Toward an Integrated Nondestructive Pavement Testing Management Information System Using Infrared Thermography

GARY J. WEIL AND LONNIE E. HAEFNER

This paper describes the theoretical basis and practical procedures for use of thermography in detection of pavement distress. It also illustrates the field use of thermography with some recent applications on airport taxiways, bridge decks, and parking garage slabs. It provides an overview of a staged research process under way by the authors to integrate nondestructive pavement testing using infrared thermography with evaluation models that form the basis for an integrated pavement testing, management information system.

The objective of this paper is to illustrate the use of a new, nondestructive testing (NDT) process, infrared thermography, for testing pavements for defects. Applied research case studies demonstrating the equipment, operation, and pavement distress data output are documented. The ultimate integration of the process with transportation systems evaluation models to yield a turnkey pavement testing and management information-capital budgeting system is conceptually presented.

Objectives of the Current Effort

The objectives of the applied research effort are to

1. Review and demonstrate effective mechanics of infrared nondestructive testing;
2. Investigate the testing procedures and state-of-the-art software for integration of data gathering and data interpretation; and
3. Structure, in preliminary form, a long-range program of integration of testing with pavement serviceability indices and capital budgeting algorithms.

Research Work Plan

Conceptually, the synthesis of a research program is shown in Figure 1. Emphasis is on field use of thermographic infrared techniques for assessing pavement and cross-section distress in both asphalt and concrete pavements related to surface cracking, subsurface voids, subgrade voids, and right-of-way drainage voids. The resultant scanner output and color image refinement yield a graphic-colorized interpretation of distress. These data, from the testing regime, can be input with a series of other data related to pavement serviceability variables to yield a basis from which to develop a number of management information system formats.

The inclusion of uncertainty analysis allows a series of "what if" questions with respect to average daily traffic, percent trucks, weather conditions, and other stochastic variables to be formatted into types of modeling often used in resource allocation, such as Markovian decision theory, or decision tree analysis, or dynamic programming–critical path method constructs. In conjunction with the database, an integrated testing–management information system–resource allocation algorithm that prioritizes location by rehabilitation-replacement policies can be built. It should again be pointed out that the preceding is a long-range research goal of the authors. Operable software exists for the information system regime from previous transportation systems evaluation computational research. This paper concentrates on the testing. A second-round paper in the future will concentrate on synthesizing the testing and the management information system evaluation software.

Use of Infrared Thermography

Infrared thermography is a noncontact, noninvasive means of producing visible images from the invisible heat energy emitted from an object. The pictures produced are in the form of a monitor picture with gray scale variations, or different colors, representing various temperatures and temperature ranges.

Thermography has limitations, as do all temperature sensing and measurement techniques. The observed radiometric temperature is affected by such things as the object's absolute temperature, ambient temperature, the objective's emissivity, the emissivity of nearby surroundings, atmospheric filtering of energy, and the distance from the objective to the scanner. Thermographic information can be adjusted for these factors, but training and experience are required to understand when these factors are important, when and where to adjust for them, and how to go about it.

G. J. Weil, EnTech Engineering, Inc., 111 Marine Lane, St. Louis, Mo. 63146. L. E. Haefner, Washington University, St. Louis, Mo. 63130.

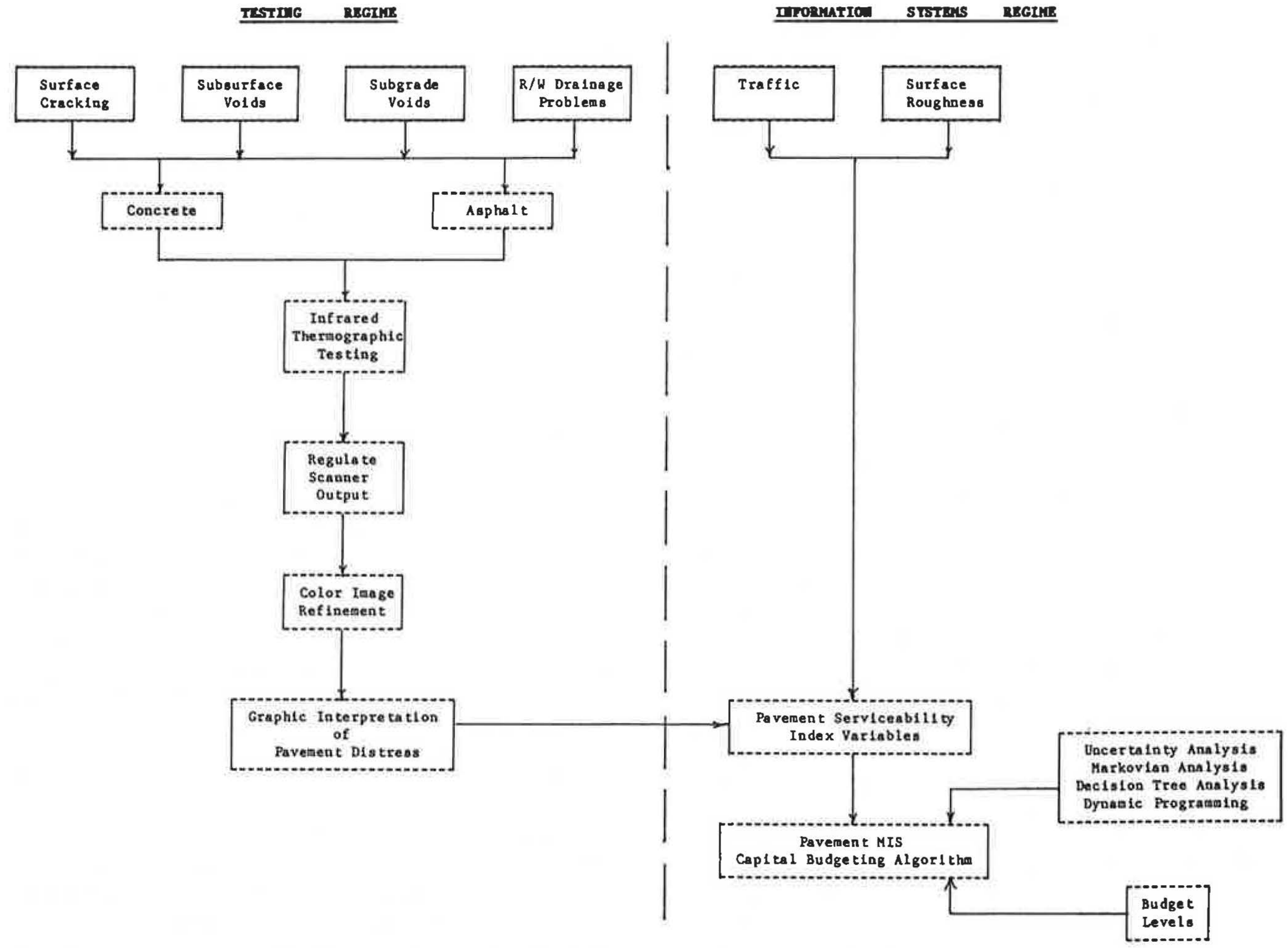

FIGURE 1 Development of an integrated nondestructive testing pavement management system.

Use of the Infrared Scanner

An infrared imaging system consists of an infrared scanner (similar in appearance to a portable video camera) with optics transparent only to infrared radiation and a real-time display monitor (similar to a portable television with a small screen coupled to a microprocessor). The scanner unit converts the radiated heat that is allowed to pass through the optics into an electronic signal. The signal is then turned into a real-time thermal image on the monitor screen of the display unit. The thermal image is composed of a gray scale with continuous tones ranging from black to white. Areas of higher relative temperature appear lighter, and areas of lower relative temperature appear darker. Intermediate shades of gray indicate variations between the extremes of temperature the unit is set to detect. A color monitor and an additional microprocessor can also be used to display the thermal image. A limited number of colors may be employed to show the full range of temperatures in the thermal picture. In this case, each color would represent a particular temperature range.

Defining a Thermogram

A thermogram is a permanent picture of the thermal image produced by the infrared scanner. By the use of special adapters, these images can be recorded on 35-mm film, instant film, or videotape. The thermograms can also be recorded in both black and white or color with the use of special microprocessor equipment. With some systems, actual temperature measurements can be determined from the thermograms. Areas or temperatures of special interest can be highlighted in both the black-and-white and color modes directly on the thermogram for easier identification.

THEORETICAL CONSIDERATIONS

An infrared thermographic scanning system measures surface temperatures only. But the surface temperatures that are measured on a pavement mass are dependent on three subsystems: (1) the subsurface configuration, (2) the surface condition, and (3) the environment.

The subsurface configuration effects are based on the theory that energy flow from warmer to cooler areas cannot be stopped. The flow can only be retarded by the insulating effects of the material through which it is flowing. Various types of construction materials have different insulating capabilities. In addition, various types of pavement defects have different insulating values.

There are three ways of transferring energy: (1) conduction, (2) convection, and (3) radiation. Good pavement should have the least resistance to conduction of energy, and the convection effects should be negligible. But the various types of problems associated with poor pavement, particularly voids, increase the insulating ability of the pavement by reducing the energy conduction properties without substantially increasing the convection effects. This is due to the presence of voids or dead air spaces, which do not allow the formation of convection currents.

To have an energy flow, one must start with an energy source. Since pavement testing can involve large areas, the heat source should be both inexpensive and capable of giving the pavement surface an even distribution of heat. The sun, which fulfills both of these requirements, will normally supply all the energy needed for areas under test. During nighttime hours, the process may be reversed, with the ground as the heat source and the night sky as the heat sink. For pavement areas not accessible to sunlight, an alternative is to use the heat sinking ability of the earth to draw heat from the pavement under test.

The second critical factor to consider when evaluating pavement for temperature differentials (i.e., anomalies) is the surface condition of the test area. There are three ways to transfer energy. Radiation is the method that has the most profound effect on the ability of the surface to transfer energy. The ability of a material to radiate energy is measured by its emissivity. This is defined as the ability of the material to release energy as compared to that of a perfect blackbody radiator. This is strictly a surface property. It normally exhibits itself in higher values for rough surfaces and lower values for smooth surfaces. For example, rough concrete may have an emissivity of 0.95, while a shiny piece of tinfoil may have an emissivity of only 0.05. In practical terms, this means that inspecting large areas of concrete requires an awareness of differing surface textures caused by such things as broom-roughed spots, tire rubber tracks, oil spots, or loose sand and dirt on the surface.

The final system that affects the temperature measurement of a pavement surface is the environmental system that surrounds the pavement to be measured. Some of the various parameters that affect the surface temperature measurements are as follows:

1. *Solar radiation:* Testing should be performed during times of the day or night when the solar radiation or lack of it would produce the most rapid heating and/or cooling of the pavement surface.
2. *Cloud cover:* Clouds reflect infrared radiation. This has the effect of slowing the process of heat transfer to the sky. Therefore testing should be performed during times of little or no cloud cover to allow the most efficient transfer of energy out of or into the pavement.
3. *Ambient temperatures:* Ambient temperatures should have a negligible effect on the accuracy of the testing since the important consideration is the rapid heating or cooling of the pavement surface. This parameter will affect the length of time (i.e., the window) during which high-contrast temperature measurements can be made.
4. *Wind speed:* High gusts of wind have a definite cooling effect on surface temperatures. Measurements should be taken at wind speeds of less than 15 mph.
5. *Moisture on the ground:* Moisture tends to disperse the surface heat and mask the temperature differences and thus the subsurface anomalies. Tests should not be performed while the ground has standing water or snow.

Once the proper conditions are established for scanning, a relatively large area should be selected for calibration purposes. This area should encompass both good and bad pavement areas (i.e., areas with voids, potential delaminations, cracks, or powdery concrete). Each type of anomaly will display a unique graphic signature depending on the conditions present. Most anomalies will be between 0.1°C and 5°C cooler than the surrounding solid pavement, depending on configuration at night (see Figure 2). A daylight survey will show reversed results.

TESTING EQUIPMENT

To test a pavement for subsurface voids and other types of anomalies, a sensitive contact thermometer is needed. In even the smallest test area, thousands of readings would have to be made simultaneously in order to outline the anomaly precisely. To inspect large areas of pavement efficiently and quickly, it is recommended that a high-resolution infrared thermographic scanner be used. (See Figures 3 and 4.) This type of equipment allows entire areas to be scanned and the resulting data to be displayed as pictures with areas of differing temperatures designated by differing gray tones on a black-and-white image or by various colors in a color image. A wide variety of auxiliary equipment can be used to facilitate the data recording and interpretation.

The actual scanning and analysis system can be divided into four main subsystems. The first is the infrared scanner head and detector that normally can be used with interchangeable lenses. It is similar in appearance to a portable video camera. The scanner's optical system, however, is transparent only to shortwave infrared radiation in the spectrum field of 3 to 5.6 microns or the medium-wave infrared spectrum field of 8 to 12 microns. Normally, the infrared scanner's highly sensitive detector is cooled by liquid nitrogen to a temperature of −196°

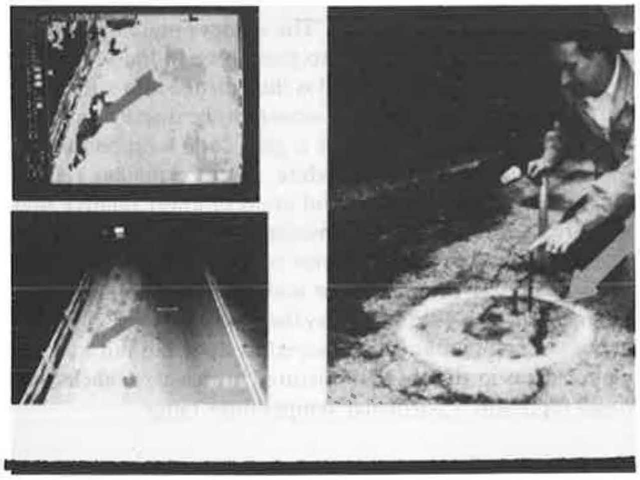

FIGURE 2 Computer-enhanced infrared thermogram (*top left*), visual picture (*bottom left*), and confirmation test (*right*), of defective pavement on the Martin Luther King Jr. Memorial Bridge spanning the Mississippi River at St. Louis, Missouri.

FIGURE 3 Infrared scanner mounted on portable body harness.

C and can detect temperature variations as slight as 0.1° C. Alternative methods of cooling the infrared detectors that use either compressed gases or electric cooling are available. These last two cooling methods may not give the same resolution, since they cannot bring the detector temperatures as low as liquid nitrogen can. In addition, compressed gas cylinders may present safety problems during storage or handling.

The second major component of the infrared scanning system is a real-time microprocessor coupled to a black-and-white display monitor. With this component, cooler items being scanned are normally represented by darker gray tones, while warmer areas are represented by lighter gray tones. To make the images easier to understand for those unfamiliar with interpreting gray-tone images, a color monitor and associated hardware and software may also be installed in the monitoring system. The hardware and software, in conjunction with the color monitor, will quantify the continuous gray-tone energy images into two or more "buckets" of energy levels and assign them contrasting visual colors representing relative thermal energy levels.

The third major component of the infrared scanning system is data acquisition and analysis equipment. It is composed of an analog-to-digital converter, a digital computer with high-resolution color monitor, and storage and analysis software. The computer allows the transfer of moving instrumentation videotape or live images of infrared scenes to single-frame computer images. The images can then be stored individually and later retrieved for enhancement and individual analysis. The computer allows specific analysis standards to be set, based upon destructive sample tests, such as corings, and applies them uniformly to every square inch of pavement. Standard off-the-shelf-type image analysis programs may be used, or custom-written software may be developed.

The fourth major component of the system consists of various types of image recording and retrieving devices. These should be used to record both visual and thermal images. They may be composed of instrumentation videotape recorders, still-frame film cameras with both instant and 35-mm or larger formats, or computer-printed images.

All of the preceding equipment may be carried into the field, or parts of it may be left in the laboratory for additional use. A van may be used to set up and transport the equipment for field testing. This van should include energy supplies to power all the equipment, either batteries and inverter or a small gasoline-driven generator. The van should also include a method to elevate the scanner head and accompanying video camera to allow scanning of the widest pavement area possible, depending on the system optics used.

TESTING PROCEDURES

To initiate an infrared thermographic pavement test, a movement of energy or heat must be established. For testing an open concrete bridge deck surface, the day preceding the test should be dry with substantial sunshine. The test may begin either 2–3 hours after sunrise or 2–3 hours after sunset, both being times of rapid heat transfer. The deck should be cleaned of all debris, and traffic control should be established to prevent vehicles from stopping or standing on the pavement to be tested. The infrared scanner is mounted in a mobile van with the necessary peripheral equipment for data storage and a computer for assistance in data analysis.

The next step is to choose a section of pavement deck and, by coring, establish that it is sound pavement. The reference area is then scanned, and the equipment controls are set to enable an adequate temperature image to be viewed and recorded.

Subsequently, a section of pavement known to be defective by containing a void, delamination, or powdery material is located. This reference area is scanned to assure that the

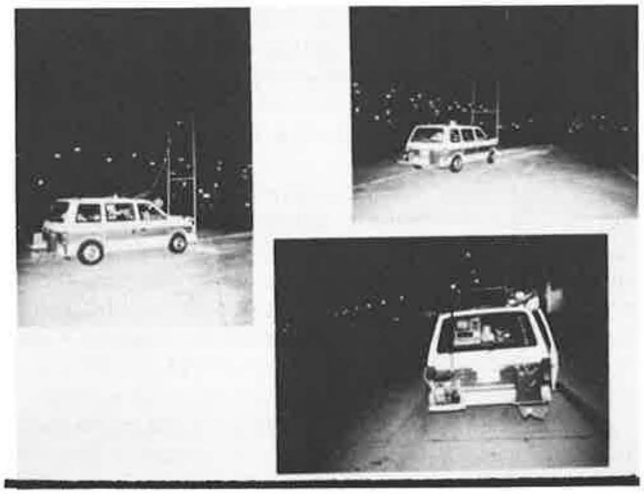

FIGURE 4 Mobile computer-enhanced infrared thermographic scanner, data acquisition, and processing system designed by EnTech Engineering, Inc., in use at the St. Louis International Airport.

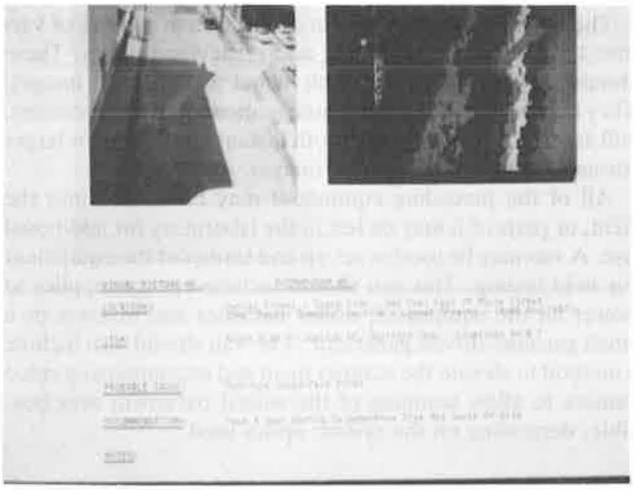

FIGURE 5 Infrared thermographic scan illustrating building shadow-caused temperature differentials.

equipment settings allow viewing of both the good and bad reference areas in the same image with the widest contrast possible. These settings normally reflect a full sensitivity scale of width no greater than 5 degrees.

If a black-and-white monitor is used, better-contrast images are normally produced when the following convention is used: black is defective pavement, and white is sound material. If a color monitor or computer enhancement screen is used, three colors are normally used to designate definite good areas, definite bad areas, and indeterminate areas. When tests are performed during daylight hours, the defective pavement areas usually appear warmer, while during tests performed after dark, defective areas appear cooler.

Once the controls are set and traffic control is in place, the van may be moved forward as rapidly as images can be collected, normally 1–10 mph. If marking the pavement is desired, white or metallic paint may be used to outline the defective deck areas. As an alternative, videotape may be used to document the defective areas, or a scale drawing may be drawn with reference to bridge deck reference points. Production rates of up to 500,000 sq ft per hour (approximately 8 lane-miles) have been attained. During long testing sessions, reinspection of reference areas should be performed approximately every 2 hours, with more scheduled during the early and latter parts of the session when the testing "window" may be opening or closing.

For areas where the sun cannot be used for its heating effects, it may be possible to use the same techniques except for using the ground as a heat sink. The same equipment should be set up in a fashion similar to that described earlier, except that the infrared scanner's sensitivity will have to be increased. This may be accomplished by setting full-scale deflection to 2° C and/or using computer enhancement techniques to bring out detail and to improve image contrast.

Once the data are collected and analyzed, the results should be plotted on scale drawings of the area inspected. Defective areas should be marked clearly so that trends can be observed. Computer enhancements can have varying effects on the accuracy and efficiency of the inspection system. Image contrast enhancements can improve the accuracy of the analysis by bringing out fine details, while automatic plotting and area analysis software can improve the efficiency of the finished, written report.

One note of caution is worthwhile: When inspecting areas that contain shadow-causing elements, such as bridges with superstructures or pavements near buildings, it is preferable to perform the inspection after sundown (see Figure 5). Since the shadows will constantly move, their resulting temperature variations will average out to a uniform level.

CASE HISTORIES

To illustrate the most diverse applications for infrared thermographic pavement testing, three case histories are reviewed in this section:

1. Bridge deck concrete,
2. Airport taxiway concrete, and
3. Garage deck concrete.

Each of these inspections emphasizes a different important feature of this nondestructive, remote sensing evaluation technique.

The first case history reviews the 1985 inspection of a concrete deck on the Martin Luther King Jr. Memorial Bridge spanning the Mississippi River at St. Louis, Missouri (see Figure 6). In this location, weather conditions can quickly change, and conditions can alter from clear sky to fog and rain in a matter of minutes. Therefore it was decided to perform the field inspection in one 8-hour period or less. The deck and its associated ramps were four lanes wide and almost a mile long, and included various sections with and without an overhead superstructure. It was determined to use a mobile lift platform capable of constant movement at up to ¾ mph while simultaneously lifting the infrared equipment, an operator/engineer, and a vehicle driver to heights sufficient to view all four lanes in a single pass (see Figure 7).

Because traffic restrictions prevented the inspection team from fully closing the bridge during inspection, the survey was performed on March 16, 1985, a weekend night between 7:30

FIGURE 6 Martin Luther King Jr. Memorial Bridge spanning the Mississippi River between St. Louis, Missouri, and East St. Louis, Illinois.

FIGURE 7 Self-propelled mobile lift platform used to hold engineer during infrared thermographic inspection of the Martin Luther King Jr. Memorial Bridge.

P.M. and 2:00 A.M. Actual survey time on the bridge deck itself was only 4 hours. The data, both infrared and visual, were recorded on both instrumentation videotape and 35-mm film formats. Before, during, and after the inspection, reference areas were scanned to determine equipment settings that would give the greatest contrast on the infrared imager. The main sensitivity of the equipment was set at 5 degrees for full screen deflection (see Figures 2A and 2B).

After the inspection, a simple technique was used to confirm the infrared data and interpretations to the supervising engineering company; three separate areas were chosen from the void, delamination, and anomaly drawings developed from the infrared data. Then an 8-in. nail was driven into the pavement, and its penetration was determined under a standard blow. The depth of penetration measurements correlated exactly with the test inspection party's determinations (see Figure 2C). Because of the large area of the bridge deck that was found to be defective, savings were realized by curtailing further pavement tests and by immediately initiating a complete bridge rehabilitation program during 1988–1989. Minimum savings in further testing programs were estimated at $80,000, and another estimated $150,000 was saved in unnecessary patching. The cost of the inspection was approximately $8,900.

A second case study involved the inspection of more than 3,125 slabs of reinforced concrete on the taxiway of one of the busiest airports in America, Lambert St. Louis International Airport. This inspection was performed during August 1987, and the field inspection took a total of 5 nights of work.

Owing to the need for no interruptions to air traffic, the decision was made to perform the inspection from 11:00 P.M. to 5:00 A.M. when traffic was slowest. To move the infrared equipment about rapidly, a mobile van was employed for inventory, recording, and analysis (see Figure 4). The van was custom-designed to allow the scanner head and visual cameras to be raised to a 14-ft height during scanning runs to allow the surveying of a 25-ft-wide by 25-ft-long slab in a single view. Production rates, including the activities of the scanning operation, storage of images on computer disks and videotape, 35-mm photographs, and related analysis, approximated 500,000 sq ft of concrete slabs per night.

Prior to the beginning of the inspection, reference and calibration areas were determined for good, solid pavement and for pavement with subsurface voids and delaminations. These areas were rescanned during the inspection window each night at regular intervals to make sure that equipment settings allowed for accurate data collection. This information was fed continuously into a digital computer, and a color monitor was used to assist in the determination and location of anomalies. To speed interpretation, the thermal data presented on the computer monitor were divided into three categories represented by three separate colors: green for solid pavement, yellow for pavement areas with minor temperature deviations most likely caused by minor surface deterioration, and red for pavement areas with serious subsurface cracks/voids. The computer was also used to determine the area designated on each slab by the aforementioned color determinations. These data were used to designate each individual slab for no corrective action, spot repairs, or major replacement.

The results of taxiway pavement inspection showed that approximately one-third of the concrete was in good condition. Another one-third of the area needed only cosmetic rehabilitation, and the remaining one-third needed complete slab replacement. This meant a potential savings in rehabilitation costs of approximately $16 million out of $33 million. This included approximately $11 million saved by not replacing good slabs and $5 million saved by performing surface reconditioning instead of full slab replacement of one-third of the slabs.

The third case history involves inspection of garage concrete and adjacent roadway concrete at the same facility, Lambert St. Louis International Airport. In January 1986, garage facilities and associated roadways were thermographically inspected. The same techniques as described earlier were used, but particular attention was paid to expansion strip areas between concrete slabs. Figure 8 illustrates one of the computer-enhanced thermograms with an expansion strip in mixed condition. The left side of the expansion strip of an elevated roadway shows clearly defined edges on the temperature thermogram, while the right side of the same expansion joint shows ragged edges of the temperature profile. Also perpendicular to the expansion joint is another expansion strip showing ragged edges on the temperature profile. Close inspection of the visual photograph will indicate that some of the areas show surface deterioration (see arrow) while other areas exhibit no surface spalling. All deteriorated areas shown in the thermographs were confirmed and rehabilitated the following year. The circular areas in the thermogram were caused by heat transfer of the circular support columns beneath the elevated roadway.

ADVANTAGES AND LIMITATIONS OF THE METHOD

Nondestructive, thermographic, remote sensing pavement testing techniques for determining pavement subsurface voids, delaminations, and other anomalies have major advantages over destructive tests, such as coring and chloride methods, and other NDT techniques, such as radioactive/nuclear, electrical/magnetic, acoustic, and ground probing radar.

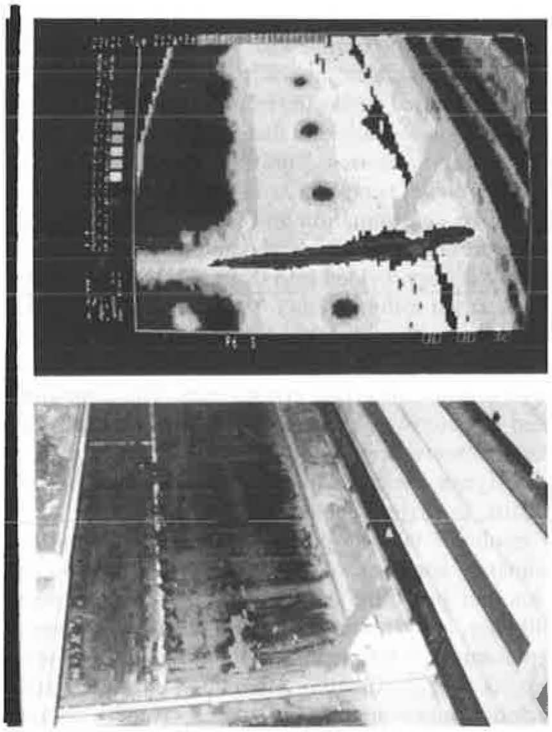

FIGURE 8 (*Top*) Ragged temperature distribution profiles near arrow illustrate areas of pavement deterioration. (*Bottom*) Expansion joint located on elevated roadways at Lambert St. Louis International Airport.

There are several advantages of infrared thermographic analysis compared with the destructive testing methods. No major pavement areas must be destroyed during the testing. Only small-calibration corings must be used. This results in major savings in time, labor, equipment, traffic control, and scheduling problems. In addition, when esthetics are important, no disfiguring of the pavement to be tested occurs. Rapid setup and take-down are also advantages when vandalism is possible. Finally, since no destruction is caused, no concrete dust or debris is generated that could cause health and housekeeping problems.

Further, infrared thermographic equipment is extremely safe. It emits no radiation. It records only thermal radiation that is naturally emitted from the pavement, as well as from all other objects, both living and nonliving. It is similar in function to any normal thermometer, only much more efficient and easier to use.

In comparison, other forms of NDT testing have a variety of inherent problems. Radioactive/nuclear and electrical/magnetic methods emit various types of radiation that can be harmful to people, animals, and other equipment. They may need various forms of licensing for and restriction on use outside of the lab.

Acoustic emission testing and ground probing radar are greatly affected by the type of material to be tested. Such objects as buried water lines and structural steel can distort the test signals and make their interpretation almost impossible. Acoustic emission testing is also affected by the surrounding environment. Noise generated by passing truck and automobile traffic can make the acoustic equipment difficult to use.

It is critical to note that infrared thermography is designed to be used as an area testing technique, while the other methods are all either point- or line-testing methods. A two-dimensional area of various combined lengths and widths may be scanned with images illustrating areas of voids, delaminations, and anomalies displayed on a televisionlike picture of the entire area.

The other methods, including radioactive/nuclear, electrical/magnetic, acoustic, and ground probing radar, are point tests and depend upon a signal propagating downward through the pavement at a discrete point. This gives a reading of the pavement condition at a single spot. If an area is to be tested, then multiple readings must be taken, sometimes numbering in the thousands. Ground probing radar has the advantage over the other point-testing techniques in that the sensor may be mounted on a vehicle and moved in a straight line over pavement materials. This improves efficiency somewhat, but if an area is wide, many line passes would still have to be made. In addition, this could present problems of test mapping alignment.

Infrared thermographic testing has two disadvantages. At this stage of development, it cannot determine the depth or thickness of a void, although the outer dimensions of the void are evident. It cannot determine if a subsurface void is near the surface or farther down, possibly below the enclosed reinforcing bars. A technique such as ground penetrating radar can determine the depth of the void and its thickness but is not as accurate as infrared thermographic testing at determining dimensions and location.

In most testing instances, the thickness of the anomaly is not nearly as important as its other dimensions. In those instances where information on a specific anomaly thickness or depth is needed, however, it is recommended that infrared thermography be used to survey the large areas for problems. Once specific problem locations are found, ground penetrating radar can be used to spot-check the anomaly for its depth and thickness. This combined technique would give the best combination of accuracy, efficiency, economy, and safety.

The second disadvantage of infrared thermography is concerned with the size of the anomaly that can be located. The size of the locatable voids, delaminations, or cracks depends upon the infrared optics, video camera optics, and the speed of the infrared scanner-video system. Cracks as small as 50 mm have been located by stationary systems. However, optics and speeds of data collection must be matched to the type and size of anomalies to be found. The wider the area scanned in a single frame, the less the physical resolution. The faster the motion of the sensor, the greater the image blur.

SUMMARY

1. Infrared thermographic techniques can be used to detect pavement defects, such as subsurface voids, cracks, and changes in density.
2. Infrared thermographic testing techniques are nondestructive.
3. Infrared thermographic pavement anomaly testing techniques are based on the theory that various pavement defects change the rate at which energy flows through normal pavement.

4. Infrared thermographic pavement testing may be performed during both day- and nighttime hours, depending on environmental conditions and what results are desired.

5. Infrared thermographic pavement anomaly testing techniques can distinguish various types of anomalies, although test borings for each type of defect must be made for calibration purposes.

6. Infrared thermographic scanning techniques are more efficient and more accurate than other destructive and nondestructive, manual and electronic methods when testing large pavement areas.

7. Computer analysis of thermal images greatly improves the accuracy and speed of test interpretations.

8. Computer analysis of pavement thermographic data can improve the ability to set repair priorities for areas in a state of change.

FURTHER RESEARCH AGENDA

The long-range research effort will attempt integration of testing activity with data interpretation, storage, and computation of priorities using reasonably robust evaluation modeling formats, employing uncertainty analysis. The operational capability of a turnkey testing and management information system for budget allocation and policy decisions would greatly enhance the highway planning and maintenance process.

Publication of this paper sponsored by Committee on Pavement Monitoring, Evaluation and Data Storage.