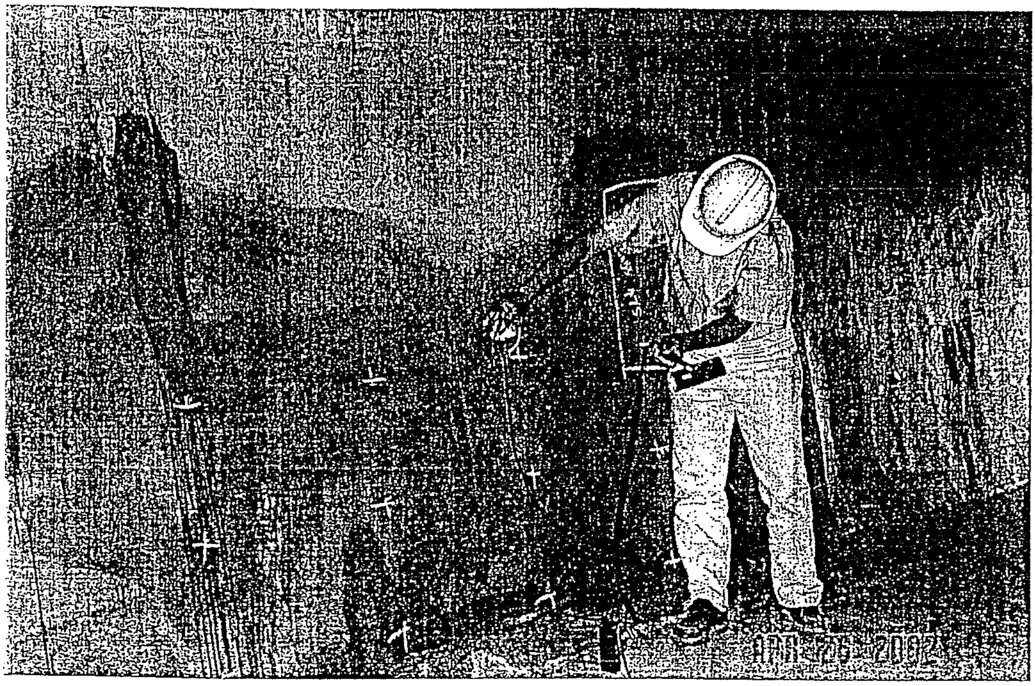


Fig. 4 IR Test on Girder Web

V/F

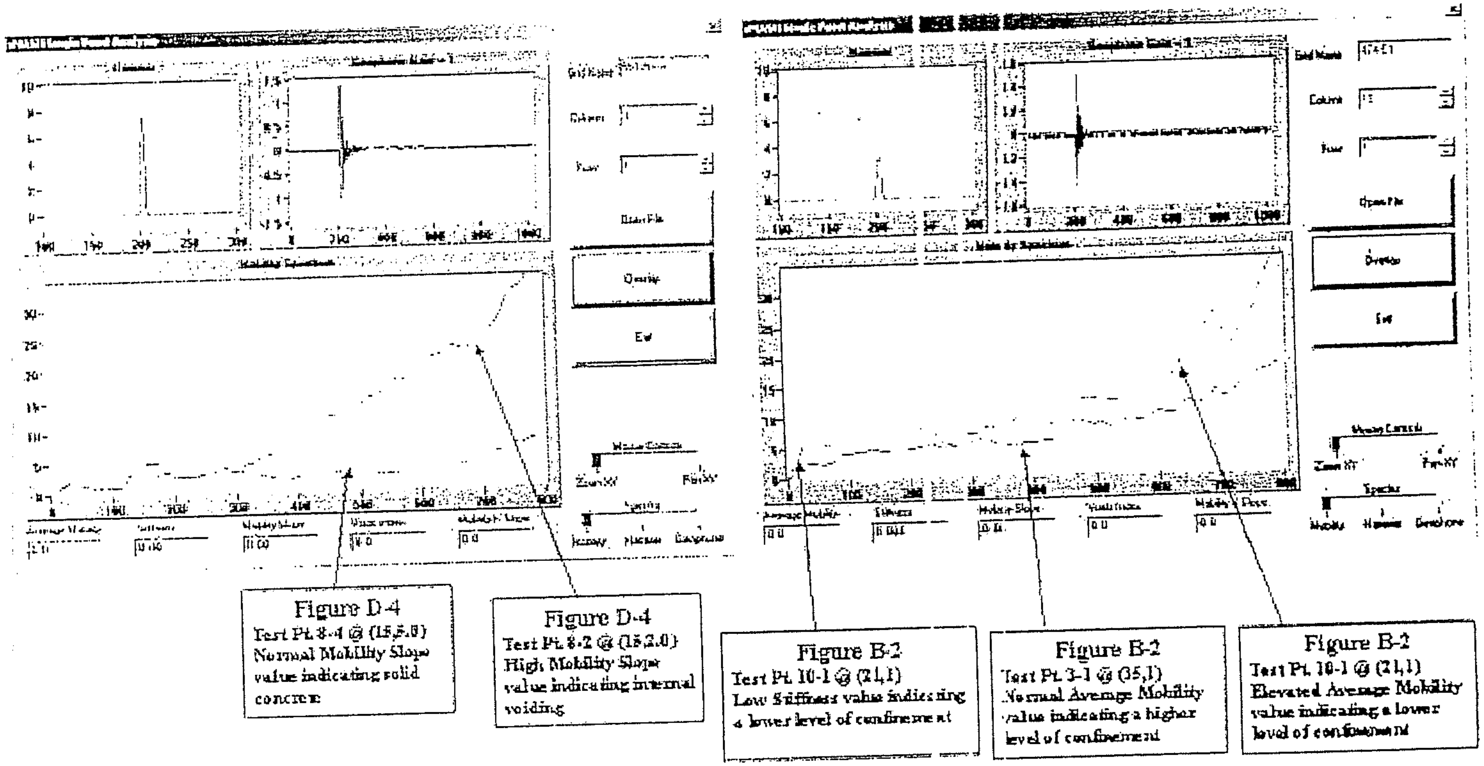


Figure D-4
Test Pt. 8-4 @ (15,5.0)
Normal Mobility Slope value indicating solid concrete

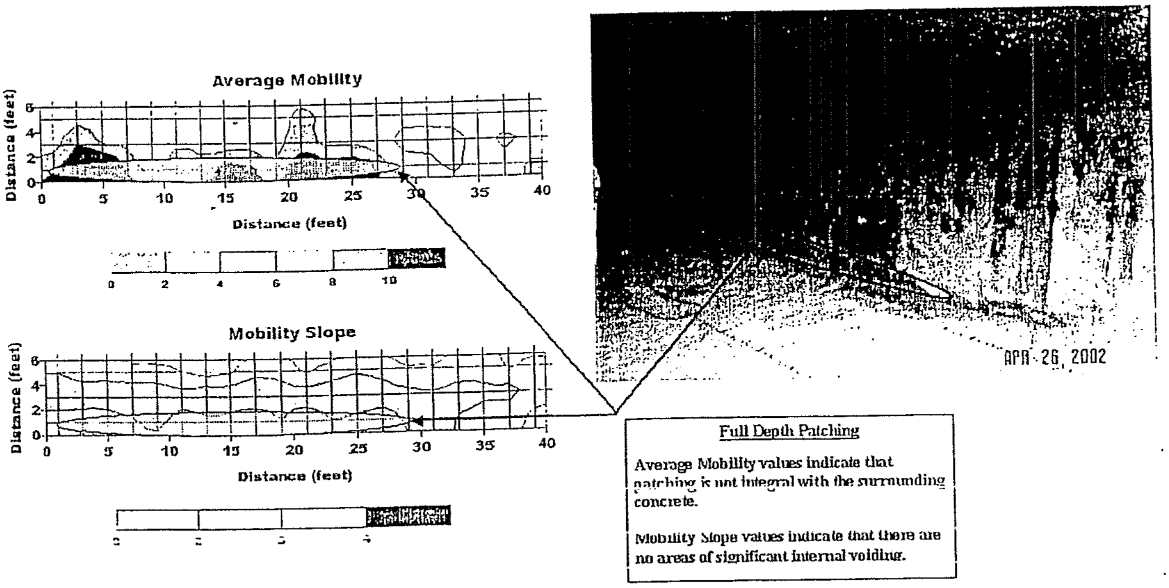
Figure D-4
Test Pt. 8-2 @ (15,2.0)
High Mobility Slope value indicating internal voiding

Figure B-2
Test Pt. 10-1 @ (21,1)
Low Stiffness value indicating a lower level of confinement

Figure B-2
Test Pt. 3-1 @ (35,1)
Normal Average Mobility value indicating a higher level of confinement

Figure B-2
Test Pt. 10-1 @ (21,1)
Elevated Average Mobility value indicating a lower level of confinement

Fig. 5 Examples of IR Test Output

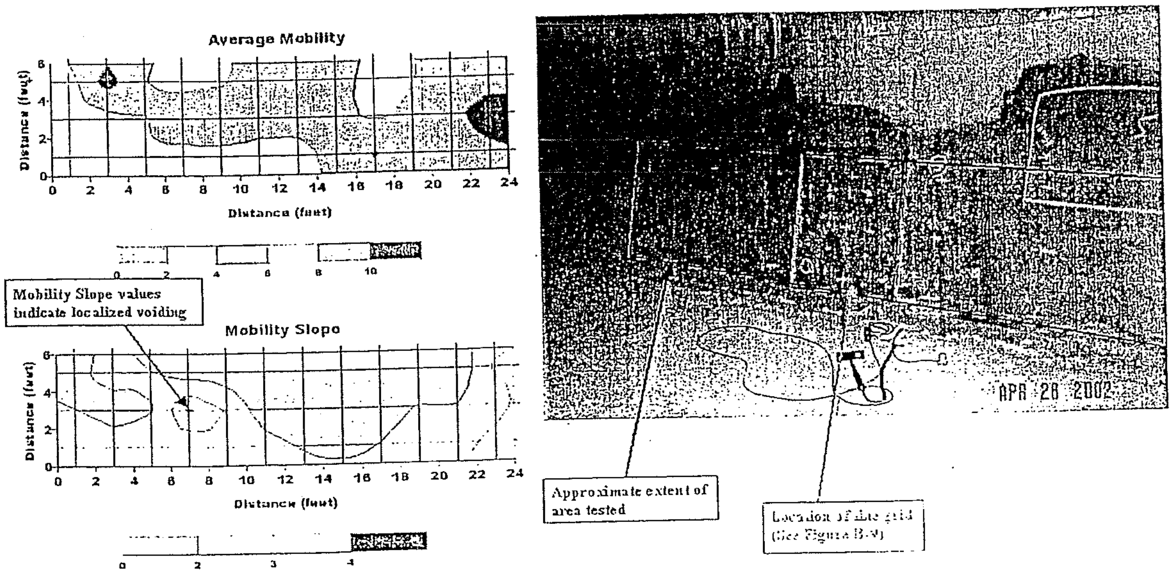


Full Depth Patching

Average Mobility values indicate that patching is not integral with the surrounding concrete.

Mobility Slope values indicate that there are no areas of significant internal voiding.

Fig. 6 Poor Patching Shown by Mobility Contours



Mobility Slope values indicate localized voiding

Approximate extent of area tested

Location of site grid (See Figure B-[illegible])

Fig. 7 Localized Internal Voiding Shown by Mobility Slope Contours