Development of Hand-held Thermographic Inspection Technologies: Draft Final Report

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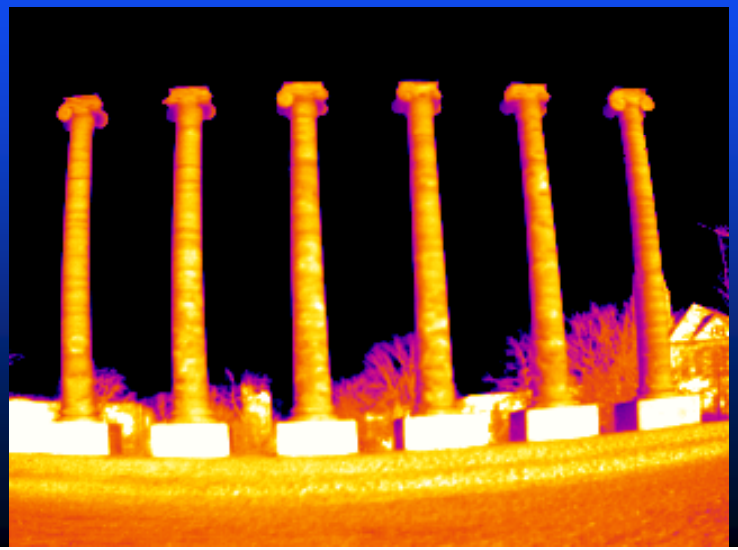


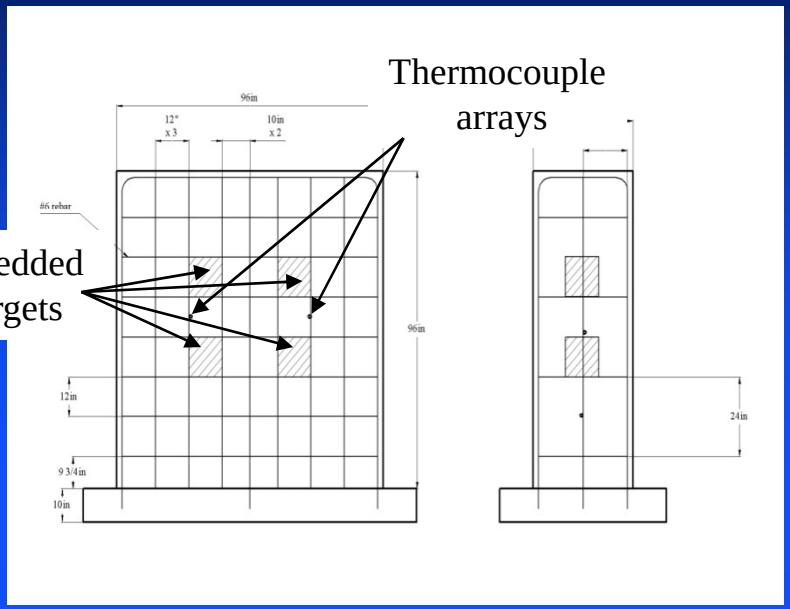
Agenda

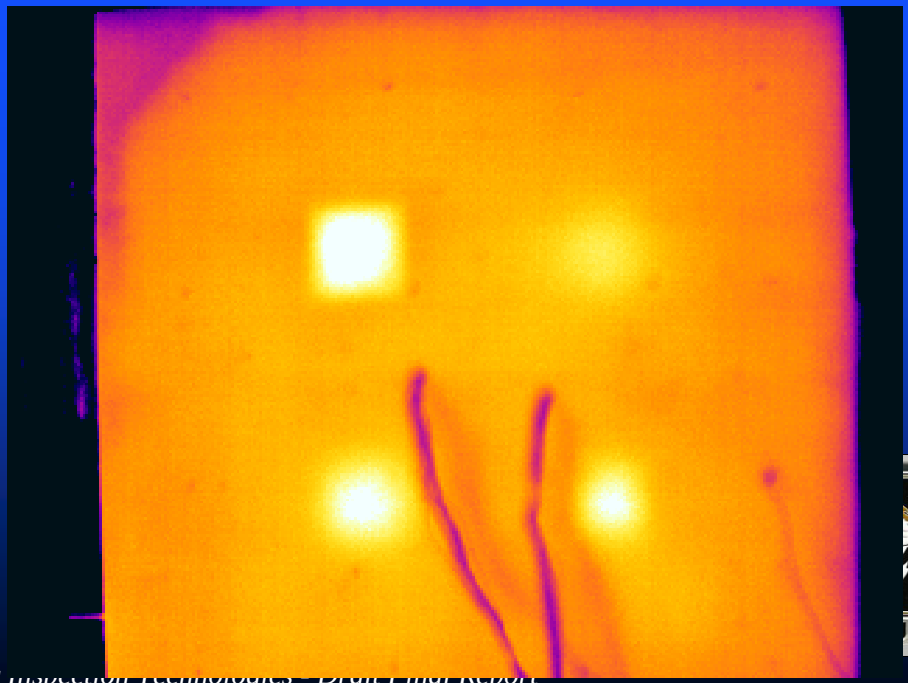
- Intro / Overview
- Results of the experimental study
- Field testing results
- Conclusions
- Guidelines
- Implementation Recommendations

Introduction

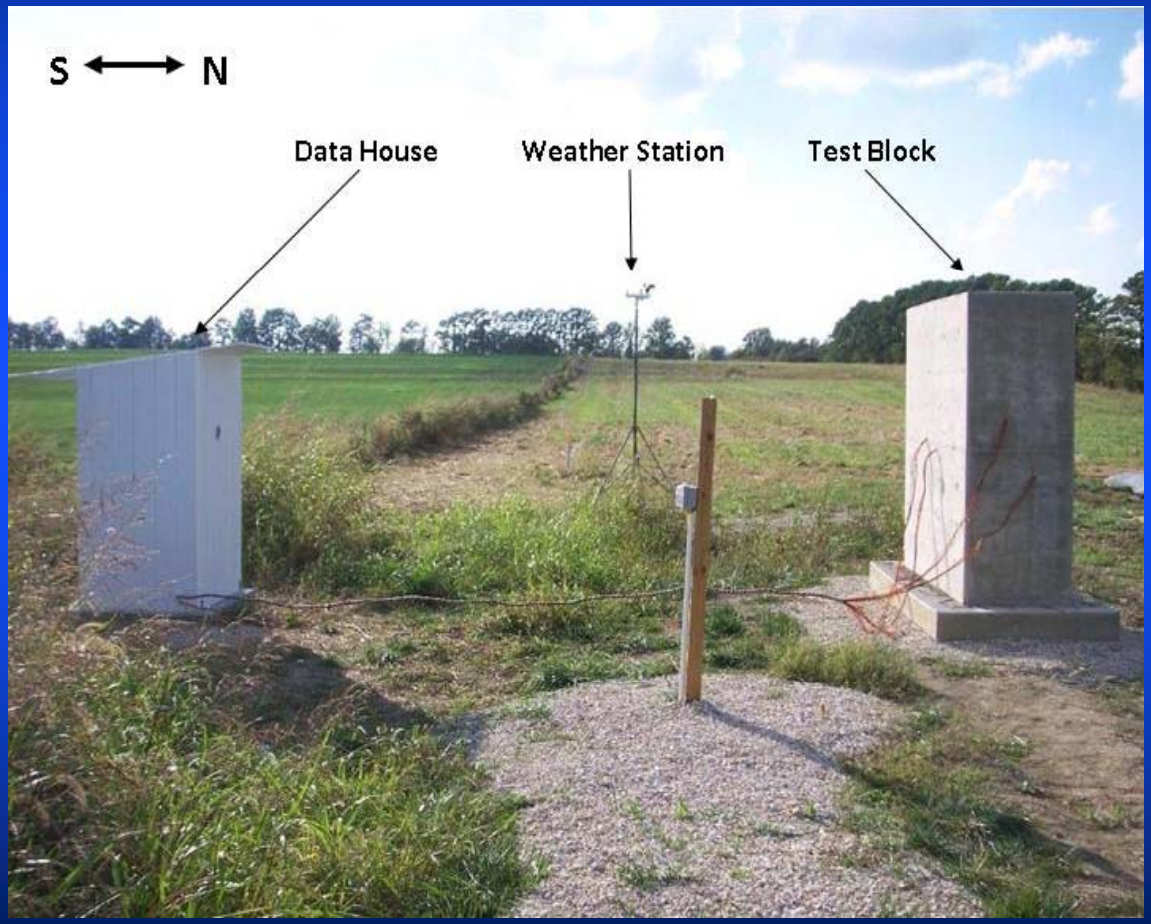
- Research Study included:
  - Development of a experimental test station to evaluate environmental effects on detectability of subsurface targets in concrete
  - Development and delivery of training materials for States; Cameras put in use by States
  - Development of field data box (infra-units)
    - Development of weather website for tracking recent weather trends
  - Data analysis or results from test block:
    - 3 months of data from both North and South sides

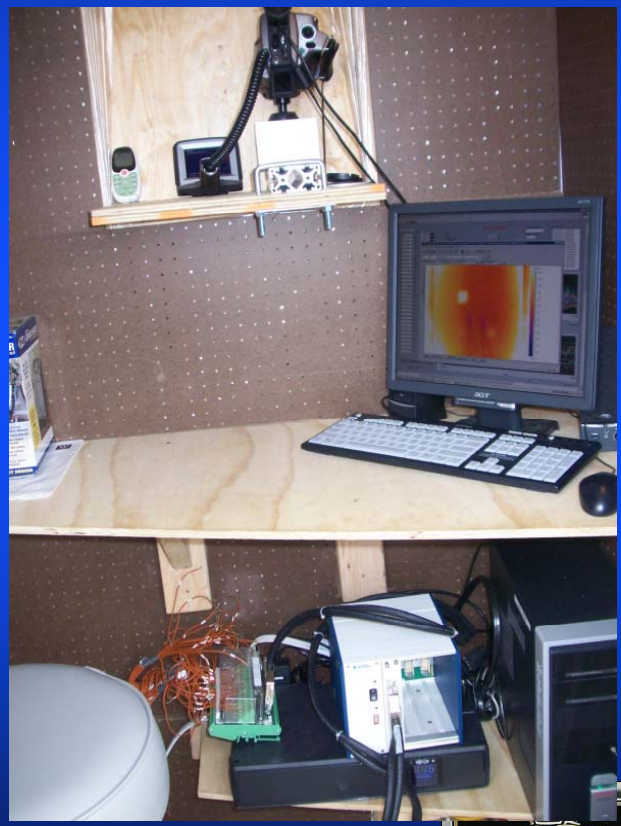
Test Block


Thermocouple arrays
Embedded Targets
96in
12" x 3
10in x 2
#6 rebar
96in
12in
9 3/4in
10in
24in

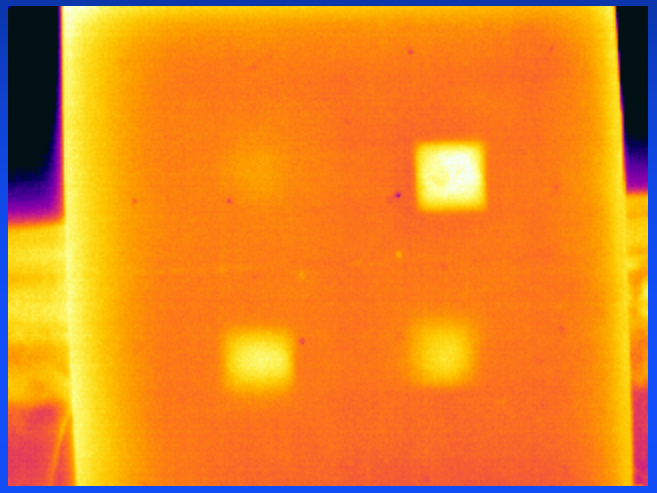


Test Block Data Acquisition

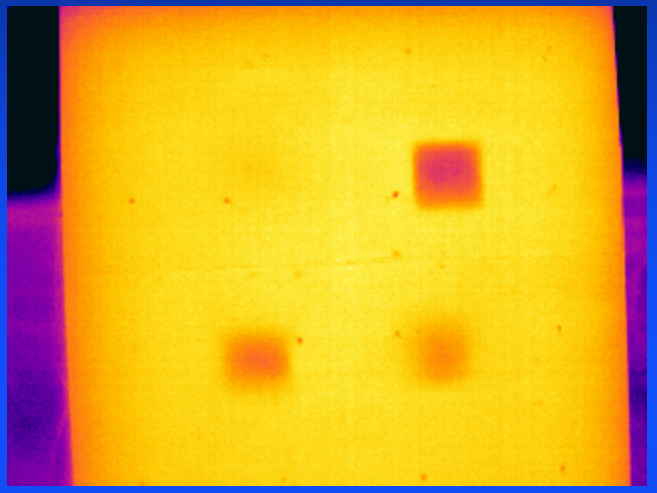




Example of delaminations as observed during warming period and cooling period



(5/4/08 3:00pm)
Positive contrasts due to warming period

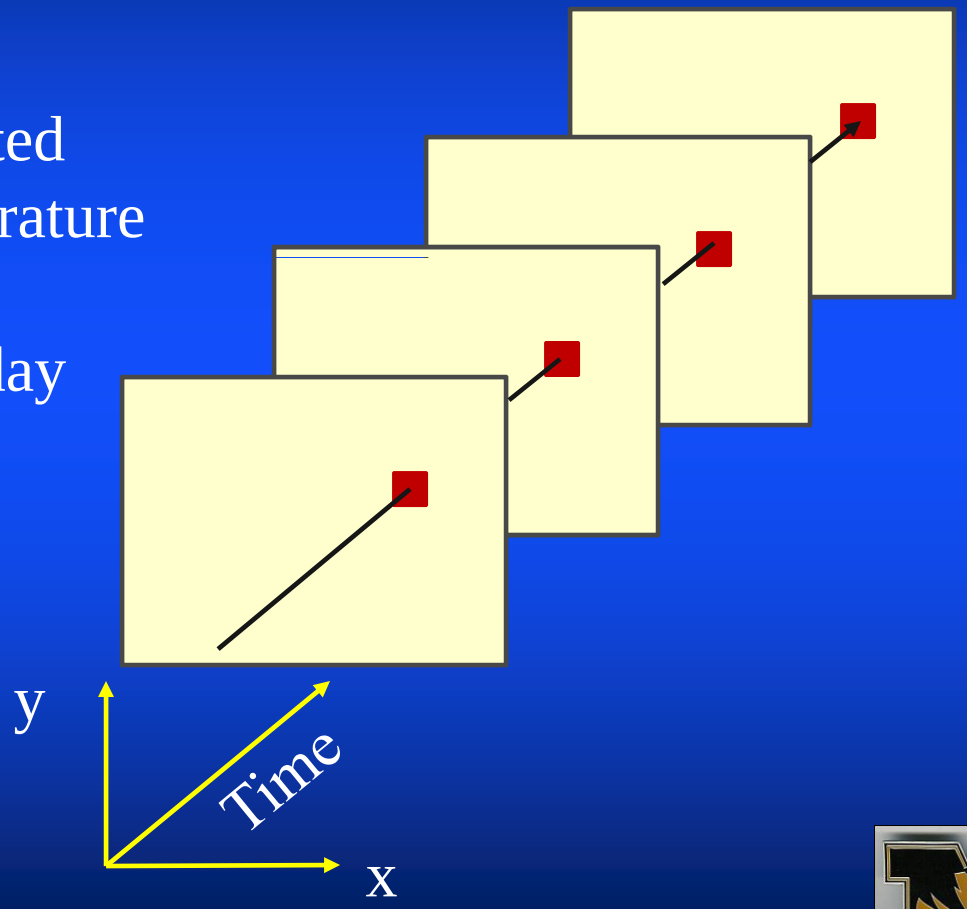


(5/5/08 3:00am)
Negative contrasts due to cooling period

Data Reduction

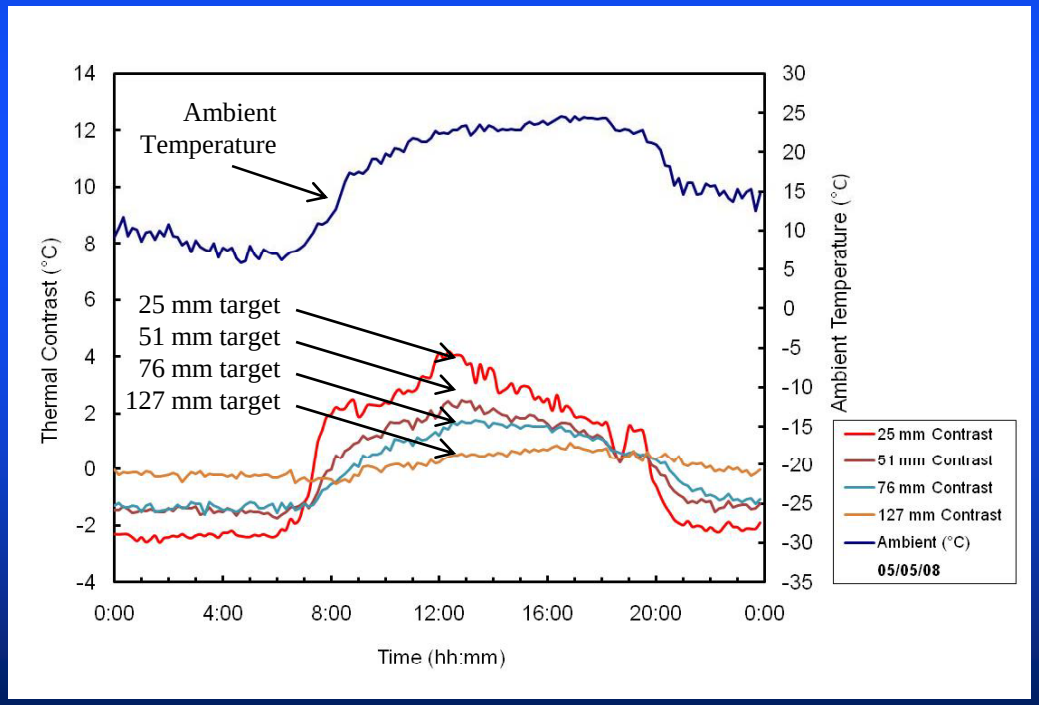
Thermal Contrast calculated by individual pixel temperature values over time

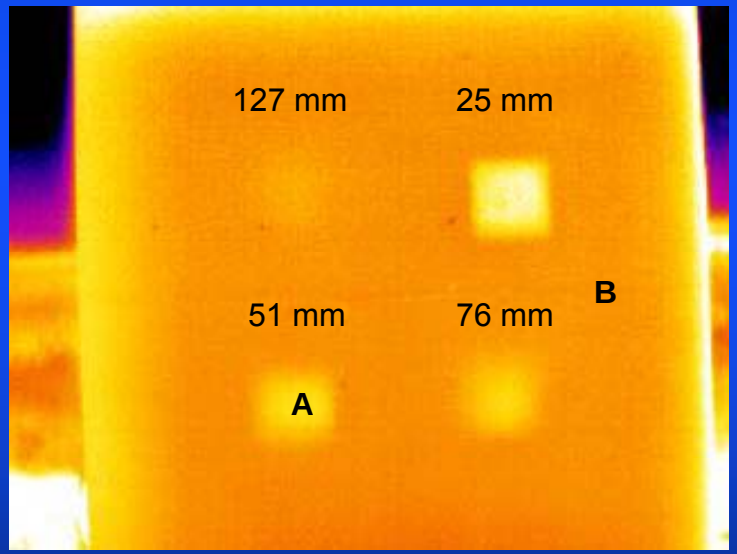
- 10 min., 24 hrs/day



Data Reduction with application

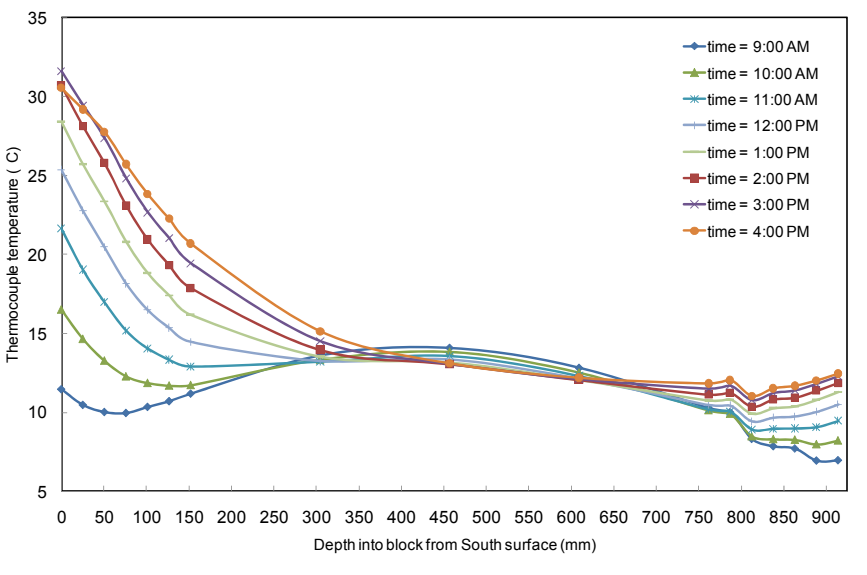
- Graph on left has 2 (y) axis
  - On LHS, the thermal contrast between a pixel over a target and a pixel in acreage
  - On RHS, environmental variable is shown
    - Ambient temperature, solar loading, wind speed, or humidity



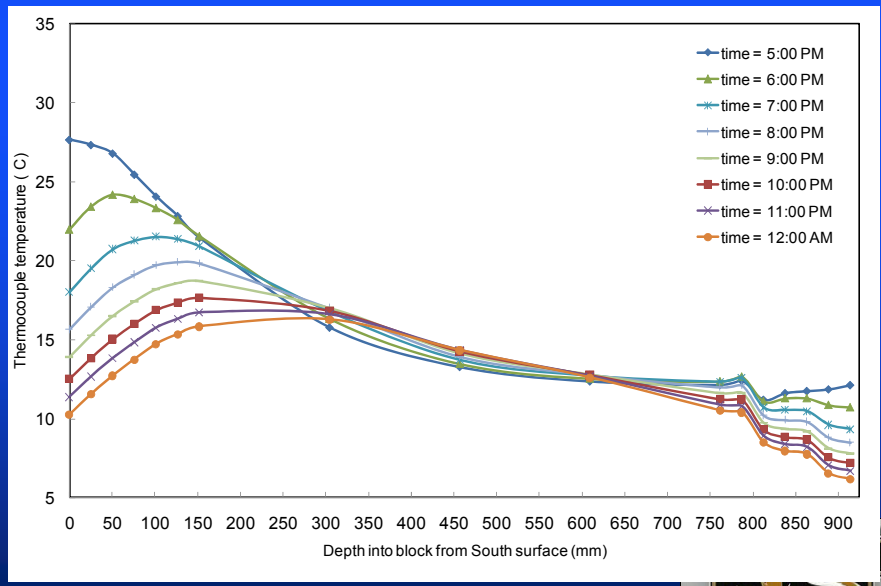


Thermal Gradient in Test Block

Daytime – Pos. thermal contrast



Nighttime – neg. thermal contrast



Data and Analysis

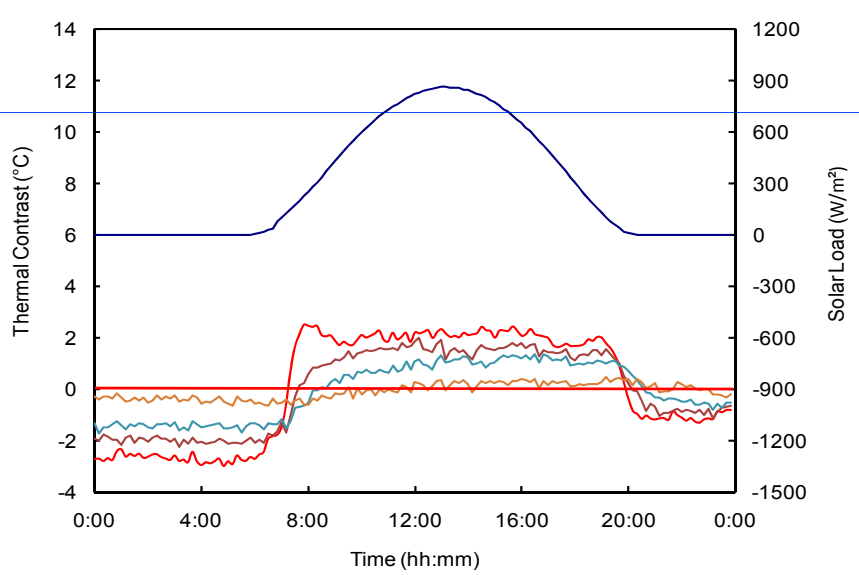
- 3 months of data on south side of block collected
- 3 months of data on North side of block collected
  - Shady side of the block
- Data was analyzed to determine environmental conditions that are best for IR inspections

Data Analysis

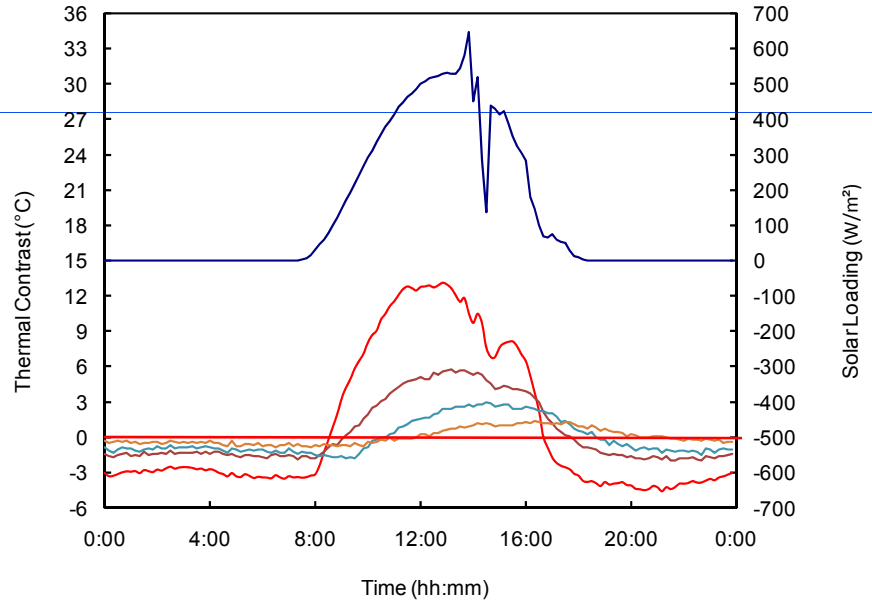
- 1 and 2 º C (1.8 and 3.6 ºF) typically used as a threshold for conditions that would have observable contrast under field conditions
  - Arbitrary threshold selected because
    - 20 to 40 x the sensitivity of the B400 camera
    - 2 to 4 x the ASTM recommendation for detecting a delamination in a concrete bridge deck
  - There is no transfer function between a styrofoam target and a real delamination
    - Uneven surface, varying contact of surface, irregular shape and angle relative to surface, may contain moisture
    - As technology progresses, characterization of naturally occurring flaws can help define reliability better in the field.
- Thresholds used to estimate detectability
- 51 mm (2 in. deep) target used for analysis

Contrast Results

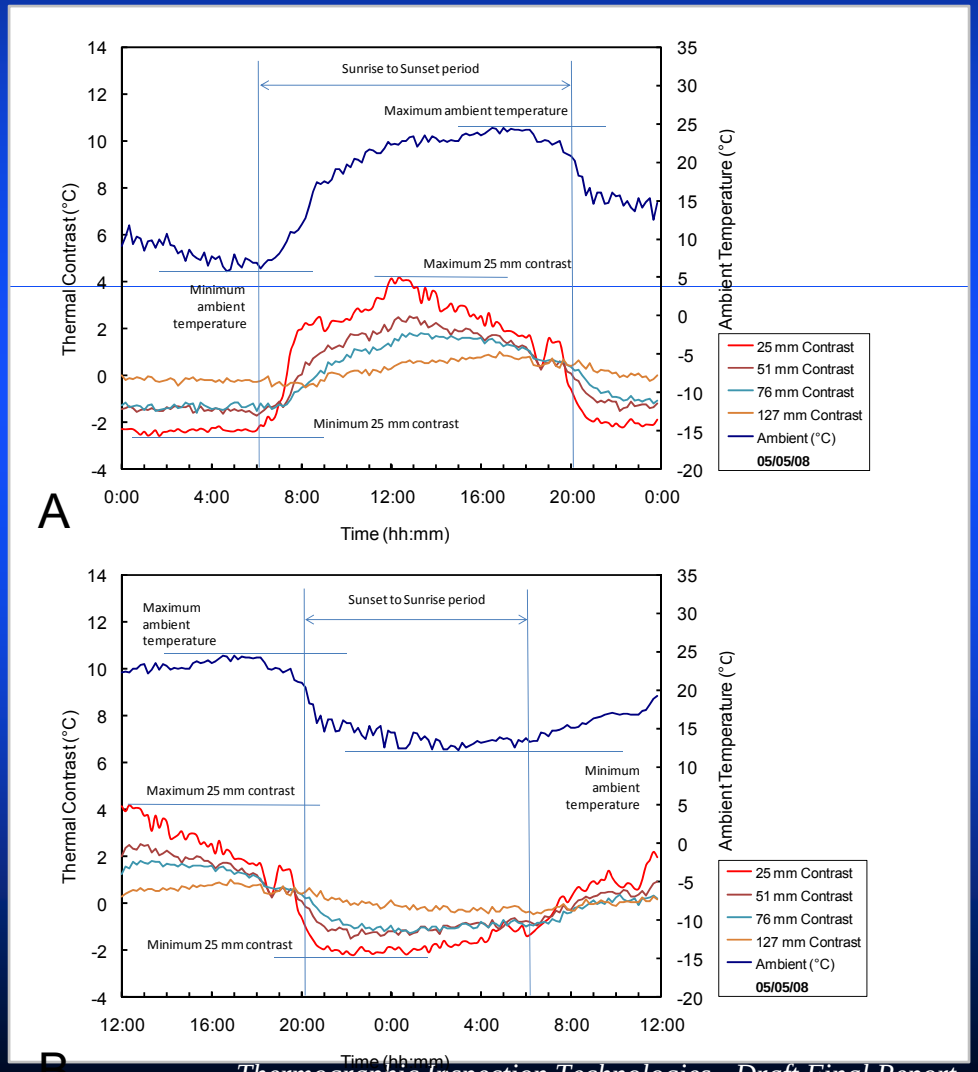
North Side



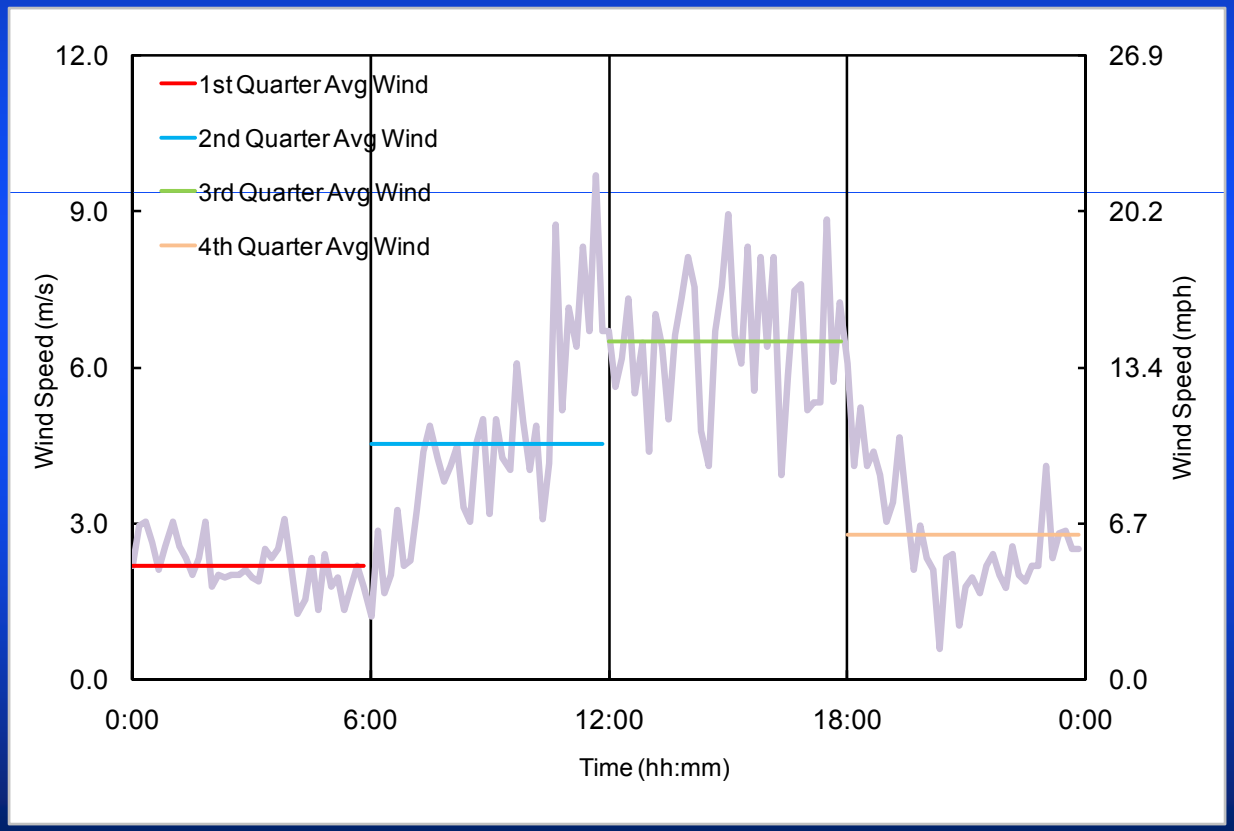
South Side



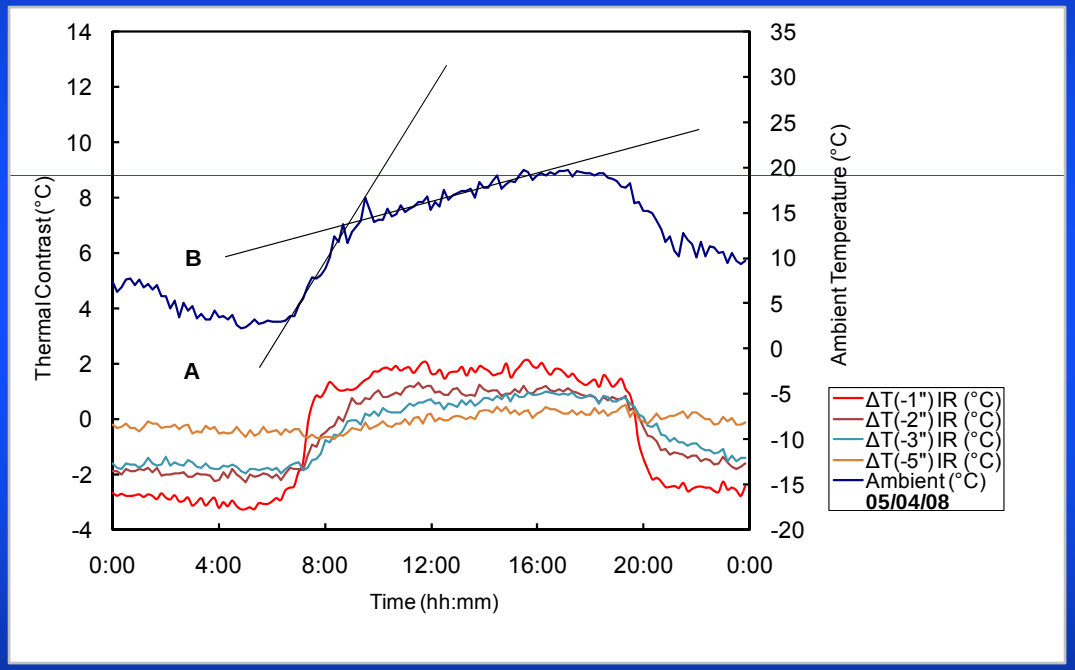
Data Analysis – Ambient Temperature Change



Average Wind Speeds - Quarters

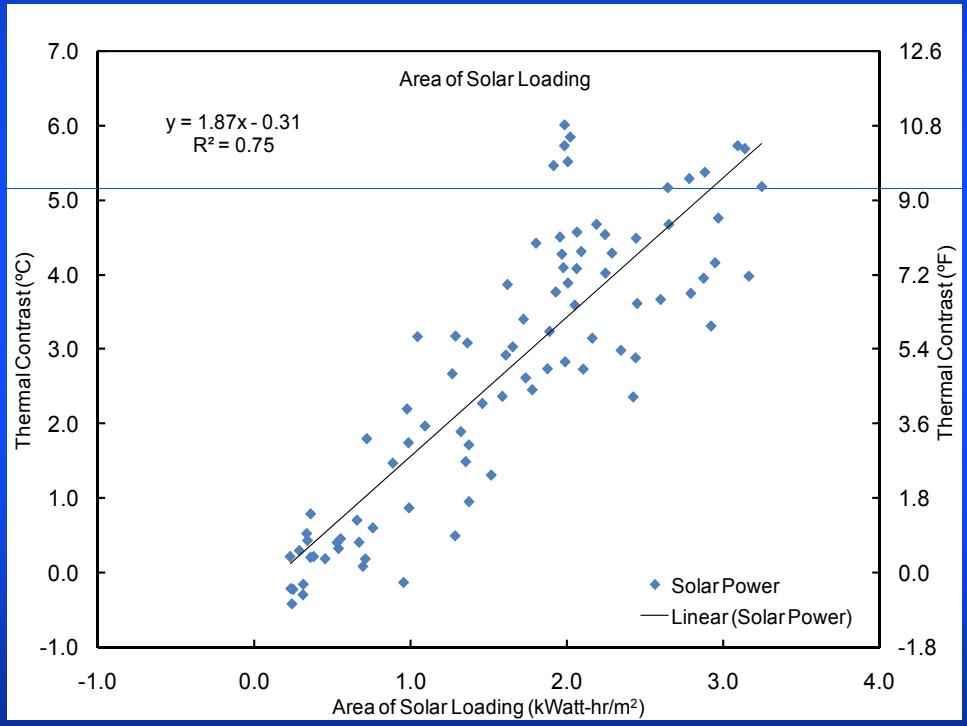


Rate of Change Analysis (ROC)



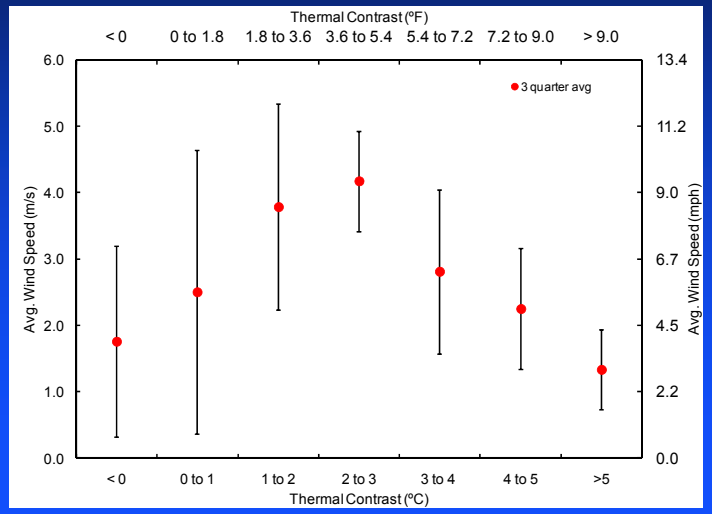
Results – South Side

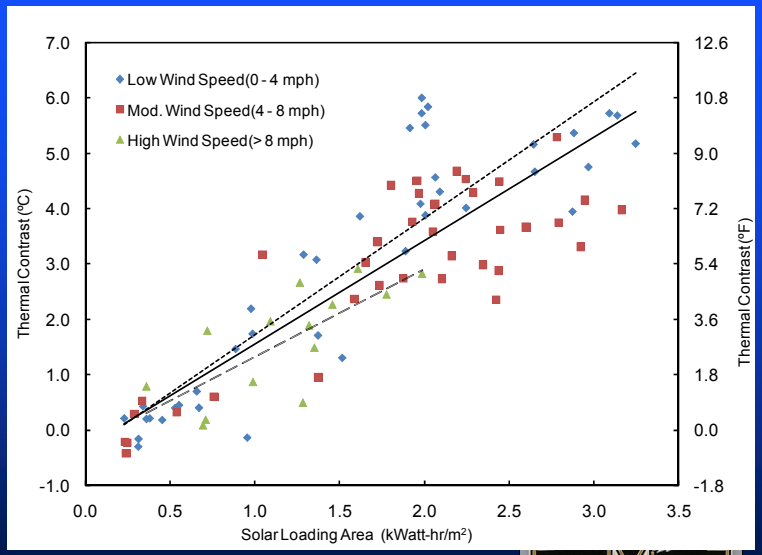
Area of Solar loading:
Intensity of sun x time
-For 1 ºC contrast, 0.7 kW-hr/m²
Min.



Results – South Side, Wind Speed Analysis

- For the sunny (south) side, low winds are characteristic of days with high contrast
- Trend of wind speed (lower figure) shows that winds are detrimental
  - Under solar loading, the wind cools the concrete (which is warmer than the ambient environment) and as such reduces the effect of the sun (reduces contrast for defects)
  - Note: Long dashed lines = high wind speeds, short dashed lines = low wind speed



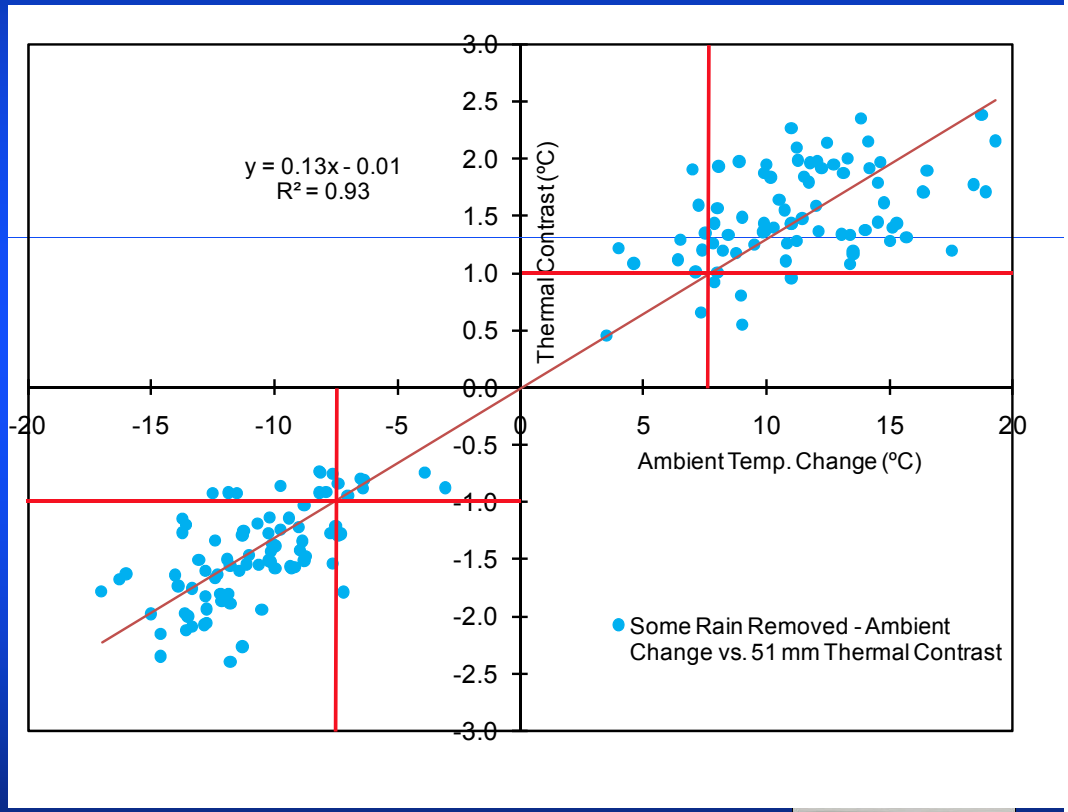


Results – North Side

- For the north side, there is no solar loading
- Contrasts develop from the changes in temperature of the ambient environment
- Convection is the primary heat transfer mechanism

Ambient Temperature Change vs. Thermal Contrast

- On average, 1.4 ºC of contrast either positive (day) or negative (night)



Ambient Temperature Change - Statistics

- Applying a threshold of at least 1ºC (1.8 ºF) and corresponding x-axis intercept
- Using at least 8 ºC (~15 º), significant majority of data points achieve threshold
- Rain had little effect on results

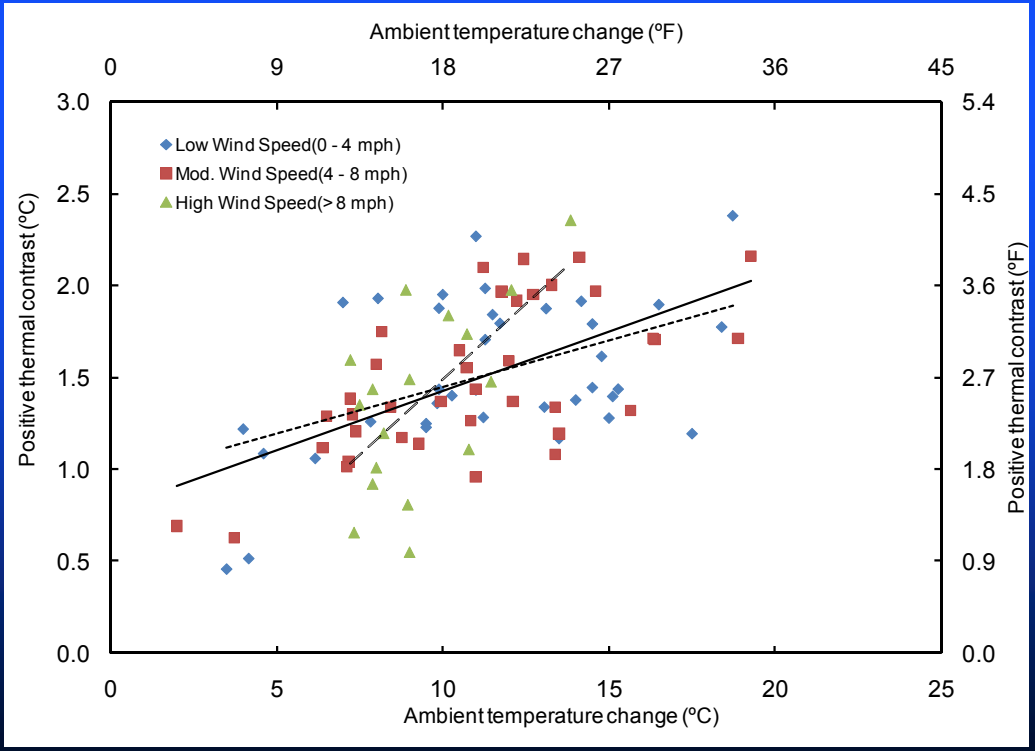
Condition	Type	Threshold (°C) (Intercept value)	% of data above threshold and greater than +/- 1° C
No rain removed	Positive	7.5	95
	Negative	-7.9	86
Moderate Removed	Positive	7.8	94
	Negative	- 7.6	88
All rain removed	Positive	8.2	96
	Negative	- 7.2	90

Wind Speed Effects

- Because convection is relied on for developing contrast, wind speed trends indicate improved contrast for higher wind speeds (during the day); at night, conditions are typically calm….
- The direction of wind was not analyzed due to difficulty in practical application of the results; this may be the source of scatter in the following graph

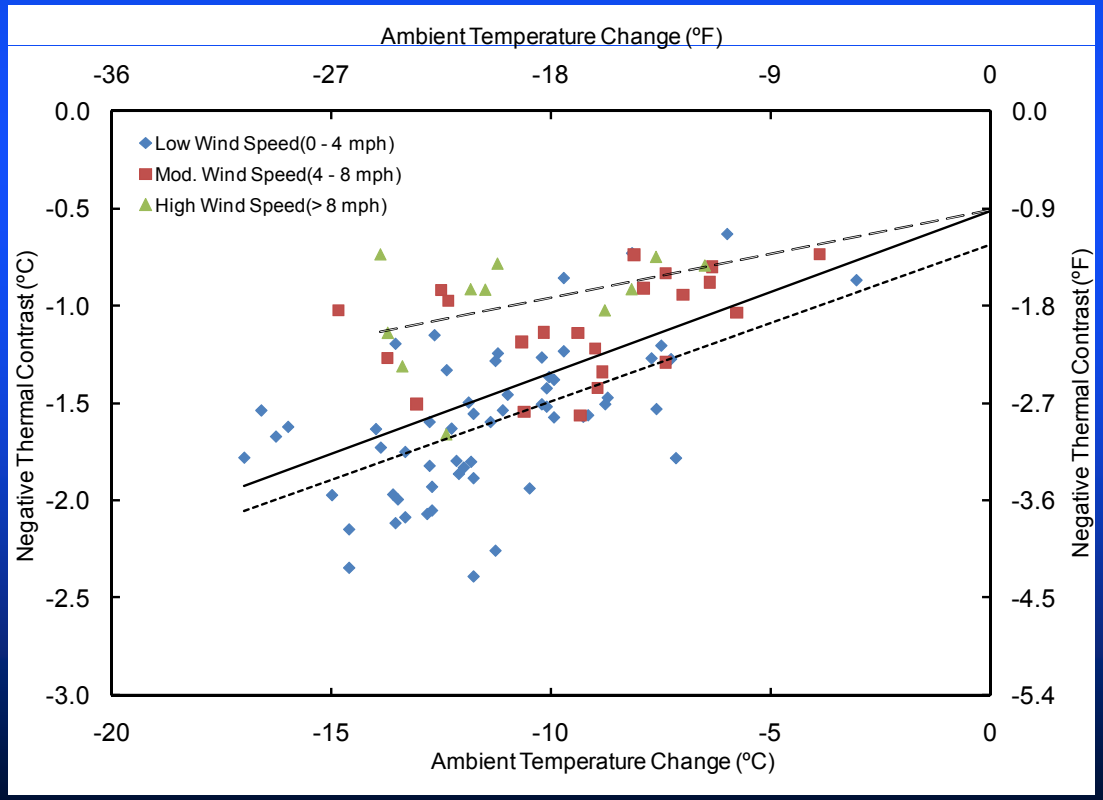
Wind Speed Effects - Day

- Long dashed lines = high wind speed
- Short dashed lines = low wind speed
- High wind speeds trend to have greater contrast
- Convective heat transfer



Wind Speed Effects - Night

- At night, low wind speeds were found to be a characteristic of high ambient temperature change (negative)
- High wind speeds tended to result in reduced thermal contrast



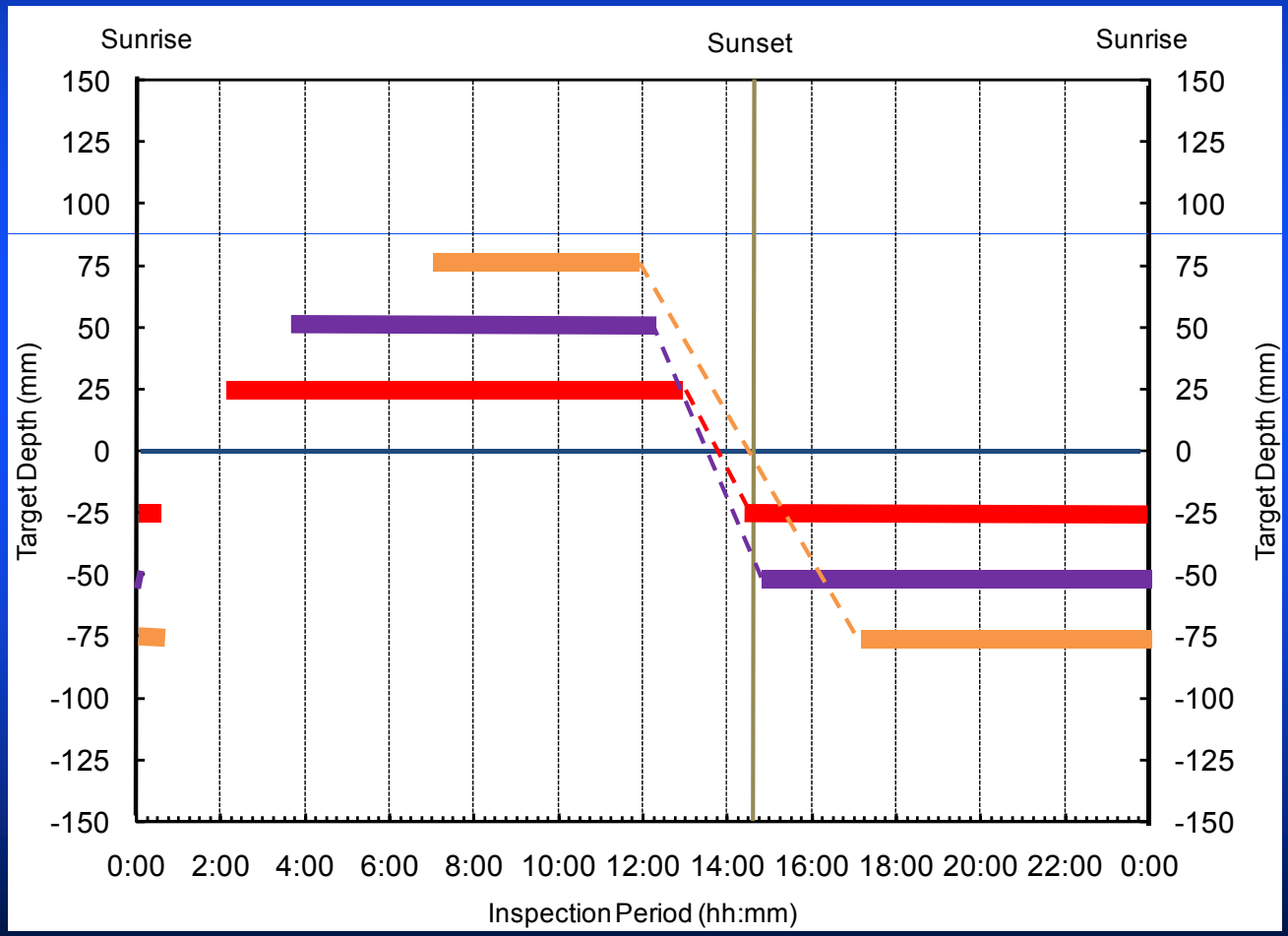
Inspection Periods

- Inspection periods were calculated based on threshold values of 1 ºC (1.8 ºF)
- Start time and length of inspection periods vary as a function of depth of the target as would be expected
- Periods are calculated for the time of year that the data was collected
  - For south side, Nov 2007- Jan. 2008
  - For north side, May 2008 – June 2008
- Due to the changes in the length of the day, the times should be adjusted for different times of year
  - Could be done using proportional values

Inspection Period – North Side

- Inspection period for 1, 2 and 3 in. deep targets
  - 5 in. deep target only rarely had sufficient contrast
  - Start/end of inspection period is a function of depth
- Depends on ambient temperature change

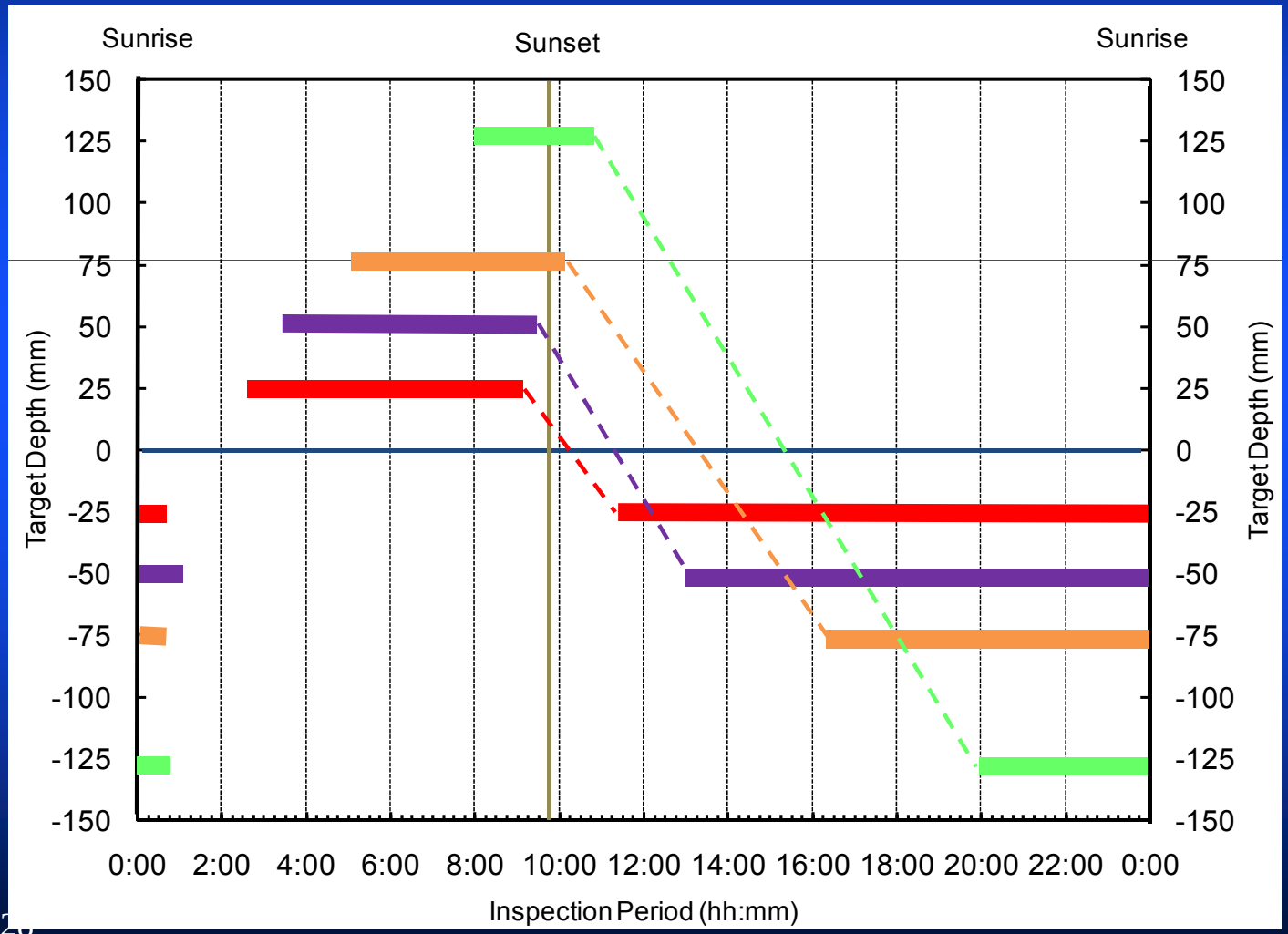
Inspection Period – North Side



Inspection Period – South Side

- Due to the driving force of the sun, the 5 in. deep target is observable, both day and night (thermal gradient is higher from sun)
- Inspection times are based on the shortest period of the year; will be longer for the summer (daytime)
- The thermal wave in the concrete causes delay in the end of inspection times for the deepest targets

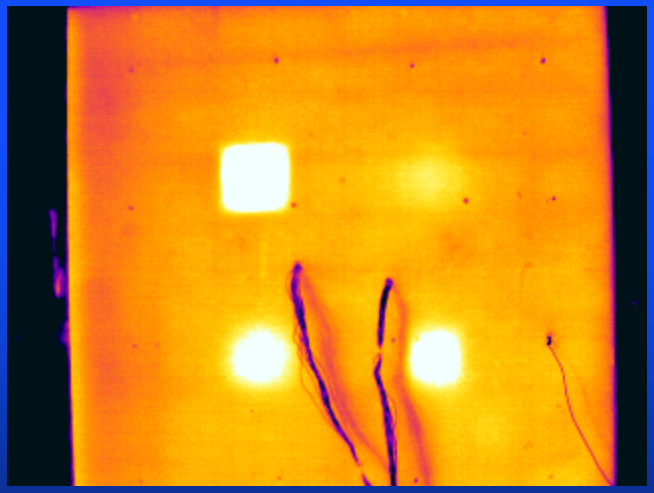
Inspection Periods – South Side

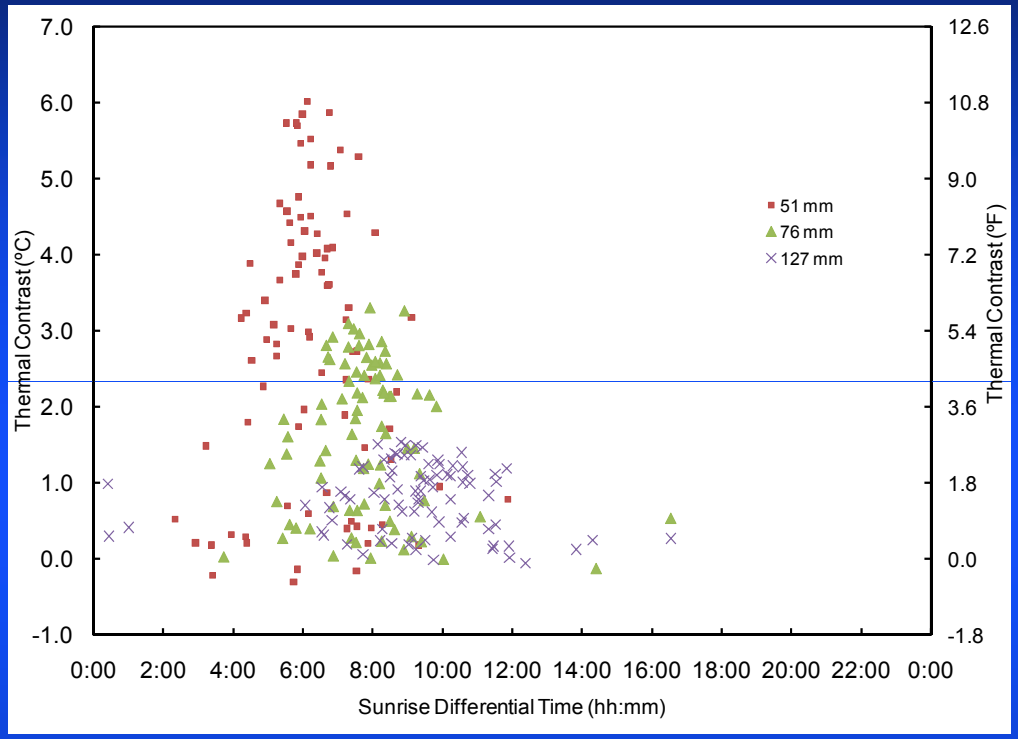


Maximum Contrast Times

- For the south side, the thermal contrast is sinusoidal in shape, showing a clear maximum
- An optimum time for inspection can be determined based on maximum contrasts
- The optimum times vary as a function of depth
  - Maximum also vary as a function of depth
- For 2 in. deep target ~6 hrs, 5 in. target ~9 hrs

Reinforced concrete block with targets at 1”, 2”, 3” and 5” (south side)





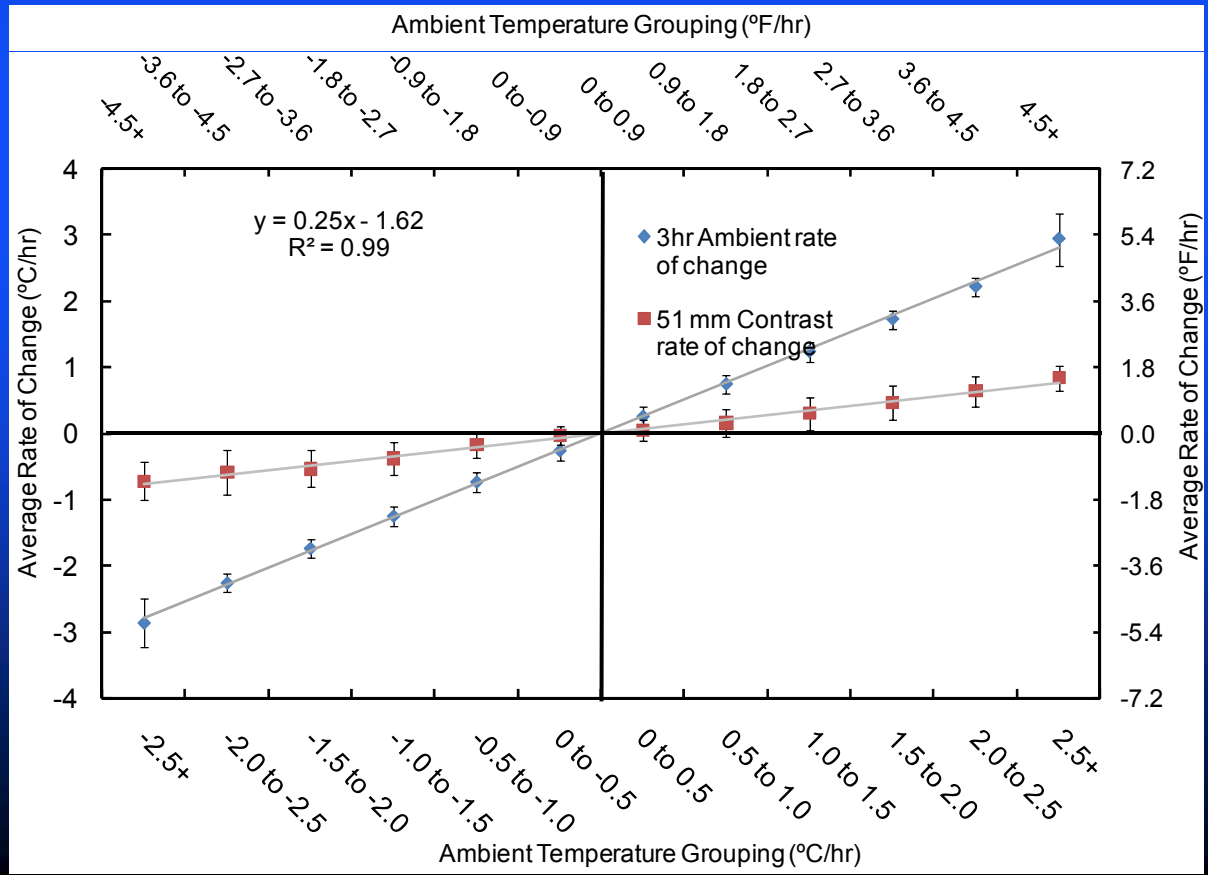
Plot of image contrast maximums vs. time of day (3 months of data) (direct solar loading)

Rate of Change for Ambient Temperature

- The rate of change was analyzed to determine conditions for detection of defects
- The 2 in. deep target was used for the analysis

Ambient ROC, 2 in. Deep Target

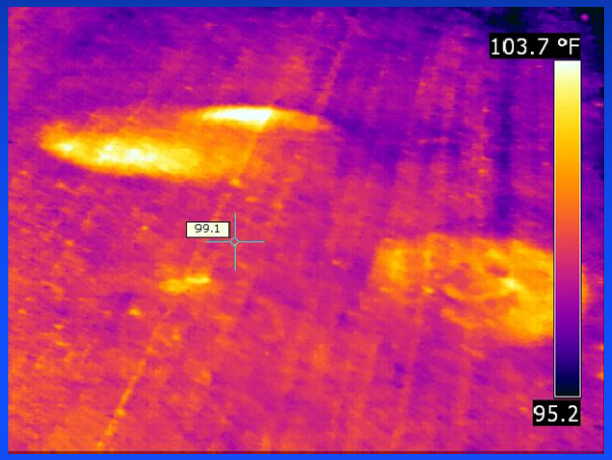
- It was found that contrast is diminishing when ROC < 0.5 deg C/hr
  - During times of constant temperature, contrast is diminishing, avoid inspections during this time for 2 in. deep defects
  - Inspection should be done during changing ambient temperature

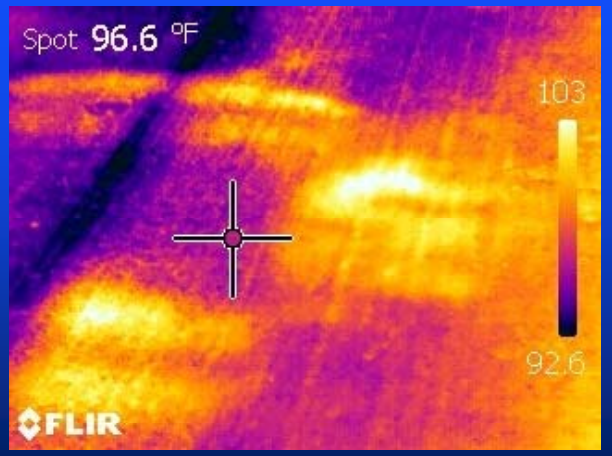


Field Testing

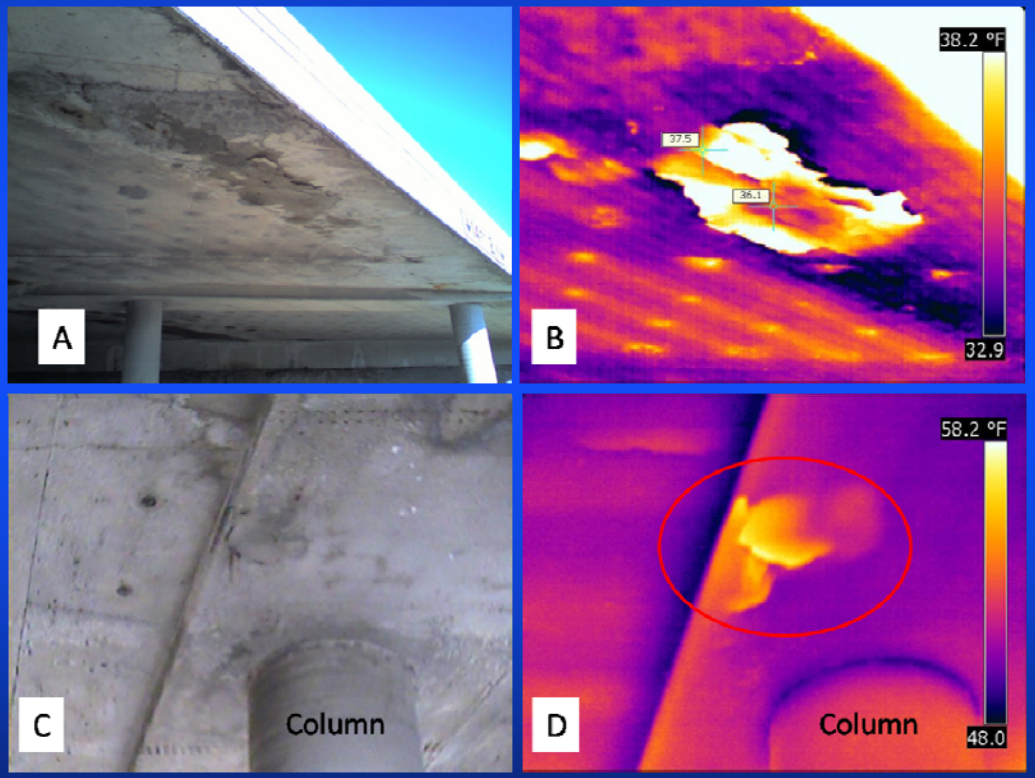
- Some field testing has been conducted
- Examples of results are presented

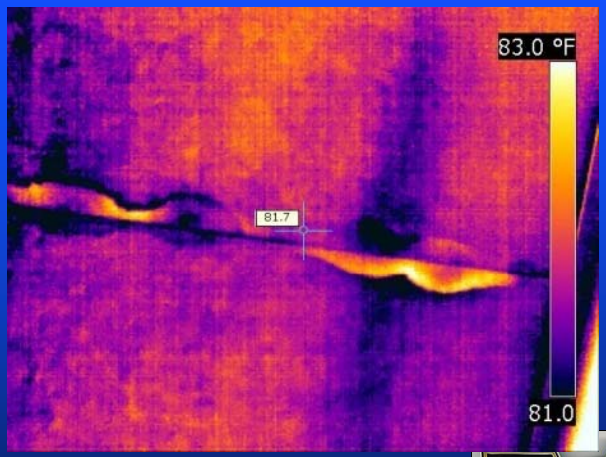
Deck Delaminations -TX



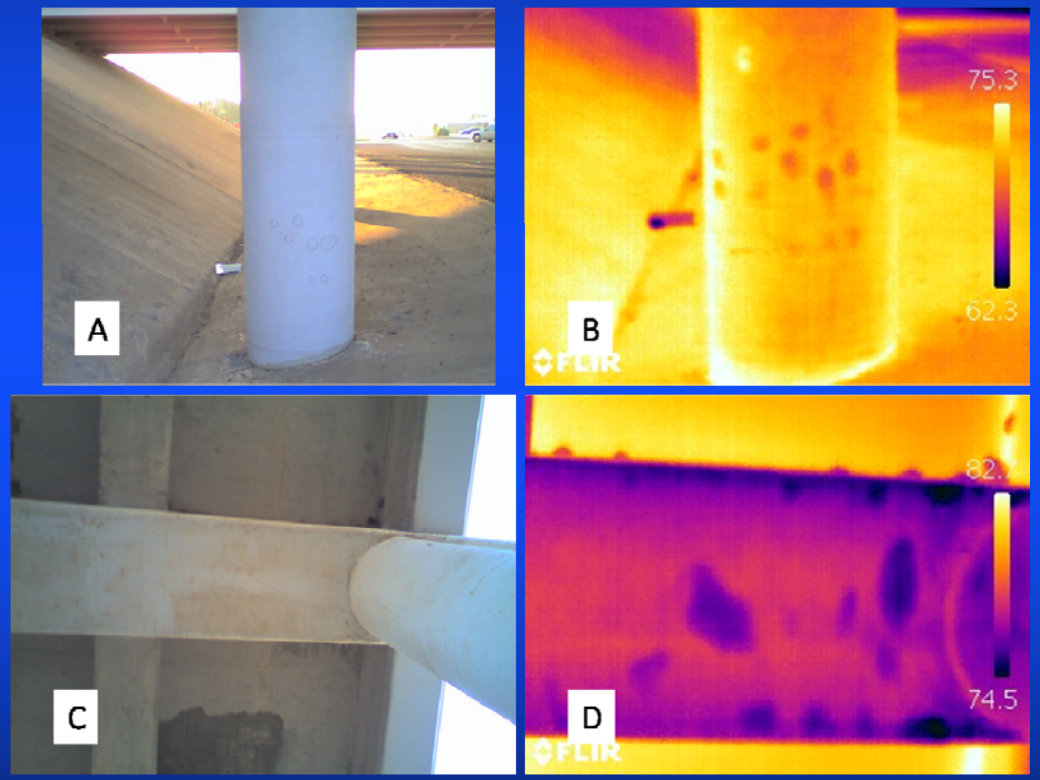


Soffit Delaminations - MO

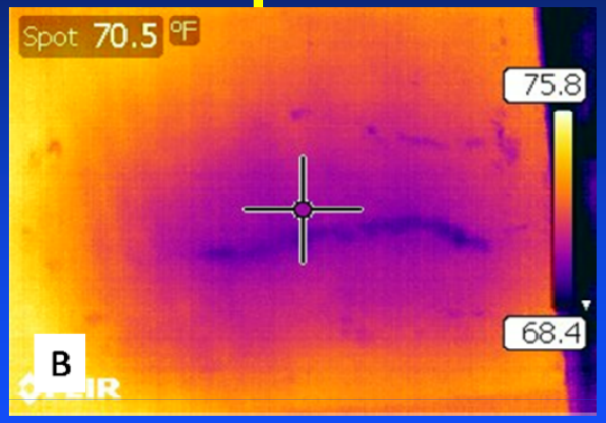


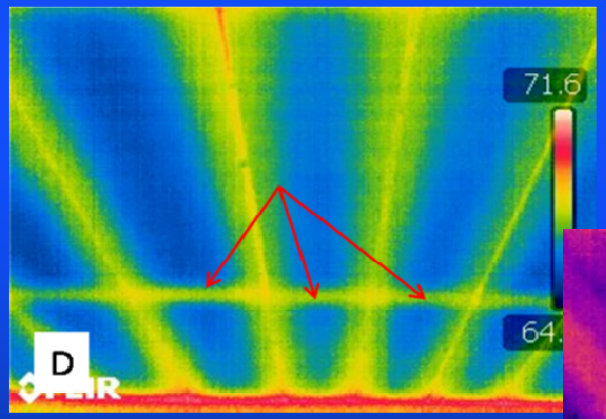


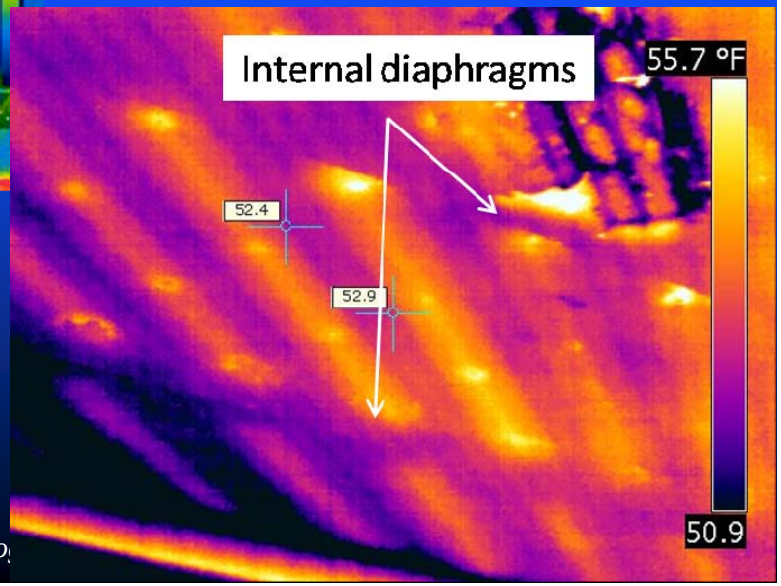
Composite Overlay - TX



Soffit Inspections - NY







Conclusions

- Summary
  - South Side (solar exposed surfaces)
    - Direct, uninterrupted solar loading and low wind speeds provide optimal conditions
    - Wind speed average less than 8 mph
    - Optimum inspection times vary as a function of depth
    - Inspection periods of 5 to 6 hours for 2 in. deep targets (depending on threshold, 5 hrs = 2 ºC, 6 hrs = 1 ºC)

Conclusions (Cont.)

- North Side
  - Magnitude of thermal contrast was found to be the same for day and night, ~1.4 ºC for 2 in. target
  - Ambient temperature change of 8 ºC (~15 ºF) resulted in contrast of at least 1ºC (1.8 ºF)
  - High wind speed appeared to improve thermal contrast during the day
  - At night, low wind speeds were characteristic of day with the best thermal contrast
  - Ambient temperature ROC of at least 0.5 ºC /hr (0.9 ºF/hr), thermal contrast is steady or increasing for 51 mm (2 in.) deep target, decreasing below 0.5 ºC /hr (0.9 ºF/hr).
  - Ambient temperature ROC of at least 1.5 ºC (1.8 ºF) resulted in thermal contrast >1 ºC for the 51 mm (2 in.) deep target

Guidelines

- Guidelines were developed based on these conclusions
- Guidelines indicate:
  - Solar exposed surfaces:
    - Conditions for solar exposure - direct, uninterupted solar loading, minimal cloud cover
      - Total solar loading area estimate method based on measurement
    - Average wind speed limit of 8 mph (6 hr. average)
    - Estimate inspection periods
      - 2 in. deep delamination, 4 hrs after sunrise, inspection period lasts 6 hrs
      - 3 in. deep delamination, 5 to 6 hrs after sunrise, inspection period of 5 hours
      - NOTE: based on shortest days of the year

Guidelines (cont.)

- Shaded surfaces, daytime
  - Ambient temperature change for the day of at least 15 º F
  - ROC for ambient temperature change: At least 10 ºF in the first 6 hrs after sunrise
  - When ambient temperature becomes steady or begings to decrease, thermal contrast will be decreasing for 2 in. deep delaminations
  - Local environment: Ambient changes need to be at the surface being inspected
    - Simple temperature monitoring device could be used to confirm changes
  - Wind Speed: Not necessarily detrimental, but a practical limit of 10 mph is suggested (based on 6 hr average)
- Inspection periods:
  - 2 in. deep delamination, 4 to 5 hours after sunrise, inspection period of 8 hrs
  - 3 in. deep delamination, 7 hrs after sunrise, inspection period of ~ 4 hrs
  - Note: Based on longest days

Guidelines (cont.)

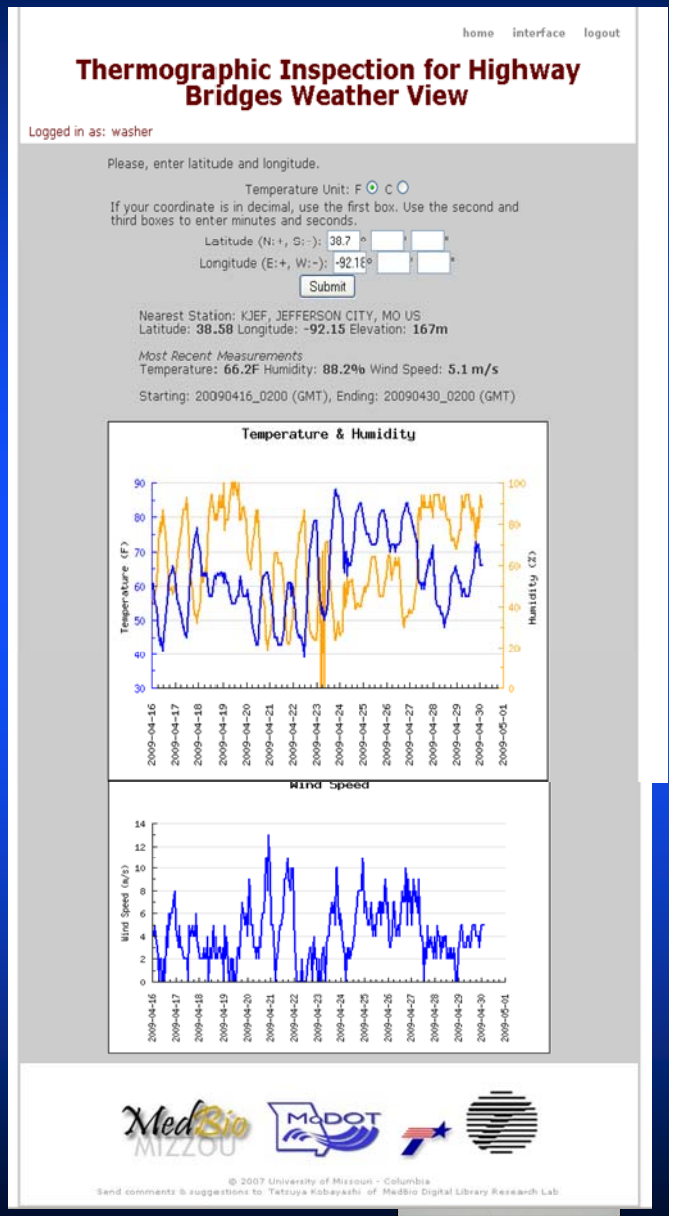
- Shaded surfaces, nightime
  - Ambient temperature change for the day of at least -15 º F
  - ROC for ambient temperature change: At least 10 ºF in the first 6 hrs prior to sunset
  - When ambient temperature begin to decrease, thermal contrast will be decreasing for 2 in. deep delaminations
  - Local environment: Ambient changes need to be at the surface being inspected
    - Simple temperature monitoring device could be used to confirm changes
  - Wind Speed: Not necessarily detrimental, but a practical limit of 8 mph is suggested (based on 6 hr average)
- Inspection periods:
  - 2 in. deep delamination, 1 hr after sunset, inspection period of 9 hrs
  - 3 in. deep delamination, 3 hrs after sunset, inspection period of ~ 7 hrs
  - Note: Based on longest days

Guidelines (cont.)

- Camera Settings
  - Focus
  - Level and Span
  - Angle of observation

Web Site

- Data for implementing the guidelines can be obtained at the web site developed for this project
  - Ambient temperature changes and wind speeds are obtained from the nearest weather stations based on GPS coordinates
  - Smart phones have the technology to implement this in the field
  - iphone has been test with the weather web site
- Web site needs some changes, currently being implemented at MU
  - Originally developed for 2 weeks of data, needs to be changed to 2 days and average wind speed displayed



Implementation Recommendations

- A more focused study of the use of the technology in the field could assist with implementation
  - Field testing results are incomplete; collaborative efforts could assist with developing knowledge and experience
  - Test/validate developed guidelines
  - Technology transfer
  - Ensure results of study are fully utilized
  - Develop a IR users group to share experiences and advance technology

Implementation Recomendations

- Validation study: A validation study on a test bridge with delaminations could be used to validate the guidelines
  - Frequent or continuous monitoring of a real bridge with known defects
  - Demonstrate the use of the technology, document response from real delaminations
  - Forensic analysis of defect characteristics after study

Implementation Recomendations

- Expand field testing with additional States
  - Additional States have expressed interest in using the technology, these State could join the study and participate in the users group
  - Additional validation testing, technology transfer and implementation of the results
- Web site: The weather web site should be further developed for use in the field
  - Show the user the ambient temperature change, average wind speed and solar loading conditions (TBD)
  - Red light/green light for inspection (TBD)

Thank you

- I appreciate your support of this study.

Questions?

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