experiments, it can be concluded that CIR is an appropriate technology for evaluating the condition of concrete up to 75 cm (30 in) in depth by differentiating between serviceable concrete and deteriorated concrete, which consists of delaminations, deteriorations, microcracks, and cracks up to and including small voids. This is further supported by the field experiences described in the paper by Cantor and Kneeter elsewhere in this Record.

The following recommendations are made:

1. Theoretical analyses followed by field tests have successfully demonstrated the ability of radar to detect changes in materials and locate where these changes occur. It is therefore recommended that the system be enhanced for field operations.
2. It is further recommended, as considered in the paper by Cantor and Kneeter in this Record, that the CIR be made completely automatic, including signal processing and data handling, so that the radar system can be used as a maintenance management tool to provide greater cost benefit for roadway repair with minimum inconvenience to the riding public.

ACKNOWLEDGMENT

The contents of this paper reflect our views and do not necessarily reflect the views of Penetrader Corporation or the Port Authority of New York and New Jersey.

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Publication of this paper sponsored by Committee on Performance of Concrete.

Radar as Applied to Evaluation of Bridge Decks

T.R. CANTOR AND C.P. KNEETER

Approximately 90 percent reliability has been achieved in nondestructively identifying good and deteriorated concrete on a bridge deck, based on experimental research in the laboratory and field. The ability of concrete inspection radar to function reliably and repeatably in identifying the condition of concrete is established. Ability to detect voids is commented on. Present signal processing, data analysis, and interpretation via cluster analysis constitute a lengthy manual operation. However, with computer-assisted data automation, the system should be a viable field instrument operable by a technician.

Concrete inspection radar (CIR) has demonstrated its capability to reliably perform in the field as a nondestructive evaluation (NDE) tool for determining the condition of concrete (1-3). CIR has identified good and distressed concrete with 90 percent confidence (4).

Physical laboratory studies performed to calibrate the equipment and understand physical parameters include detection of voids, effects of steel, multiple material layers, antenna direction and angularity, water, temperature, and edge (5).

Included in the laboratory analytical studies were various signal-processing techniques, among which were topographic displays, photographic superimposition, graphic signature identification techniques, and mathematical models (3). Of the mathematical models, cluster analysis has resulted in the most reliable and least time-consuming classification of concrete (6).

The field operations were conducted on several major structures. Among the factors studied were reproducibility, influence of reinforcing steel, and varying void depths. The field investigation culminated in the physical verification of the concrete condition as interpreted by the analysis of the radar data (4).

To verify the radar-predicted conditions of distressed and good concrete, a physical evaluation was undertaken by field drilling. Depth of drilling was ranked and statistically analyzed and led to a physically verified confidence of 90 percent (4).

Automation of the present manual data processing by direct computer operation will make CIR a field system operable by a technician and capable of identifying and differentiating good and distressed concrete.

INTRODUCTION TO CIR

Starting at pouring of concrete, every structure in the infrastructure begins to deteriorate with time. The first evidence of this, generally, is surface cracking. With roads, riding surfaces may hide these defects until, in many cases, serious problems exist. Once water enters the cracks, deterioration increases more rapidly, because of either freeze-thaw stresses or rebar corrosion. The earlier the fault or impending fault can be detected, the less costly and easier it is to repair, with minimum inconvenience to the users of the facility (7).

The search to obtain an NDE tool capable of detecting deterioration as early as possible led Port Authority of New York and New Jersey (PANYNJ) Engineering Research and Development engineers down many paths, the most successful of which has been CIR (8).

Interest in radar as a possible NDE tool stemmed from radar development work by Calspan Corporation (9) in the mid-1960s, under U.S. Army contract, to detect buried nonmetallic mines. Subsequent CIR modifications allowed it to be used in the early 1970s to detect voids under pavements (1,2). Follow-up studies of this radar development work by PANYNJ Engineering Research and Development staff in 1974 led to the program of radar NDE testing and development described in this paper (10).

Engineering Research and Development has developed techniques for using CIR to experimentally evaluate concrete pavement conditions. Radar NDEs made in 1977 on bridge-deck pavement were substantially confirmed by core samples (10). Since 1977, the radar NDE effort has been primarily concerned with acquiring equipment, developing equipment reliability, accumulating radar laboratory and field experience, and experimenting with techniques to speed up and eventually automate the signal analysis process. There now exists a high degree of confidence (90 percent) in the ability of CIR to function reliably in the field and to distinguish good from defective concrete in pavement traverses at speeds from 12.9 to 16.1 km/h (8-10 mph).

The signal analysis and interpretation process is not yet automated, although progress is being made. Currently, signal analysis is a lengthy procedure that requires fairly extensive use of research skills.

It is estimated that millions of dollars per year in benefits may be achieved by extensive use of radar for NDE (11). These potential benefits result from greater certainty in maintenance scheduling, minimizing emergency repairs, detecting developing weaknesses, effecting repairs before failure, and more exact determination by radar survey of the amount of work to be performed prior to preparing contracts or inviting bids. It is recommended that the radar NDE program continue to speed up the analysis and interpretation of the radar signals. The training of technicians to perform radar NDE will be the final step.

EXPERIMENTAL DATA

The following section considers a combination of laboratory experiments and field diagnostic tests that, along with data processing and analysis, were undertaken to reach the present state of 90 percent confidence in identifying the condition of concrete by use of CIR.

Laboratory

The laboratory operations were undertaken to understand how radar interacted with concrete to calibrate radar signals or signatures. Among the wide range of studies conducted were the following: resolution; multiple reflections; stability; repeatability; concrete block studies of various thicknesses, singly and in combination; surface location by metal target; separation determination; modeling of roadway, bridge decks, etc.; air standardization studies; equipment compatibility; antenna angularity and directionality; rebar, water, and boundary effects; effect of temperature; and low power supply voltage. Space limitations allow only the following study examples to be developed here.

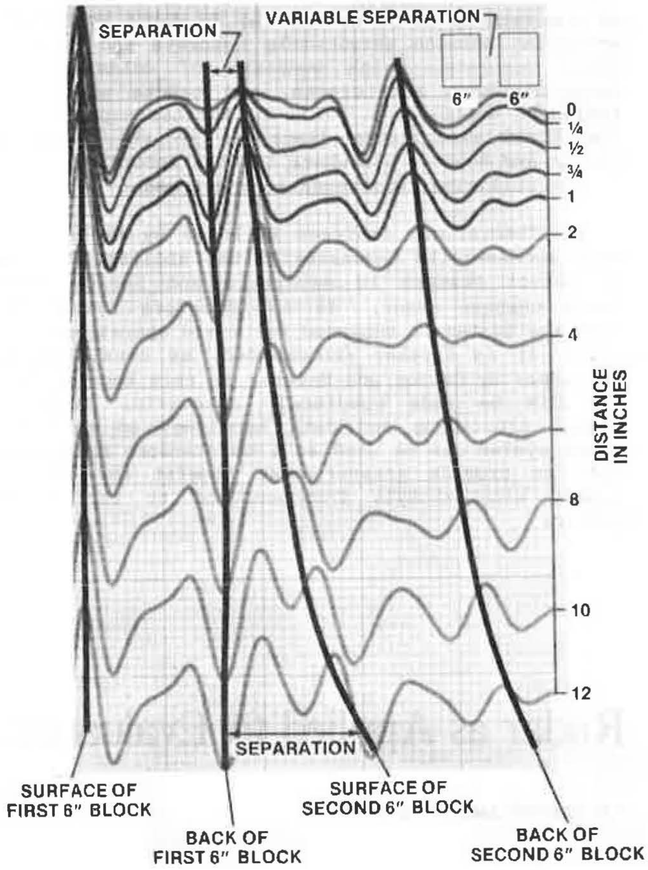
In one major study, two 15.2-cm (6-in) thick concrete blocks were positioned vertically in front of the CIR, with the rear block on rollers so that it could be moved to create a separation that could be varied from 0 to 30.5 cm (0-12 in) (see Figure 1). This work was the key to evaluating field void data. This study is described and analyzed in considerable detail in the paper by Alongi and others elsewhere in this Record.

Another calibration study was the use of several concrete slabs of different thicknesses to determine the appearance and reflections caused by the interface (see Figure 2). Trace modifications due to rebar inclusion proved to be negligible (12,13).

Field

The field operations were undertaken, first, to prove feasibility and, second, to quantify the ability of CIR to assess concrete condition and locate voids.

Figure 1. Variable separation of two 6-in-thick concrete blocks.



Several field studies follow: A 3-mile, four-lane, cantilevered truss bridge was the first structure to be field surveyed from a moving van at a speed of 12.9-16.1 km/h (8-10 mph) (see Figure 3) (10). At some locations, data were also taken with the vehicle stationary. The stationary data, when compared with data taken at the same location four years later, showed excellent repeatability (see Figure 4) (4) and the possibility of the onset of aging.

At the same speed, two wheel tracks in each of the four lanes of a 1.6-km (1-mile) long bridge were surveyed in about 3 h. This provided a trace for every 7.6 cm (3 in) of bridge deck.

In earlier work, trace superimposition (see Figure 5) was used to select some 60 locations to core. Where the traces overlaid each other, the concrete was found to be good--i.e., in good condition. Where there was poor superimposition of the traces, the quality of the concrete was poor--i.e., distressed. The excellent correlation achieved between CIR predictions and actual physical condition verified radar feasibility (10).

In a recent study covering 213 m (700 ft) of bridge deck, readings taken every 2.1 m (7 ft) accumulated more than 100 samples. The data were analyzed in the laboratory, and condition prediction was determined by cluster analysis (4). Physical verification of conditions was established by what is essentially a wearing test. The test consisted of measuring the depth drilled into the concrete by using a new 1.6-cm (0.625-in) carbide drill driven at fixed speed and with a fixed force for 2 min (see Figure 6). The data displayed in Figure 7 show a correlation between radar and drilling (wearing) of 90 percent, which establishes the ability of CIR to determine concrete condition.

A subsurface void or washout was suspected to exist under a taxiway (1-4, 13). The topographic presentation of the radar data delineating the void is shown in Figure 9 of the paper by Alongi and others elsewhere in this Record.

The signature of a tunnel roadway was considerably different from that of a bridge deck. Each had a distinctive signature because of differences in support steel and physical design. It was demonstrated both in the field and the laboratory that these signature differences caused no difficulties in data analysis. This was also true for rebars spaced over a large area. Once the signature is established, the analysis is only negligibly affected.

Figure 2. Trace identification: model of 4-in overlay on 6-in base.

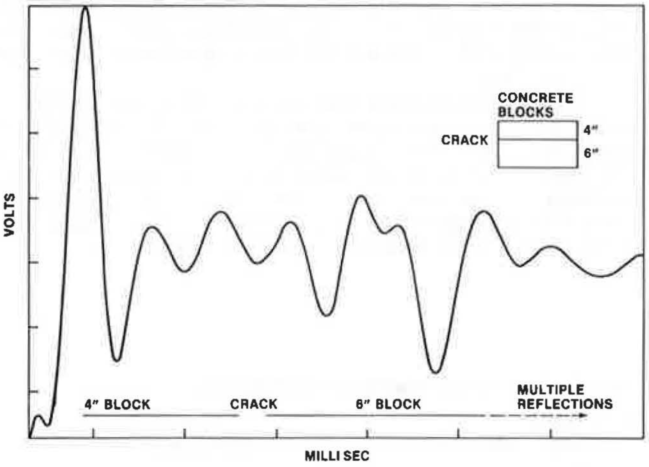
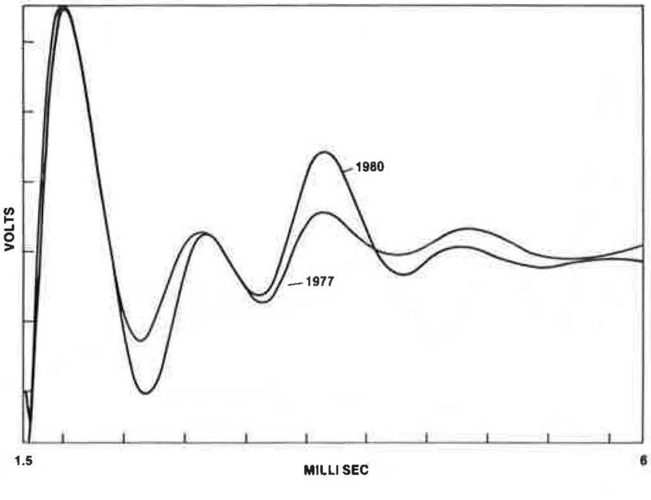


Figure 3. Van-mounted radar system.

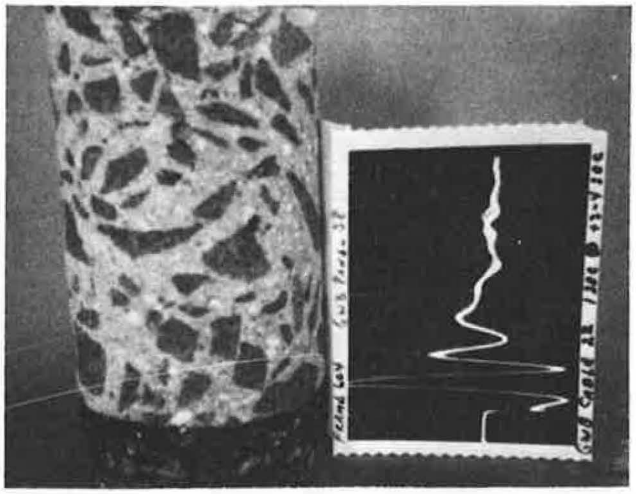
Figure 4. Repeatability of data.

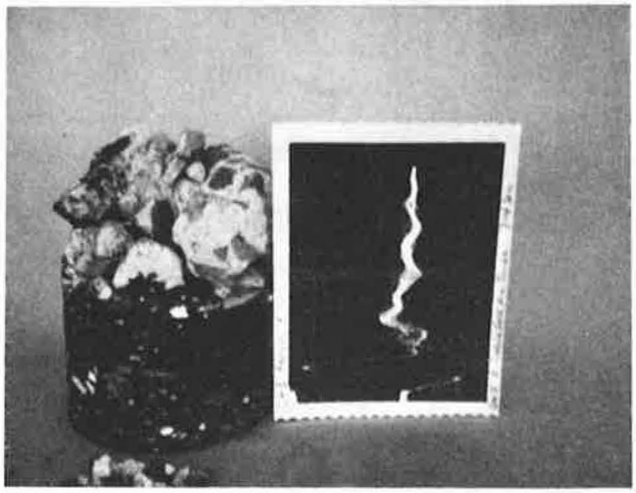


Data Analysis and Processing

Perhaps the most challenging feature of converting theoretical CIR concepts into an operating NDE system was the data analysis and processing. This derives from two considerations: (a) the complexity of data analysis and (b) the huge quantity of data to be processed. For example, surveying pavement at 12.9-16.1 km/h (8-10 mph) provided a trace for every 7.6 cm (3 in) of linear roadway in a 33-cm (13-in) wide swath. For one study of a 1.6-km (1-mile) long, four-lane bridge surveyed at the above speed, all eight wheel tracks were surveyed in 3 h of field operation, 975 m (3200 reel ft) of magnetic tape was recorded, and more than 80 Polaroid oscilloscope photographs of unique features were generated.

Figure 5. Radar conformation: (top) steady superimposable radar traces and good core and (bottom) erratic nonsuperimposable radar traces and poor core.





At least four major approaches have been tried: (a) topographic display, (b) photographic superimposition, (c) graphic signature identification techniques, and (d) mathematical modeling. Cluster analysis, a mathematical modeling technique, has proved to be most successful. A test of 213 m (700 ft) of bridge deck gave a 90 percent correlation between radar evaluation predictions of condition and actual field physical conditions.

Cluster Analysis

The field data are recorded in analog form on magnetic tape. In the laboratory, the analog data are converted to digital and "x-y" plotted. Manually derived information from the plot is fed to a computer and, via suitable programming, the traces are mathematically compared and placed in clusters of like morphology. The clustering results in three general groups of traces: good concrete, distressed concrete, and an intermediate, not clearly classified, group with possibly a limited number of outliers.

By using cluster analysis of a series of 100 traces from a bridge deck, radar predicted three groups: 72 percent good, 11 percent distressed, and 17 percent not clearly defined but generally lying between the other two groups. Physical verification was made by drilling 1.6-cm (0.625-in) holes into the deck at 21 locations. Ten of these locations were anticipated as distressed by CIR; 9, or 90 percent, of the drilled holes correlated. Eleven of the locations anticipated as good by CIR were also drilled and 10, or 91 percent, were judged good (Figure 7).

The range of concrete varied from very good to quite poor with no sharp break. This condition would normally be anticipated on a working maturing structure and is clearly and significantly shown in the drilling-depth distribution (Figure 7).

A 4.6-cm (1.8-in) depth was considered the dividing line; greater depth was considered distressed and lesser depth good (Figure 7). Only one good CIR signal gave a greater depth--5 cm (2 in)--and none were deeper than this. Conversely, there were no distressed CIR readings at holes shallower than 3.4 cm (1.75 in).

Further correlation was derived from the theoretical concept that good concrete should exhibit a smoother curve than distressed concrete (8). When 10 curves of good concrete were averaged, the resulting curve was quite smooth. This contrasted with the average of 10 distressed curves, which resulted in a more peaked curve (see Figure 8).

Figure 6. Standardizing drill rig.

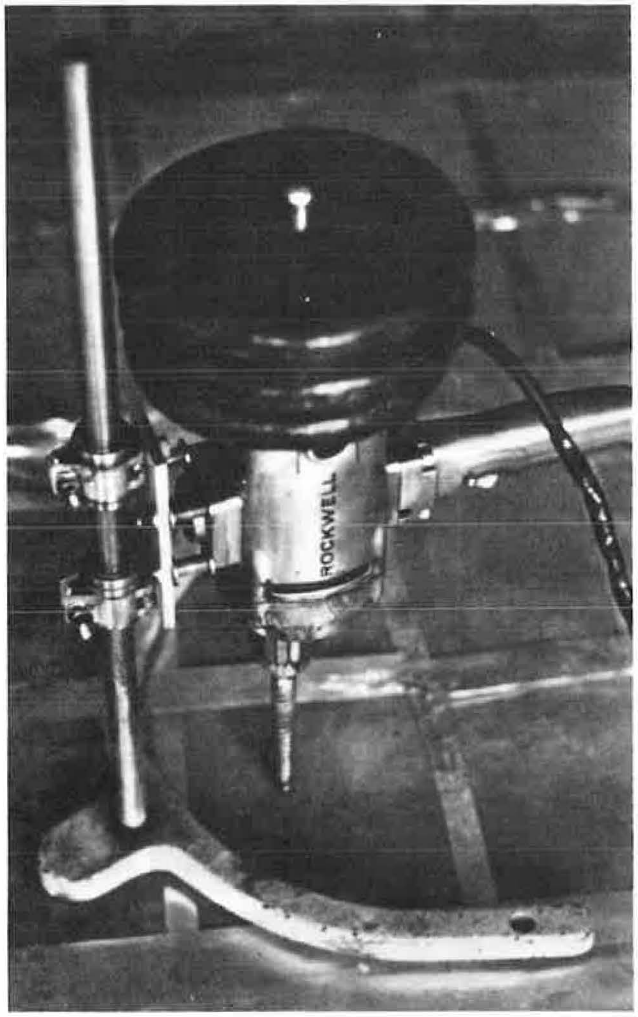


Figure 7. Radar field verification: cluster predictions.

DRILL DEPTH (INCHES)	DISTRESSED	SERVICEABLE
3.0		
2.9	—427'—	
2.8		
2.7	—714'—	
	— 28'—	
2.6	—686'—	
2.5		
2.4	—721'—	
2.3		
2.2	—700'—	
	—707'—	
2.1		
2.0		— 63'—
	— 42'—	
1.9	—679'—	
1.8		
		CORE #20 —315'—
1.7	—728'—	—326'—
1.6		—434'—
1.5		CORE #18
1.4		— 35'—161'—
1.3		—511'—
		—693'—
1.2		
1.1		—378'—191'—266'—
1.0		

Figure 8. Generalized radar traces.

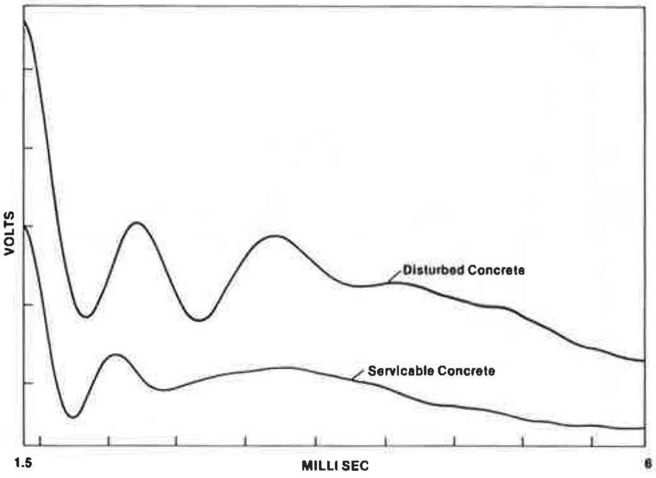
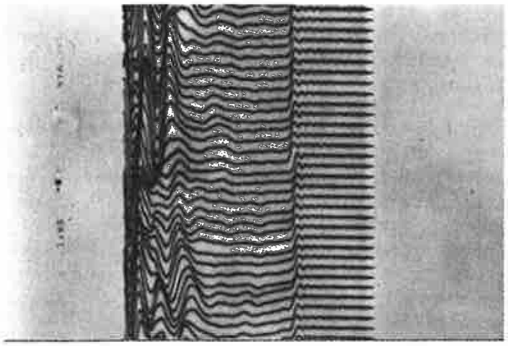
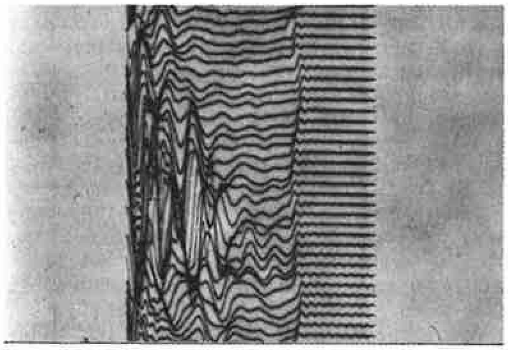


Figure 9. Topographic traces from moving vehicle.

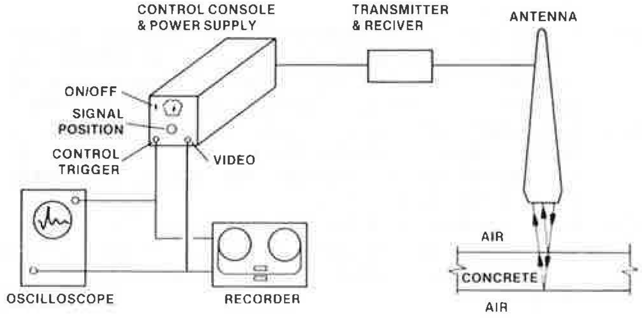


SERVICEABLE CONCRETE



DISTURBED CONCRETE

Figure 10. System block diagram.



Topographic Display

The topographic display procedure (10) consisted of displaying the original analog data recorded on magnetic tape on an oscilloscope, photographing the display with a synchronized shutterless motion picture camera, and then projecting the film on a viewing screen. The results are shown in Figure 9. Disturbance can be easily recognized by eye, but the procedure is extremely tedious and time consuming and causes rapid operator fatigue. The method, although somewhat functional, cannot really be regarded as satisfactory.

Photographic Superimposition

In photographic superimposition (10) the shutter of a Polaroid camera is left open for 10 s as the traces are displayed on an oscilloscope and recorded as a multiple exposure. When the traces superimpose on each other, the concrete is good. When superimposition is poor, wavy, or noisy, the concrete is distressed (Figure 5). This technique was used effectively in locating distressed and good areas on a bridge deck and was verified by coring. Although it is a proven procedure, it is extremely slow.

Graphic Signature Identification Techniques

In theory, it is possible to determine the condition of the concrete at any location by examining the radar trace. In practice, this is difficult, because of both the complexity of the trace and the time required to dissect the trace and understand its component parts. The method is generally relegated to the laboratory to be used for calibrating or other special conditions.

EQUIPMENT AND OPERATING THEORY

Penetradar Model PS-24 (8) is a lightweight, low-power, all-solid-state, high-resolution, nondestructive, ground-penetrating radar device. It is mobile and can be mounted in a light truck or van (Figure 3). The monostatic antenna (for transmitting and receiving) illuminates a 0.09-m^2 (1-ft^2) area at 20 cm (8 in) above the surface for inspecting pavements at speeds up to 19.3-25.7 km/h (12-15 mph).

The radar transmitter couples short bursts of low-power radio frequency (RF) energy through the perpendicularly oriented antenna into the pavement or material under investigation (5). Each burst or pulse is about 1 ns (one-billionth of a second) in duration and occurs more than 1 million times per second. A portion of the RF energy is reflected whenever there is a change or discontinuity in the propagation medium--for example, air to asphalt to concrete to soil, etc. The RF reflection, or radar echo, is picked up by the antenna, connected to the receiver, and processed for display and recording (see Figure 10).

The receiver measures the time for the transmitted pulse to travel to a target discontinuity and for the echo to return. In free air the pulse will travel out 15.2 cm (6 in) and return in 1 ns, whereas in concrete the velocity of propagation is reduced so that the corresponding distance is about 5.7 cm (2.25 in) in 1 ns, depending on the quality and condition of the concrete or other material under investigation.

As the pulse travels in air (less dense material) to concrete (more dense material), the trace goes sharply positive, then negative at the interface, whereas the polarity swing is reversed as the pulse travels from concrete (more dense) to air (less dense), the typical void condition. In practice, these interface changes can be difficult to resolve because of reflections and interference patterns caused by multiple reflections.

The radar echo from a pavement surface (first return) is generally much stronger than echoes from beneath the surface (as shown in Figure 9 of the paper by Alongi and others in this Record). Theoretically, the depth of a discontinuity is derived from the time separation between the surface and fault echoes. Examples of fault-echo sources from within the pavement are delamination, voids, and fracturing. The last distinct echo is generally the reflection from the bottom boundary of the pavement. Usually, the return signal from poor concrete is more complex and may have higher amplitudes and more peaks than the return signal from good concrete (Figure 2).

For a more thorough treatment of the theory of radar and the principles involved, the reader is referred to the paper by Alongi and others in this Record.

In addition to the radar unit, the following minimal support equipment is required (Figure 10): a three-channel, reel-to-reel, high-quality magnetic tape recorder and an oscilloscope.

The radar generates data at a rate of approximately 1800 traces/min, which overloads the manual method of analysis and thus limits the value of the system. Therefore, the final configuration will consist of a high-speed analog-to-digital signal converter and a dedicated computer of sufficient capacity to process the data by using cluster analysis techniques. This will increase data analysis capacity; reduce analysis time, perhaps, to real-time conditions; increase the reliability of the analysis; and enable the fringe-area uncertainties to be resolved or reduced.

CONCLUSIONS

The following conclusions can be made based on laboratory and field studies of radar as an NDE tool for determining the condition of concrete:

1. Radar survey equipment has proved to be a functional and reliable field device capable of determining the condition of concrete pavements and structures.
2. A 90 percent correlation has been obtained between radar evaluation predictions and pavement physical condition.
3. Present analysis and interpretation of radar data require a research engineer and manual processing and constitute a time-consuming procedure. By developing a computerized, automated system of data interpretation, manual data processing will be eliminated. Time will be saved and real-time operation may be achieved.
4. Addition of automated-data-processing equipment will make radar a practical NDE tool for use by field technicians.
5. When the condition of concrete is slightly less than good but not appreciably deteriorated, radar comparisons with cluster analysis generally indicate an uncertain transition zone, which suggests that the material may be starting to show distress, thus "flagging" the locations for further observation and scheduling of least-cost maintenance.

RECOMMENDATIONS

The material presented in this paper has demonstrated the ability of CIR to determine the condition of concrete. Therefore, it is urged that further development of radar data-processing signal analysis and interpretation techniques to reduce the skill level and time required to make pavement condition evaluations be vigorously pursued.

ACKNOWLEDGMENT

We wish to express our thanks to Anthony Alongi of Penetradar Corporation for his invaluable consultation and assistance in planning and developing the project. We also wish to thank Patrick Quinn for his assistance in several phases of the work and various other PANYNJ staff members for help in the field and office.

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Publication of this paper sponsored by Committee on Performance of Concrete.