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Infrared thermography as a diagnostic tool for subsurface assessments of concrete structures

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Abstract. This paper presents on-going research into the application of infrared (IR) thermography as a means of diagnosing the presence of delaminations in concrete structures. Infrared thermography, as a diagnostic tool, has demonstrated the potential to detect and visually display areas of delamination in concrete structures, offering a feasible supplement to the traditional techniques used for delamination surveys. However, the thermal gradients that develop in the concrete, and that are essential for the detection of the delaminations, are the result of the prevailing ambient conditions that surround the structure. Depending on the nature of these conditions, certain delaminations may be more visible than others while some may not be visible at all. Solar radiation has a significant effect on these thermal gradients and consequently, the temperature contrasts that develop between the areas of delaminated and intact concrete. This paper addresses the effect that solar radiation has on the ability of infrared thermography to detect and reveal areas of delamination in concrete structures. This effect has been studied by quantifying the temperature contrasts that developed at the surface of a concrete panel into which delamination type defects were intentionally embedded at different depths.

Keywords. Infrared, thermography, delamination, concrete, diagnostic, thermal, gradients, ambient, solar, radiation, temperature, contrasts

Introduction

As a non-destructive, two dimensional means of evaluation, infrared thermography has demonstrated the potential to detect, and in real time, visually display areas of delamination in concrete structures. The application of this technology has seen a significant increase in recent years as infrared cameras have become increasingly sophisticated and far better suited to the civil practitioners needs. In addition to this, the costs of these instruments have reduced considerably, making them more accessible and thus a more feasible means of evaluation. However, there are associated limitations with infrared thermography, most significantly, its reliance on the prevailing ambient conditions that surround the structure to provide the necessary thermal gradients needed in the concrete for delamination detection [1].

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In order to detect areas where delaminations of the concrete cover have occurred, a thermal gradient must be present in the concrete so as to initiate the flow of heat through the concrete itself. In the presence of a delamination, this flow of heat is disrupted [2], the consequence of which reveals itself at the surface of the concrete. The disruption in heat flow manifests in an observable variation in temperature at the surface of the concrete relative to areas of concrete that are intact [1]. That is to say, temperature contrasts develop on the surface between those areas of concrete that are intact and those above the subsurface locations of the delaminations. It is these surface temperature variations that are detected by infrared cameras which in turn reveal the presence and areas of delamination.

The thermal gradient that drives the flow of heat through the concrete is the result of the prevailing ambient conditions that surround the structure [3]. Solar radiation provides the radiant heating that warms the surface of the concrete, establishing the thermal gradient necessary for delamination detection. The ability to detect areas of delamination is heavily influenced by the intensity and duration of radiant heating absorbed by the concrete. Meteorological conditions such as cloud cover reduce the intensity of radiant heating received from the sun and thus hinder the ability to detect areas of delamination. Atmospheric attenuation, perpetuated by factors such as air temperature and relative humidity, is compensated for through camera settings and input parameters of these meteorological phenomena.

It is important to understand what ambient conditions are required in order to provide optimum surface temperature contrasts between areas of concrete that are intact and any potential areas of delamination. However, it is also important to understand how the prevailing ambient conditions on any given day may influence the outcome of a delamination survey using infrared thermography. The research presented in this paper focused on addressing the effect that solar radiation has on the ability of infrared thermography to detect and reveal areas of delamination in concrete structures. To quantify this effect, a concrete panel was constructed, into which delamination type defects were intentionally embedded at different depths, simulating the presence of delaminations that would disrupt the flow of heat through the concrete.

1. Background

As it has previously been established, areas of delamination in concrete structures reveal themselves at the surface of the concrete in observable variations in temperature relative to areas of concrete that are intact [1]. The cause of this is the influence the delamination has on the rate at which the concrete, anterior to the delamination, warms and cools under the prevailing ambient conditions surrounding the structure. The effect of the delamination is to increase the rate of warming or cooling of the anterior concrete depending on the direction of heat transfer. The delamination increases the rate of warming or cooling as the air void, created by the delamination, acts as an insulating discontinuity reducing the ability of heat to conduct through and beyond the delamination.

When the ambient conditions begin to warm after sunrise, a positive thermal gradient develops in the concrete resulting in an increased rate of warming of the anterior concrete, leading to higher surface temperatures of the areas of concrete above the subsurface locations of the delaminations. Conversely, when the ambient conditions begin to cool following solar noon, a negative thermal gradient develops in the

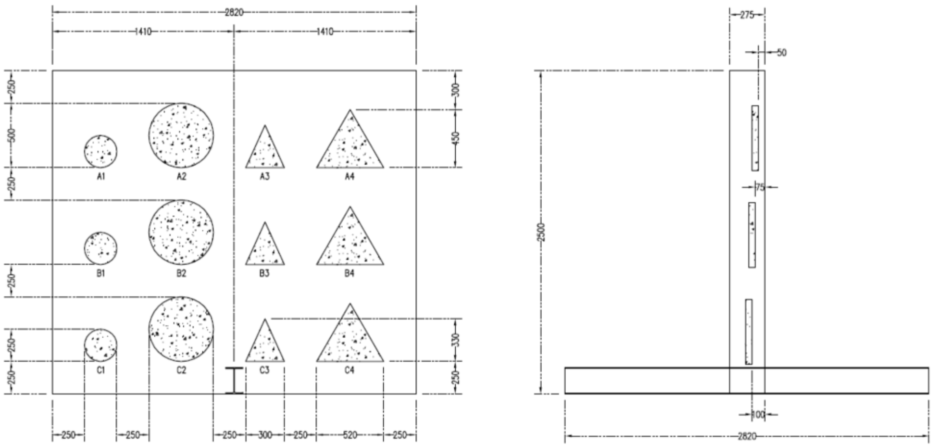

Figure 1. Diagram of the concrete panel with embedded targets at depths of 50 mm (A1, A2, A3, A4), 75 mm (B1, B2, B3, B4) and 100 mm (C1, C2, C3, C4)

concrete, resulting in an increased rate of cooling of the anterior concrete, leading to lower surface temperatures of the areas of concrete above the subsurface locations of the delaminations. However, if the concrete finds itself in a state of equilibrium with the prevailing ambient conditions, the thermal gradient in the concrete will cease to exist and any potential areas of delamination will go undetected.

2. Experimental

A concrete panel was constructed as shown in Figure 1. Resting on a circular footing, the panel was 2.82 m x 2.5 m with thickness of 0.275 m. To provide stability against overturning a universal beam (I-section) was cast through the panel at mid-base as shown in Figure 1. Circular and triangular sheets, cut from 50 mm thick high density expanded polystyrene, were used as embedded targets to provide subsurface features that would disrupt the flow of heat through the concrete. The targets were placed at depths of 50 mm (A1, A2, A3, A4), 75 mm (B1, B2, B3, B4) and 100 mm (C1, C2, C3, C4) from the north facing elevation of the panel.

A FLIR SC620 infrared camera which monitored the panel was positioned in an observation enclosure located 8 m from the panel. Thermal images of the panel were captured at 30 minute intervals over duration of approximately 11 hours, a period governed by the local rising and setting times of the sun. In addition to this, global horizontal irradiance was measured and logged during the observation of the panel. The global horizontal irradiance was measured using a horizontally mounted pyranometer. Irradiance is the instantaneous value of radiation, or the flux of radiation, expressed in watts per square meter (W/m^2).

Figure 2 details a thermal image of the north facing elevation of the concrete panel. From the image it is evident that all of the embedded targets, at all three depths, are clearly visible with twelve distinct temperature contrasts appearing on the surface of the concrete. In order to obtain quantitative data from these visual contrasts, the apparent temperature differences, inferred by the thermal images, between the

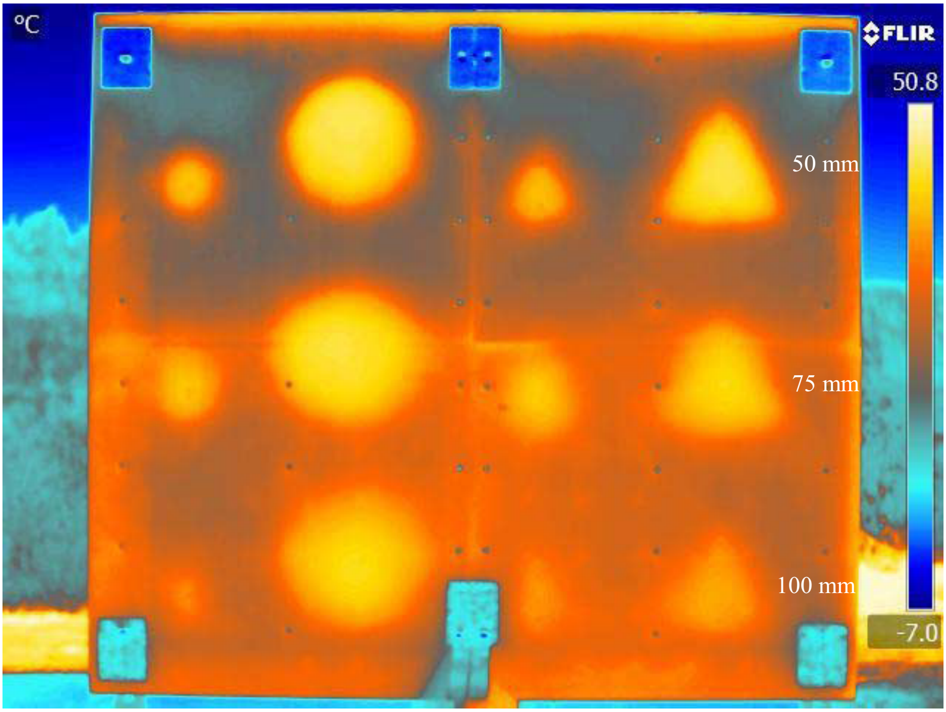

Figure 2. Thermal image of the concrete panel showing the embedded targets at depths of 50 mm, 75 mm and 100 mm

embedded targets and the surrounding intact concrete were measured and analysed. The temperature differences were measured for each target over the complete duration of observation.

3. Results

The actions of this experimental work are reported herein with results that were used to evaluate the degree to which the 50 mm deep delamination type defects (A1, A2, A3, A4) affect the relative time period during which the observable variations in temperature that manifested at the surface of the concrete panel are optimized under local conditions in Johannesburg, South Africa. Observations of the north facing elevation of the concrete panel were conducted with data collected over the winter months of May and June 2013. This data included the apparent temperature differences between the embedded targets and the surrounding intact concrete as well as local on-site measurements of global horizontal irradiance.

Figure 3 illustrates the temporal distribution of global horizontal irradiance over a 12 hour period on a particular day in May 2013. It is a graphical representation of the power of the solar radiation per unit area incident on a horizontal surface. It serves as a site reference, quantifying the local solar energy resources on that particular day. In addition to this, Figure 3 illustrates the temporal distribution of the temperature contrasts that developed at the surface of the concrete panel over the same period, on

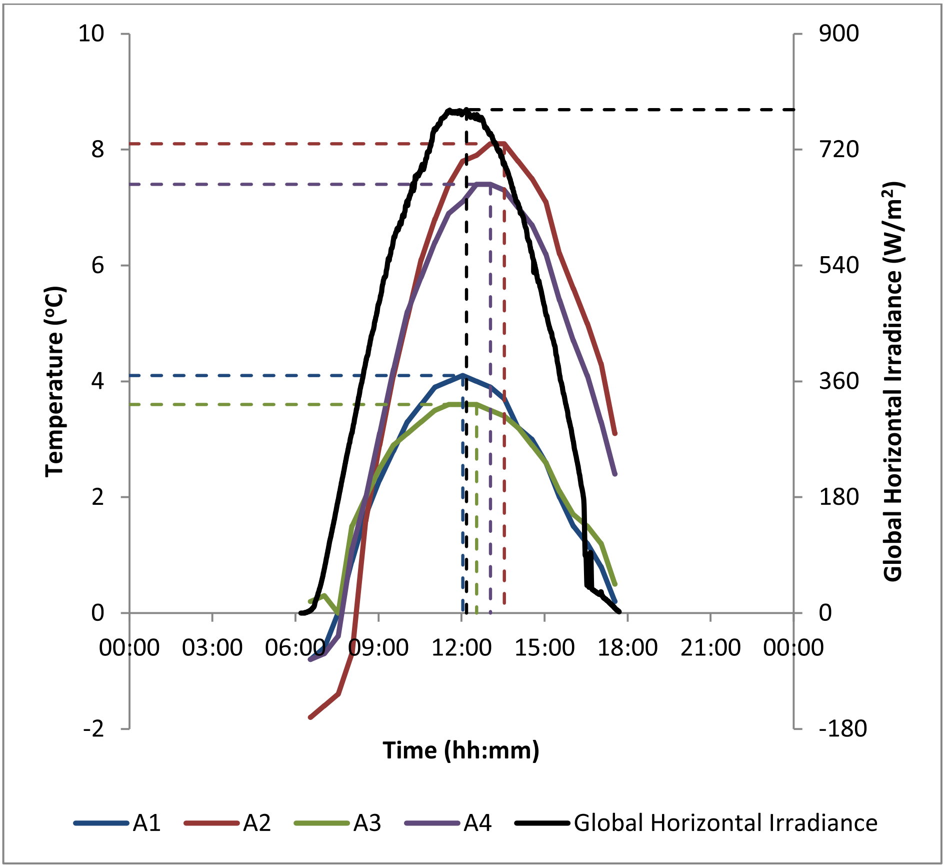

Figure 3. Effects of solar radiation on the temperature contrasts created by the embedded targets at a depth of 50 mm (02/05/13)

the same day, for each of the 50 mm deep embedded targets. The figure shows the similarities between the development of the temperature contrasts and the pattern of global horizontal irradiance, as illustrated by the shape of each temporal distribution.

It shows a delay between the peak temperature contrasts for Target's A2 and A4 and the maximum irradiance for that particular day, leading to the conclusion that the delay between maximum solar radiation and peak temperature contrast increases for an increased target size. Moreover, the peak temperature contrasts suggest that larger targets develop larger contrasts. The temperature contrasts for Target's A1, A2, A3 and A4, at maximum, are 4.1°C, 8.1°C, 3.6°C and 7.4°C, occurring at approximately 12:00, 13:30, 12:30 and 13:00 respectively. This in contrast to the maximum irradiance occurring at approximately 12:00. The smaller targets reached their maximum contrasts at roughly the same time as maximum irradiance whereas the larger targets reached their maximum temperature contrasts approximately one hour later.

Data over the two months of observations were analysed in this manner to quantify the time of day and duration after sunrise that each target reached its maximum temperature contrast. It was found that the duration after sunrise for maximum temperature contrast to occur for Target's A2 and A4 were identical at roughly six hours, 30 minutes after sunrise, with a standard deviation of approximately 25 minutes. Target A1 reached its maximum temperature contrast in the shortest space of time, roughly four hours, 30 minutes after sunrise, with a standard deviation of approximately 20 minutes. Sunrise on this particular day occurred at approximately 06:30 which suggests that the optimum time to conduct the delamination survey would have been between 11:00 and 13:00.

4. Conclusions

This paper has reported selected results from on-going research into the application of infrared thermography as a means of diagnosing the presence of delaminations in concrete structures. A concrete panel was constructed to address the effect that solar radiation has on the ability of infrared thermography to detect and reveal areas of delamination in concrete structures. The paper focused on evaluating the degree to which a 50 mm deep delamination would affect the relative time period during which the observable variations in temperature that manifested at the surface of the concrete panel, relative to areas of intact concrete, created by the presence of the delamination, are optimised under local conditions in Johannesburg, South Africa.

Observations of the north facing elevation of the concrete panel were made over a period of two months during winter. Data collected included thermal images of the panel which were used to extract quantitative data of the apparent temperature differences between the embedded targets and the surrounding intact concrete. In addition to this, global horizontal irradiance was measured and logged to provide a site reference of local solar energy resources. This data was analysed in order to quantify the time of day and duration after sunrise that a 50 mm deep delamination would reach its maximum temperature contrast. The results suggested that optimum contrasts would be achieved during a late morning, early afternoon survey.

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