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Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion

Volume 1: State of the Art of Existing Methods

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Abstract

This volume reviews and summarizes the existing methods and equipment for evaluating the condition of concrete bridge components. The purpose is to identify viable techniques that can be combined with the new techniques described in Volumes 2 through 7 of this report in order to provide the "toolbox" for an integrated approach to the condition assessment of concrete bridges (Volume 8 of this report).

This volume discusses methods for detection of damage resulting from corrosion of steel in concrete, poor quality or deteriorated concrete, and damage to prestressed/posttensioned tendons embedded in concrete. The discussion covers only the methods or procedures that are currently used for field evaluations. The discussion of each method includes any experiences with the method/procedure as reported in available literature sources and in interviews with state and provincial department of transportation inspection and maintenance personnel. An appendix summarizes comments from these engineers.

Executive Summary

This volume reviews and summarizes the existing methods and equipment for evaluating the condition of concrete bridge components. The purpose is to identify viable techniques that can be combined with the new techniques described in Volumes 2 through 7 of this report in order to provide the "toolbox" for an integrated approach to the condition assessment of concrete bridges (Volume 8 of this report).

This volume discusses methods for detection of damage resulting from corrosion of steel in concrete, poor quality or deteriorated concrete, and damage to prestressed/posttensioned tendons embedded in concrete. The discussion covers only the methods or procedures that are currently used for field evaluations. The discussion of each method includes any experiences with the method/procedure as reported in available literature sources and in interviews with state and provincial department of transportation inspection and maintenance personnel. An appendix summarizes comments from these engineers.

The selection of techniques and procedures is based on several criteria. The most important is the ability of the method to carry out the required function at an acceptable performance level. Simplicity of operation is another important criterion. The method or procedure must be field-ready, rugged, and possess a high degree of reliability.

The recommendations are:

- Delamination Detection: Sounding of concrete surfaces is recommended. Methods using stress waves may be economical if used concurrently to detect other types of damage or deterioration.

- Corrosion Detection: Half-cell potential measurement is recommended.

- Structural Damage: Stress wave (impact-echo and pulse velocity) methods are recommended.

- Reinforcing Cover and Location: Magnetic flux methods are recommended.
- Deteriorated Concrete and Voids: Stress wave methods are recommended.
- Moisture Content: Neutron methods are recommended.
- Strength Assessment: Rebound Hammer or penetration methods, backed up by compressive strength of drilled cores, are recommended.
- Prestressed and Posttensioned Structures: At this time, only visual methods can be recommended; no quantitative methods are field-ready.
- Petrography: This is recommended only when conditions related to concrete quality are involved and data cannot be obtained by any other method.

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Introduction

Needs

The nation's concrete highway bridges are deteriorating at an alarming rate. It has been estimated that the cost of this damage stands at over $20 billion, and that it is increasing at the rate of $500 million per year (*1*). The primary cause for the deterioration of reinforced concrete bridge components is corrosion of reinforcing steel due to the presence of soluble chlorides from deicing chemicals or marine exposure.

It is generally agreed that life-cycle cost analyses of viable alternatives are necessary in order to develop rational strategies for the repair, rehabilitation, and replacement of concrete bridge components. This, in turn, necessitates the acquisition of reliable information on the level and rate of deterioration.

Volumes 2 through 7 of this report cover the development of techniques for assessing the condition of concrete bridge components where no suitable methods presently exist. This volume (Volume 1) reviews current practice and identifies procedures that should be employed with the new techniques in an integrated bridge condition assessment program.

Objective

The objective of the state-of-the-art study reported in this volume is to provide a critical evaluation of existing methods for assessing the condition of concrete bridge components and to provide an evaluation of applicable procedures developed outside this program. These methods will be combined with the techniques developed in Volumes 2 through 7 of this report in an integrated, comprehensive system for the evaluation of concrete bridge components in Volume 8.

Scope

This report focuses on methods able to detect damage resulting from corrosion of steel in concrete, poor quality or deteriorated concrete, and damage to prestressed/posttensioned tendons embedded in concrete. Corrosion damage assessment includes corrosion potential measurement, delamination detection, rebar cover measurement, and detection of corrosion products. Poor quality concrete can be determined by strength tests, moisture content, porosity, resistivity, and petrographic methods. Methods used to determine the extent of damage to tendons in prestressed/posttensioned members due to corrosion or wire breakage are discussed.

The discussion of techniques is limited only to techniques that are currently being used for field evaluation of the condition of bridge components. Descriptions of the methods or procedures and their reliability and ease of use are included. The discussion of each method also includes any experiences with the method/procedure as reported in available literature sources and experiences reported during interviews with state and provincial department of transportation inspection and maintenance personnel.

In many cases, information is also included on any "demonstration" or experimental methods that have been developed and introduced recently. While actual field experiences with these methods/procedures are limited, they are included in areas where it is anticipated that they may have a significant impact in the near future.

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Methodology

The information reported was gathered from two sources, a literature review and interviews with maintenance and inspection personnel at state and provincial departments of transportation.

Literature Review

Both computerized and manual literature searches were performed to identify methods/procedures for assessing damage to concrete bridges.

The computerized search was performed using DIALOG Information Services. The DIALOG system allowed access to numerous data bases, including:

- TRIS (Transportation Research Information Service)
- NTIS (National Technical Information Service)
- Engineering Index Monthly
- PASCAL--a European-based engineering/technology data base
- Current Technology Index

These data bases were searched for methods and procedures used to detect deterioration in concrete structures. To maximize success in locating sources, a very general search was performed, which was manually edited to provide only methods being used in the field. The pertinent sources were then obtained and reviewed, and any applicable references were then acquired. This process continued until all references were exhausted.

Interviews

In order to acquire a list of field-tried methods used for determining deterioration, it was decided that all state and provincial departments of transportation would be canvassed regarding procedures used for assessing the extent of deterioration.

The usual method for obtaining information of this type is to send out a questionnaire. In order to acquire detailed information about effectiveness and accuracy as well as manpower requirements and applicability, it is necessary to ask very specific questions about each method. Also, a questionnaire must be in a form that will facilitate its completion. These factors would have necessitated the use of a long and time-consuming written survey form, to which the response rate could be expected to be low.

It was decided to try to obviate these problems by means of telephone interviews with the appropriate people at the departments of transportation. It was believed that this method would provide a better response rate in much less time than a mailed questionnaire. During the interview, it was possible to determine the methods used by a particular department of transportation and ask specific questions only about those methods. This allowed in-depth responses while minimizing misinterpretation of information.

The first point of contact was the SHRP state and provincial coordinators. The project was summarized and the specific intentions of this task were discussed. The coordinators were then asked to recommend someone in the maintenance and materials testing divisions capable of discussing methods and procedures employed for detecting deterioration.

The next phase entailed contacting the recommended individuals and verifying their ability to provide the necessary information. It was intended that the interviews would last approximately 15 to 20 minutes. If the person did not have time for the interview immediately, a convenient time was scheduled, and a list of topics (Table 2-1) was mailed or faxed to allow preparation for the interview.

Table 2-1. Evaluation procedures for detecting deterioration.

Method	Type of Deterioration
Visual	Cracking, staining, spalling, efflorescence, wet areas, scaling
Rebound/penetration methods	Areas of poor consolidation/strength
Sounding methods	Delamination detection
Hammers	
Chain drag	
Delamatect®	
Ultrasonic	Overall material quality
Pulse velocity	Crack detection
Pulse echo	
Impact echo	
Electrical tests	Concrete and membranes
Resistance measurements	Presence of corrosion
Potential measurements	
Electrochemical	
AC impedance	
Polarization resistance	
Rate of corrosion	
Magnetic methods	Cover depth
Pachometer	
Electromagnetic	
Profilometer	
Magnetic scanning (prestressed)	
Chemical	Chloride ion
Petrographic examination of cores	Carbonation
	Aggregate characteristics (F.T. durability, etc.)
	Cement paste characteristics (F.T. durability, etc.)
	Strength
	Air void analysis
Radiography (SCORPION)	Deterioration or voids within concrete
Thermography (Infrared)	Delamination detection
Radar	Delamination detection and deterioration or voids
Permeability	Concrete quality
Prestressed/Posttensioned	Strand condition

The response rate was very high. Of the 49 states contacted (Hawaii and Puerto Rico were not contacted), 47 interviews were completed. In Canada, only 9 of the 12 provinces were contacted (the Yukon and Northwest Territories, Newfoundland, and Labrador were not contacted), and interviews were completed with 8 of these.

The information gained in these interviews was invaluable in collecting the opinions of practicing field engineers regarding the technical feasibilities of various methods and procedures. The results are summarized in Table 2-2, and the comments are listed in the appendix. The literature searches revealed that there were many potential methods available, but the majority consisted of reports of laboratory results or limited field usage. The interviews permitted inclusion of expert opinion that otherwise would not have been available.

Table 2-2. Summary of questionnaire results.*

	In Situ													Cores					
State, district, province, or territory	visual	chain drag	hammer	delamatect	chloride ion	cover	potential	ultrasonic	impact echo	resistance	I.R.T.	radar	x-ray	visual insp.	strength	Cl content	F-T tests	air voids	permeability
Alabama	R	R	R	N	O	O	N	N	N	N	D	N	D	N	N	N	N	N	N
Alaska	R	R	R	N	R	O	N	N	N	N	D	D	N	N	S	S	N	N	N
Arizona	R	R	-	D	S	R	O	N	N	N	N	N	N	R	R	N	N	N	S
Arkansas	R	R	R	N	N	-	S	N	R	N	N	N	N	N	S	S	O	N	N
California	R	R	R	R	N	-	R	D	N	N	D	N	N	N	S	R	O	N	N
Colorado	R	R	R	N	O	-	N	N	N	N	N	N	N	N	N	N	N	N	-
Connecticut	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Delaware	R	R	-	N	R	-	N	N	N	N	S	S	N	N	N	-	N	N	-
Florida	R	-	R	N	S	-	S	N	N	N	N	S	N	N	N	-	N	N	R
Georgia	R	R	R	N	R	N	N	N	N	N	N	N	N	R	S	R	N	N	-
Idaho	R	R	R	N	N	-	O	N	N	N	D	D	N	R	N	N	O	N	-
Illinois	R	R	R	R	S	-	S	D	N	N	O	D	S	N	S	-	N	N	-
Indiana	R	R	-	N	N	-	O	N	N	N	D	N	N	R	S	R	N	N	-
Iowa	R	R	R	R	S	-	N	N	N	N	O	N	N	N	N	-	N	N	-
Kansas	R	R	R	S	R	R	R	N	N	N	N	N	N	N	N	S	N	N	-
Kentucky	R	O	O	N	R	R	S	N	S	N	N	S	S	N	S	S	S	O	N
Louisiana	R	-	-	-	N	R	N	N	N	N	N	N	N	N	O	O	N	N	N

R = routinely; O = only if requested or problems; N = do not use or test for;
S = some use or experience; D = demo; - = no comment on test.

Table 2-2. *(continued)*

State, district, province, or territory	In Situ: visual	chain drag	hammer	delamatect	chloride ion	cover	potential	ultrasonic	impact echo	resistance	I.R.T.	radar	x-ray	Cores: visual insp.	strength	Cl content	F-T tests	air voids	permeability
Maine	R	R	R	N	N	-	S	N	N	N	S	N	N	N	O	O	S	N	-
Maryland	R	R	R	N	R	-	O	N	S	N	N	N	N	R	R	N	N	N	N
Massachusetts	R	-	-	N	S	-	R	D	S	N	N	S	N	N	R	N	O	N	N
Michigan	R	R	R	N	S	R	N	N	N	N	S	S	N	R	R	-	N	N	N
Minnesota	R	R	-	N	-	-	S	N	N	N	N	S	N	N	R	-	N	N	N
Mississippi	R	-	-	N	N	N	N	N	N	N	N	D	N	N	N	-	N	N	-
Missouri	R	-	-	N	R	-	R	N	N	N	D	N	N	N	N	N	N	N	N
Montana	R	R	-	N	R	-	R	N	N	N	N	N	N	N	N	N	N	N	N
Nebraska	R	R	-	N	R	R	R	N	S	N	N	N	N	N	R	R	N	N	N
Nevada	R	R	R	N	-	N	N	N	N	N	D	N	N	R	R	R	O	N	N
New Hampshire	R	-	R	D	R	R	N	N	N	N	D	S	N	R	N	R	N	N	N
New Jersey	R	R	-	N	N	R	R	R	N	S	D	D	N	N	R	R	N	O	N
New Mexico	R	R	R	N	O	O	O	O	N	N	N	N	N	N	N	R	N	N	N
New York	R	R	R	N	R	-	R	N	N	N	R	S	N	N	0	R	R	N	S
North Carolina	R	R	R	D	R	-	R	D	N	N	N	D	N	N	R	N	N	N	N
North Dakota	R	R	R	N	R	-	R	N	N	R	R	N	N	N	O	-	O	O	N
Ohio	R	R	R	N	S	-	S	N	N	N	S	S	N	R	N	-	N	N	S

R = routinely; O = only if requested or problems; N = do not use or test for;
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Table 2-2. (*continued*)

State, district, province, or territory	In Situ													Cores					
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Oregon	R	-	-	N	R	R	N	N	N	N	N	N	N	N	R	R	N	N	N
Pennsylvania	R	0	-	S	R	-	N	S	N	N	R	S	N	N	N	N	N	N	-
Rhode Island	R	R	R	D	R	-	N	N	N	N	D	D	N	R	N	N	N	N	-
South Carolina	R	R	R	N	N	-	D	S	N	N	N	N	N	N	S	R	N	N	-
South Dakota	R	-	-	N	O	R	R	N	N	N	N	N	S	N	O	R	N	N	S
Tennessee	R	R	-	N	-	-	R	N	N	N	N	S	N	R	N	O	S	N	N
Texas	R	R	R	N	S	O	N	N	N	N	N	N	N	N	R	R	N	N	O
Utah	R	R	R	N	-	-	S	N	N	N	D	N	N	R	R	N	N	N	N
Vermont	R	-	-	N	S	-	R	N	N	S	D	D	N	N	N	-	N	N	N
Virginia	R	R	R	N	R	-	R	D	N	N	S	N	N	N	N	S	N	N	-
Washington	R	R	R	D	R	R	R	N	S	N	D	N	N	R	N	R	R	R	O
West Virginia	R	-	-	N	N	-	O	N	S	N	N	N	N	R	R	O	N	N	-
Wisconsin	R	R	R	N	O	O	N	N	N	N	S	S	N	R	S	R	N	N	N
Wyoming	R	R	R	N	N	R	R	S	N	N	D	N	N	N	R	R	N	O	-
District of Columbia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ontario	R	R	-	N	N	R	R	N	S	S	S	S	N	N	O	R	N	O	S
Alberta	R	-	-	N	S	R	N	S	N	N	S	S	N	N	S	-	N	N	S

R = routinely; O = only if requested or problems; N = do not use or test for;
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British Columbia	R	R	-	N	S	N	S	N	N	N	N	N	N	R	R	-	N	N	N
Manitoba	R	R	R	S	N	-	S	N	N	N	D	N	N	O	O	N	N	N	N
New Brunswick	R	R	R	S	R	R	S	N	N	N	N	N	N	N	R	N	N	N	O
Nova Scotia	R	-	-	S	N	N	O	N	N	N	D	N	N	N	O	S	N	N	N
Saskatchewan	R	R	-	S	N	S	R	N	N	N	N	N	N	R	O	N	-	N	N

R = routinely; O = only if requested or problems; N = do not use or test for;
S = some use or experience; D = demo; - = no comment on test.
*Hawaii and Puerto Rico departments of transportation were not contacted for this survey.

3

Findings

In the following sections, methods and procedures that have been found to be useful in detecting deterioration in reinforced and prestressed/post-tensioned structures are described. Each section includes a discussion of a particular type of damage and identified methods that have been used successfully to determine the extent of this damage. As stated previously, only methods that have been used successfully or show promise of successful use in the field are discussed. Techniques that will be included in research described in Volumes 2 through 7 of this report are not discussed here.

For each method, the discussion includes a description of the procedure/method, comments from the literature review, and interviews about the methods, reliability, ease of use, and so on.

Delaminations

The expansive reaction products from the corrosion of steel in concrete may cause sufficiently high stresses to result in the tensile failure of concrete. Depending on the ratio of cover to bar spacing, the resulting fracture planes will either form V-shaped trenches or cause a delamination parallel to the surface of the concrete member.

With time, the size of the delamination will continue to grow. Freeze-thaw cycles and the impact of traffic also add to delamination growth. If delaminations are detected early, they can be repaired before severe damage occurs. Two avenues of approach are available for delamination detection at present--those involving the propagation, reflection, or interference of either mechanical energy (stress waves) or electromagnetic energy (e.g., radar or infrared thermography).

Stress Waves

When a disturbance is caused on the surface of an elastic mass, body waves and surface waves result. Body waves propagate radially outward from the source throughout the mass along a hemispherical wavefront, and surface waves propagate radially outward along the surface (*2,3*). The two types of body waves are primary, P-, or compression waves, and secondary, S-, or shear waves. There are also two types of surface waves, Love and Rayleigh waves. Love waves are generated only in multilayered systems in which a softer material overlays a stiffer layer. Love waves may have some applications in the evaluation of asphalt-covered decks, but very little work has been done in this area.

The velocity of travel of the compression, shear, and Rayleigh waves through a material is a function of its modulus of elasticity. Note that the velocity of propagation of the wave is not necessarily the same as the particle velocity. The wave propagation velocity is only a function of material property, but the particle velocity is also a function of the induced stress.

The frequency at which these waves are generated can be varied. In some cases, the frequency is in the audible range and the results can be heard. This is the case for sounding methods. In other cases, the waves propagate at a frequency above the audible range and are called ultrasonic. The source of the disturbance can be either mechanical, such as a hammer, or electronic.

Delaminations have only been effectively detected with compression and Rayleigh stress waves. Methods such as soundings, Delamatect®, impact echo, and pulse echo make use of compression wave theory and have reportedly been used in the United States since the mid-1940s. On the other hand, methods employing the use of a spectral analysis of surface waves (SASW) were first introduced in the early 1980s.

These methods are based on the change in resistance to stress waves at boundaries of different layers. For example, at a delamination, the stress wave may be reflected, refracted, or deflected from its path of travel. This changes the energy of the wave, which is picked up at a receiver and displayed.

Sounding

The most commonly used method for determining the existence and extent of delaminations is sounding (*4-9*). Depending on the orientation and accessibility of the concrete surface, sounding can be performed using a steel hammer, rod, or chain. The concrete is struck with a hammer or rod, or a chain is dragged across the surface. Good quality concrete with no delaminations produces a sharp, ringing sound; delaminated areas emit a dull, hollow sound.

An experienced technician can determine the extent of the delaminated area accurately and quickly by sounding. The areas can then be marked directly on the surface, facilitating repair, or they can be mapped and recorded for future comparison.

Because sounding is a manual method, several factors can affect the accuracy of the investigation. Exposure to constant sounding may lead to temporary or permanent operator desensitization to high-pitched tones (*8*). Operator fatigue can also be a problem (*6*). Comments from interviews indicate that due to the large areas that must be sounded on bridge components, fatigue and desensitization play a critical role in accurately establishing edges of delaminations.

The problems encountered with the high-pitched ringing associated with striking good quality concrete can be eliminated by using a nonresonating steel mass. Engineers at the Texas Department of Transportation found that when a steel mass attached to a rope or steel chain is dragged across a deck, very little sound is produced on good quality concrete, but a distinctive dull sound is heard over poor quality or delaminated concrete (*10*).

The overwhelming consensus of maintenance and materials engineers was that, of all methods used to detect delaminations, soundings provided the best results in terms of accuracy, speed, ease of operation, and repeatability.

ASTM Standard Practice D 4580-86 (*11*) provides an industry standard method for measuring delaminations by sounding. That specification specifically relates to bridge decks, but the procedures and equipment can also be used on other concrete surfaces. The method should not be used on decks overlayed with asphalt, but may be used to detect debonding and delaminations when portland cement concrete mixtures are used as overlays.

Delamatect®

In 1973, the Texas Transportation Institute reported the development of an automated delamination detection device called Delamatect® (*10,12*). This machine is designed to remove all operator judgement from the detection process. This is accomplished by recording the acoustic response of the bridge deck to an automated tapper. A strip chart recorder logs the signal from the two 3-in. (7.6-cm) wide parallel paths that are 6 in. (15.2 cm) apart. The strip chart recorder paper is driven by the Delamatect®'s wheels, allowing accurate mapping of the delaminated areas. The record produced by the Delamatect® dramatically indicates the existence of a delaminated area. The record is flat and very close to zero for good concrete but becomes irregular when indicating a delamination.

The first round of field testing of the Delamatect® was performed on 10 bridge decks with the machine perfectly predicting delaminated areas on asphalt-covered and unsurfaced bridge decks (*10*). Later field tests by the Texas Department of Transportation on more than 130 bridges were successful in detecting delaminations up to 4 1/2 in. (11.5 cm) below the surface of the deck (*12*). These tests were performed on asphalt-covered and epoxy-overlayed bridge decks in which delaminations are difficult to detect with conventional sounding techniques.

Further independent testing performed by the Ministry of Transportation and Communication of Ontario, Canada, indicated that the Delamatect® was considerably less accurate than manual methods (*13*). This test indicated that the automated machine recognized only 67 percent of the delaminations that were found using manual sounding techniques. Also, a Delamatect® survey of an asphalt-covered deck indicated extensive delaminations, but when the asphalt was stripped, the deck showed no delaminations. In this case, the false signal was attributed to the poor bond between the asphalt and deck.

Maintenance engineers who had experience with the Delamatect® and who were interviewed reported similar experiences to those in Ontario. These engineers claimed that the false-negative indication rate was too high to be used for contract quantity calculation, and they suggested that it be used for preliminary surveys. To the credit of the Delamatect®, though, all engineers surveyed said that there were no false-positive occurrences with the machine when using it on non-asphalt-covered decks.

Maintenance engineers also shared the opinion that there was an increase in the amount of work required to map the delaminations using the Delamatect®. The output from the strip chart recorder had to be plotted for each pass of the Delamatect®. With interpass distances of 3 ft (0.9 m), a large amount of data must be reduced to determine delaminated areas.

With manual sounding methods, the delaminated area is usually marked on the deck and then transferred onto a plan.

Echo Methods

The echo methods of detecting compression wave travel in concrete are basically the same. The only differences between these methods are the frequency of the wave (either sonic or ultrasonic) and the method of creating the wave (either mechanical or electromechanical). In any instance, two transducers are used, one to transmit the signal and the other to receive responses. Both transducers are placed on the same surface and the signal is sent (Figure 3-1). If the velocity of the pulse is known, the distance to a defect or the thickness of the member can be found.

In practice, however, the results of the impact echo testing are not as clear as those in Figure 3-1. Because concrete is not a homogeneous material, there is a considerable amount of noise in the return signal, and it is necessary to condition this signal to provide usable information. The frequency of P-wave arrival at the receiver is shifted by the use of a Fast Fourier Transform (FFT) from a time-displacement waveform into the frequency domain (*14*). The peaks in the amplitude frequency domain spectrum can be used to determine the depth of the reflecting surface.

The impact/pulse echo area has been the subject of quite extensive research in the last several years (*14-24*). The referenced research projects represent a concerted effort to investigate methods to improve the accuracy and precision of the echo methods.

Echo methods have been used successfully in field applications, and the results have agreed well with destructive methods, such as coring (*21*). In still other tests, it was claimed that the methods accurately detailed the location and depth of delaminated slabs with and without asphalt overlays (*14*).

The claims that the echo methods have successfully detected delaminations in concrete decks have been substantiated in field testing (*14-25*). However, there have been conflicting reports on the accuracy of these methods for asphalt-covered decks (*14,25*). The controversy surrounds the area of the energy required to detect all potential defects in the slab. As the

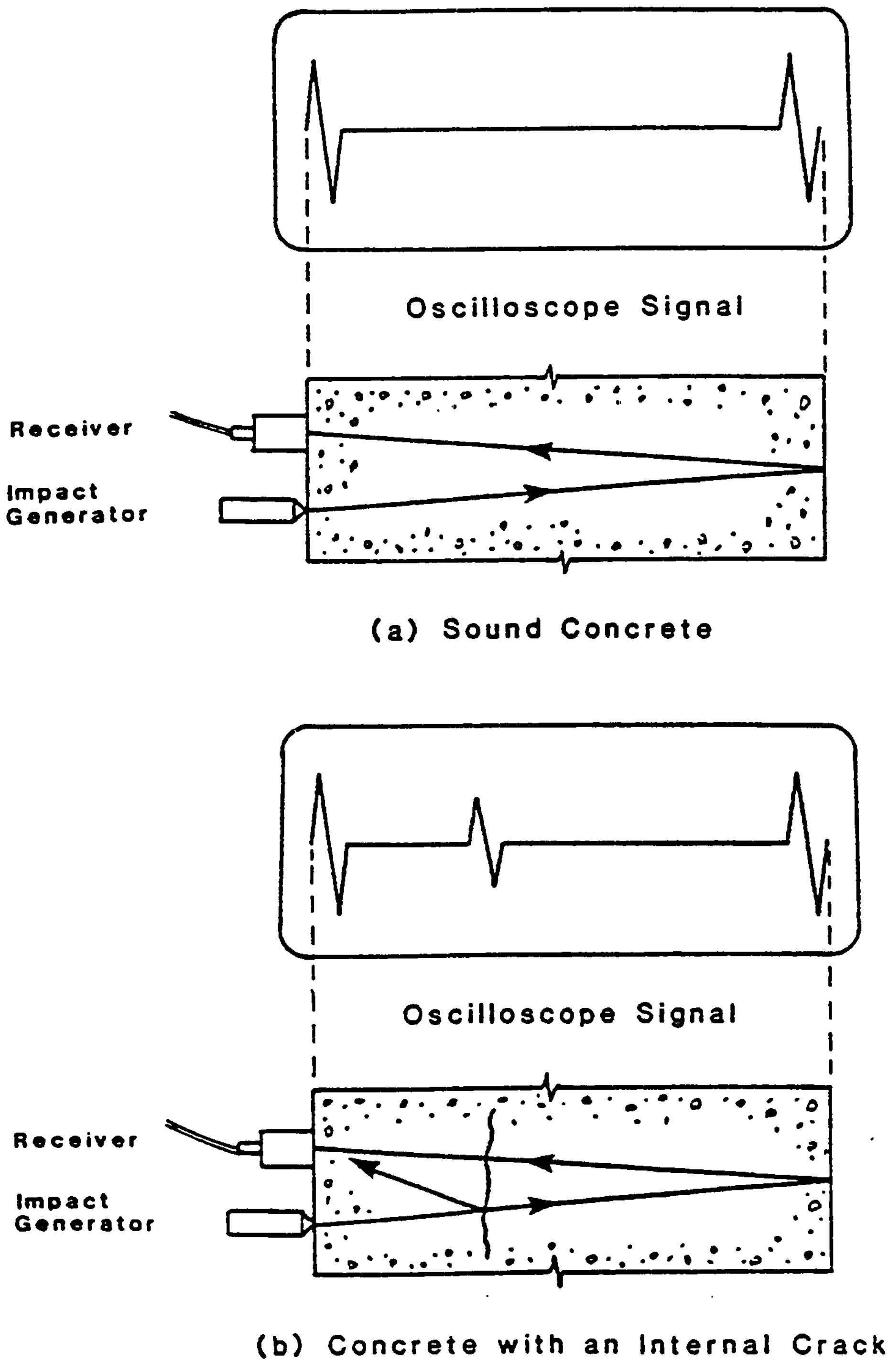


Figure 3-1. Examples of pulse-echo reflections (*5*).

stress wave passes through a defect or layer boundary, some energy is reflected and some passes through. This process occurs every time the stress wave encounters a defect. The more defects or layers in the deck, the more degraded the signal becomes and the more difficult it is to make predictions on the depth of defects. Development of methods to produce sufficient energy to enable detection of several stacked defects or boundaries is ongoing, but not yet field-ready.

Even though the results are quite promising, echo methods are still very labor-intensive. In one test run, Sansalone and Carino initially performed tests at a distance interval equal to the depth of the slab (*14*). Once the approximate locations were found, a closer spacing was used. Recent progress by Sansalone and others at Cornell University in developing an automated data acquisition system may make the impact-echo method more feasible in the near future (*26-28*).

Pulse velocity of compressional waves in concrete can be used to locate and estimate the depth of delaminations and cracks in concrete. A method for doing this has been standardized as ASTM Standard Test Method C597-83 (*29*).

According to the interviews, impact echo methods have seen very little use. Any materials or maintenance engineer with opinions on impact echo based them on limited experimental or demonstration exposure. The one drawback expressed in the interviews was the need for a method that gives precise location and depths of deck delaminations. Any delaminations in decks that have not been overlayed will generally occur at the level of the top reinforcing, so the maintenance engineers question the need of providing such detailed information on bridge decks. However, such information is quite useful for determining whether the delamination is at the level of the reinforcing or at the asphalt-concrete interface for overlayed decks. All engineers also agreed that for components other than decks, for example, substructure elements, the ability to locate size and depth of delaminations or voids is very important.

Surface Waves

As stated previously, three types of stress waves are produced when a disturbance is caused on a surface. Previous methods have documented the success of using the P-waves to detect delaminations, but recent research has indicated that Rayleigh waves can also yield valuable information about slab delaminations (*30-35*).

In previous geotechnical and pavement applications, the SASW method has been used to determine the stiffness profile. These investigations have been performed using sonic waves.

Nazarian (*32*) and Bay and Stokoe (*33*) propose the use of ultrasonic SASW tests to locate voids and delaminations in concrete. The R-wave only effectively penetrates the concrete to a certain depth since it is a surface wave. The depth of penetration is a function of the frequency of the wave. When a series of different frequency waves is produced, there will be a distinct change in the behavior of the wave representing the depth of the defect.

To date, there has been limited testing on the SASW method for detecting delaminations. Bay and Stokoe (*33*) have limited their research to laboratory experiments, while Nazarian (*32*) reports some field experience. Both reports offer encouraging results, but more time is needed before complete success can be claimed.

One benefit of the SASW method is that, if there are a sufficient number of receivers on a structure and if it is possible to log a sufficient amount of data, only one setup is necessary on a structure (*36*). This allows for a savings of manpower and reduces the tedious nature of repeating a test several times on a structure.

Other Methods

Other methods have been used to determine the extent of delaminations in concrete slabs. Infrared thermography (IRT) and radar have both been shown to produce information on the size and location of delaminations. The use of pulsed radar for the evaluation of bridge decks overlaid with asphalt concrete is the subject of one of the technical areas of research in this project. It is covered in detail in Volume 3 of this report.

IRT involves the analysis of variations in heat conduction, due to subsurface discontinuities, as reflected in surface temperature patterns. The detection of small surface temperature variations is accomplished by means of infrared sensing devices (cameras). The method has been used for about a decade for detecting delaminations on bridge decks. Transient heating or cooling is required in order to produce the heat flow that results in the thermal gradient detection patterns. In the bridge deck application, natural solar radiation provides this driving force. Therefore, data collection is limited to sunny days. The thermal gradients in a bridge deck are minimum before dawn--a marked transition occurs at sunrise. The delaminations are most visible in the afternoon when sunlight is most intense. Experience has shown IRT to be a fast, reliable method for detecting delaminations in bridge decks as confirmed by coring (*13,37,38*). Video imagery is used in conjunction with IRT in order to distinguish debris and surface discolorations from true thermal patterns. The major drawback to IRT is its extreme weather dependency.

The use of radiography has also been suggested for detecting delaminations in slabs. Since most of the applications of this method have been in the location of voids rather than delaminations, this method will be discussed later under "Prestressed/Posttensioned Structures."

All investigations reported by maintenance and materials engineers involving IRT and radar were performed by consultants or contractors. Those who had experience with both methods felt that they both provided rapid, relatively accurate results. The engineers were most impressed with the speed at which the data could be collected but felt that the information gained was less accurate than sounding. The field engineers were discouraged by the small window of opportunity for employing IRT, due to the necessity of specific weather conditions for optimum operation. The experiences with radar generally dealt with the location of voids beneath pavement slabs. Although the engineers had little or no experience with deck delamination detection, all felt that, based on previous uses, radar would provide a successful method.

Corrosion Detection

When steel corrodes in concrete, the electrochemical reactions that occur cause differences in potential, resulting in anodic and cathodic areas on the rebars. A standard specification has been adopted by the American Society for Testing and Materials (ASTM C876) for determining this difference in potential (*39*). The ASTM specification also includes information that allows the engineer to formulate a probabilistic evaluation of the state of corrosion in the system. It states that laboratory and field testing show that a corrosion potential reading more negative than -0.35 V indicates a 90-percent probability of the existence of active corrosion, while a reading more positive than -0.20 V indicates a 90-percent probability of the absence of active corrosion. The readings are referenced to the copper-copper sulfate (CSE) half cell.

The half-cell potential method provides an indication of where possible trouble spots may be in a concrete structure. A potential map is usually made to indicate the areas of possible corrosion activity. Several researchers have discussed practical uses of the half cell to detect corrosion *(40-45)*. These authors agree that the half cell does indicate, with good reliability, the existence of an active corrosion cell. However, there have been instances where an area has been deemed passive when in fact active corrosion was occurring (*45*). This was believed to have resulted from the interference of electrical conduits in the structure. False readings have also been indicated when the test was not performed correctly, the concrete surface was dry, or attempts were made to measure potentials through asphalt and impervious membranes (*5,45*). Measurements are also sensitive to temperature variations. ASTM C876 provides procedures for identifying and dealing with lack of sufficient moisture and for providing temperature correction. Possible problems associated with the interpretation of half-cell readings obtained under other extreme conditions, such as excessive moisture, carbonation of the concrete, or the presence of rebar coatings, are also presented in ASTM C876.

Half-cell potential mapping is usually performed on some type of predetermined grid system. A device called the potential wheel solves the problem of disjointed readings by providing a wheel for the tip of the half cell (*44*). This allows for a continuous readout of corrosion potentials very rapidly. This improvement reduces the cost of surveys due to lower manpower requirements.

The half-cell potential method for determining the presence of corrosion should only be used when plain reinforcing steel has been used in construction. Caution should be used when interpreting the results when the method is used for epoxy-coated and galvanized reinforcement (*46-48*). Since the epoxy coating acts as an electrical insulator, it will be difficult to obtain the electrical continuity required to perform the test. Due to poor continuity and possible severe localized corrosion, the potential readings may be highly negative. A large negative potential is usually indicative of severe corrosion, but the possibility of poor continuity and localized corrosion warrants caution in assessing the condition.

Problems also arise when the ASTM C876 method is used to interpret corrosion potentials of galvanized reinforcing. In this standard, potentials more negative than -0.35 V CSE are indicative of corrosion. However, tests by Stark and the Pennsylvania Department of Transportation indicate that corrosion may not be present until the readings are more negative than -0.6 V CSE (*47,48*).

During the interviews, most engineers felt that measuring half-cell potentials provides valuable information on the state of corrosion activity. Some highway engineers have observed that when reinforcement cover depths and concrete quality are relatively consistent, areas with potentials more negative than -0.40 V (CSE) will have a 95-percent probability of concrete delaminations, which has led several states to use potential measurements for selecting areas for concrete removal. However, others felt that the information gained was costly to collect, in terms of manpower, and that because it does not include rate of corrosion, it was of limited use for scheduling maintenance. It was agreed that the most beneficial result occurred with the use of potential surveys over time. This chronological mapping showed the increase in corrosion activity with time. From this information, some engineers gained insight into the corrosion activity.

Structural Damage

Stress Waves

The most commonly used method for determining internal structural damage in concrete structures is analysis of stress waves. These methods are discussed earlier in this chapter under "Delaminations" on p. 15 and include soundings and sonic and ultrasonic echo and surface waves. While most of the work in this area has been in the location of delaminations, the same technology allowed the exploration of massive concrete arch structures (*21*). The thickness of members may require an increase in the disturbing force for the echo methods and an increase in the frequencies of waves generated for the SASW method.

Among the stress wave techniques, pulse velocity (ASTM C597-83) (*29*) enjoys the longest experience record. However, the impact-echo procedure may prove to be the method of preference in the near future with the current developmental efforts in the area of automated data acquisition to reduce operator skill level requirements and to increase testing speed, partially offsetting high first (equipment) cost (*26-28*).

Acoustic Emissions

Acoustic emissions monitoring (AE) is a relatively new technique for application to concrete structures as a nondestructive testing (NDT) tool. Not only does AE enable the detection of cracks, but its proponents believe that it aids in estimating remaining structural life (*49-51*). The energy released by cracking propagates small amplitude stress waves through the member.

Several detectors are placed around a member to identify the location of the emission. These monitors also permit the observation of any changes in the rate of emissions, indicating formation of new defects. This information is used to relate the rate of emission to the defect size and remaining life (*49*).

This method has been used to locate cracking due to external loading, corrosion, and also freeze-thaw cycling (*49-51*). Its advantages include flaw sizing and location, complete structure coverage, and a need for only limited accessibility to the structure. At this time, all testing has been performed in the laboratory, and it does not appear that this method will be ready for productive use in the field for concrete structures in the near future.

Radiography

Two types of radiography have been used to determine deterioration in concrete structures: X- and gamma radiography (*6*). These methods are both at the high-energy end of the electromagnetic spectrum and will penetrate concrete structures, providing a "picture" of the interior. The energy available from X-rays has traditionally been one order of magnitude less than gamma rays.

The use of X-rays to evaluate concrete has been performed chiefly in the laboratory due to the cost, the immobility of the equipment, the high voltage requirements, and the safety considerations. Studies have included arrangements of aggregate particles, air voids, paste film thickness, and segregation and location of cracks (*6,52*).

Radiography with gamma-rays has been developed in Europe and is capable of detecting voids in concrete as small as 3/16 in. (5 mm) in 5-in. (13-cm) thick beams (*5*). The recent development of the system known as SCORPION (by the Laboratoire Regional des Ponts et chaussees de Bois, France) has allowed the detailed inspection of voids in prestressing cable ducts. Unfortunately, since the SCORPION uses the radioactive cobalt 60 source, the long exposure times required to penetrate concrete pose a health risk (personal communication with Roger Owen of Schoneberg Radiation, Santa Clara, California).

To alleviate the health hazard and still maintain the ability to "see" through concrete, a miniaturized linear accelerator has been developed. One such device is the MINAC linear accelerator developed by Schoneberg Radiation. This portable linear accelerator has been shown in laboratory and field uses to be capable of detecting voids, locating a 1/2-in. (13-mm) diameter rebar through 5 ft (1.5 m) of concrete, and distinguishing individual wires in a 3-in. (7.6-cm) cable through 1 ft (0.3 m) of concrete (personal communication with Roger Owen of Schoneberg Radiation, Santa Clara, California).

This equipment has been used successfully to determine the condition of cable hangers on suspension bridges in California and Pennsylvania (*52*, personal communication with Roger Owen of Schoneberg Radiation, Santa Clara, California). However, it is unlikely that it will ever become a common NDT method due to the extremely high equipment costs.

Other Methods

Computerized tomography is a method that permits the development of three-dimensional radiograph views of an object (*53,54*). The use of linear accelerators in tomography to produce very high energy beams allows penetration of concrete with a resolution of 0.04 in. (1 mm) through 6 in. (15 cm) of concrete (*43*). While the ability to see inside concrete with such resolution is exciting, several problems must be overcome before tomography is available for field use. To obtain a three-dimensional image, it is necessary to have several different views, and this may not be possible in the field. Another drawback is the cost of these systems. According to one estimate, a system would cost approximately $500,000 (1987 dollars) (*53*).

Another method that tries to resolve some of the problems involved with radiography is Compton scattering (*55*). This method allows gamma radiation to be used when only one side of the object is accessible. The scattered signal allows the determination of the density of the material and can be used with concrete to detect rebar and void locations (*55*). However, this method does not seem to be a feasible NDT method with applications to concrete bridges due to the radiation shielding requirements. Further, it has not yet been sufficiently developed for field application in general.

Reinforcing Cover and Location

Magnetic Flux Method

One of the most important factors in determining the probability of reinforcement corrosion in concrete slabs is the depth of cover. The most commonly used method for locating the size and/or depth of reinforcement is by magnetic flux means (*56*). The presence of the steel reinforcing bar causes a disturbance in the induced magnetic field. The influence of steel on the induced current is nonlinear in relation to distance and size of bar.

It has been reported that covermeters can measure the cover to $\pm$ 1/4 in. (6 mm), but repeated calibration can provide more accurate results (*23*). These magnetic instruments provide accurate results in lightly reinforced members, but for more heavily reinforced members, the effects of deeper steel must be considered (*6*).

There are several companies that manufacture and/or sell covermeters. The instruments available vary greatly in price due to the varying features available on the different models.

The field engineers who were interviewed used the covermeter for two reasons. The first is to determine if, after construction, the specifications for cover depth have been met. The other is to locate bars prior to rehabilitation.

Other Methods

If a more accurate location or size determination of a reinforcement bar is required, then it may be necessary to use either radiographic or radar methods. While these two methods may provide much more accurate information, the high cost and slow speed of survey have to be balanced with the need for greater accuracy.

Deteriorated Concrete and Voids

Stress Waves

As previously described on p. 16 ("Stress Waves"), both compression and surface waves provide a tool to determine the internal condition of concrete. With adequate experience and calibrated equipment, an operator can use these methods to locate voids, honeycombed concrete, and other anomalies related to deterioration. The size and depth of a void that can be detected are functions of the energy used and the frequency of the transmitted wave.

Radiography

Just as radiography has proved useful in detecting structural damage in concrete, it can be used to detect poor quality or deteriorated concrete as well as voids. While this method can be valuable, its use may be prohibited by high cost and difficult geometry. Rather than using radiography to locate problem areas, stress waves are often used for location, with radiography being reserved to determine the extent.

Radar

The advances in the field of radar have provided engineers with another method to determine subsurface conditions. This method is not discussed in detail here because it is the subject of Volume 3 of this report.

Resistivity

Corrosion of reinforcement is an electrochemical process. The ability of corrosion currents to flow through the concrete is one of the factors that govern the rate of corrosion. The resistance of the concrete is related to salt content, moisture content, temperature, and concrete quality (*20*). Since it is not practical to remove a sample of concrete to determine resistivity, the Wenner four-probe technique is used. The four probes of the device are spaced equal distances apart in a line and placed in contact with the concrete. A current is then passed between the outer probes and the corresponding potential drop is measured across the inner two probes. With this information, the resistivity of the concrete can be determined.

In order for these results to be indicative of the concrete, proper techniques must be used. If the probes are placed too close together, the calculated resistivity will be for the surface of concrete. If the probes are spaced too far apart, then the reading may be influenced by reinforcement. Generally, the likelihood of corrosion occurring varies with the inverse of resistivity: as resistivity increases, the probability of corrosion decreases (*57*).

In interviews, field engineers indicated that other methods, such as half-cell potential measurements (*39*), have taken the place of resistivity measurements to indicate the probability of corrosion. Resistivity measurements have been used to determine the effectiveness of sealers and membranes for asphalt-covered decks. The technique used in the latter instance consists of measuring the electrical resistance between a sponge-faced copper plate electrode at the pavement surface and the top reinforcing steel mat. The method is described in ASTM D3633 (*58*). This method suffers from a frequent problem of short circuiting through end dams, deck drains, or other metallic appurtenances when the asphalt overlay is wet.

Moisture Content

The primary reason for determining the moisture content of concrete is the influence of moisture content on the various modes of deterioration. These include reinforcement corrosion, alkali-aggregate reactions, freezing and thawing attack, and attack by sulfates and other aggressive ions. Thus, it is desirable to have a tool that allows the assessment of moisture content.

Neutron Methods

In this method, neutrons emitted by the decay of an X-ray source provide the ability to detect hydrogen present in water in the concrete. This is a surface-applied method, and it is only possible to determine the moisture content to approximately 3 1/2-in. (9-cm) deep (*15*). The accuracy of this method improves with increasing moisture content. This method has been used extensively in soil tests where the results have been found to correlate well with moisture contents.

Electrical Methods

The use of electrical methods to detect moisture content has been reported (*15*). These methods are generally either geared to laboratory testing or are partially destructive.

One electrical method involves the measurement of the dielectric constant and dissipation factor. Two conductive plates are placed on parallel faces of a concrete member and a potential is applied. It has been reported that moisture contents can be determined to $\pm$ 0.25 percent for values less than 6 percent (*15*). The difficulty in adapting this method for field use is in the problem of attaching plates to the members.

Another method using electrical techniques is a relative humidity (RH) probe. This method requires that a probe be sealed in a hole in the specimen. The probes can be permanently placed or used temporarily. A range of 20- to 90-percent RH can be detected; maximum accuracy is calibrated at 75-percent RH. While this may be considered a destructive method, the required hole (approximately 1 in. (2.54 cm)) can also be used to provide pulverized concrete samples for chloride analysis.

Other Methods

The increase in research into the applicability of radiographic, radar, and infrared thermography has shown that all of these methods are capable of determining moisture contents. However, before these methods can be used with confidence, more laboratory and field work is needed. The ability of radar to sense changes in moisture content is explored in Volume 3 of this report in conjunction with identification of deteriorated (punky) concrete beneath asphalt overlays on bridge decks.

Strength Measurement

Because it is difficult to predict the in situ strength of concrete based on mix design and test cylinders, it is often necessary to employ some other method that will accurately reflect the concrete strength. Many methods are available to predict strength, and they include nondestructive, noninvasive to destructive and invasive procedures. The most direct approach, taking cores and testing them, may give the most direct results, but it is expensive, time consuming, and destructive. Even though it is desirable for the methods to be totally nondestructive, it should be realized that there are some methods that will damage the surface and others that may damage the concrete to a minimal depth.

Stress Waves

Stress waves, both compressive and surface waves, are one of the most promising methods currently being used to determine concrete strength. The tests are based on correlations between the velocity of travel of the sound waves and strength properties of the concrete (*4-6,15,29,59-62*). The most important factors determined to be influential in comparing pulse velocities and strength are the age and curing history, moisture content of the concrete, and member geometry. Other factors that may have some influence are air entrainment and cement type.

These methods correlate well at any specific age, but caution must be exercised when using relationships obtained at one age to predict strength at another. Another factor that influences the strength is the presence and orientation of reinforcing. Measurements should be avoided near steel reinforcing, but, if not possible, corrections should be made to prevent erroneous strength values.

This test method has been found to have a low within-batch coefficient of variation because of the relative insensitivity of the method to the heterogeneity of the concrete (*62*). However, this does not necessarily imply high accuracy in the determined strength. The factors affecting the travel of the sound waves must be considered before determining strength. The most familiar method that is applicable here is pulse velocity (ASTM C597) (*29*). The new impact-echo technique may also be applicable here (*26-28*).

Rebound Methods

The Schmidt Rebound Hammer [ASTM C805 (*63*)] tests the surface hardness of concrete. The hammer provides only a rough indication of the quality of the concrete, but this information can be valuable. Correlation of hardness with strength can only be determined through empirical methods (*4-6,15,63-65*). Once calibrated, the Schmidt Hammer can be used to compare a concrete of one quality to another of similar or different age, and curing history. The accuracy of predicting the strength is approximately ± 25 percent; therefore, the method is best used in determining areas that are of significantly different strength, such as poor quality or deteriorated concrete (*6*). These areas then can be more completely investigated using other methods.

Pullout

In this method, a headed rod is embedded in the concrete at the time of placing, and the force necessary to pull it out is measured. The details for carrying out the test are found in an industry standard, ASTM C900 (*66*). The failure is generally in a cone shape and is indicative of a tension-and-shear failure. The force required for pullout can then be used to determine the stress by dividing the force by the fracture surface area (*66-70*).

Since the failure is a tension-shear mode, a correlation must be made with compression tests. This has been accomplished by casting cylinders with pullout devices and using pulse velocity, rebound numbers, and compressive tests on companion cylinders (*66-70*). The pullout test can be affected by any anomalies near the test site, for example, large aggregate particles, localized dampness, and carbonation. However, this rapid, simple test has an acceptable degree of reproducibility and accuracy, and, unlike rebound and penetration methods, is a direct measure of the strength of the concrete.

The major drawback to the pullout method is that it is only applicable to new construction because the pullout mechanism (headed rod) must be cast into the concrete.

Penetration

Penetration methods, for example, the Windsor probe, involve measuring the penetration of a special probe fired into the concrete (*71-73*). They are described in a standard test procedure--ASTM C803 (*71*). This test, like the rebound method, tends to determine the hardness of the concrete. Unlike the rebound method, the penetration method measures the hardness of concrete between 1 and 3 in. (2.5 and 7.6 cm) below the surface (*72*). There is no theoretical relationship between strength and penetration, but consistent laboratory results allow for an empirical relationship. It is necessary to determine the empirical relationship for different aggregate types, since this was found to significantly affect the results (*72*). Because the depth of penetration is deeper than that achieved with the rebound method, there is less of an effect of age, aggregate content, and moisture condition. With adequately prepared correlation charts, it is possible to determine the strength of the concrete to ± 20 percent (*72*). This is felt to be as accurate as ultrasonic methods and testing of small diameter cores (*74,75*).

Pretensioned/Post-tensioned Prestressed Concrete Structures

One of the most pressing needs in the field of NDT is a method to determine the condition of tendons in prestressed (pre- and post-tensioned) concrete structures. In interviews with state and provincial department of transportation engineers, consulting engineers, and NDT specialists, no one could offer a field-ready NDT method for assessing these cables. Two methods are currently being used to determine distress in these structures. The first is a visual inspection. Inspectors look for evidence of corrosion in rust stains, wet spots, and cracking. The second method is exposure of the pretensioning strand. Care should be used to avoid rupturing post-tensioning ducts or cutting into the strand.

Neither of these methods provides acceptable results in determining the extent of corrosion. By the time the bridge structure is showing visible signs of deterioration, the condition of the structure may be too far deteriorated to be rehabilitated and may pose a safety risk. If proper care is not taken with repairing the core hole, this could lead to accelerated corrosion. At this time, there are no nondestructive methods to detect corrosion in pretensioning or post-tensioning strands, but several methods show potential.

Radiography

Advances in radiography in both the United States and France have made it a possible candidate for determining corrosion in strands. These systems allow the penetration of up to 3 ft (1 m) of concrete. Also, the better the quality of the concrete, the better the results. Radiography has been claimed to be able to determine a 1-percent change in density, and it can distinguish one strand in 3-in. (7.6-cm) diameter cable through 1 ft (0.3 m) of concrete (personal communication with Roger Owen of Schoneberg Radiation, Santa Clara, California, *52, 53, 76*). In thicker concrete, it is more difficult to see individual strands, but it is possible to detect areas of corrosion.

Another advantage of radiography is that it is possible to detect voids in the grout filling of post-tensioning ductwork. Advances in this field also include new recording systems. It is no longer required that film be processed; the entire process is recorded on videotape.

The biggest drawback of these systems is their size. While recent work has greatly reduced the size while increasing the power of the linear accelerators, it is still difficult to use these systems in areas of complex geometry or extremely thick concrete.

Stress Waves

All of the methods described in previous sections relating possible applications of stress waves to detection of deterioration can also be used for prestressed structures. However, these methods have been primarily used to determine deterioration in the concrete. Because of the higher quality of concrete mixes used and higher level of quality control at precasting plants, deterioration in the concrete is not usually a significant problem for prestressed and post-tensioned members. The most significant problem with these members is that there is no way to determine the state of corrosion or structural capacity of the tendons.

Preliminary work has begun in two areas, using stress waves, that may help alleviate these problems. The first method is pulse echo. Tests were performed by The University of Manchester Institute of Science and Technology/Corrosion and Protection Center-Industrial Services exploring the possibilities of sending pulses down a single 5/16-in. (7-mm) prestressing wire to determine its condition (*77*). Without special preparation, the lengths of specimens that were able to be examined ranged up to 13 ft (4 m). Then, to determine this method's ability to assess damage, a simulated crack was made by a saw cut, and the results showed it was possible to detect the crack. A second simulation was of a corroded area. An area was filed flat to represent a loss of section due to corrosion, and this was also readily observed by the pulse decay. Unfortunately, the promise indicated by the preliminary work has not materialized. The higher frequencies employed were attenuated far more in concrete than in air and water. Thus the capabilities of the system now appear to be quite modest, and the system in its present state has very little practical use.

The second method is acoustic emission. As stated previously, acoustic emissions are produced in a structure when cracking occurs. By placing receivers around the structures, it is possible to determine the location of the failure. Previous work has shown success in determining the failure of individual wires in cables used for lifting, but this has not been applied in concrete. While this method has previously been used to locate cracking in concrete due to expansion of corroding steel, in tensioned cables earlier detection of corrosion (before concrete failure) will be indicated by failing wires. Unfortunately, this method requires constant monitoring of the structure, which may cause some problems due to the number of structures involved.

Magnetic Field Disturbance

In the early 1980s, work was begun using the magnetic field disturbance (MFD) method to detect flaws in prestressed structures (*78*). This method uses a strong magnetic field that is passed through the concrete structure to magnetize embedded steel. Sensors are used to measure the field produced by metal in the structure. If there is a flaw in any of the magnetized steel, it will produce a disturbance that is recorded.

These discontinuities produce a distinctive anomaly depending on the size and distance from the sensor. This signal is analyzed automatically by computer comparison with typical flaws. This method can also be used when the cables are encased in grout-filled ducts.

Laboratory experiments showed that the MFD method can detect fractures and corrosion of reinforcing strands in air and concrete, as well as in filled plastic and metal ducts in concrete. Field testing revealed problems involving background structural disturbances, which resulted in an improved system. The system was also tested on a full-scale laboratory specimen that was loaded to failure. In all cases, the MFD system indicated all failures of plain reinforcing and two or more wires in a seven-wire strand.

Continued work is required for the MFD system in development of methods to be used for the several possible beam sections as well as for other structural members. There is also a need for inclusion of other possible flow types and signal patterns into the computer recognition algorithm. However, the MFD system has shown that it is one of the most feasible methods for detecting corrosion and failure of both strands and plain steel in pretensioned and post-tensioned structures.

Petrographic Examination

Description and Discussion

In certain instances, nondestructive evaluation (NDE) methods may not be sufficient to completely assess the condition of concrete bridge components. Table 3-1 summarizes the more common situations in this regard. In these cases, it is necessary to obtain drilled core specimens for petrographic examinations of the concrete.

Petrographic examinations consist primarily of visual and detailed microscopic examinations of polished and freshly fractured concrete surfaces in order to assess the quality of the concrete and its constituents and to reveal the causes for concrete distress or poor performance. The basic procedure is formalized in ASTM C856, "Standard Practice for Petrographic Examination of Hardened Concrete" (*79*). The petrographic examination of concrete normally consists of these steps: the procurement of specimens, inspection with the unaided eye, microscopic examination using the stereoscopic microscope at magnifications of 6x to 100x, and, depending on the situation, thin section or grain mount (transmitted light) microscopy using the petrographic microscope at magnifications of 100x to 1000x. In addition to microscopic techniques, other analytical procedures may be employed as needed to provide required information. These include porosimetry, strength testing, wet chemical analysis, x-ray diffraction or fluorescence, infrared or ultraviolet or atomic absorption spectroscopy, tomography, and sonic or ultrasonic procedures (*80, 81*).

The sampling plan for obtaining the specimens for examination is critical to the success of assessing the condition of the concrete. Guidance in sampling may be obtained from ASTM C823 (*82*). However, as pointed out by Abdun-Nur (*83*), it is rarely practical to apply the full statistical treatment to sampling for concrete condition assessment. For one thing, variances are not generally known, and, second, sample acquisition by coring is expensive and destructive. As a compromise, it has been suggested (for the case of bridge decks) that at least one random core specimen be extracted per 2,000 ft^2 (186 m^2) of uncovered deck or at least one per 500 to 700 ft^2 (46 to 65 m^2) of asphalt-covered deck (*84*). ASTM C856 calls for, minimally, the equivalent of one core, preferably 6 in. (15 cm) in diameter and 1 ft (0.3 m) long, for each mixture or condition category of the concrete (*79*). ASTM C856 also states that the core diameter should be at least two, and preferably three times the maximum size of the coarse aggregate in the concrete.

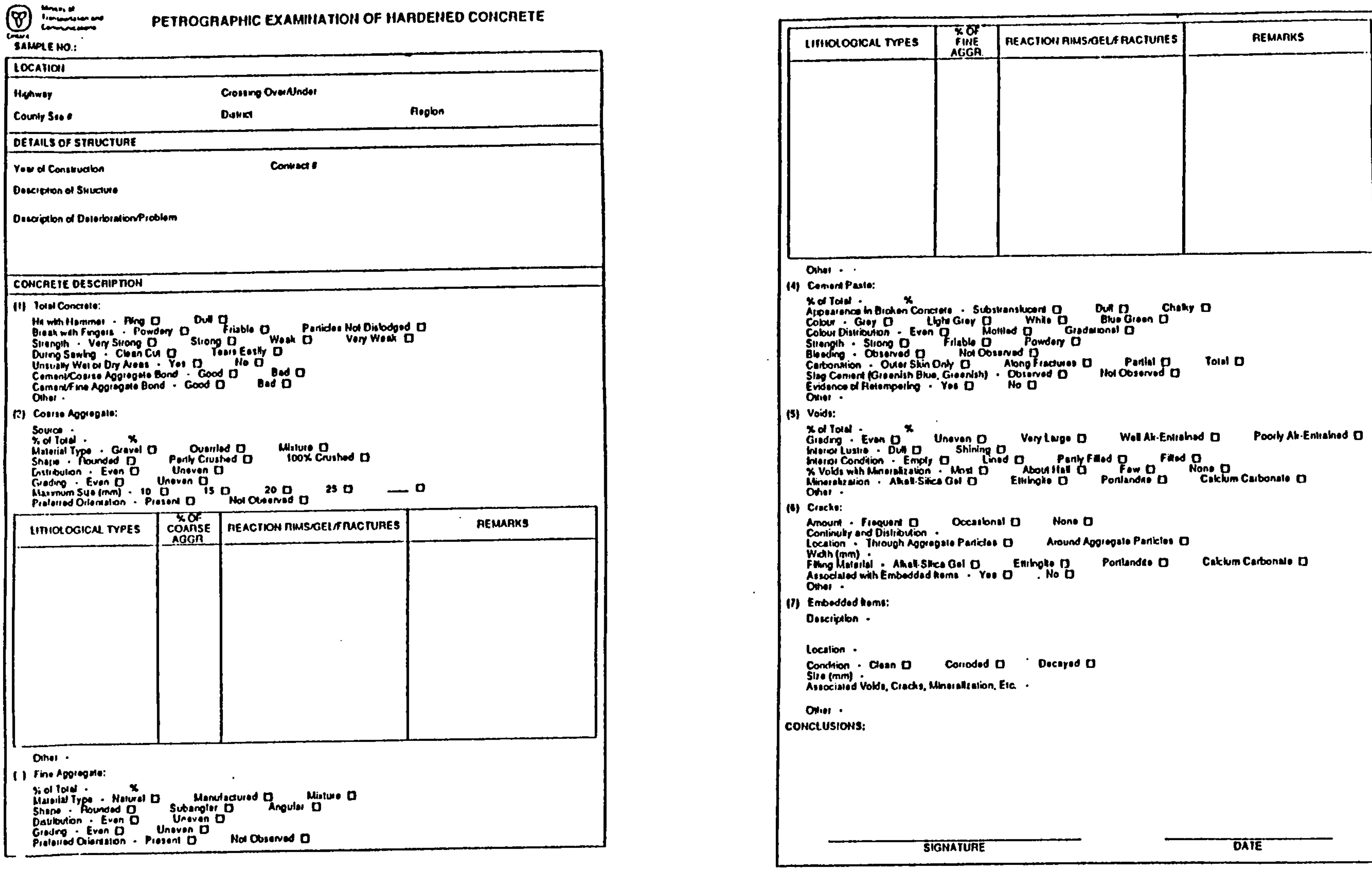
In preparation for microscopic examination, the core specimens are sectioned using a diamond-bladed saw, and the exposed faces are ground smooth through the process of lapping with successively finer grades of grinding compounds. Core remnants are used to produce freshly fractured surfaces for microscopic examination and for other testing. The

Table 3-1. Concrete conditions that may require evaluation by petrographic examination.

Observed Condition					
Cracking	Spalling	Scaling	Disintegration	Popouts	Possible Cause(s)
					Materials-Related:
X			X	X	• unstable or reactive aggregates
X		X	X		• improper mixture proportions
X			X		• improper admixture dosages
X		X	X		• out-of-specification cement or aggregate
					Construction-Related:
X		X			• improper placing
X		X			• improper finishing
X					• improper curing
					Environment-Related:
X	X		X		• sulfate-bearing surface or ground water contact
		X	X		• dissolution or acidic attack
	X	X	X		• deicing chemical exposure
X	X	X	X	X	• freezing and thawing attack
					Unique Events-Related:
X	X		X		• early freezing (of fresh concrete)
	X			X	• fire damage
X					• impact (e.g., crash) damage

types and ranges of detail sought in the microscopic examination (based on ASTM Standard Practice C856) are illustrated in the data form developed by the Ontario Ministry of Transportation and Communications, shown in Figure 3-2.

If freezing and thawing damage is suspected, it will be necessary to also carry out a microscopic analysis of the entrained air-void system in the concrete using one of the procedures described in ASTM C457 (*85*). During this procedure, it is often advisable to take the extra steps necessary to also obtain estimates of the relative proportions of coarse and fine aggregate, cement paste, and air voids (*86*).



Ministry of Transportation and Communications Ontario

PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE

SAMPLE NO.:

LOCATION

Highway — Crossing Over/Under

County Site # — District — Region

DETAILS OF STRUCTURE

Year of Construction — Contract #

Description of Structure

Description of Deterioration/Problem

CONCRETE DESCRIPTION

(1) Total Concrete:
Hit with Hammer - Ring ☐ Dull ☐
Break with Fingers - Powdery ☐ Friable ☐ Particles Not Dislodged ☐
Strength - Very Strong ☐ Strong ☐ Weak ☐ Very Weak ☐
During Sawing - Clean Cut ☐ Tears Easily ☐
Unusually Wet or Dry Areas - Yes ☐ No ☐
Cement/Coarse Aggregate Bond - Good ☐ Bad ☐
Cement/Fine Aggregate Bond - Good ☐ Bad ☐
Other -

(2) Coarse Aggregate:
Source -
% of Total - %
Material Type - Gravel ☐ Quarried ☐ Mixture ☐
Shape - Rounded ☐ Partly Crushed ☐ 100% Crushed ☐
Distribution - Even ☐ Uneven ☐
Grading - Even ☐ Uneven ☐
Maximum Size (mm) - 10 ☐ 15 ☐ 20 ☐ 25 ☐ ___ ☐
Preferred Orientation - Present ☐ Not Observed ☐

LITHOLOGICAL TYPES	% OF COARSE AGGR	REACTION RIMS/GEL/FRACTURES	REMARKS

Other -

( ) Fine Aggregate:
% of Total - %
Material Type - Natural ☐ Manufactured ☐ Mixture ☐
Shape - Rounded ☐ Subangular ☐ Angular ☐
Distribution - Even ☐ Uneven ☐
Grading - Even ☐ Uneven ☐
Preferred Orientation - Present ☐ Not Observed ☐

LITHOLOGICAL TYPES	% OF FINE AGGR	REACTION RIMS/GEL/FRACTURES	REMARKS

Other - -

(4) Cement Paste:
% of Total - %
Appearance in Broken Concrete - Subtranslucent ☐ Dull ☐ Chalky ☐
Colour - Grey ☐ Light Grey ☐ White ☐ Blue Green ☐
Colour Distribution - Even ☐ Mottled ☐ Gradational ☐
Strength - Strong ☐ Friable ☐ Powdery ☐
Bleeding - Observed ☐ Not Observed ☐
Carbonation - Outer Skin Only ☐ Along Fractures ☐ Partial ☐ Total ☐
Slag Cement (Greenish Blue, Greenish) - Observed ☐ Not Observed ☐
Evidence of Retempering - Yes ☐ No ☐
Other -

(5) Voids:
% of Total - %
Grading - Even ☐ Uneven ☐ Very Large ☐ Well Air-Entrained ☐ Poorly Air-Entrained ☐
Interior Lustre - Dull ☐ Shining ☐
Interior Condition - Empty ☐ Lined ☐ Partly Filled ☐ Filled ☐
% Voids with Mineralization - Most ☐ About Half ☐ Few ☐ None ☐
Mineralization - Alkali-Silica Gel ☐ Ettringite ☐ Portlandite ☐ Calcium Carbonate ☐
Other -

(6) Cracks:
Amount - Frequent ☐ Occasional ☐ None ☐
Continuity and Distribution -
Location - Through Aggregate Particles ☐ Around Aggregate Particles ☐
Width (mm) -
Filling Material - Alkali-Silica Gel ☐ Ettringite ☐ Portlandite ☐ Calcium Carbonate ☐
Associated with Embedded Items - Yes ☐ No ☐
Other -

(7) Embedded Items:
Description -

Location -
Condition - Clean ☐ Corroded ☐ Decayed ☐
Size (mm) -
Associated Voids, Cracks, Mineralization, Etc. -

Other -

CONCLUSIONS:

SIGNATURE — DATE

Figure 3-2. Data form for the petrographic examination of hardened concrete; based on ASTM C856 for use by the Ontario Ministry of Transportation and Communications. [Reproduced with the permission of the Ontario Ministry of Transportation and Communications.]

4

Summary

Conclusions

The ideal nondestructive testing procedure for reinforced or prestressed concrete structures would provide information about the existence and location of deterioration, corrosion, and structural damage. Rates of corrosion are important as well in order to project service lives. Given the variables of exposure, geometry, and materials that are present on a bridge, there is no procedure that can provide all the desired information. However, the methods covered here can provide a good picture of the condition of a structure.

The purpose of this review is to determine which methods warrant consideration for bridge evaluation. These methods are combined with the methods developed in Volumes 2 through 7 of this report in an integrated bridge evaluation procedure (Volume 8).

Recommendations

The selection of the techniques and procedures to be considered for the development of the "Procedure Manual" (Volume 8) is based on several criteria. Obviously, the most important of these is the ability of a method to carry out the required function at an acceptable performance level, and in this regard, the experiences of the department of transportation engineers carry considerable weight. Simplicity of operation is another criterion: the method should not be highly labor-intensive. Further, it must be field-ready and rugged and possess a high degree of reliability. The levels to which these criteria can be met will vary considerably, and a degree of subjectivity may be incurred in the decision process. Note that the criterion of need, relative to specific applications, is not included here since this factor falls into the purview of Volume 8 of this report.

Delaminations

Based on the criteria set forth above, the recommended method of determining delaminations is sounding (refer to page 17, "Sounding," for operator health considerations) (ASTM D4580) (*11*). This method has been used extensively in the field, and it quickly provides accurate and precise information on the location of delaminations. It does not provide information on the depth of delamination. This can be provided by use of impact-echo or pulse velocity methods, but the equipment required is expensive and the methods are labor-intensive. However, if these techniques are going to be used at a given site to find deteriorated concrete, voids, and other structural damage, then they could also be used for delamination detection. The standard method for pulse velocity is ASTM C597 (*29*).

Corrosion Detection

The only field-ready method capable of providing information on the presence of corrosion is the measurement of half-cell potentials. ASTM C876 gives the procedure and equipment required to perform the measurement of the half-cell potentials and determine the corrosion activity of the reinforcing steel. There are a number of commercially available devices that aid in the collection and analysis of this data. One such device is the potential wheel (*44*), but sufficient field experience has not been presented to date, and it should still be considered experimental.

It is recognized that this method provides only half the information required; it does not provide the rate of corrosion. However, techniques for the evaluation of corrosion rate are covered in Volume 2 of this report.

Structural Damage

The only methods that are field-ready and have shown that they are capable of determining the extent of structural damage are the stress wave techniques, in particular the pulse velocity and impact-echo methods. The pulse velocity method is standardized under ASTM C597 (*29*).

Other methods, such as acoustic emission and radiography, have been explored theoretically and in limited field testing. However, at this time, these are not considered to be viable methods for incorporation into field procedures.

Reinforcing Cover and Location

Magnetic flux methods have been shown to quickly and accurately locate and determine reinforcement depth and location. It is important to determine the accuracy required of the meter so that the appropriate instrument can be chosen. Other important features are the instrument weight, time of operation with fully charged battery, battery charging time, operating temperature range, maximum and minimum rebar size for which the device is calibrated, maximum depth of cover at which a bar can be located, and bar diameter gauging accuracy.

Other methods, such as ground penetrating radar and radiography, have not been fully developed or have had only limited field experience.

Deteriorated Concrete and Voids

While the results from radar and radiography have been promising, they are not the most feasible method for detecting deteriorated concrete and voids, particularly for bridge elements other than decks. It is recommended that stress wave methods be used, i.e. sounding, echo, or surface wave (depending on the location, accessibility, and depth of the defect in question).

Resistivity

Resistivity measurements are not recommended for determining the presence or possibility of corrosion in reinforced concrete. The half-cell potential tests provide a more accurate indication of the presence of corrosion. The technique described in ASTM D3633 (*58*) might provide information regarding membranes for asphalt-covered decks and the effectiveness of sealers. However, more appropriate means of evaluating these conditions are discussed in Volumes 4 and 5 of this report.

Moisture Content

Moisture content has a significant influence on the deterioration of concrete, and it is recommended that the neutron methods be used to determine the moisture content. These methods have had success in soil applications and can provide information on moisture content to about the rebar depths. The other methods are partially destructive or are not developed to the extent required for field use.

Strength Assessment

For new construction, the pullout method, ASTM C900 (*66*), is recommended. For evaluating existing structures, the rebound ("Schmidt Hammer"--ASTM C805) (*63*) or penetration ("Winsor Probe"--ASTM C803) (*71*) methods should be used as screening tests, with compressive strength testing of drilled core specimens (ASTM C42) (*75*) conducted at critical locations or where the results of rebound or penetration readings are inconclusive.

Pretensioned and Post-tensioned Prestressed Concrete Structures

Except for visual methods, no other method is recommended for detecting deterioration in prestressed and post-tensioned structures at this time. However, it seems that radiography, stress waves, and magnetic field disturbance have potential applications. The most encouraging work involves the magnetic field disturbance (MFD) method.

Petrography

Petrographic examinations are expensive and time-consuming. A high level of technical expertise is required to perform the examinations, and sample acquisition is destructive (coring). Therefore, the decision to use petrographic examinations should be employed very judiciously, limiting it only to instances where the data needed to adequately assess the condition of a concrete bridge component cannot be acquired by other means.

Appendix A

Summary of Comments from State and Provincial Departments of Transportation

Table A-1. Use of visual inspections by states and provinces.

State	Comments
Alabama	Yes
Alaska	Yes
Arizona	Yes
Arkansas	Checks for leaking, rusting, cracks, and spalling
California	Cracking
Colorado	Yes
Delaware	Visual on underside and substructure every year
Florida	Yes
Georgia	Yes
Idaho	Checks for spalls, cracks, etc.
Illinois	Core T-beams through girders, visual inspection above and below overlay mapping
Indiana	Yes
Iowa	Yes, substructure
Kansas	Entire bridge
Kentucky	Yes--checks for spalling, scaling, cracking, etc.
Louisiana	No
Maine	Yes
Maryland	Yes--FHWA
Massachusetts	As per FHWA, visual delaminations on substructure, then indepth
Michigan	Crack mapping, spalls
Minnesota	Every year; checks for cracks
Mississippi	Yes
Missouri	Yes
Montana	Yes
Nebraska	Videotape once, photographs, sketches, damage report, checklist

Table A-1. Use of visual inspections (*continued*).

State	Comments
Nevada	Checks for cracks, spalls, etc.--substructure, superstructure, deck
New Hampshire	Yes
New Jersey	Checks for spalling, staining, etc.
New Mexico	Checks for delaminations. Also do visual underwater inspections on all bridges
New York	Checks for spalls, etc.
North Carolina	Checks for spalls, staining, etc.
North Dakota	Yes
Ohio	Yes
Oregon	Yes
Pennsylvania	Yes
Rhode Island	Checks for delaminations, spalls, etc., on the top and bottom of structures; uses binoculars for hard-to-reach areas
South Carolina	Yes
South Dakota	Yes
Tennessee	Yes--spalls, etc., noted in report
Texas	Yes--stains
Utah	Yes
Vermont	Yes
Virginia	Cracks, spalls, stains
Washington	Yes
West Virginia	Yes
Wisconsin	Yes
Wyoming	Yes
British Columbia	Yes--to identify problems

Table A-1. Use of visual inspections (*continued*).

State	Comments
New Brunswick	Yes
Nova Scotia	Yes
Ontario	Yes
Saskatchewan	Yes

Table A-2. Use of Delamatect® by states and provinces.*

State	Comments
Arizona	Demos--three bridges; just as good results but quicker with chain drag--limited problems with Delamatect®
Illinois	Good information if operator is good
Iowa	One Delamatect® per district--more accurate than infrared
Kansas	Delamatect® with data logging/plotting; problems - hardware/software; accuracy is worse than chain drag
Michigan	No longer used--not reliable enough; less error with hand methods
Missouri	Yes
Montana	Yes--didn't pick up smaller areas of delaminations
New Hampshire	Demo only
New Jersey	Yes--for overlays use chain drag
North Carolina	Demo--fair correlation with chain drag
Ohio	Used to use Delamatect® (15 years ago); found to be slow, impractical; manual methods just as good
Pennsylvania	Yes
Rhode Island	Demo only
Washington	Demo only
Manitoba	Accuracy was good--checked manually; stopped using it--chain drag just as good
Nova Scotia	Problems with rough surfaces
Saskatchewan	Delamatect® is expensive--no better results than manual methods

*States and provinces not listed do not use Delamatect®.

Table A-3. Use of radar by states and provinces.*

State	Comments
Alaska	Considering for purchase; demo project use only by FHWA
Arkansas	Not for structures, only for voids beneath pavement
Delaware	Yes, 50 percent effective
Florida	Use in concrete pavements only
Idaho	Demo scheduled
Illinois	Not very accurate according to demo's and research
Kentucky	Delamination detection on severe decks - accurate results
Louisiana	On pavements only
Massachusetts	Use for overlay depth
Michigan	Currently evaluating along with IRT
Minnesota	Problems with interpretation of results
Mississippi	Demo only
New Jersey	Not for delaminations in structures; determine voids under pavement slabs
New York	Evaluation only; needs work
Ohio	For delamination detection on decks
Pennsylvania	Interpretation problems
Rhode Island	Demo only
South Dakota	Demo only
Virginia	Yes
Washington	Yes
Wisconsin	Used for pavement slabs--voids underneath
Alberta	Negotiating contract for use
Ontario	Asphalt decks only

*States and provinces not listed do not perform radar tests.

Table A-4. Use of air void analysis by states and provinces.*

State	Comments
Kentucky	Lab; but routine
New Jersey	Only if problems
North Dakota	Extreme cases only
Washington	Yes
Wyoming	As required
Ontario	Only if necessary

*States and provinces not listed do not routinely perform air void tests.

Table A-5. Use of infrared thermography by states and provinces.*

State	Comments
Alabama	Demo only
Alaska	Going to try it in August and September
California	Demo only
Delaware	Contracted to Donahue and Associates, Inc.
Idaho	Demo scheduled
Illinois	Occasionally--mixed results
Indiana	Demo--looks okay
Iowa	By consultants; research project on 9 - 20 decks
Maryland	Used a limited amount; some good and some bad results--mostly demos
Michigan	Used experimentally to compare with other delamination methods
Minnesota	Research only--not quite as accurate as delamatect or chain drag; too expensive, too many weather-related problems
Missouri	Used to demo--couldn't verify if as accurate as other methods
Nevada	Demo only
New Hampshire	Demo (Donahue) very accurate for delaminations
New Jersey	Demo only
New York	Yes--Donahue
North Dakota	Donahue--satisfactory, checked and compared well
Ohio	Not much success for delamination detection
Pennsylvania	Visual representation--good and bad areas are easily distinguishable; fast
Rhode Island	Demo
Utah	Demo--doesn't do the job well enough
Vermont	Experimental--pretty good, not very consistent
Virginia	Research only--pretty good correlation
Washington	Demo only--problems with temperature variation

Table A-5. Use of infrared thermography (*continued*).

State	Comments
Wyoming	Demo only
Alberta	Costs too much
Manitoba	Demo only
Ontario	Research branch--parallel with radar to compare results

*States and provinces not listed do not perform IRT tests.

Table A-6. Use of ultrasonic testing by states and provinces.*

State	Comments
California	Not routine--demo, not field ready--no calibration standard
Colorado	Used only with steel, experimentally
Florida	Not good experiences with demos
Idaho	Only steel
Illinois	Demos--but not used for delaminations
Louisiana	Mainly steel; not in concrete
Massachusetts	Presently testing
Mississippi	Not much use; only steel
Nevada	Only in steel
New Jersey	Cracks in steel only/condition only--no follow-up tests
New Mexico	FHWA Demo project

*States and provinces not listed do not perform ultrasonic tests.

Table A-7. Use of potential measurement by states and provinces.*

State	Comments
Arizona	Only if required during full-scale inspection
Arkansas	Half cell--lab technicians
California	Yes, routine
Delaware	Half cell--5-ft (1.5-m) grid
Florida	Use on substructure; in-depth mappings trace on pier/abutment
Idaho	No equipment--contract if needed
Illinois	Half cell
Indiana	Not routine--contract out if needed--used for cathodic protection
Iowa	Half cell was used but gotten away from it--repeatability questions
Kansas	Potential mapping--every deck; complete survey
Kentucky	Not any more--used mostly on interstates
Louisiana	Used in past--research mostly; not any longer
Maryland	Routinely performed--decks, substructure, beams
Massachusetts	Half cell--used to be but not any longer
Minnesota	Done by research--limited use
Missouri	Routine for rehabilitation
Montana	Half cell at 5-ft (1.5 m) grid--used to determine location for chloride samples from good and bad deck areas
Nevada	Not routine
New Hampshire	Half cell
New Jersey	Extent of corrosion--mandatory test for rehab
New Mexico	Only if problems or if requested
New York	Yes
North Dakota	Yes
Ohio	Capable--not routine
Vermont	Yes, on all decks considered for rehabilitation, in order to provide design estimate quantities for concrete repair and to designate areas for removal.

*States and provinces not listed do not perform potential tests.

Table A-8. Use of core removal by states and provinces.*

State	Comments
Alabama	If problems exist--delamination detection verification
Alaska	Not routine
Arizona	Chloride tests; alkali silica reactivity backup method if problem
Arkansas	Analysis includes potential measurements, strength properties (not routine), chloride content
California	Chloride content
Delaware	Where necessary to maintain integrity
Florida	Only if problems indicated
Georgia	Examination for corrosion; section loss--only if problem
Idaho	If required to check corrosion, delamination, chloride content--if problems exist; materials section does further coring
Illinois	Verify effects of delamination; strength, chloride penetration
Indiana	Overlays bonding and thickness; only if problems
Iowa	Only if necessary; overlay checking bond
Kansas	Not regular petrographs--only if problems--cores of delaminated and good areas
Kentucky	Routine
Louisiana	Only for rehabilitation
Maine	Not usually for substructure or deck; only if problems
Maryland	Compression testing; delamination determination
Massachusetts	Routine
Michigan	Strength tests; determine extent of delaminations
Minnesota	To check condition
Mississippi	Not unless severe problems exist
Montana	Not routine; only if requested
Nebraska	Compression tests; chloride content at steel level
Nevada	Yes

Table A-8. Use of core removal (*continued*).

State	Comments
New Hampshire	Yes
New Jersey	Chloride tests; strength analysis; verifies delamination checks
New Mexico	Yes
New York	To determine extent of repair
North Carolina	Yes--strength tests
North Dakota	Only if problems
Ohio	Selective coring
Oregon	Yes--strength and chloride tests
Pennsylvania	Not routine
Rhode Island	Cores removed through bituminous overlays to exposure concrete deck
South Carolina	Infrequently
South Dakota	Strength and chloride tests, if needed; check delaminations also
Tennessee	Yes
Texas	Sulfate tests; chloride content, strength tests
Utah	2-in cores; chloride content, strength tests
Vermont	Use coring as ground truth for radar or checking delamination edges
Virginia	Only if problems
Washington	Yes
West Virginia	Yes--visual inspection of cores for delaminations and problems
Wisconsin	Not as matter of course
Wyoming	Only to determine extent of delaminations
Alberta	Not routine
British Columbia	Yes--strength, visual check of core
Manitoba	Regular basis to detect deterioration--if chain drag reveals problems

Table A-8. Use of core removal (*continued*).

State	Comments
New Brunswick	Yes
Ontario	For analysis if necessary
Saskatchewan	Only if necessary

*States and provinces not listed do not perform core tests.

Table A-9. Visual inspection of cores by states and provinces.*

State	Comments
Arizona	Visual--check quality throughout deck
Georgia	Examine for corrosion
Idaho	Visual inspection of cores
Indiana	Visual inspection of cores
Maryland	Visual inspection to determine deterioration and delaminations
Michigan	Visual inspection of cores
Nevada	Visual inspection of cores--always
New Hampshire	Visual exam of cores
Ohio	Visual exam of cores
Rhode Island	Visual exam, rebar quality, stains
Tennessee	Visual inspection of cores
Utah	Visual mostly for delaminations and rehabilitation
Washington	Aggregate reaction
West Virginia	Yes
Wisconsin	Visual
British Columbia	Visual
Manitoba	Visual--concrete problems
Saskatchewan	Visual

*States and provinces not listed do not perform quality checks on core samples.

Table A-10. Use of strength tests by states and provinces.*

State	Comments
Alaska	Strength tests from cores, not routine
Arizona	Compressive strength, backup method
Arkansas	Strength tests from cores, not routine
California	Strength tests from cores, not routine
Georgia	Strength tests from cores, not routine
Illinois	Strength tests from cores, not routine
Indiana	Strength tests from cores, not routine
Kentucky	Strength tests from cores, not routine
Louisiana	Only for rehab
Maine	Not usually for substructure; only if problems
Maryland	Compressive testing for strength from cores
Massachusetts	Strength tests from cores
Michigan	Strength tests from cores
Minnesota	Strength tests from cores
Nebraska	Compressive strength tests from cores
Nevada	Strength tests from cores
New Jersey	Strength anomalies
New York	Strength tests from cores, determine extent of repair
North Carolina	Strength tests from cores
North Dakota	Strength tests from cores, if problems
Oregon	Strength tests from cores
South Carolina	Strength tests from cores, infrequently
South Dakota	Strength tests from cores, if needed
Texas	Strength tests from cores
Utah	Strength tests from cores--full depth

Table A-10. Use of strength tests (*continued*).

State	Comments
West Virginia	Visual "determination" of strength from cores
Wisconsin	Not as matter of course
Wyoming	Strength tests from cores
Alberta	Compressive strength tests--not routine
British Columbia	Strength test from cores
Manitoba	Regular basis if chain drag reveals problems
New Brunswick	Strength by impact hammer readings
Nova Scotia	Occasionally strength tests
Ontario	Yes--from cores, only if necessary
Saskatchewan	Only if serious problem is detected

*States and provinces not listed do not perform strength tests.

Table A-11. Use of freeze-thaw tests by states and provinces.*

State	Comments
Arkansas	Not unless significant problems arise
California	Only if problem
Idaho	Only in design of mixes
Indiana	Only if a problem arises
Kentucky	Lab, not routine
Maine	Not usually, early on new concrete plants
Massachusetts	Only when needed
Nevada	Only if requested
New York	Yes--to determine extent of repair
North Dakota	Extreme cases only
Tennessee	Not normally
Washington	Yes

*States and provinces not listed do not perform freeze-thaw tests.

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