Principles of Infrared Thermography and Application for Assessment of the Deterioration of the Bridge Deck at the "Zoo Interchange"

By John Zachar¹ and Tarun R. Naik²

Abstract

This paper details the principles of infrared thermography from the underlying theoretical considerations to the physical constraints involved with performing the test.

Infrared (IR) thermography testing may be conducted at any time of the day or night as long as heat transfer is taking place through the medium being examined. During the day, subsurface anomalies cause localized increases in heat absorption, so the surface above these areas registers warmer than the surrounding areas. At night, the anomalies cause the surface above them to dissipate heat faster than the surrounding solid areas, so they register cooler to the IR thermography.

An IR thermographic study of a freeway interchange in Milwaukee, WI. was conducted in late 1991. The study was designed to find delaminations and other pre-spalling subsurface anomalies that are not detectable by visual surface inspection. A pre-spalling condition occurs when the salt used to deice the road permeates the concrete and creates a corrosive environment around the top rebar mat. The resulting sub-surface cracking can be detected using IR thermography.

¹ Professor, Architectural Engineering Department, Milwaukee School of Engineering, Milwaukee, WI 53202.

² Director, Center for By-Products Utilization, College of Engineering and Applied Science, UW-Milwaukee, WI 53201.
Introduction

This paper is designed to provide a detailed explanation of the principles of infrared (IR) thermography. All aspects of IR thermography are examined, from the underlying theoretical considerations to the physical constraints involved with performing the actual thermographic evaluation.

To expand the theoretical investigation of infrared thermography into a practical application, the author of this paper, in cooperation with Donohue Consulting Engineers, participated in an IR thermographic study of the "Zoo Interchange", a freeway interchange in the northwest corner of Milwaukee county where I-94 and Wisconsin HWY 45 meet.

The subject matter of this paper is divided into four sections:

(1) Background information and reasons why a method such as IR thermography is needed.

(2) Theoretical basis of IR thermography and its limitations.

(3) Equipment used in an IR thermographic survey.

(4) Description of the Zoo Interchange study.

Background Information

Pavement and bridge deck deterioration is a significant problem, especially in climates where salt or other chloride compounds are used to deice the roadway. The chlorides permeate into the concrete and create a corrosive environment around the top reinforcement mat. The corrosion products expand, causing cracking of the concrete at the level of the reinforcement. The term used to describe this type of cracking is "delamination", and is usually not discovered by visual inspection during its initial stages. If water seeps into these delaminations and then is subjected to freezing and thawing cycles, the result is usually spalled concrete. The spalling can also lead to "pot holes". It is desirable to be able to find and repair delaminations before they
reach the spalling stage, particularly if the repairs can be made during the temperate seasons.

One traditional method used to find delaminations is by 'sounding'. In the sounding method, the difference in solid and delaminated concrete can be heard by tapping on the surface with a hammer, or by dragging a chain across the concrete surface. The delaminated area generally has a duller or more hollow sound than the solid concrete. However, the difference in the sound between solid and delaminated concrete is dependent upon the interpretation of a technician and varies with the size of the delamination. "Persons using sounding to identify delaminated areas need judgement and a great deal of time to test a given bridge deck." [Benz and Ulrikson 1990]. Also, the ambient sound level can affect the operator's judgement. Another consideration is that the sounding method is ineffective if the concrete has been covered with an asphalt wear surface, which is a common occurrence, so an alternative method is required. The method of IR thermography as one of the "most promising" of the new technologies available. [Maser and Roddis 1990] It has the advantage of faster data collection, less operator judgement, and more accurate results than the sounding method. A study of eight different non-destructive methods concluded that IR thermography and ground penetration radar had the greatest potential for routine detection of deterioration of asphalt covered bridge decks. [Manning and Holt 1982]

The first reported research into the use of IR thermography was published by the Ontario Ministry of Transportation in 1973. [Weil 1991] Since then, numerous private and government sponsored studies have verified that IR thermography is an economical and accurate method for the determination of pavement and bridge deck conditions. Typical of the results of these studies, it was found that the IR thermography method found essentially all (97 percent) of the delaminated areas on a bridge deck at a cost competitive with less accurate methods. [Love 1986]

Infrared Thermographic Principles and Techniques

Infrared thermography is used to measure the temperature or temperature differences of the surface of the pavement. The temperature measurements may be done at any time of the day or night as long as heat transfer is taking place, that is, as long as the surrounding environment is warmer or cooler than the concrete mass being investigated.

It is a fundamental principle of thermodynamics that thermal energy will always flow from warmer areas to cooler areas. The three ways that thermal energy can be transferred are:

(1) Conduction;
(2) Convection; and,
(3) Radiation.

Thermal energy passes from the surface to the interior by means of conduction and convection within the mass. Similarly, any internal heat must be transferred to the surface by internal conduction or convection. Solid concrete is a reasonably good conductor of heat and any effects of convection within the mass can be considered negligible. If the concrete has voids caused by delaminations or poor placement, the conduction paths will be disrupted. The disruptions in the flow of thermal energy lead to temperature differences on the surface, which can be detected by IR thermography. During the day, subsurface anomalies cause localized increases in heat absorption, so the surface above these areas registers warmer than the surrounding areas. At night, the anomalies cause the surface above them to dissipate heat faster than the surrounding solid areas, so they register cooler.

Maser and Roddis report that the width of the delamination crack has a pronounced effect on the temperature differences between the solid and delaminated concrete. Considering that fact, the IR thermography method not only detects delaminations but also indicates their severity. One important consideration is that the temperature difference between the solid and delaminated areas is only detectable if the cracks are dry (air filled). A debonded area with a 0.05 inch air filled crack has up to a 4°C temperature difference compared to a solid slab. If the same crack is filled with water the temperature difference is essentially undetectable (less than 0.2°C).

IR thermography detects the temperatures radiated by the surface of the pavement. Radiation is the process that allows the mass of the concrete to transfer energy to and from the ambient environment. The ability of a body to radiate energy is affected by surface characteristics such as the roughness and color. The measure of the ability to radiate thermal energy is called emissivity. A perfect "black body" has an emissivity of one. This means that, at any given temperature difference with the environment, it radiates the maximum possible energy. The emissivity is higher for rougher surfaces and higher for darker colors. Radiant emission is described by the Stefan-Boltzmann law, which states that the infrared power radiated by a body is directly proportional to the fourth power of its absolute temperature.

Radiant heat transfer is also affected by environmental factors. Clouds reflect the infrared energy, so the heat transfer process is slowed. Wind accelerates surface cooling and may negate temperature differences caused by subsurface anomalies. Moisture tends to increase the dissipation of heat, which also can negate temperature differences caused by subsurface anomalies. Also, as mentioned previously, if the moisture penetrates the cracks the temperature differences are minimized. Thermographic testing should be done on days with no solid cloud cover, with the wind speed below 15 mph, and with the surface dry. [Kunz and Eales 1985] There was general agreement with these IR thermography operating parameters at a recent
In summary, the factors affecting the radiated energy are: surface emissivity, surface temperature, surface moisture, ambient air temperature, wind velocity and environmental factors such as cloud cover and the intensity of sunlight.

Infrared thermography can also detect debonding between an asphalt overlay and the underlying concrete. There is a distinctive thermal signature difference between a delaminated and a debonded area. [Kunz and Eales 1985] They state that delaminations are generally circular in plan view and have a uniform temperature within the delaminated area. Debonded areas on the other hand, are generally larger, non-circular, and have non-uniform temperatures within the debonded area. Through the infrared scanner, the debonded areas have a marbled appearance. Eales, also a speaker at the recent Workshop on Nondestructive Testing and Evaluation of Concrete, showed slides of the infrared scans that illustrated the difference in thermal appearance between a debonded and delaminated area as described above.

**Equipment Used in an IR Thermographic Survey**

The primary measuring equipment consists of an infrared scanner mounted on a telescopic boom on the front of a specially equipped van. The infrared scanner is similar to a video camera, except that the optical system is sensitive to short (3 to 5.6 μm) and intermediate (8 to 12 μm) wave radiation. [Weil 1991] Infrared radiation has a frequency less than the red visible light but behaves similarly to light in that it can be reflected and refracted. The camera uses a mercury cadmium telluride detector that, for maximum sensitivity, is cooled to a very low temperature (-200°C) by the circulation of liquid nitrogen or by an integral refrigeration system. By maintaining a low temperature on the detector it is possible to measure temperatures differences of 0.2 degrees C or less. The cost of the infrared camera (in 1991) is approximately $45,000. [Weil 1991] A 45 degree expander lens is used to allow a full pavement width (14 feet) to be viewed at one time. Also on the boom, mounted adjacent to the infrared scanner, is a video camera. The video camera has a zoom lens that is focused and aimed on the same area of pavement that is being scanned in the infrared. This combination of real and infrared image allows the correct interpretation of temperature differences caused by environmental factors such as oil spots, asphalt and tar patches, and paint. Weil prefers conducting the thermographic study at night because of reduced traffic and elimination of thermal differences due to shadows. Eales prefers to work during the day so that the video camera can have the maximum resolution, thereby minimizing errors in interpretation of the thermal anomalies. The important consideration to remember is that infrared thermography can be performed at any time of the night or day as long as heat transfer is taking place. The actual time of testing is a matter of preference with the operator.
As the testing van moves along the roadway, both the real and infrared image is recorded on a video tape, along with a digitally superimposed distance counter that is coupled with the vehicle's drive train. In the office, the two tapes are played back, and a technician digitizes the infrared anomalies onto a CADD based plan view of the bridge deck. A sample of the output of the CADD system is presented in the appendix.

**Description of the Zoo Interchange Study**

The following description is a compilation of notes made during an IR thermography scan of the bridge deck at the "Zoo interchange". The testing was performed by the Donohue consulting firm, under the direction of Mr. Dan Ulrikson.

In performing an IR thermography test, the roads leading to the area to be tested were marked with 'ROAD CONSTRUCTION' signs as a warning to the traffic. The thermography test van was followed by two traffic control trucks that had arrow boards directing traffic. Following the sign trucks was a marked Sheriff's squad car. Ulrikson stated "drivers often ignore the sign trucks, but they usually slow down when they see the squad car." One important reason to use the infrared thermography method is that traffic does not normally have to be stopped, just slowed down or diverted. Also, the infrared thermography test does not require any closure of the roadway, thereby minimizing costs and inconvenience. The van, traffic control trucks, and the squad car, drive at about five miles per hour, so the freeway traffic normally can go around except when inspecting a single lane roadway.

To calibrate the system the van is driven along the road to be tested until the infrared camera senses an anomaly. The infrared image is coordinated with the real image to see if the anomaly is caused by any environmental factor (paint, water, or oil on the pavement, asphalt patch, etc.). The image from the two cameras is also fine adjusted for focus, aim, depth of field and brightness. If the infrared camera finds an anomaly that appears to be solid concrete, the technician leaves the truck to check the anomaly by sounding the spot with a hammer. If an exact size and shape of the delaminated area is desired the surface can be covered with a fine sand prior to hammer tapping. The tapping causes vibrations in the delaminated area which moves the grains of sand to the edges and thus outlines the area in fine detail. The size of the sounded anomaly is then compared to that predicted by the infrared image. A contact thermometer is placed on the surface of the anomaly and also the surface of the surrounding solid concrete. The measured temperature difference is compared to the indicated temperature difference from the infrared camera, and, if necessary, the infrared camera is calibrated to match. The entire checking and calibration process only takes a few minutes. Once all factors are in agreement, the van resumes scanning and recording the data. After the data is recorded, it is taken back to the office and digitally analyzed as described earlier.
Conclusions and Recommendations

Infrared thermography has been shown to be an important and accurate tool in the detection of delamination and debonding of pavement and bridge decks, often before any visible signs of damage exist. Although the equipment is costly, the test can be performed quickly over a large area resulting in a minimal operating cost per unit area. An important consideration is that the test is completely non-destructive and involves minimal disruption of the traffic pattern and flow.

It is recommended, based upon this study, that bridge decks, roads, etc. be scanned at regular intervals as a form of preventative maintenance.

A data base should be created and maintained of how the deterioration of the pavement progresses from year to year. In this systematic evaluation, any pattern of deterioration could be discovered before it reaches critical levels needing massive repairs. Similarly, trends might be found relating severity of weather, amount of deicing salt used, traffic counts, and other factors to the deterioration of the pavement. With an accurate database, road repair budgets and plans for preventative maintenance could be prepared with greater accuracy.
Appendix 1: Example of Thermography Results
References


Keywords: Concrete, Used/Discarded Foundry Sands, Compressive Strength, Fine Aggregate Replacement, Splitting Tensile Strength, Modulus of Elasticity.