

cess. Some agencies that use deicing chemicals during the winter months try to clean the seats and bearing areas where possible with a power water spray each spring.

The solution to the problem of protecting the elements below the joint is normally to add a flexible seal in the opening or a drainage trough under the opening. Neither of these solutions has a very good success record. The flexible seals tend to leak. They are damaged by the mechanical wear of the traffic and the noncompressible debris that jam the space above the seal and eventually cause a puncture. The adhesive fails in bonding the seal to the concrete or the surface of the concrete fails adjacent to the adhesive. The seal deteriorates by weathering, and its elastic properties are diminished by many cycles of being stretched and compressed.

Thousands of bridges currently in service have been seriously damaged by joint problems. Repairs are difficult and expensive. The repair dollar buys less than the new construction dollar due to the traffic problems involved, the smaller quantities, the estimating uncertainties, and the fact that much of the work is labor intensive. User costs are significantly increased, since motorists are delayed while the repairs are in progress.

Choosing the best available alternative for the deck expansion joint will continue to be an important consideration in the design, rehabilitation, and maintenance of bridges. Requirements for ensuring long-term service for deck joints in a given situation are a thorough knowledge of the past performance of available products, construction quality control procedures that ensure proper installation, and a responsive maintenance organization with the knowledge and capability to ensure that the joint performs properly.

Past attitudes have often been not to worry about a disintegrating structure unless there were traffic problems, as it would be obsolete or the roadway

alignment would be relocated before the condition became unsafe. With three out of four bridges in the United States more than 45 years old (6, p. 5), replacement obviously cannot solve the problem. The current system of bridges has to be repaired and maintained, which places greater emphasis on resolving the bridge joint problem.

In most areas, the first step has been initiated. The problems are being documented by inspection. Current funding for repairs, however, permits only a feeble attempt to buy time. As funds become available, a consistent policy of systematic rehabilitation and preservation is needed. Rehabilitation will be useless and preservation impossible if funding is not linked with a commitment to maintenance.

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Publication of this paper sponsored by Committee on Sealants and Fillers for Joints and Cracks.

Detecting Deterioration in Asphalt-Covered Bridge Decks

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Information on the condition of bridge decks is required for reasons of safety and to develop a comprehensive program of maintenance, rehabilitation, and replacement. Where the deck has a bituminous surfacing, detecting deterioration in the concrete slab presents serious technical difficulties. In many cases, existing procedures are not adequate to produce reliable information. This paper reports the technical and economic evaluation of the following test techniques: chain drag, sonic reflection, ultrasonic transmission, microseismology, resistivity, electrical potential, radar, and thermography. All of the techniques were investigated under controlled conditions at a full-scale test site. The results were compared with the criteria developed for an ideal test method. Radar and thermography were found to have the most potential for development into routine operational procedures for detecting deterioration in asphalt-covered bridge decks. Also, additional development work needed was identified.

Knowledge of the condition of the bridges within its jurisdiction is essential for a highway agency to ensure a safe and adequate system and to develop a comprehensive program of maintenance, rehabilitation, and replacement. In recent years, bridge decks have been especially prone to rapid deterioration wherever deicing salts are used. Although time

consuming, collecting reliable information on the condition of exposed concrete decks is relatively straightforward (1,2). Determining the condition of asphalt-covered decks presents an entirely different set of problems. Not only can the asphalt hide defects until they are well advanced, but it is often difficult to distinguish between deterioration in the concrete deck slab and debonding of the overlay.

The investigation that is reported here was undertaken to identify those procedures that have the potential to detect deterioration in asphalt-covered bridge decks more accurately than conventional procedures. Although the prime objective of the study was to improve the quality of information supplied by the traditional method of visual inspection supplemented by coring, reducing costs would be an important secondary benefit.

REQUIREMENTS FOR TEST PROCEDURE

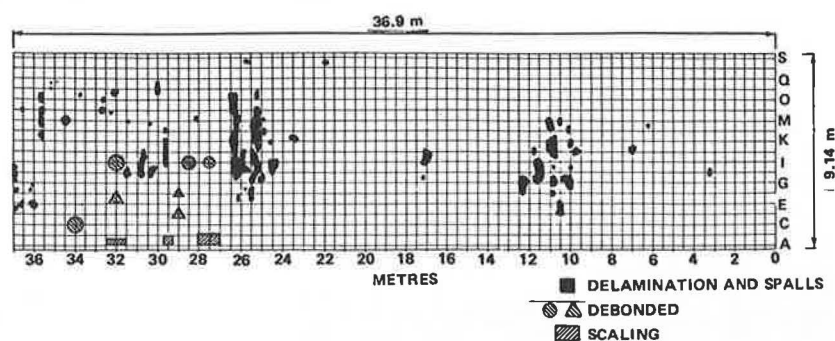
The requirements for the ideal test procedure can be defined as follows:

Table 1. Screening of candidate systems.

Test Procedure	Slab Thickness	Independent of			Temperature (above 0°C)	Surface Only	Nondestructive	Noncontact	Speed
		Overlay Thickness	Waterproof Membrane						
Chain drag	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Slow
Sonic reflection	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Moderate
Ultrasonic transmission	No	No	No	Yes	Yes	No ^a	Yes	No	Slow
Microseismic refraction	No	No	No	Yes	Yes	Yes	Yes	No	Slow
Resistivity	Yes	Yes	No	Yes	Yes	Yes	No ^b	No	Slow
Electrical potential	Yes	Yes	No	- ^c	Yes	Yes	No ^b	No	Slow
Radar	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Moderate
Thermography	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Fast

^a Yes, if indirect transmission mode used.^b Holes are normally drilled through bituminous surfacing.^c Above 10°C.

Figure 1. Deck deterioration prior to paving (chain drag).



1. The procedure should be independent of (a) concrete deck type and thickness, (b) thickness of bituminous surfacing, and (c) presence and type of waterproofing.

2. Testing should be required only on the top surface of the deck; it should be nondestructive and preferably noncontact.

3. Test results should not be influenced by climatic conditions, especially temperature and precipitation.

4. The procedure should be rapid, accurate, and inexpensive.

5. The results should be quantitative and should preferably be transcribed to a scale plan of the bridge deck by using automated equipment.

The extent to which these ideal requirements can be compromised will vary. For example, in urban areas where the costs of traffic-control measures for lane closures are high, there is a greater priority for a procedure that can be carried out from a moving vehicle than in low-traffic-volume rural areas. Similarly, a procedure that was rapid and accurate but effective only under specific weather conditions would still be useful, provided that several bridges could be inspected when the appropriate conditions prevailed.

CANDIDATE SYSTEMS

A review of the technology of nondestructive testing was undertaken to identify those techniques that might have application to asphalt-covered bridge decks. Each technique was assessed for its potential to satisfy the criteria developed for the ideal test procedure. A summary of the assessment is given in Table 1. Other techniques, such as nuclear radiation and x-rays, were considered but were not evaluated, either because they are insensitive to locating fracture planes perpendicular to the direction of the radiation or because the time required for data collection rendered them impractical.

A procedure that is shown in Table 1 to be inde-

pendent of deck and overlay thickness means that the thickness does not need to be known in order to calculate or interpret the results. This does not imply that the results are not affected by overlay thickness and, in fact, the sensitivity of most methods decreases as the overlay thickness increases. Temperature (above 0°C) has been listed as the only weather variable, since none of the test methods would normally be used during precipitation, when free moisture is present on the deck surface, or in subfreezing temperatures.

PAPINEAU CREEK TEST SITE

Preliminary testing of some of the procedures indicated that the correlation between anomalous areas and the physical condition of the deck slab would be expensive and presented serious logistical problems.

The decision was made to create a test site that included the types of deterioration of interest and one where all of the test procedures could be evaluated under controlled conditions. The Papineau Creek Bridge, located near Bancroft, Ontario, was selected for the test site. The structure, built in 1968, has three spans and consists of a thin slab deck on prestressed concrete beams. It is 36.9 m long and 9.14 m wide between curbs and typical of a large number of bridges in the province. The bridge was built with an exposed concrete deck surface, and by 1980 the deck exhibited corrosion-induced distress. The condition of the structure was documented, instrumentation was installed, and a bituminous surfacing was placed without making repairs to the deck slab.

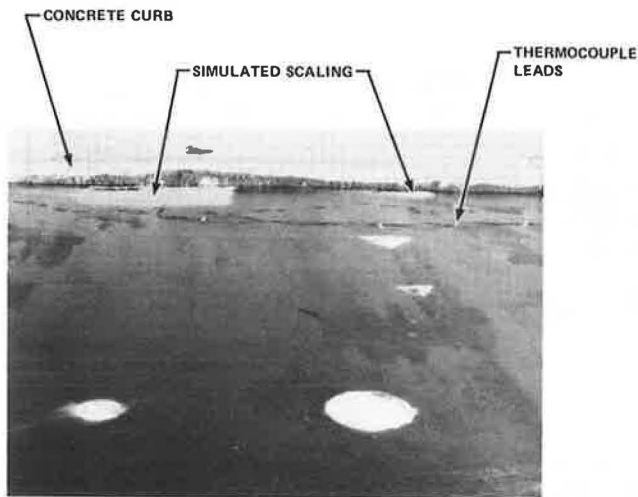
The condition of the existing deck slab was recorded by measurement of the electrical potential and cover of the reinforcing steel on a 0.5x0.5-m grid and by plotting the delaminated areas and spalls on a site plan. The delaminations were detected by using both a chain drag and a hammer. The spalls occupied 0.2 percent of the deck area and the delaminations 6.4 percent. The locations of the delaminations are shown in Figure 1. They were in the

form of a large number of small delaminations predominantly associated with the reduced cover present over the two piers. Cover measurements were in the range of 17 to 44 mm with an average of 32 mm. Electrical potentials ranged from -0.07 to -0.58 V CSE with 14 percent of the deck area more negative than -0.35 V CSE.

Prior to paving, thermocouples were installed at several locations in the deck and on the deck sur-

face. A section of the deck was also selected to simulate the presence of scaling and to introduce lack of bond between the bituminous overlay and the concrete deck slab. The scaling was simulated by placing coarse sand to a thickness of approximately 10 mm at three locations. The debonding was accomplished by attaching circular and triangular masks to the deck at six locations prior to application of an asphalt emulsion tack coat to the entire deck. After the tack coat had cured, the masks were removed and a thin layer of powdered talc was spread directly on the concrete surface. The areas of debonding and scaling are shown in Figure 2. The deck was paved with two 40-mm lifts of bituminous concrete by using conventional materials and equipment. Thermocouples were installed at two locations between the two overlay courses.

Figure 2. Area of deck showing scaling and debonding after tack coating and before paving.



Note: Circles and Triangles are Debonded Areas

EVALUATION OF TEST PROCEDURE

Tests were undertaken of the procedures listed in Table 1 to determine their effectiveness and to assess the practicality and economy of the procedures in identifying the known areas of deterioration and debonding at the Papineau Creek test site.

Chain-Drum Survey

Two sonic techniques were investigated, both of which depend on monitoring the audible sound that results from striking the deck surface. The chain drag is the traditional method of identifying delamination in exposed concrete bridge decks and has been found effective for this purpose (3,4).

The chain-drum survey at the test site was performed by a technician experienced in the technique but who had no prior knowledge of the condition of

Figure 3. Chain-drum survey.

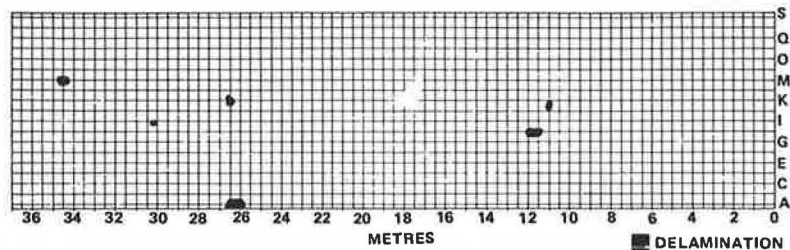


Figure 4. Sonic-reflection survey, August 1980.

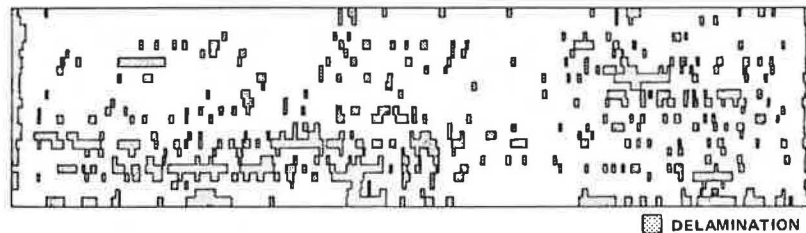
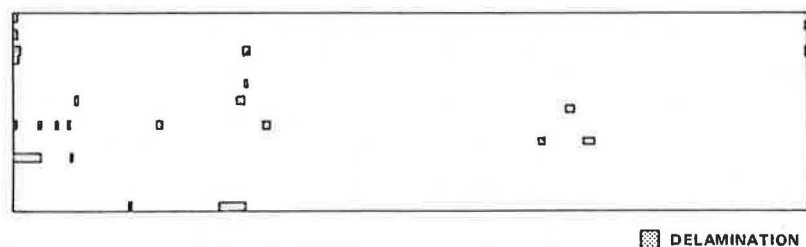


Figure 5. Sonic-reflection survey, June 1981.



the deck. The survey results are shown in Figure 3. Six areas were identified as delaminated. Five corresponded to known delaminations, but the areas were smaller than the actual delaminations. The sixth area corresponded with the largest area of scaling, and the technician indicated that the sound was different from the other delaminations but could not explain the difference in terms of physical distress. The five areas of delamination represented 0.5 percent of the deck area, or 13 percent of the known delamination. The areas of debonding were not detected.

Sonic Survey

The second sonic technique involved the use of a commercial instrument developed and used for delamination detection on exposed concrete bridge decks. It has also been claimed to be capable of detecting delamination up to 115 mm below the surface of asphalt-covered decks (5). A complete description of the equipment is found elsewhere (5,6).

Two surveys were made, one in 1980 and the other in 1981. Because the instrument surveys only a 150-mm-wide band on each pass, a grid-line spacing of 0.4 m was used to minimize the possibility of missing small, isolated delaminations. This grid-line spacing is much less than would be considered normal in commercial practice, where grid lines are typically 1.5-m apart.

The calibration procedure used in the first survey was the same as that used on exposed concrete decks. The results, shown in Figure 4, indicated that 10 percent of the deck was delaminated, but the correlation with the location of the actual delaminations was poor. The lack of precision was attributed to the calibration procedure, which was considered unsuitable because of the different attenuation characteristics of asphalt and concrete.

In the second survey, the instrument was again calibrated by using the standard bar, and then an operator, who was experienced in working on asphalt-covered decks, adjusted the gain controls to reduce the sensitivity. The results are shown in Figure 5 and indicated deterioration in 1 percent of the deck area, or approximately 16 percent of the known delamination. The correlation between the location of the deterioration indicated and existing was only fair. The instrument could not distinguish between the scaling and delaminations and did not identify the areas of debonding.

Ultrasonic Transmission

In ultrasonic techniques, high-frequency sound waves are introduced into the test material. The sound waves travel through the material at a velocity that, in homogeneous materials, is related to the density and elastic constants of the material. In heterogeneous materials such as concrete, the wave velocity is also a function of the composition of the material and its porosity. The sound waves are reflected at interfaces in all materials, and this enables discontinuities and flaws to be detected. Ultrasonic techniques have been used to detect defects and as a measure of the strength of concrete for many years (7,8).

Measurements were made by using commercial ultrasonic equipment equipped with transducers operating at a frequency of 50 kHz and 10 pulses/s. A low frequency is necessary to minimize attenuation and scatter losses that result from the heterogeneous nature of concrete. Consequently, frequencies in the range of 20-100 Hz are normally used (9).

The instrument was used in the direct transmission mode with the transducers placed on each side

of the deck. Glycerine was used to reduce coupling losses. The survey was commenced in the area of simulated scaling.

The pulse velocities through the deck did not correspond with known areas of deterioration, and testing was terminated because the equipment was considered impractical for this application. Calculation of the pulse velocity in the deck depends on a knowledge of the path length between the transducers. Not only was it not possible to align the transducers directly opposite each other, but variations in the thickness of the deck slab and bituminous surfacing can be expected to change the path length by the order of 10 percent. This is the same order of magnitude as the differences that would be expected from changes in the quality of the concrete. Ultrasonic measurements are especially sensitive to changes in the thickness of the asphalt because of its very high attenuation characteristics. Velocities in concrete are also known to be moisture dependent (8). It is also worth noting that at the Papineau Creek bridge, as is common with many other bridges, the delaminations were predominantly over the piers, where the presence of the diaphragms makes the deck soffit inaccessible.

Indirect transmission, in which both transducers are placed on the deck surface, did not yield meaningful results because of the unknown path length in three different materials, i.e., the bituminous surfacing, the concrete deck slab, and the reinforcing steel.

Microseismic Survey

Microseismic refraction was investigated in the 1940s as a method of measuring the quality of concrete (10) and in the mid-1960s as a means of detecting deterioration beneath asphalt wearing courses (11), although it has not been used extensively for this purpose. The method measures the time, and hence the velocity, of the propagation of a mechanical disturbance through a medium.

A limited survey was carried out with a 12-channel seismograph commonly used in studies of rock strata. Two 10-m grid lines were investigated, one of which was in an area of sound deck and the other in an area that included delaminations. A 9-kg hammer was used to strike a metal plate on the deck surface to generate the shock wave. The number of blows and the spacing of the geophones were varied to produce an optimum response.

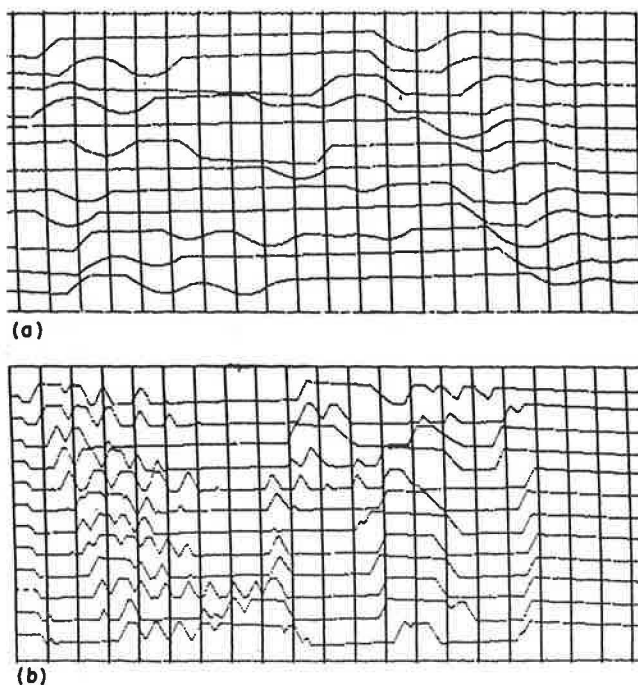
Typical wave traces for the sound and delaminated areas are shown in Figure 6. The equipment was found to be capable of differentiating between sound and unsound areas of the deck. However, interpretation of the data, even with the assistance of seismic experts, was difficult, and it was not possible to define the location of the discontinuities in order to estimate the area of deterioration. It was concluded that, although the test had potential, it was time consuming and not as promising as some of the other procedures evaluated. Consequently, further testing was not undertaken.

Resistivity Survey

The standard resistivity test method for assessing the integrity of membranes (ASTM D3633) was evaluated for its potential to indicate the quality of the concrete. Although the method was considered unlikely to be useful for detecting delamination, it was thought possible that moisture within severely scaled areas might change the resistivity sufficiently to identify these areas.

The test was performed on two occasions. The first time the sponges were placed on the deck sur-

Figure 6. Seismograph output for (a) sound and (b) delaminated areas.



face and the resistivity was measured periodically over 4 h by using an alternating current resistance meter. On the second occasion, holes were drilled through the bituminous surfacing to the concrete surface and resistance readings were taken instantaneously and after a period of 30 min. The readings were erratic during both tests and there was no correlation between the resistivity and the physical condition of the deck slab. The procedure was deemed to be unsatisfactory from the standpoint of both the value of the results and the time required for its completion.

Electrical Potential

The measurement of half-cell potentials to indicate corrosion activity is well established. When used on an asphalt-covered deck, drilling through the surfacing to ensure contact with the concrete surface is desirable. It is essential when a waterproofing membrane is present.

All of the grid points were drilled, the holes were filled with a wetting solution, and the half-cell potentials were measured in accordance with the ASTM C876 test method. The potential measurements were found to be less than those recorded prior to paving, and the range of values was -0.37 to $+0.03$ V CSE. Positive values and low negative values of potential are usually indicative of dry concrete. However, it is not only the absolute value of potential that is important, but the range of values also is important. In this case, the range of 0.4 V indicates the existence of well-developed anodic and cathodic areas in the deck slab. The pattern of the isopotential lines for the prepaving and postpaving conditions is very similar, as shown in Figure 7, although the absolute values are different and may reflect a change in the moisture content of the deck slab. It may also explain why there appeared to be little change in the area of delaminations in the two years after the deck was paved.

The results of the potential survey on the Papineau Creek Bridge are not typical of experience

in Ontario on other asphalt-covered decks where there has been a good correlation between corrosion activity and the values of -0.35 and -0.20 V CSE normally used to indicate the presence and absence of corrosion activity, respectively. Even though the correlation with corrosion activity is usually good, it is important to recognize that the measurement of potentials will only indicate areas of corrosion-induced distress. It will not identify the deterioration of the concrete by other mechanisms, nor will it identify areas of debonding.

Radar

The use of low-power, high-resolution, ground-penetrating radar for detecting deterioration in concrete bridge decks was first reported in 1977 (12). Additional work resulted in improvements in the accuracy of the technique (13,14). The system consists of a monostatic antenna, a control console that contains a transmitter and receiver, and an oscilloscope. A 1 nanosecond (ns) pulse of low-power radio frequency energy is directed into the bridge deck and the echo is received and displayed on the oscilloscope. A very high frequency is required in order to identify delaminations because the size of the discontinuity perpendicular to the impulse is very small. The equipment was mounted on a hand-pushed cart and the deck was surveyed at the same grid points as used for all the test methods. The waveforms were recorded by an instant camera and analyzed manually.

Figure 8 shows a typical radar signal for a sound portion of the deck and Figure 9 shows the signal for a section known to be delaminated. The part of the waveform of greatest interest is that that corresponds to the upper regions of the concrete deck slab and to the interface between the surfacing and the slab. These regions are indicated in Figures 8 and 9 together with the other significant features of the waveform. In areas where the concrete is deteriorated or the character of the interface changes, the amplitude and time of the echo also changes.

The ability to detect the interface between the concrete and the asphalt has the important benefit of being able to measure accurately the thickness of the asphalt surfacing. Thicknesses as large as 250 mm have been found in Ontario on some older decks for which records are incomplete. Such large thicknesses have repercussions on the live load capacity of the bridge as well as increasing the costs of condition surveys and repair contracts. On newer decks, which have a good quality waterproofing membrane, it may be possible to use radar to determine if the concrete slab is sound and, by measuring the asphalt thickness, remove most of the surfacing by cold-planing and replace it without disturbing the waterproofing membrane. Such a procedure would result in a substantial reduction in cost from the current practice of replacing the waterproofing membrane when the adjacent roadway is resurfaced approximately every 15 years.

The radar identified 51 percent of the grid points located over the delaminations and the simulated scaling. It did not identify the areas of debonding, and the operators also falsely indicated numerous grid points to be delaminated, thereby reducing the overall accuracy to 26 percent. The results are shown in Figure 10. However, further examination of the data indicates that the accuracy can be improved considerably. Many of the false readings were actually located close to delaminated areas, and since the radar senses an area of approximately 150 cm^2 , the presence of these areas influenced the waveform. Continuous recording of

Figure 7. (a) Prepaving and (b) postpaving electrical potentials.

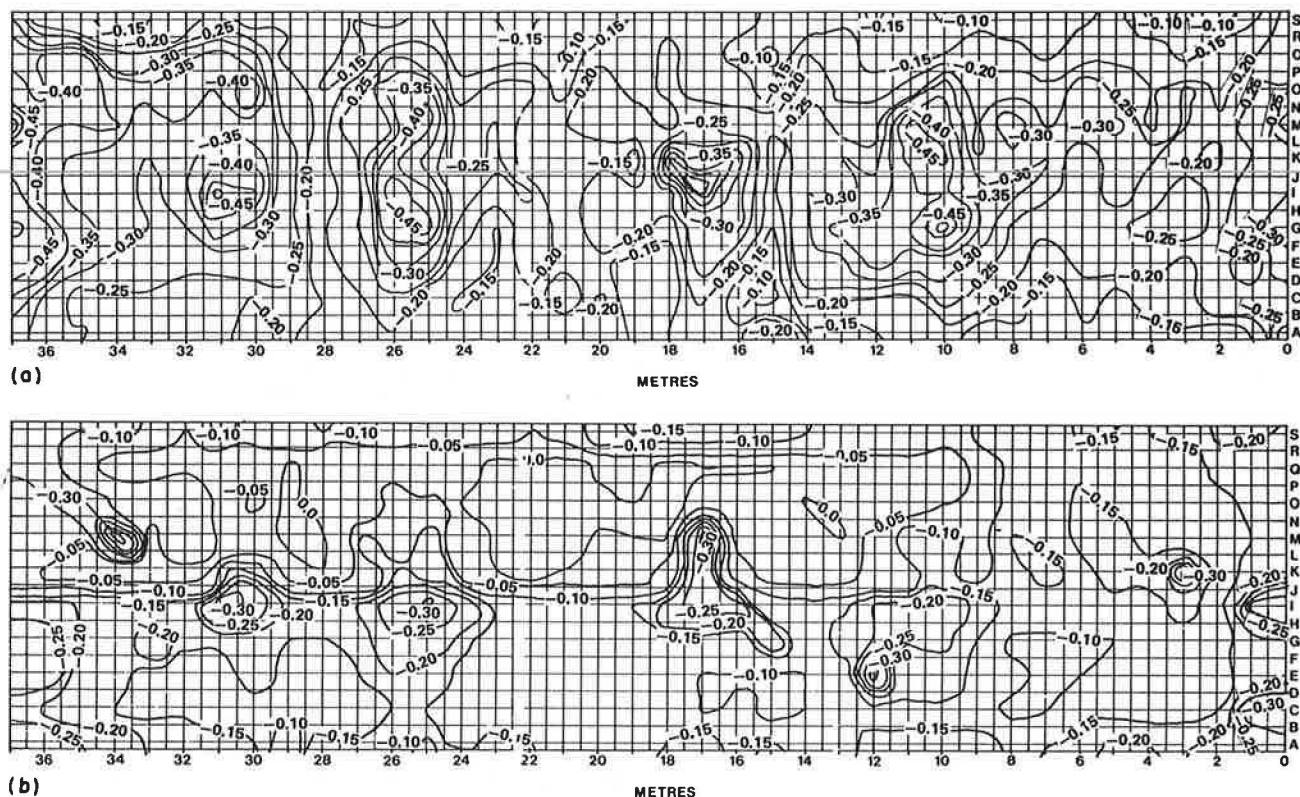


Figure 8. Radar output for sound concrete.

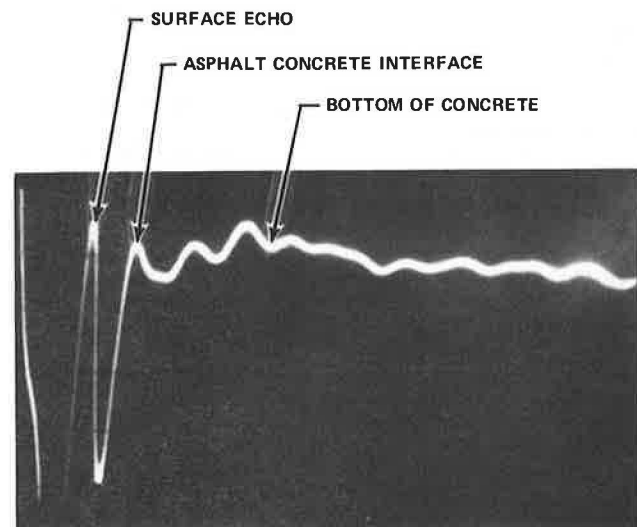
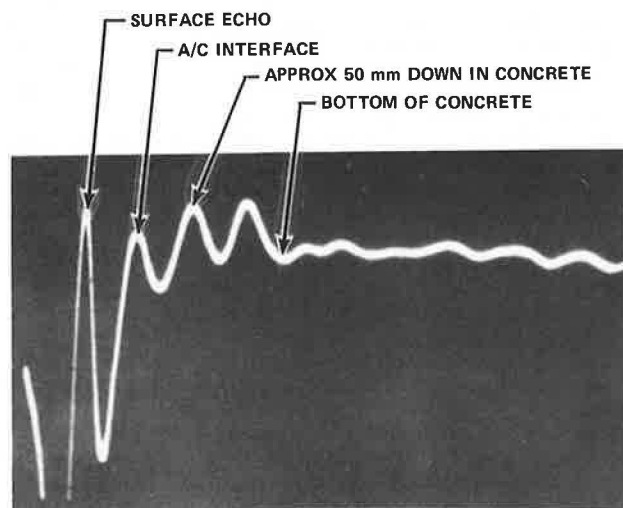


Figure 9. Radar output for delaminated concrete.



the data rather than measurements at discrete grid points would define the areas of deterioration more precisely.

The system as used was rather crude, and the interpretation of the wave traces, although done by the developers of the equipment, was subjective because of their limited experience on bridge decks and the absence of correlations between waveforms and the physical condition of decks. The equipment has the potential for significant improvement by mounting the radar on a vehicle in addition to recording the data continuously on analog magnetic

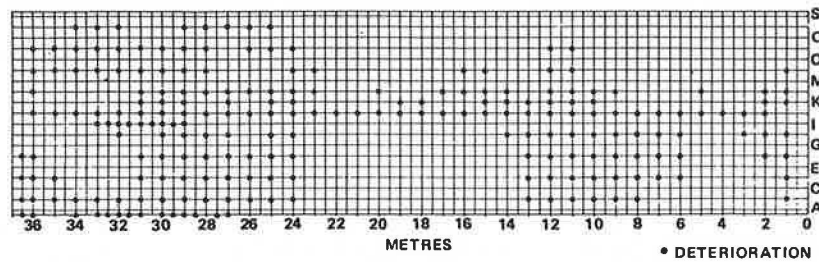
tape for off-line processing. The test time could then be reduced by using several antennae to collect one lane-width of data and driving the deck at a speed of no more than 20 km/h. Appropriate software could be developed to analyze the data automatically.

The radar system satisfies most of the requirements for the ideal test method. The only environmental influence is the presence of moisture within the surfacing, which will affect the waveform.

Thermography

Temperature measurements were made as part of the

Figure 10. Radar survey.



investigation of the validity of thermography by using thermocouples installed in the deck prior to and during paving.

Figure 11 shows a temperature profile through the deck on a summer day with minimal cloud cover. The profile is very similar to that recorded on exposed concrete decks (4). In the early morning, the temperatures were sensibly uniform throughout the deck. This represents the transition period as the temperature of the surfacing changes from being cooler than the concrete deck slab during the night to warmer during the day. As the deck began to heat, a substantial temperature gradient developed through the deck. By 11:00 a.m., the difference in temperature between the thermocouples at various levels in the deck was well established. There was also a clear difference between the temperatures measured 5 mm below the concrete deck surface in solid and delaminated areas (thermocouples 4 and 5). This difference was also present, although less pronounced, on the thermocouples (15 and 12) located between the two lifts of asphalt directly above thermocouples 4 and 5 and on the deck surface, as shown in Figure 11 and Table 2. Surface temperature measurements were made with a contact probe. Because the infrared scanner also measures surface temperature, the temperature measurements explain why thermography is capable of detecting delaminations in the concrete slab. The time and power required for the temperature gradient to develop also explains why artificial sources of heat are not feasible. The difference in surface temperatures over the solid and delaminated sections reached a maximum of 2° at 2:00 p.m. and then gradually diminished until it was only 0.2° at 6:00 p.m. This pattern is very similar to that reported for exposed concrete decks through the "window", during which thermography can be used to detect delamination is much smaller on asphalt-covered decks.

Several commercial infrared systems were tested by using various configurations of the equipment. The systems were tested at ground level from a boom truck and, in some cases, from a helicopter. Airborne testing was found to be beyond the capability of even the most sensitive equipment, since both the spatial and thermal resolution is inadequate to recognize delaminations from the minimum altitude required by air regulations. The viewing angle at ground level was found to be too flat and the field of view too small. Delaminations were visible but poorly defined, and there was interference from radiation reflected from the deck surface. The boom truck was found to be the most practical platform from the point of view of both accuracy and speed. The optimum height above the deck for the camera was in the range of 4-6 m to give the best definition of delaminated areas with the least interference from reflected radiation. Spatial resolution was good, and changes in surface emissivity caused by tire marks and oil spills could be identified and were not confused with delaminations.

Figure 12 enables a comparison to be made in three areas between thermograms taken from the boom

and the delaminations that were present in the deck prior to paving. The delaminations are visible as white or hot areas against a dark or cooler background. The correlation with the prepaving condition of the deck slab was excellent, although the outline of the delaminations was less distinct or "softer" as a result of dissipation of heat in the bituminous surfacing. The delaminations first became visible at 11:30 a.m., and the definition improved until about 3:00 p.m. when the thermograms illustrated in Figure 12 were taken. The resolution then deteriorated until by 6:00 p.m. the delaminations were barely visible. These observations are consistent with the data contained in Table 2. The scanner detected more than 90 percent of the known delaminations, some of which were less than 150 mm in diameter. The areas of scaling and debonding were not visible in the thermal images. Debonding was not detected because the bituminous surfacing and the deck slab were in intimate contact and did not cause a thermal discontinuity. The inability to detect the scaling was ascribed to the fact that the areas were located adjacent to the curbs, and any difference in surface temperature was masked by flares on the image that result from the difference in emissivity between the asphalt deck surface and the concrete curbs. Of the commercial systems that were used, only those that had a full gray scale setting of two isotherm units and a minimum thermal resolution of 0.2°C were found capable of detecting the delaminations.

A potential problem with the use of thermography is that, while a positive result is valid, a negative result may mean that the deck is free from delaminations or that the deck contains delaminations but that these could not be detected under the weather conditions prevailing at the time of the test. As already noted, differences in surface temperature develop more slowly on asphalt-covered decks than exposed concrete decks and are more sensitive to weather conditions. It was found that a period of early morning heating, during which the cloud cover was less than 40 percent, was essential to the development of differences in surface temperature. Thermography was successful in identifying the delaminations on days when the air temperature was not less than 18°C , the wind no greater than 40 km/h, and the relative humidity less than 50 percent. Under these conditions, delaminations were never visible before 10:00 a.m. but could be identified during the period 11:30 a.m. to 6:00 p.m. Although further testing and experience will better define the conditions under which thermography is applicable, the above parameters constitute a useful and practical guide. Methods of predicting the temperature distribution in bridge decks from a knowledge of atmospheric data, member sizes, and the properties of the deck materials have been developed (15,16). It is possible that analytical studies may assist in defining the conditions under which the necessary differences in surface temperature will develop.

CORING PROGRAM

After evaluation of the different test procedures, cores were taken at selected locations to confirm the existence of defects and to investigate the reason for anomalies identified by some of the test methods. The results are given in Table 3, and the condition of the cores taken at four of the grid points is illustrated in Figure 13.

The cores confirmed the existence of the delamination and scaling known to be present in the deck and the fact that the surfacing was well bonded to the deck except where bond was deliberately prevented. No new areas of delamination were identi-

fied, even where some of the test methods indicated deterioration. Deterioration indicated by the chain drag and themography was confirmed. In all but one of the cores taken in areas indicated as deteriorated by radar, but where no deterioration was present, the anomaly was the result of steel reinforcement at the grid location. Further experience in interpretation of the signal and the continuous recording of data should enable this condition to be recognized. Concrete, and especially reinforced concrete, is a difficult material to analyze because, being heterogeneous, several dielectrics exists and separate waveforms may be reflected in sound material.

Figure 11. Temperature survey.

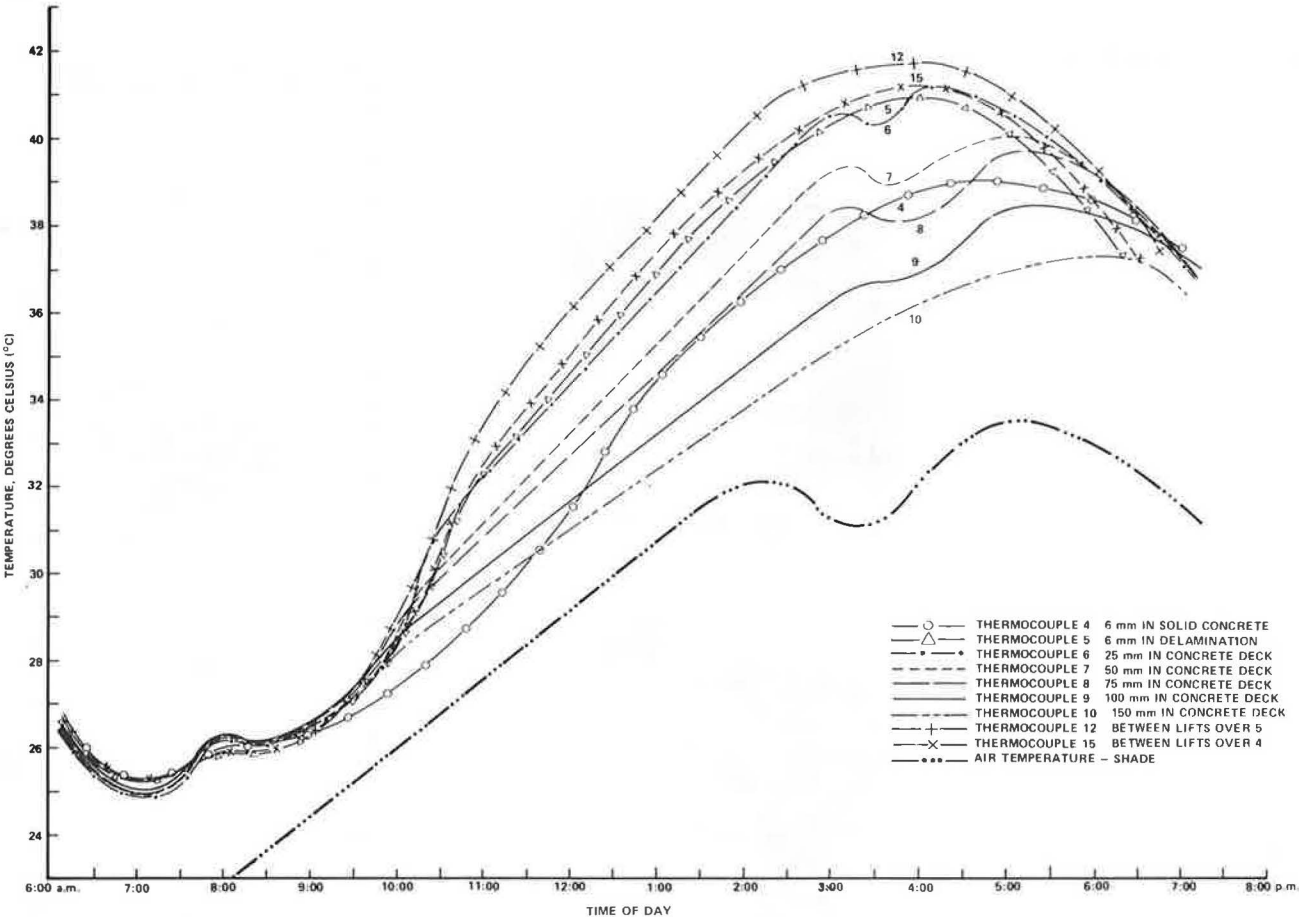


Table 2. Temperature data.

Time of Day	Temperature (°C)					
	5 mm Below Concrete Surface		Between Courses of Asphalt		On Deck Surface	
	Delaminated	Solid	Delaminated	Solid	Delaminated	Solid
9:00 a.m.	26.3	26.2	26.4	26.2	28.9	28.9
10:00 a.m.	28.1	28.0	28.2	28.1	31.9	31.8
11:00 a.m.	33.1	29.4	33.3	33.3	35.8	35.0
12:00 noon	34.8	31.1	35.8	35.0	38.4	36.8
1:00 p.m.	37.3	34.5	37.8	37.5	40.5	37.9
2:00 p.m.	39.2	36.1	40.1	39.4	41.5	38.6
3:00 p.m.	40.2	38.1	41.1	40.3	41.7	39.7
4:00 p.m.	40.5	38.5	41.6	40.6	41.9	39.9
5:00 p.m.	39.9	39.2	41.0	40.0	41.6	39.3
6:00 p.m.	38.5	38.5	39.7	38.5	39.4	39.2

DISCUSSION OF RESULTS

A summary of the evaluation of each test procedure is given in Table 4, which also indicates the additional work that is needed to develop some of the methods into practical investigative procedures. An estimate of the cost of each of the procedures not rejected in Table 4 is given in Table 5. Although costs will vary with local conditions, the estimates are sufficiently accurate for comparative purposes. Where a service was purchased to include personnel and data analysis, only the total cost is given.

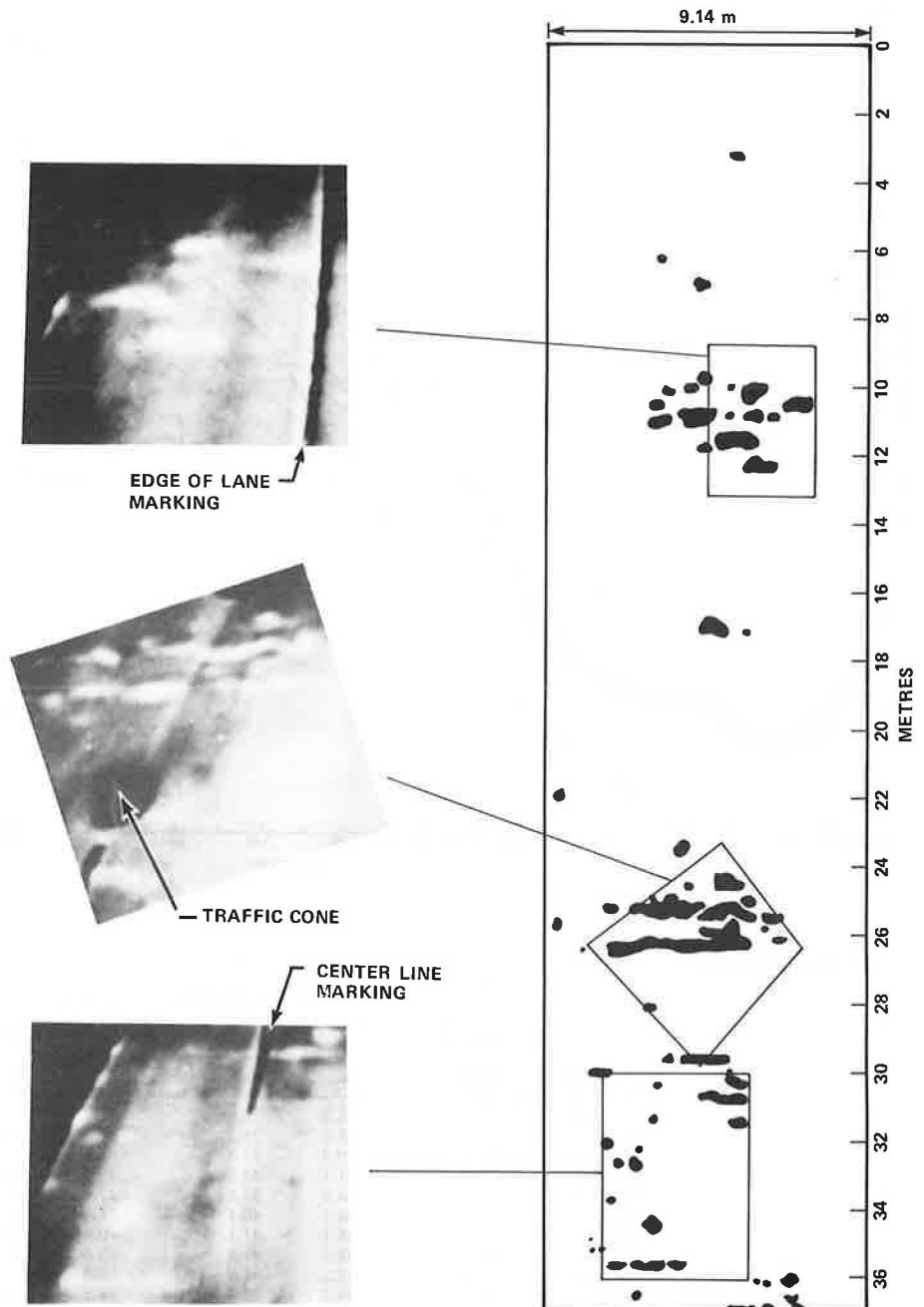
The chain drag and the measurement of electrical potentials did not give sufficient information to be used as a single test procedure. However, they were found to be useful components of the conventional approach to condition surveys, which includes detailed visual inspections and selective removal of

the bituminous surfacing and coring. The chain drag has the advantages of being simple, inexpensive, and useful in identifying anomalous areas for further investigation.

A more precise calibration procedure is required for the sonic-reflection device, since the capability of the instrument to detect deterioration must be improved significantly for it to have application to asphalt-covered decks. The ultrasonic and resistivity surveys did not yield meaningful results. The microseismic survey was successful in showing differences between sound and delaminated concrete, but the procedure was slow, data analysis was tedious and qualitative, and microseismology appeared to be less likely to result in a routine operational procedure than either radar or thermography.

Radar most nearly satisfies the criteria for the

Figure 12. Thermograms for selected deck areas.



ideal test method, and the technology exists or is being developed to overcome the deficiencies noted in this investigation. The principal requirements are to automate the data analysis and to improve the correlation of the signal with the physical condition of deck slab to eliminate false results. It is also anticipated that, with more experience and an automated system, the cost of using radar would be reduced substantially if used in routine production work.

Table 3. Core results.

Core Location	Test Method That Indicated Deterioration	Core Condition
B27.5	Sonic, chain drag, and radar	Scaled area, 10-mm sand on deck surface
F36	Sonic and radar	No defects
H9	Sonic and radar	No defects, steel present
H11.5	Chain drag and thermography	Concrete delaminated
I31.5	Radar ^a and thermography	Concrete delaminated
I32.5	None ^b	No bond
J20	Sonic and radar ^a	No defects, steel present
K34	Radar ^a	No defects, steel present
L5	Sonic and radar ^c	No bond
L36	Radar ^a	No defects, steel present
M34.5	Chain drag and thermography	Concrete delaminated at two horizons
R10	Radar ^a	No defects, steel present

^aDeterioration indicated in top one-third of concrete.

^bDone to verify debonded area.

^cDeterioration indicated at asphalt/concrete interface.

Thermography produced the best correlation with the known deterioration at the Papineau Creek test site and was also one of the quickest and least-expensive test methods. It is recognized that the information produced is not the same as that produced by a conventional condition survey and that physical testing of the concrete in the deck slab will be necessary in some cases. However, the method does have considerable potential for assessing the condition of a large number of asphalt-covered decks in a short time. This information would be adequate for determining whether deterioration is present and for establishing priorities for repair. When used in this manner, the dependence on weather conditions would become less restrictive, since several structures could be investigated on days when weather conditions were suitable.

CONCLUSIONS

1. Of the several systems that were investigated, radar and thermography have the greatest potential for development into routine operational procedures for detecting deterioration in asphalt-covered bridge decks. Both methods are better suited to the rapid assessment of the overall condition of a large number of decks than to defining exact areas of concrete deterioration for contract purposes.

2. Radar requires further development to automate the data collection and analysis and to improve the interpretation of the signals.

Figure 13. Condition of cores removed from deck.

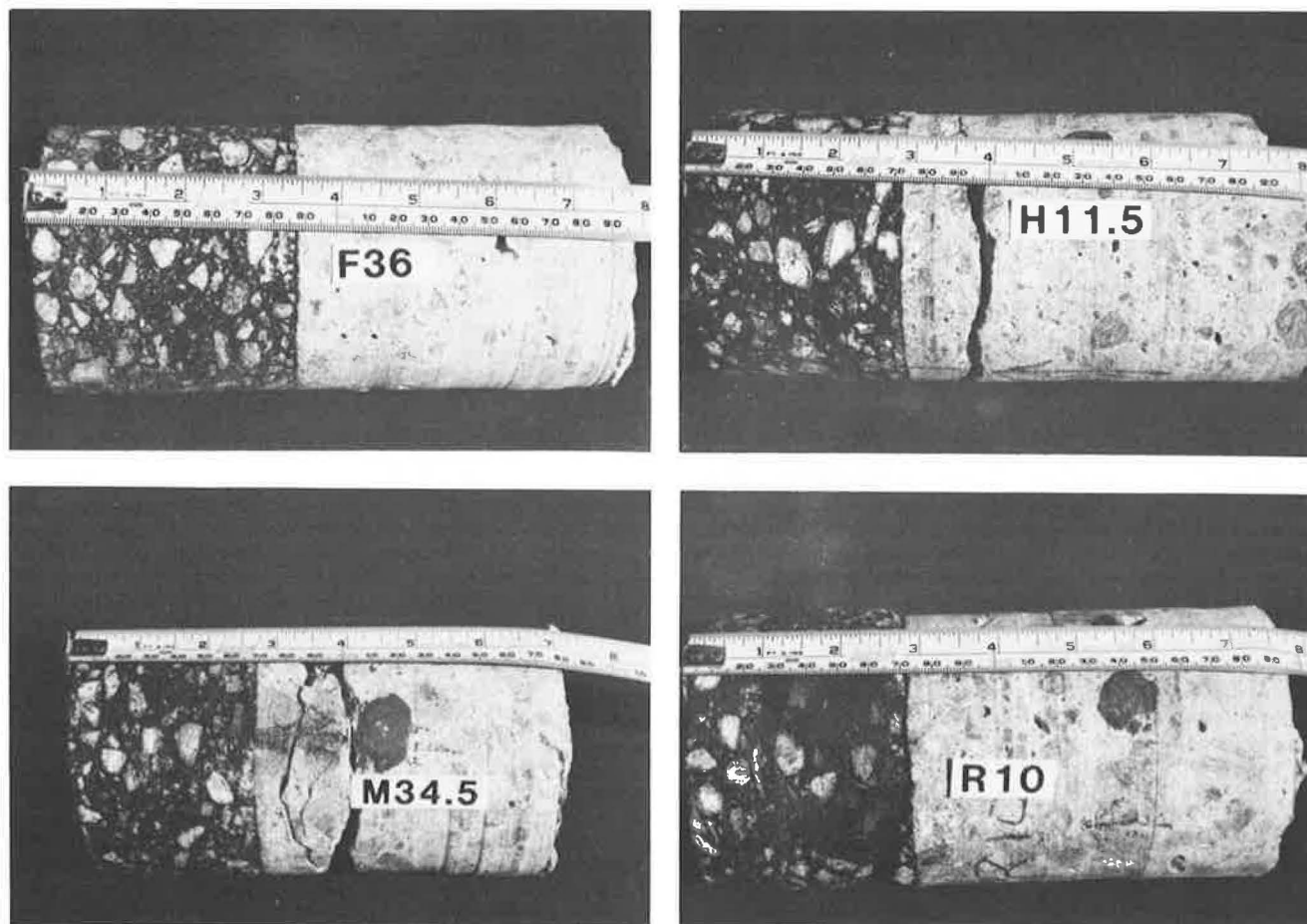


Table 4. Summary of results.

Test Procedure	Summary of Evaluation	Further Work Needed
Chain drag	Identified 13 percent of delaminated areas; no false results; independent of weather and inexpensive; useful screening device when conventional inspection procedures are used	
Sonic reflection	Very low accuracy	Develop calibration procedure for asphalt-covered decks
Ultrasonic transmission	Impractical	
Microseismic refraction	Identified anomalies but interpretation difficult; procedure is slow	Optimize and automate data collection and analysis; even with improvement, unlikely to outperform radar and thermography
Resistivity	Results not meaningful	
Electrical potential	Useful indication of corrosion activity; does not identify other forms of deterioration	
Radar	Good correlation with known deterioration but also many false results; most nearly satisfies the criteria for the ideal test method	Mount in a vehicle and record data continuously; improve interpretation of data and automate
Thermography	Excellent correlation with deterioration with no false results; main disadvantage is dependence on weather	Record data on videotape and develop software to permit hard copy of scaled image; define weather conditions for use

Table 5. Cost estimates for test procedures.

Test Procedure	Equipment Cost (\$)		Field Time (h)	Personnel Required		Traffic Control ^a (\$)	Data Analysis (\$)	Total Cost (\$)
	Purchase	Rental		No.	Time (h)			
Chain drag	15		4	1 2 ^c	3 ^b 1	300	60	435
Microseismic refraction	26 000	3900/month	8	1	8 ^d	500	400	1295
Sonic reflection		650	2	1 ^e	1 ^e	200	1 ^e	850
Electrical potential	400 ^f		6 ^g	2	6 ^b	400	60	640
Radar	37 000	2000/bridge	2 ^h	1 ^e	1 ^e	200	1 ^e	2200
Thermography	30 000	2000/month	1	1	1 ^d	150	200	475
Conventional condition survey	~4 000	~240/day	8	1	8 ^d 8 ^b	500	2200 ⁱ	3500

Notes: Costs are in 1982 Canadian dollars.
Deck size is assumed to be 300 m².

^a Assumes \$100 mobilization plus \$50/h.

^b At \$15/h.

^c To mark out grid lines.

^d At \$25/h.

^e Included.

^f Equipment also required for drilling through surfacing.

^g 1 x 1-m grid.

^h Uses magnetic tape for recording data.

ⁱ Includes physical testing of cores.

3. Thermography requires better definition of the weather conditions for its use and the development of software to produce a scaled hard copy from videotape.

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Publication of this paper sponsored by Committee on Structures Maintenance.