DETECTION OF BRIDGE DECK DETERIORATION

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Delamination is probably the most serious form of deterioration that is commonly found in bridge decks. It ultimately results in large-scale spalling that necessitates costly repairs. This type of failure is believed to be caused chiefly from salt-induced corrosion of the reinforcing steel. An instrument designed to detect delamination and the validation tests are described. The instrument has been used by Texas Highway Department maintenance personnel and has been found to be an effective and practical tool, especially on resurfaced decks. Other bridge deck evaluation techniques that were investigated are delamination detection, corrosion potential, acoustic velocity, Windsor probe, Schmidt rebound hammer, and direct tensile strength. It appears that all of these techniques have considerable merit. It is believed that any of them can be used to search out weak spots or deterioration in bridge decks.

•TWO defects have been considered to be of paramount importance in the evaluation of concrete bridge decks: delamination (a separation of the original slab into two or more approximately horizontal layers) and poor quality concrete.

The present report describes several measurement techniques for evaluating concrete and discusses the interpretation of their results.

DELAMINATION DETECTION

Probably the most serious form of deterioration commonly found in reinforced concrete bridge decks is delamination, which ultimately results in large-scale spalling and costly repairs. This type of deterioration occurs most frequently where salt is used for winter de-icing and is believed to result chiefly from salt-induced corrosion of the reinforcing steel (1-4).

The normal maintenance procedure for repairing delaminated areas in bridges is to remove the material above the plane of delamination and replace it with a relatively fast-setting material (Fig. 1). Epoxy or fast-setting cement mixes are normally used for these repairs to minimize delay to traffic.

Delamination has been detected by maintenance personnel based on their subjective judgment of the sound produced by striking the deck with a hammer or some other object. Wooden blocks, drag chains, steel rods, and specially designed hammers have been used for such detection (Fig. 2). These techniques are very dependent on the operator's ability to judge the distinctive hollow sound produced at the location of a delamination.

An instrument for detecting delamination was developed in this study to replace the techniques that involve subjective judgment (Figs. 3 and 4). The basic design of the instrument and the results of preliminary field evaluations were described in an earlier report (5). The ability of the detector to distinguish delaminated concrete from solid concrete has been verified by using specially constructed test slabs (both delaminated and solid) and by coring 10 different bridges. On each bridge, one core was taken at a location where delamination was not indicated and another at an apparently identical location where delamination was indicated (Fig. 5). Agreement has been perfect. No evidence of delamination or horizontal cracking could be found on examination of the

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Figure 1. Delamination repair.

Figure 2. Locating shallow delaminations in nonresurfaced bridge decks.

Figure 3. Instrument developed to detect delamination on bridge decks.

Figure 4. Typical record produced by delamination detector.

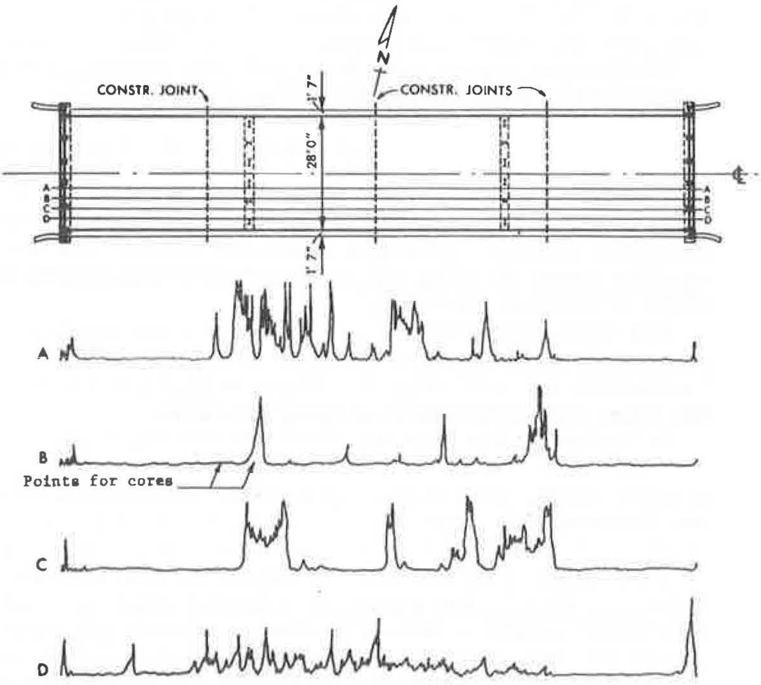


Figure 5. Verification of detector's accuracy.

walls of the core holes at the 10 locations where delamination was not indicated, whereas delamination was visible in each of the other 10 core holes. Six of the ten bridges had asphaltic surfacing layers that varied in thickness from 1/4 to 3½ in. The delaminations found in these six bridges varied in depth from 1 to 4½ in. In one instance the delamination was 3 in. below a 1½-in. asphaltic concrete overlay. In another it was 1 in. below a 3½-in. asphaltic concrete overlay. These findings were felt to be particularly significant because the characteristic hollow sound produced by conventional techniques is greatly diminished by asphaltic surfacing layers. The delaminations found in the four unsurfaced bridges varied in depth from ½ to 2½ in. It is doubtful that conventional sounding techniques could have been used to locate the delaminated areas in most of the 10 bridges cored.

Since the earlier report (5), the instrument has been used by maintenance personnel in several Texas Highway Department districts. Through this use, several design problems in the instrument were found, but they were eliminated by subsequent modifications. The major modifications consisted of the following:

1. Modification of the electrical power pack to permit more than 8 hours of continuous use,
2. Modification of the acoustic receivers to eliminate transducer deterioration, and
3. Development of a calibrator to standardize and equalize the sensitivity of the acoustic receivers.

Probably the most extensive use of the instrument was by maintenance personnel in the El Paso district, who surveyed about 130 bridges. Most of these bridges contained asphaltic concrete or epoxy overlays. El Paso maintenance personnel report that conventional sounding techniques were not effective on most of these decks because of the overlays.

CORROSION POTENTIAL

As mentioned previously, bridge deck delamination is believed to result chiefly from salt-induced corrosion of the reinforcing steel. If this corrosion can be detected before it causes delamination, it may be possible to arrest the corrosion prior to its damaging effects on a deck. Currently, cathodic protection is being investigated as a possible means of arresting corrosion.

The California Division of Highways has reported that electrical potential measurements, indicative of active corrosion of reinforcing steel (2, 6, 7), can be made on the surface of a concrete bridge deck. These measurements are obtained by making an electrical connection to the reinforcing steel and an electrolytic connection between a saturated copper-copper-sulfate half-cell and the upper surface of the deck (Fig. 6). The latter connection is made with a sponge saturated with copper-sulfate solution. The electrical potentials are measured using a high input impedance voltmeter.

Typical results of an electrical potential survey using the California technique are shown in Figure 7. These measurements were made by a Federal Highway Administration demonstration team under the Region 15 Research and Development Demonstration Projects program. In this survey, a core was taken in the area of the highest potential indicated, and rust was found on the reinforcing steel at that location.

Under this Federal Highway Administration program, the demonstration team has made measurements on bridges in 48 states and the District of Columbia. Results to date indicate that the system gives reasonably accurate indications of the degree of corrosion in bridges. Measurements have been confirmed with actual on-site inspections. Because a complete survey required measurements to be made at numerous points on a deck, considerations are being given by the Federal Highway Administration research team to automate the device.

ACOUSTIC VELOCITY

From the literature, acoustic pulse velocity measurements appeared to offer a promising method for determining the quality of concrete in bridge decks (8-15). Thus, as a first step, the relation of acoustic wave velocity to other properties of concrete was explored. Laboratory measurements were made on a wide variety of concrete specimens, and the relations among measurements of acoustic compressional wave velocity, unit weight, elastic modulus, and strength were examined. The results of this investigation, as well as a description of an instrument designed for field measurements, have been reported previously (16).

Two measuring techniques for determining acoustic velocity were investigated in the laboratory. The simplest technique, referred to as "timing through," is based on the time required for an acoustic wave train to travel the distance between a pulsed transducer and a receiving transducer that are coupled to opposite sides of a specimen. The other technique, which is applicable to making measurements on the accessible upper surface of bridge decks, is referred to as the "timing along" technique. This method is based on determining the travel time of the wave train between two points on the same surface as the pulsed transducer. Using either technique, attainment of accuracy requires consideration of the effects of time delay in the transducers and their couplings. Comparison measurements indicated a satisfactory agreement between the two techniques. Upon comparison of the measurements, substantial agreement was found between the dynamic elastic modulus as determined by ASTM C215 and an estimate based on velocity and unit weight. Similar agreement was found for the chord modulus as determined by ASTM C469. The estimating equations found are as follows:

$$\hat{E}_r = \frac{V_c^2 W}{5,670} \tag{1}$$

$$\hat{E}_c = \frac{V_c^2 W}{6,630} \tag{2}$$

where

E_r = estimated dynamic modulus in pounds per square inch,
E_c = estimated chord modulus in pounds per square inch,
V_c = compressional wave velocity in feet per second, and
W = unit weight in pounds per cubic foot.

The coefficients of variation for Eqs. 1 and 2 were found to be 9.5 and 12.0 percent respectively.

No single consistent relation to velocity was found among the compressive strength measurements made on all the cylindrical specimens; however, separate trends were found for velocity to increase with strength within each group of cast cylinders containing a specific type of coarse aggregate. These comparisons of laboratory measurements indicate that velocity measurements used with discretion are generally indicative of the concrete quality.

As mentioned previously, a portable type of field velocity measuring instrument was developed in this study for use on the accessible upper surfaces of bridge decks (Fig. 8). It employs a probe that places an array of four acoustic transducers into contact with the concrete. Velocity is measured, using the "timing along" technique, by observing the time of travel of the acoustic waves between two identical receiving transducers. Waves are produced and propagated successively in opposite directions, and the two time intervals are measured and averaged to cancel coupling delay errors. Other design features include a precise digital timer used in combination with a novel timing method in the oscilloscope display and low power consumption that permits the instrument to be operated from a vehicle battery.

Since the previous report, the field instrument has been used to make measurements on 25 different bridge slabs and 12 specially constructed laboratory slabs. Normally, the average of three velocity measurements was determined for each slab. It was found that, on many of the bridges that have been in service for several years, it is difficult to measure the acoustic velocity because of the attenuation introduced by numerous small surface cracks. Often these surface cracks were visible only after the surface had been moistened. This problem was not encountered on the new slabs.

The compressive strengths of air-dried cores taken from the slabs were found to be slightly correlated with the average acoustic velocities of the slabs. In a linear

Figure 6. Measuring electrical potentials between a copper-copper-sulfate half-cell and the steel reinforcement.

Figure 7. Typical results of an electrical potential survey.

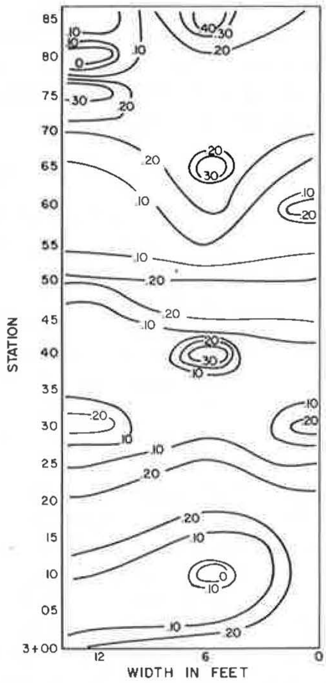


Figure 8. Control unit of the field-type velocity measuring instrument.

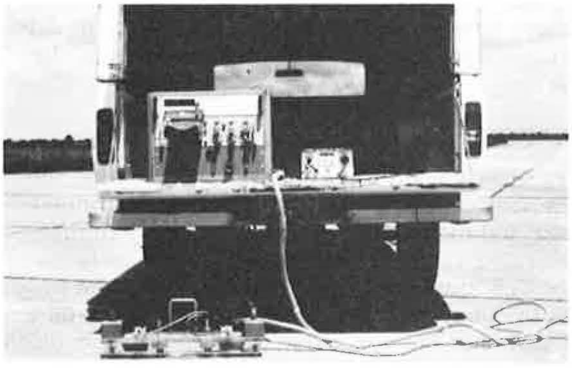


Figure 9. Use of the Windsor probe test system to determine concrete quality.

regression analysis, to estimate slab core strength from its average acoustic velocity, the coefficient of variation was found to be 19.9 percent.

The instrument is believed to be practical for use in research studies when it is desirable to nondestructively estimate the modulus of elasticity (Eqs. 1 and 2). It is not believed to be practical for routine bridge deck measurements because on too many in-service bridges the measurement process is difficult and time-consuming even for a highly trained operator. A single measurement requires about 3 min on a new slab but may require up to 30 min on an older slab that contains surface cracks.

WINDSOR PROBE

The Windsor probe test system has been used in field investigations to estimate the in situ strength of concrete in pavements, bridges, walls, and pipes (17, 18, 19). The device is easy to use and seldom requires surface preparation prior to testing. Basically, the tests consist of shooting a standard probe into the concrete with a standard cartridge. The depth of penetration is determined by measuring the height of the exposed probe. A special gun or driver unit is provided for shooting the probes (Fig. 9). Gauge plates are also provided to measure the average height of the exposed probes in a standard group of three shots. The higher the probes are (i.e., the more resistant they are to penetration) the stronger the concrete is.

Windsor Probe Test Systems, Inc., provided for temporary use at no charge in this study a complete measurement system and a set of minerals for performing scratch tests to determine Mohs' hardness. Probes and cartridges were furnished for a nominal charge. Measurements were made with this instrument on 38 different portland cement concrete slabs that contained many different kinds of aggregates.

From the average of three probe penetration values and the Mohs' hardness of the coarse aggregate, estimates of the compressive strengths were made using tables furnished by the manufacturer. These estimates were generally higher than the measured compressive strengths of air-dried cores taken from the slabs. The measured core strengths were found to be slightly correlated with the probe values. In a linear regression to estimate core strengths directly from probe values without any correction for aggregate hardness, the coefficient of variation was found to be 20.3 percent.

This test system is believed to be practical for bridge deck survey measurements to locate weak spots. The test is slightly destructive. In addition to the small hole made by the probe penetration, a spall about 6 in. in diameter and up to ¾ in. in depth at the center is often produced by the test. A standard group of three probes can be shot and measured in about 5 to 7 min.

SCHMIDT REBOUND HAMMER

The Schmidt rebound hammer is a very widely used instrument for estimating the quality of in situ concrete. Basically, the test consists of striking a rod, in contact with the concrete, with a standard hammer and measuring the height of the hammer rebound. The higher the rebound is, the stiffer (and better quality) the concrete is.

Several authors have suggested that the Schmidt rebound hammer can be used to estimate the compressive strength of in situ concrete (20, 21, 22). They agree that the type of coarse aggregate, surface condition of the concrete, its moisture condition, etc. have a pronounced effect on the relation between rebound reading and strength. Also, there is common agreement that the instrument can be used to determine the uniformity of concrete and thus is an effective tool for locating weak spots.

A Soiltest Model CT200 rebound hammer was used for this study (Fig. 10). Measurements have been made with it on 38 different portland cement concrete slabs that contained many different kinds of aggregate. From the average of 15 rebound readings at each site, estimates of the compressive strength were made using curves furnished by the manufacturer. These estimates were generally much higher than the measured compressive strengths of air-dried cores taken from the slabs. The measured core strengths were found to be slightly correlated with the rebound values. In a linear regression to estimate core strengths from rebound values, the coefficient of variation was found to be 21.2 percent.

Figure 10. Soiltest Model CT200 rebound hammer.

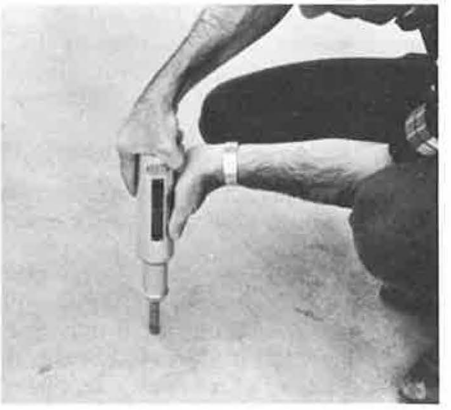
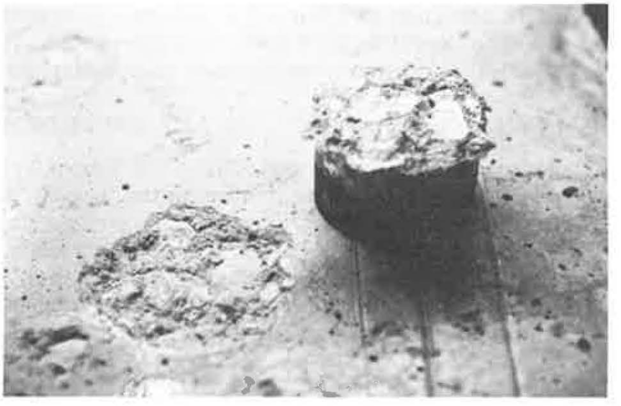


Figure 11. Device used to evaluate the tensile strength of concrete slabs.

Figure 12. Two-in. diameter aluminum cylinders epoxied to a smooth, clean concrete surface.



The rebound hammer is fast and easy to use and is believed to be practical for bridge deck measurements to locate weak spots. Prior to measurements, the surface of the deck should be ground smooth with a hand grinder. The smoothing operation and 15 tests can be made in about 3 to 5 min.

DIRECT TENSILE TEST

An important characteristic of concrete, which is seldom considered in field evaluations, is its tensile strength. This characteristic is highly significant in quality bridge deck construction.

In 1956, the Shell Chemical Corporation introduced a Highway Tensile Tester. This tester was developed for evaluating the quality of resinous cement overlays and to pre-evaluate the surfaces upon which they were to be applied. A device similar to the Shell tester was fabricated in this study (Fig. 11). The chief modification was that a hydraulic cylinder, instead of a screw, was used to apply tension to eliminate the possibility of horizontal forces on the screw handle being converted into unwanted tension.

Another tensile tester, quite similar to the Shell device, is described in Test Method California 420-A. The procedure used to measure tensile strength in this study is the same as that described in Part II of the California test method, Evaluation of Soundness of Portland Cement Concrete Surfaces.

Using this device, direct tensile strengths were measured on 30 different portland cement concrete slabs (Fig. 12). Normally, the average of three tensile tests was determined for each slab. These tensile strength measurements were found to be slightly better correlated with the compressive strengths of air-dried core samples taken from the same slabs than any of the other measurement techniques investigated. In a linear regression analysis to estimate core strengths from the average tensile strengths, the coefficient of variation was found to be 17.7 percent.

The test is somewhat time-consuming because it requires a period of about 1½ hours for the epoxy to harden prior to testing. On a warm day about 40 tests could be made in an 8-hour day. Values obtained using this test would probably be more indicative of the general quality of the concrete slabs than any of the other tests investigated, and the test is believed to be practical for bridge deck measurements.

CONCLUSIONS

The study substantiates the following conclusions:

1. The technique utilizing the delamination detector developed in this study has been found to be practical and effective for determining the extent of delamination in bridge decks;
2. It appears that all of the six measurement techniques investigated have merit and can be used to locate weak spots or deterioration in bridge decks, although each technique is designed to measure a different characteristic property; and
3. The direct tensile test, velocity meter, Windsor probe, and the rebound hammer can each be used to estimate core compressive strength within about 20 percent.

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