

Article

Revealing the Impact of Depth and Surface Property Variations on Infrared Detection of Delamination in Concrete Structures Under Natural Environmental Conditions [†]

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Abstract: Infrared thermography (IRT) is an effective nondestructive testing method for detecting delamination in concrete structures. However, erroneous data interpretation often diminishes its practical utility due to surface irregularities (e.g., color variations) during inspection. These “noisy conditions” alter the temperature distribution of the structure under solar heating cycles, making it challenging to quantify delamination based on the developed thermal contrast (ΔT). This study experimentally investigates the impact of different surface conditions (bare concrete vs. painted surfaces) on ΔT . Artificial delamination at varying depths was simulated and tested under natural environmental conditions, where the maximum ΔT values for shallow delamination were 9.40 °C (bare concrete), 7.35 °C (yellow paint), and 5.15 °C (white paint), respectively. This study measured and analyzed the absorptivity (bare concrete: 0.652, yellow paint: 0.538, and white paint: 0.369), emissivity, and the temperature difference (δT) between non-delaminated areas and air, revealing their correlation with ΔT variation. Based on the results, three typical scenarios are proposed to correlate δT with delamination detection. These findings contribute to a better understanding of the optimal detection window and present a new approach to quantifying delamination at different time windows. The conclusion also discusses the limitations of this study and future research directions.

Keywords: concrete delamination; infrared detection; surface condition variations; delamination depth



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1. Introduction

Concrete structures are susceptible to various defects such as cracks, delaminations, spalling, and voids due to factors like steel reinforcement corrosion, thermal effects, continuous freeze–thaw cycles, and concrete shrinkage [1]. Compared to common issues like spalling or pitting [2], delamination defects are characterized by their high concealment and potential for extensive development [3,4]. If delaminations are not detected and addressed in a timely manner, they can evolve into large-scale open spalling, severely compromising structural safety and reducing service life [5,6]. In practice, delaminations often originate within the concrete and remain unnoticed until significant damage occurs [7]. Therefore, gaining a comprehensive understanding of the current state of the concrete, including voids, delaminations, and other defects, is crucial [8]. Early identification of delaminations in concrete structures is essential to prevent structural damage and to provide appropriate repair methods for potentially compromised structures, which is vital for the safe operation of the structure [4,9,10].

In recent years, numerous nondestructive testing methods have been employed to detect delamination in concrete structures. These methods include traditional approaches such as chain dragging and hammer sounding, as well as advanced techniques like ground-penetrating radar [11,12], ultrasonics [13,14], and impact echoes [15,16]. However, these methods require continuous contact or limited sensing distance with the concrete structure and entail significant time and resource expenditure for testing. In contrast, the primary advantage of infrared thermography (IRT) for detecting delamination in concrete structures lies in its ability to conduct large-area assessments in relatively short time frames and identify areas of the defect [17]. Additionally, as it does not necessitate close contact with the structure, this technology enhances the safety and efficiency of the inspection.

Current diagnostic methods based on infrared imaging primarily focus on surface temperature differentials to assess the temperature difference between defective and non-defective areas. The excitation methods for delamination infrared detection can be categorized into active and passive excitation. Active excitation involves researchers heating or cooling test specimens in a laboratory using a heat source such as a halogen lamp. On the other hand, passive excitation involves researchers conducting experiments outdoors without employing additional heat sources for heating or cooling the test specimens, such as solar radiation. In research utilizing solar radiation as the thermal excitation, the American Society for Testing and Materials (ASTM-D4788 [18]) standard recommends that the surface temperature differential of concrete structures should reach 0.5 °C after at least 4 h of sunlight exposure as the baseline criterion for detection. Kee et al. [19] and Omar and Nehdi [20] have evaluated this recommendation, suggesting that it is suitable for daytime inspections without shadow effects. Their research found that the maximum temperature difference can reach 7 °C and typically occurs around the 7th hour after sunrise. Washer et al. [21] conducted a study on structural surfaces of non-sunlit bridges. They found that a minimum environmental temperature change of 1.5 °C per hour is the lowest requirement for thermal imaging detection. Mac et al. [22] conducted comprehensive thermal imaging observations on a series of square artificial delaminated regions with various sizes and depths throughout the day. Their results revealed that during the daytime heating phase, the absolute temperature contrast ranged from 0.49 °C to 6.95 °C, while during the nighttime cooling phase, the temperature difference ranged from 0.32 °C to 3 °C. Pozzer et al. [23] fabricated three specimens containing nine artificial delaminations of different sizes and varying depths. They conducted experimental studies using solar radiation as a passive excitation method. They found that delaminations with larger areas at the same depth exhibited greater temperature thermal contrast, making them easier to detect, whereas delaminations with smaller areas were more challenging to identify. Tran [24] conducted

experiments by fabricating 12 artificial delaminations of varying sizes and three different depths. The experimental results indicated that the absolute thermal contrast above the delaminations increased with the size of the delaminations and the duration of heating (both active and passive). Additionally, other studies have shown that the magnitude of thermal contrast is related to the time window [19,25], depth, and environmental conditions [26,27].

Since practical engineering applications primarily rely on sunlight as the thermal excitation method, determining the optimal detection time window is another crucial detection parameter. However, due to the high complexity of environmental factors and the uncertainty in forming delaminations, there is no consensus on the optimal detection time window in current research. Washer et al. [26] found that the optimal observation period is 5 to 9 h after sunrise. Meanwhile, Zhang et al. [28] found that the afternoon appears to be the optimal time for infrared detection during the summer. However, Yehia [29] indicated that delaminations with a diameter of less than 5 cm are more detectable from 10 a.m. to noon than from noon to 3 p.m. Furthermore, Tran [24] indicated that the optimal observation time for passive infrared radiation experiments on sunny days is from 11 a.m. to 2 p.m. These non-uniform observations suggest that determining the optimal detection time based solely on the specific time window of the maximum temperature difference, without considering geographical and climatic variations, is incomplete. More importantly, in the studies by Hiasa et al. [30,31], it was found that the temperature differential is highest at midday (resulting in stronger detectable signals). However, the signal noise is also more remarkable due to the influence of concrete surface texture (resulting in stronger interference signals). Conversely, although the signal strength is lower at night, the interference signals are weaker, making it a recommended primary time window for data collection. These results suggest that determining the optimal detection window enables detection personnel to quickly and accurately identify delamination in concrete structures.

Environmental factors such as air temperature and solar radiation are the primary factors affecting detection. In the study by Washer et al. [26], it was noted that there is a positive linear relationship between solar irradiance and temperature contrast, and a positive correlation was found between delamination depth and time after sunrise. In their further study [32], they incorporated solar intensity and air temperature into a finite element model (FEM) to predict temperature contrast. Watase et al. [25] employed a multiple regression model to predict surface temperatures of delaminated regions based on six parameters. Their analysis results indicated that air temperature was a significant influencing factor. Mac et al. [22] conducted a systematic experimental study to determine the relationship between the depth-to-diameter ratio and detectability. Mac et al. [33] studied infrared imaging detection on the concrete bridge deck surface under natural conditions. Their study found that detection reliability increases when the amplitude of environmental temperature changes throughout the day increases. Based on these findings, it is evident that the factors influencing the detectability of delaminations are the same as those influencing temperature contrast. Therefore, this study will investigate the factors influencing detection from the perspective of thermal contrast, which is defined as the temperature difference between the delaminated area and the non-delaminated area.

In infrared detection of delamination in concrete structures, the analysis of temperature differences on the concrete surface is used to identify delamination. Therefore, the surface temperature of the concrete structure is crucial in delamination infrared detection. In the study by Berg and Quinn [34], the temperature of white-painted roads with a reflectivity close to 0.55 (absorptivity close to 0.45) is almost the same as that of the surrounding environment. In contrast, the temperature of unpainted roads with a reflectivity close to 0.15 (absorptivity close to 0.85) is about 11 °C higher than the air temperature. Meanwhile, in the study by Santamouris [35], the temperature of asphalt reaches about 63 °C, while the temperature

of white road surfaces is around 45 °C. In the study by Synnefa [36], the thermal behavior of different materials varies, primarily due to differences in their reflectivity, which affects their thermal behavior during the day, while their emissivity is the main factor influencing their thermal behavior at night. For concrete, its reflectivity and absorptivity add up to 1. These studies indicate that the surface temperature of concrete is influenced by its surface material properties (such as absorptivity and emissivity), which indirectly suggests that these properties will affect the infrared detection of delamination in concrete structures.

In actual concrete structures, there are material differences and various surface treatments (such as different colored paints, different surface polishing methods, etc.) on the concrete surface. In the study by Hiasa et al. [30], wooden sticks and gravel were placed on the surface of concrete specimens, and different-colored tapes were applied. The results indicated that wooden sticks affected the detection of delaminations, while the impact of gravel depended on its size. Additionally, different-colored tapes could be observed and distinguished using infrared thermography (IRT). The differences in surface properties can affect the effectiveness of infrared detection of delaminations in concrete structures. In the study by Ta et al. [9], two types of specimens were fabricated, each with 12 artificial delaminations of varying sizes and depths. One type of specimen was painted with green paint, while the other type remained untreated. Through experiments using square pulse thermography, it was found that, at the same size and depth of delaminations, the temperature difference was greater in the concrete coated with paint, indicating that delaminations in concrete with green paint were easier to detect. These results indicate that differences in surface properties can affect infrared delamination detection in concrete.

Cool-colored coatings are commonly used in concrete structures (such as rooftops, pavements, etc.) [36]. Therefore, this study applied white and yellow paints to alter the surface properties of concrete. Infrared thermography detections were conducted on specimens with different surface treatments (painted on both sides, with the middle part untreated). A comparative study was carried out to investigate the effect of surface property variations (absorptivity and emissivity variations) on delamination detection. In addition, this study also explored the impact of depth on detecting delamination under the same surface property. The effect of air temperature was considered to determine the optimal time window for infrared detection.

Based on relevant studies, paint is widely used in concrete structures, and the thermal behavior of surfaces with different colors varies. The absorptivity of these surfaces affects their thermal behavior during the day, while their emissivity influences their thermal behavior at night [36]. These differences in thermal behavior manifest as surface temperature variations, which are critical indicators for identifying delamination in infrared detection of concrete structures. Therefore, the color of the concrete surface impacts its infrared delamination detection, as demonstrated in existing studies. Although some researchers have investigated the influence of color on infrared detection, the impact of the properties behind these colors (absorptivity and emissivity) on detection remains unexplored. Thus, this study aims to investigate the effects of surface property variations and delamination depth on the infrared detection of interlayer delaminations in concrete structures under natural conditions. The thermal contrast of delaminations with varying colors and depths was compared and analyzed. Subsequently, the characteristics and detection capabilities at different time windows were discussed. This research bridges the gap in understanding how surface colors influence infrared detection in concrete structures and provides insights for detecting delaminations under surfaces of different colors. It further aids in identifying potential delaminations for maintenance, safeguarding public safety. The conclusion section also explores this study's limitations and suggests directions for future research.

2. Materials and Methods

2.1. Research Framework

The research framework for this study is illustrated in Figure 1. First, the surface emissivity of yellow paint and white paint was obtained using the two-reference-body method, and the surface absorptivity of bare concrete, yellow paint, and white paint was derived based on the principle of energy conservation. After obtaining the surface properties, three artificial delaminated concrete specimens with different burial depths were designed. Each specimen had three delaminations, and delamination detection experiments were conducted under natural environmental conditions. The thermal contrast curve of delamination over the day was segmented into three phases based on its different trends better to understand the thermal contrast development of delamination over time. Additionally, a correlation analysis was conducted to reveal the influence of surface properties on detection at different phases. Finally, further correlation analysis and curve fitting were performed on the temperature difference between the non-delaminated regions, air (δT), and the corresponding thermal contrast (ΔT).

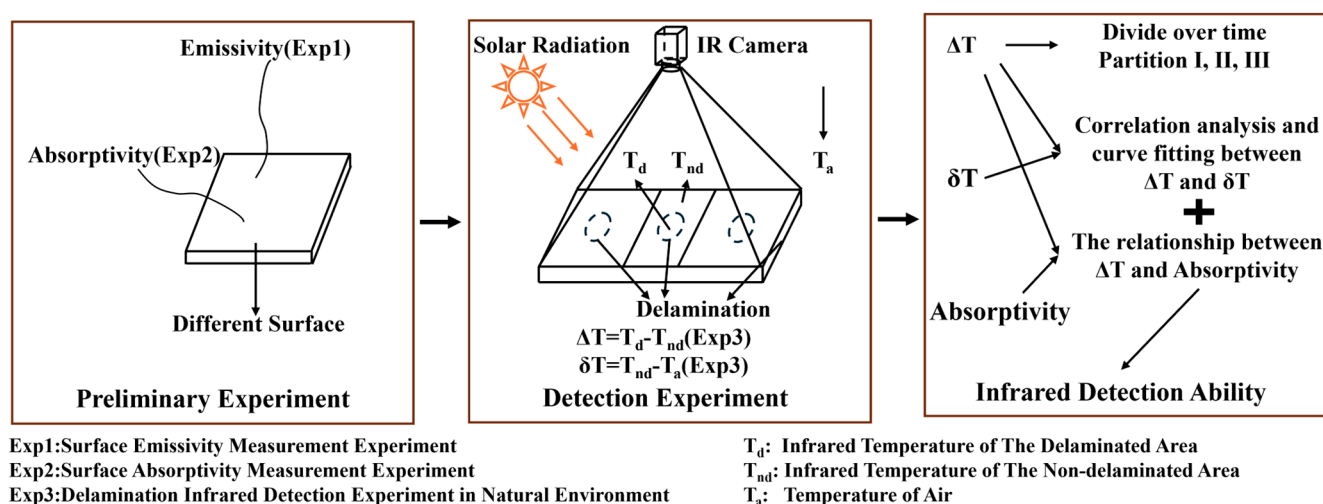


Figure 1. Research framework.

2.2. Experimental Design and Procedure [37]

Since the experiments needed to be carried out both day and night, the differences in surface properties of the concrete specimens could lead to variations in absorptivity and emissivity, potentially resulting in differences in surface thermal contrast. Therefore, three experiments were carried out: surface emissivity measurement, surface absorption measurement, and concrete delamination detection in the natural environment. The experiments were conducted at the Science City campus of Chongqing Jiaotong University in western China.

2.2.1. Surface Emissivity Measurement

The accuracy of surface emissivity affects the accuracy of surface temperature measurements [38], which in turn will affect the thermal radiation and thermal imaging of the surface of the specimen. The emissivity of a material's surface is a dimensionless quantity that characterizes the radiative capability of the material's surface and is an essential thermal property parameter [39]. Based on previous studies [39,40], the emissivity of the surface of dry, normal concrete was set to 0.95 in this study. This study designed a measurement experiment to determine the emissivity of yellow and white paints, both of which are acrylic paints. The emissivity measurement specimen (EMS) for

this experiment was made by applying 1.35 kg/m^2 of white and yellow paint to the outer surface of a stainless-steel container, with 3M Scotch Super 88 (3M, Austin, TX, USA) insulation tape applied around the painted areas, as shown in the EMS in the lower right part of Figure 2. When measuring temperature with an infrared camera, 3M Scotch Super 88 insulation tape is often used as a reference body for emissivity, with emissivity value of 0.95 [41].

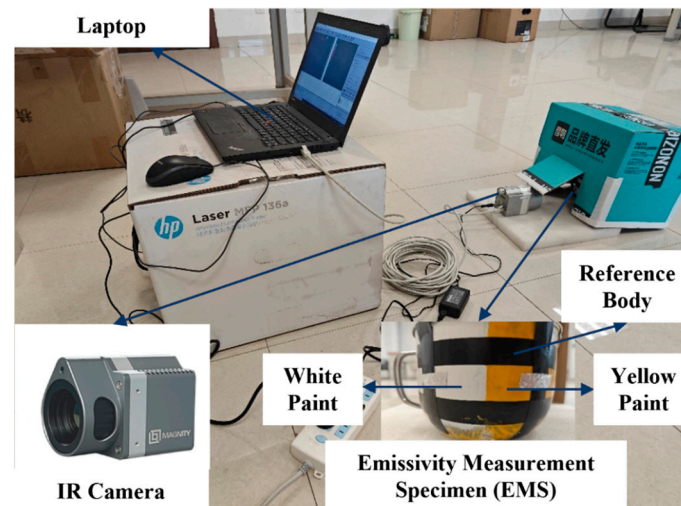


Figure 2. Emissivity measurement experiment: arrangement of experimental equipment and surface treatment of emissivity measurement specimen.

Figure 2 shows the instruments and experimental layout for the emissivity experiment. The EMS was filled with hot water at 100°C and placed on the floor to cool naturally. A cardboard box with a small opening was made to cover the EMS, allowing the collection of infrared images through the opening using a scientific-grade thermal imager (MAG-F6, Shanghai Hugee Technology Co., Ltd., Shanghai, China, parameters shown in Table 1). Data were recorded every 15 min, capturing temperature readings ranging from 34°C to 46°C . To eliminate the influence of other factors such as ambient temperature and environmental reflection temperature [38], this experiment was performed in a controlled chamber. Then, the emissivity of the paint was estimated using the dual-reference method [38]. For detailed calculations, please refer to Section 2.3.1.

Table 1. Relevant parameters of MAG-F6.

Camera Type	MAG-F6
Detector type	Uncooled microbolometer
Noise Equivalent Temperature Difference (NETD)	$<0.05^\circ\text{C}$
Accuracy	$\pm 0.7^\circ\text{C}$ or 0.7%
Resolution	640×480 pixels
Spectral range	$8\sim 14 \mu\text{m}$
Field of view	$25^\circ \times 19^\circ$

2.2.2. Surface Absorptivity Measurement

Absorptivity is the ratio of the thermal radiation energy absorbed by an object to the total thermal radiation energy incident on the object, which could directly affect the temperature field distribution inside the concrete structure. The surface absorptivity can be calculated by using the principles of heat transfer and energy balance to establish a heat balance equation on the surface of the specimen [42]. A surface absorptivity measurement experiment was designed to measure the absorptivity of the yellow and

white paint and their respective surfaces on the concrete specimen. The absorptivity measurement specimen (AMS) is depicted in Figure 3. Three concrete specimens with dimensions of $500 \times 500 \times 100 \text{ mm}^3$ (AMS1, AMS2, and AMS3) were fabricated for the experiment. AMS1, AMS2, and AMS3 represent concrete specimen surfaces without treatment, concrete specimen surfaces with yellow paint, and concrete specimen surfaces with white paint, respectively. And the concrete is standard C40 concrete, and the paints are consistent with that used in emissivity measurement experiment. A heat flux sensor (XM269C, greenteg AG, Rümlang ZH, Switzerland, parameters shown in Table 2) and four temperature sensors (PT100, Hangzhou Guizhong Technology Co., Ltd, Hangzhou, China, parameters shown in Table 3) were affixed to the surface of each specimen. These sensors were utilized to measure the heat flux at the center of each specimen and the temperatures in four directions on the surface of the specimen. Then, 1.35 kg/m^2 of yellow paint was applied to AMS2, and white paint was applied to AMS3.

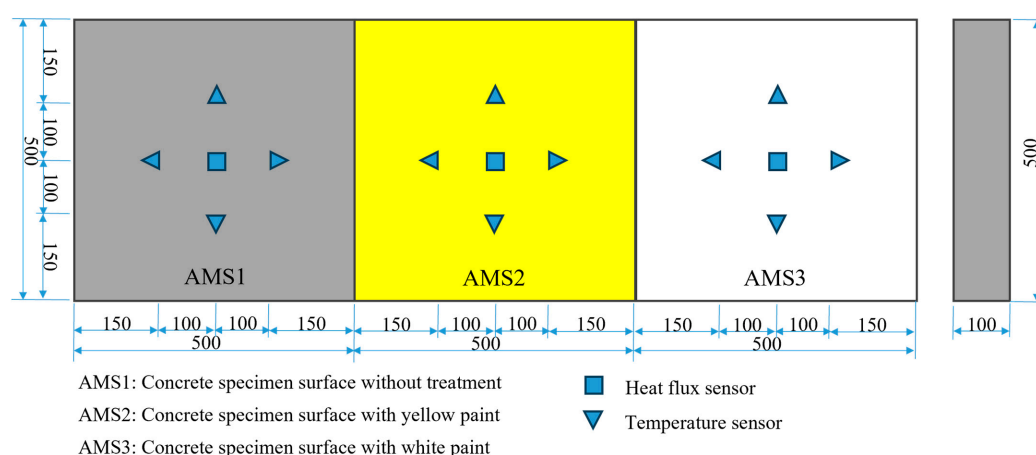


Figure 3. Absorptivity measurement specimen: dimensions of each specimen, surface treatment, and sensor arrangement (units: mm).

Table 2. Parameters of XM269C.

Name	Heat Flux Range (kW/m ²)	Sensitivity (μV/(W/m ²))	Temperature (°C)	Calibration Accuracy (%)
Measurement range	−150~150	1.5	−50~150	±3%

Table 3. Parameters of PT100.

Name	Temperature (°C)	Accuracy (°C)
Measurement range	−50~200	±0.15

Figure 4 shows the instruments and experimental setup for the absorption measurement of AMS. After transporting the AMS to the corresponding outdoor positions, a 5 mm thick glass cover was placed on its surface to prevent convective heat exchange between the AMS and the ambient atmosphere. A temperature sensor was installed in the gap between the glass plate and the specimen to measure the air temperature in the gap (the orange frame in Figure 4, T_a in Equation (3), Section 2.3.1), and another temperature sensor was attached to the inner surface of the glass to measure the surface temperature of the glass (the blue frame in Figure 4, T_2 in Equation (4), Section 2.3.1). To collect real-time weather data, a portable weather station (FT-BQX7, Shandong Fengtu Internet of Things

Technology Co., Ltd., Weifang, China, see Table 4) was set up near the specimens to collect meteorological conditions. The sampling frequency was set to 15 min, collecting information such as solar radiation (Q_t in Equation (2), Section 2.3.1). A similar glass plate was placed above the weather station to avoid discrepancies in the data compared to the specimens. Utilizing the heat flux sensor (XM269C, parameters as shown in Table 2) to measure the magnitude of heat flux (q_a in Equation (5), Section 2.3.1) passing through the specimen surface, measurements were conducted using a heat flux data acquisition instrument (DQ-100, Yi'an (Shanghai) Electronic Technology Co., Ltd., Shanghai, China), with data collected every minute. The temperature sensors (PT100, parameters as shown in Table 3) were connected to a multi-channel data logger (TP700, Shenzhen Topray Electronic Co., Ltd., Shenzhen, China, parameters as shown in Table 5) for collecting the temperature of each specimen surface (T_1 in Equation (4) and T_s in Equation (3)), the glass plate, and the air gap between the glass plate and the specimen, with data collected every minute. All data were collected during a period around noon when the sun was nearly perpendicular to the test site. Data from time periods with relatively stable solar radiation were selected for calculating the absorptivity, with detailed methods provided in Section 2.3.1.

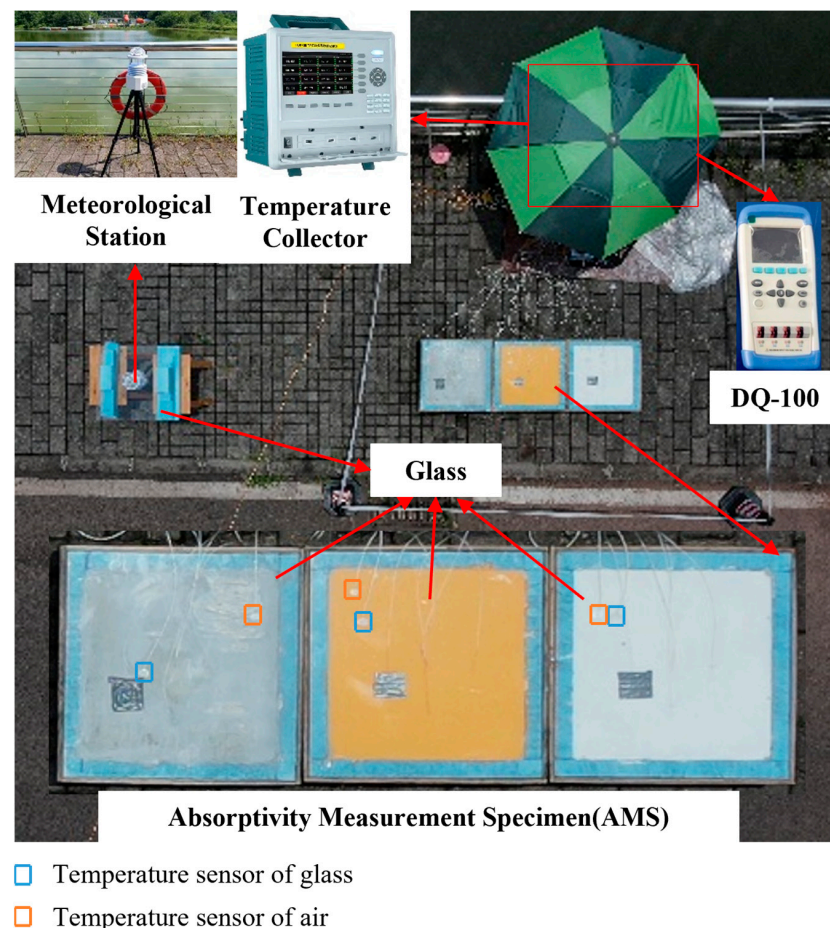


Figure 4. Absorptivity measurement experiment: arrangement of experimental equipment and placement of AMS.

Table 4. Parameters of FT-BQX7.

Name	Wind Speed (m/s)	Wind Direction (°)	Air Temperature (°C)	Solar Radiation (10^2 W/m^2)
Measurement range	0~60	0~360	−40~60	0~20
Error range	±0.1	±2	±0.3	<±3%

Table 5. Parameters of TP700.

Name	Number of Channels	Thermoresistance	Storage Interval
Range/Type	1~200	PT1000, PT100	1~19,999 s

2.2.3. Delamination Detection Experiment Under Natural Environment

As shown in Figure 5, three concrete specimens (CS1, CS2, and CS3), measuring 2100 mm × 900 mm × 100 mm, were designed for the delamination detection experiment under natural environmental conditions. The specimens were cast using the same specification of concrete as in the absorptivity measurement experiment. CS1, CS2, and CS3 represent concrete specimens with foam simulators' depths of 20 mm, 50 mm, and 80 mm, respectively. Inside each specimen, three foam simulators of delamination were embedded. These delaminations were elliptical in shape and identical in size, each enclosed within a 300 mm × 300 mm square, with a thickness of 10 mm. Each delamination was numbered, with C, Y, and W representing concrete, yellow paint, and white paint surfaces, respectively, and 1, 2, and 3 indicating delamination depths of 20 mm, 50 mm, and 80 mm. For example, CS1-C represents a delamination located 20 mm beneath the concrete surface. It is worth noting that the thermal conductivity of polystyrene foam is $k = 0.027 \text{ W}/(\text{m} \cdot ^\circ\text{C})$, which is similar to air, $k = 0.024 \text{ W}/(\text{m} \cdot ^\circ\text{C})$ [9]. For the concrete surface, white and yellow paints were brushed on both sides of the specimens at a rate of $1.35 \text{ m}^2/\text{kg}$, aimed at altering the surface properties of the concrete (such as emissivity and absorptivity). The paint used was the same type as that used in the aforementioned experiments. Each color of paint covered an area of $900 \times 800 \text{ mm}^2$, leaving the middle section as bare concrete, with an area of $900 \times 500 \text{ mm}^2$ (Figure 5). To reduce heat conduction in both directions, thermal insulation boards were installed around the specimens to prevent heat exchange between the concrete specimens (except for the surface and bottom) and the environment.

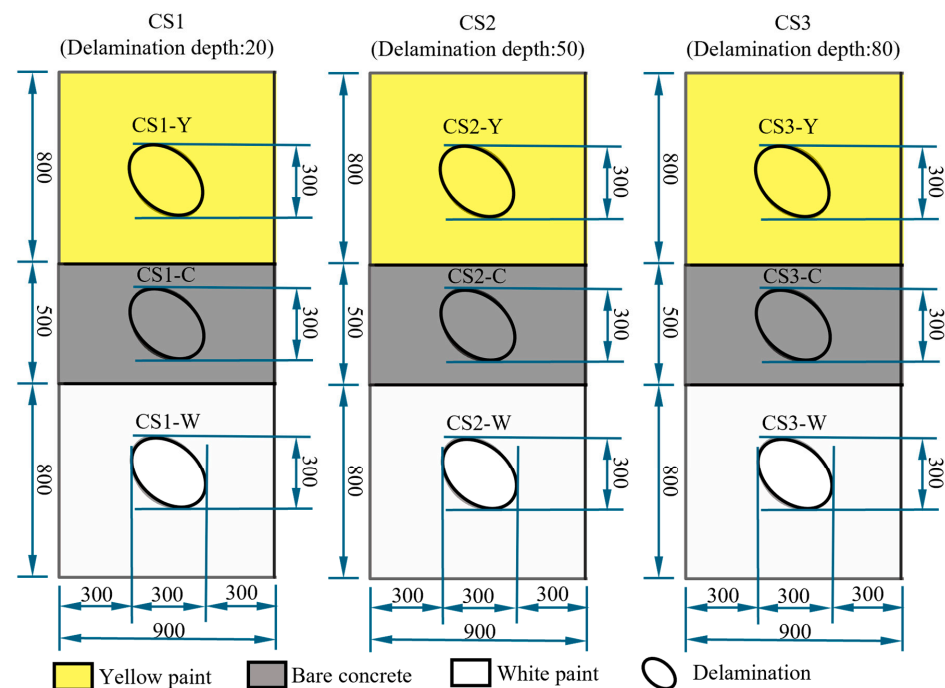


Figure 5. Delamination detection experiment: dimensions of each concrete specimen, surface treatment (units: mm), dimensions of each delamination and delamination arrangement (C, Y, and W representing concrete, yellow paint, and white paint).

Figure 6 illustrates the setup of equipment and the experimental site. In this experiment, solar radiation was utilized as the thermal excitation method for detection research. According to the American Society for Testing and Materials (ASTM-D4788) recommendation, the specimens were pre-exposed to sunlight for a minimum of 4 h before data collection commenced. The data collection equipment for meteorological data, temperature sensor data, and infrared images are described in Sections 2.2.1 and 2.2.2. Additionally, data were continuously collected over multiple day–night cycles to avoid the occurrence of incidental phenomena.

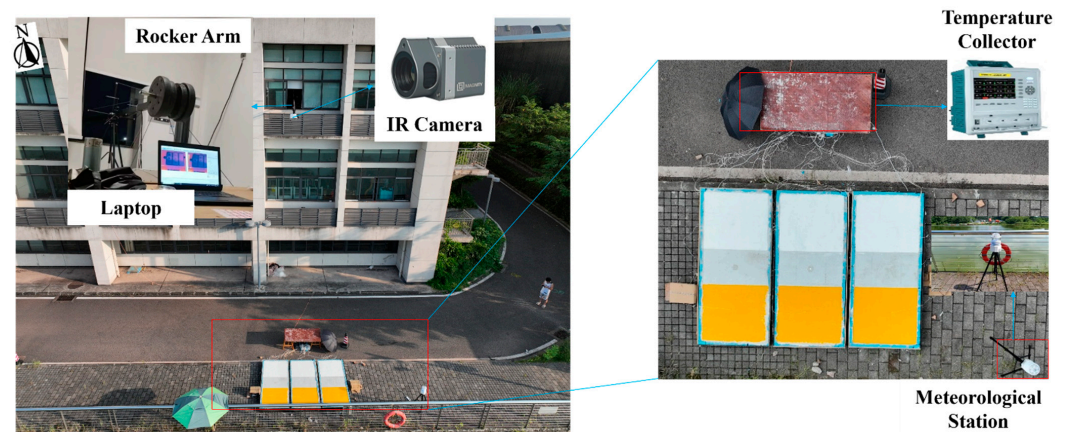


Figure 6. Delamination detection experiment: arrangement of experimental equipment and placement of concrete specimens.

2.3. Measurement and Evaluation Indicators

2.3.1. Surface Emissivity and Absorptivity Measurement Indicators

The experimental data related to EMS and AMS have been obtained in this study. This study estimated surface emissivity using the dual-reference method [38]. This approach involves using a blackbody and a high-reflectivity diffuser as references, maintaining the test object at the same temperature as the blackbody, while the diffuser temperature equals the background temperature. The radiation energy of the specimen, blackbody, and diffuser are measured using a thermal imager. The emissivity is then calculated using Equation (1) [38]:

$$\varepsilon_s = (T_r^n - T_u^n) / (T_0^n - T_u^n) \quad (1)$$

In the equation, ε_s represents the emissivity of the test object, T_r , T_0 , and T_u denote the temperatures of the test object, blackbody, and background measured by the thermal imager (Table 4), respectively, and $n = 3.9889$.

The temperature data for the two paints were obtained from the thermal images extracted from multiple measurements in this experiment. Then, using Equation (1), multiple emissivities were calculated, and the average value was computed as the emissivity of the test object.

For absorptivity, this study utilized heat transfer principles and energy balance equations to establish a thermal balance equation for the surface of the specimens, from which the absorptivity of various materials on the surface of the specimens was calculated [42]. The relevant formula is as follows:

$$\alpha = Q_a / Q_t + Q_c / Q_t + Q_r / Q_t \quad (2)$$

In the equation, α represents absorptivity, Q_t denotes the total solar radiation on the surface of the concrete, Q_a signifies the heat absorbed by the concrete, Q_c represents the convective heat exchange between the concrete surface and the surrounding air, and Q_r

denotes the long-wave thermal radiation between the concrete surface and surrounding objects. The total solar radiation Q_t is measured using the portable weather station FT-BQX7.

The magnitude of convective heat transfer is generally calculated based on the temperature difference between the concrete surface and the surrounding air. In a state of complete stillness, natural convection heat exchange occurs between the concrete surface and the surrounding air. If the surface natural convection heat transfer coefficient is known, the convective heat transfer can be represented using Newton's cooling formula as follows:

$$Q_c = \alpha'(T_s - T_a)A \quad (3)$$

where α' is the natural convection heat transfer coefficient; T_s is the concrete surface temperature; T_a is the surrounding air temperature; and A is the surface area of the concrete exchanging heat with the air. According to the principles of heat transfer and engineering experience, α' is taken as $5.8 \text{ (W/m}^2\cdot\text{K)}$ [42].

Radiative heat transfer is another form of heat exchange, referring to the emission of primarily long-wave thermal radiation from an object due to its temperature. As long as the object's temperature is above absolute zero, it emits long-wave thermal radiation outward, exchanging heat with surrounding objects. The radiative heat transfer between the surfaces of any two objects per unit area can be calculated by the following equation:

$$Q_r = \sigma \cdot (T_1^4 - T_2^4) / \left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \right) \cdot \varphi_{12} \cdot A \quad (4)$$

In the equation, ε_1 is the surface emissivity of plane 1, ε_2 is the surface emissivity of plane 2, T_1 is the surface temperature of plane 1, T_2 is the surface temperature of plane 2, σ is the Stefan–Boltzmann constant, $\sigma = 5.67 \times 10^{-8} \text{ W/(m}^2\cdot\text{K}^4)$, and φ_{12} is the view factor from plane 1 to plane 2. Here, the emissivity of concrete is taken as 0.95, and the emissivity of glass is taken as 0.83 (according to Chinese standard GB/T 2680-2021 [43]).

The heat absorbed by concrete can be measured using a heat flux sensor, and the equation is as follows:

$$Q_a = q_a \cdot A \quad (5)$$

In the equation, q_a is the data measured by the heat flow sensor, and A is the area of the AMS.

The relevant data obtained from the absorption rate experiment are used to substitute Equations (2)–(5) to obtain the corresponding absorption rates. The absorption rate's average value is calculated when the radiation intensity is relatively stable. The temperatures mentioned in the absorption rate are all obtained from the temperature sensor.

2.3.2. Evaluation Indicators for Delamination Detection Under Natural Conditions

In this study, we analyze the detectability by examining the temperature difference between the delaminated and non-delaminated regions. Delamination is considered detectable when it can be visually discerned from the infrared images (qualitative) or when its thermal contrast (ΔT) is not less than $0.5 \text{ }^\circ\text{C}$ (following ASTM D4788-03). Thermal contrast is calculated using Equation (6) [1,9,44]:

$$\Delta T = T_d - T_{nd} \quad (6)$$

In the equation, T_d , T_{nd} , and ΔT represent the average surface temperatures of the delaminated area (red box in Figure 7), non-delaminated area (blue box in Figure 7), and the temperature difference between the delaminated and non-delaminated areas,

respectively. The areas within the yellow, gray, and purple rectangles represent regions of the concrete specimen coated with yellow paint, bare concrete, and coated with white paint, respectively. These average temperatures are extracted from the infrared images. When $\Delta T > 0$, it indicates that $T_d > T_{nd}$, meaning the temperature in the delaminated area is higher than that in the non-delaminated area (referred to as the “heat island” area); conversely, if the temperature in the delaminated area is lower than that in the non-delaminated area (referred to as the “cold island” area), $\Delta T < 0$.

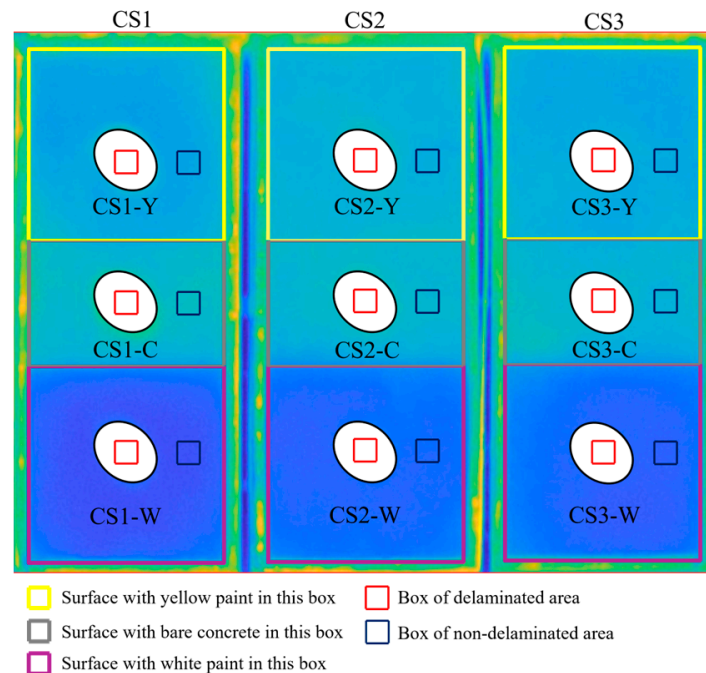


Figure 7. Sensitive areas of delaminated and non-delaminated areas.

3. Results and Discussions

3.1. Results of Absorptivity and Emissivity of Surface Materials

The emissivity was obtained using Equation (1) from Section 2.3.1. Figure 8a shows the box plot of emissivity for different materials, where the short lines on the top and bottom of the boxes represent the maximum and minimum values in the data set. The solid black line represents the mean value of the data. The mean emissivity value for each material falls within the box, and the variances are nearly 0, 0.00003, and 0.00004, respectively. The emissivity values for yellow paint and white paint were found to be 0.960 and 0.965, respectively. The emissivity of concrete, based on relevant studies [45], was taken as 0.950. The absorptivity was obtained using Equation (2) from Section 2.3.1. The average values were then derived from these calculations. Figure 8b shows the box plot of absorptivity for different materials, where the short lines on the top and bottom of the boxes represent the maximum and minimum values in the data set. The solid black line represents the mean value of the data. The mean absorptivity value for each material falls within the box, and the variances are nearly 0, 0.00008, 0.00014, and 0.00022, respectively. The absorptivity values for bare concrete, yellow paint, and white paint were found to be 0.652, 0.538, and 0.369, respectively. According to relevant studies [46], the absorptivity of normal concrete ranges from 0.57 to 0.66, yellow concrete ranges from 0.52 to 0.58, and white concrete ranges from 0.31 to 0.40, which are comparable to the measurement of this study.

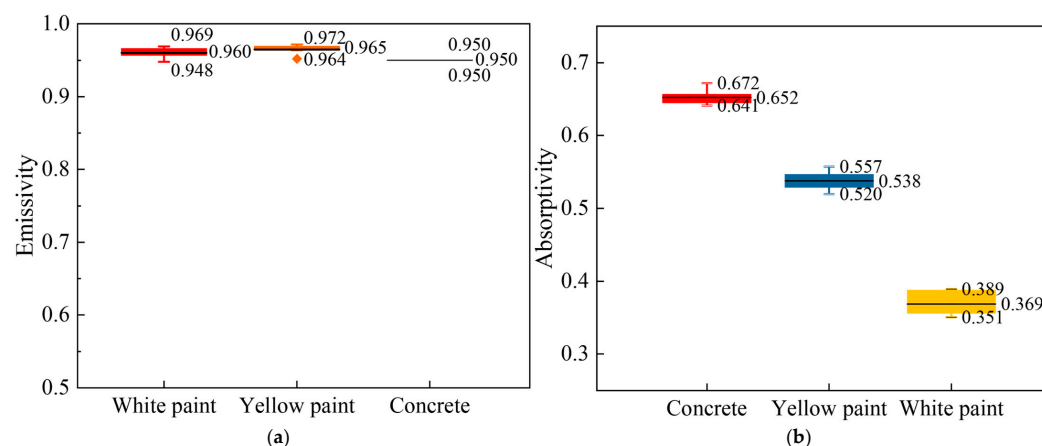


Figure 8. Box plot of surface emissivity and absorptivity; (a) box plot of emissivity for different materials; and (b) box plot of absorptivity for different materials.

3.2. Analysis of Variation in Delamination Thermal Contrast over Time

Figure 9 displays the thermal contrast distribution of CS1 with a delamination depth of 20 mm. The thermal contrast (ΔT) shown in the figure is obtained from the surface of CS1 using an infrared thermal imager. The curve is segmented into different zones based on different time intervals throughout the day, illustrating the process of calculating thermal contrast for various surface materials of CS1, including yellow paint, white paint, and exposed concrete.

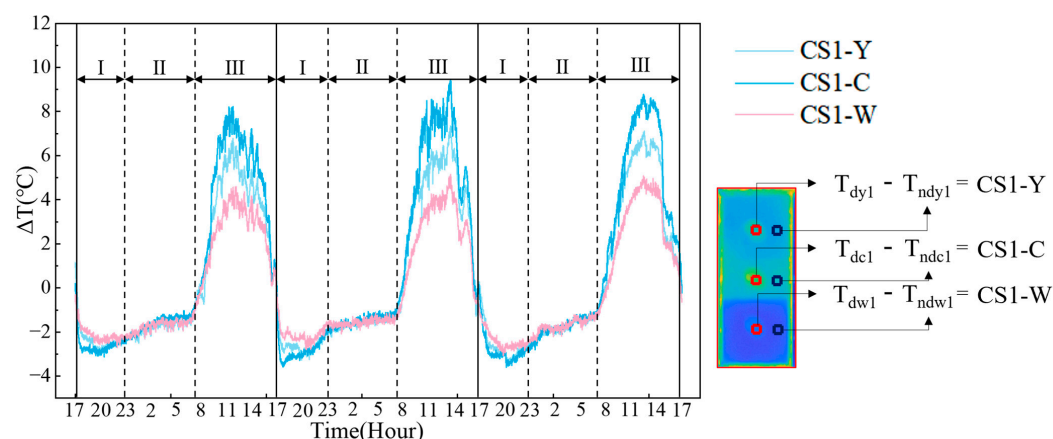


Figure 9. Partitioning of the thermal contrast diagram.

Zone I corresponds to the period when the radiative heat dissipation ceases, and there is intense internal heat conduction within the concrete specimen and heat exchange with the environment (approximately from 17:00 to 23:00). During this period, all three ΔT curves sharply decrease, followed by an increase, exhibiting significant gradients. The minimum values of ΔT are approximately -3.1°C (CS1-C), -2.8°C (CS1-Y), and -2.5°C (CS1-W), respectively.

Zone II corresponds to a period of relatively stable internal heat conduction within the concrete specimen and heat exchange with the environment (approximately from 23:00 to the next day at 7:00). During this period, the three ΔT curves are nearly overlapping and gradually rise. ΔT increases gradually from around -2°C to approximately -1°C .

Zone III represents a period of rapid temperature changes within the concrete specimen after the appearance of radiation (approximately from 7:00 to 17:00). During this period, the three ΔT curves experience sharp increases, intense oscillations, and rapid declines. There

are distinct gradients during the intense oscillations, and the maximum ΔT values are approximately 9 °C (CS1-C), 7 °C (CS1-Y), and 5 °C (CS1-W), respectively.

Partitioning the thermal contrast enables this study to more intuitively perceive the trends of the thermal contrast in different periods.

3.3. Analysis of the Influence of Surface Properties and Ambient Conditions on Detection

This section focuses on the influence of surface properties and ambient conditions on detection.

In Zone I, the median values of ΔT for white, yellow, and concrete are -2.25 , -2.71 , and -3.00 , respectively. A linear fit of these values gives an Adj-R^2 of 0.9993, indicating a robust linear relationship. Additionally, numerically, ΔT increases with the increase in absorptivity. Moreover, the factors influencing detection are surface absorptivity and ambient conditions. Due to heating from solar radiation, the surface absorptivity varies for differently treated surfaces of the specimen, leading to variations in energy accumulation in this region. Additionally, due to the restriction caused by delamination, the thermal exchange between the specimen and the surroundings occurs after the radiation disappears, gradually causing the temperature in the delaminated area to be lower than that in the non-delaminated area, as shown in Figure 10a.

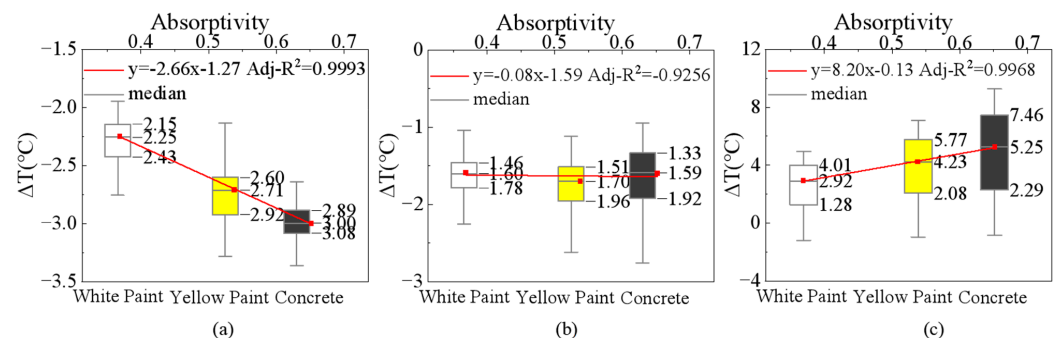


Figure 10. The relationship between ΔT and absorptivity (concrete, yellow paint, and white paint are 0.652, 0.538, and 0.369, respectively): (a) Zone I; (b) Zone II; and (c) Zone III.

In Zone II, the median values of ΔT for white, yellow, and concrete are -1.60 , -1.70 , and -1.59 , respectively. A linear fit of these values gives an Adj-R^2 of -0.9256 , indicating a poor correlation. At this point, ΔT is not related to absorptivity. Moreover, the factors influencing detection are surface emissivity and ambient conditions. After intense heat exchange, the specimen undergoes a relatively stable heat exchange with the surroundings. Due to the similar surface emissivity, the thermal contrast curves for different regions tend to converge or overlap, as shown in Figure 10b.

In Zone III, the median values of ΔT for white, yellow, and concrete in this region are 2.92, 4.23, and 5.25, respectively. A linear fit of these values gives an Adj-R^2 of 0.9968, indicating a strong linear relationship. Additionally, ΔT increases with the increase in absorptivity. Moreover, the factors influencing detection include surface absorptivity and ambient conditions. The specimen's surface rapidly accumulates energy from solar radiation upon the emergence of radiation. Due to differing absorptivity, energy accumulation varies among different regions. At this point, thermal exchange between the specimen and the environment can be disregarded. The presence of delamination restricts thermal conductivity, resulting in higher temperatures in delaminated areas compared to non-delaminated areas, as shown in Figure 10c.

3.4. The Characteristics of Infrared Detection for Concrete Delamination in Different Time Windows

3.4.1. Zone I (Approximately 17:00 to 23:00)

Figure 11a shows the plot depicting the temperature difference between the non-delaminated area and the air (δT) and thermal contrast (ΔT) in Zone I. In the figure, the scatter points of δT with respect to ΔT for each delamination form a coherent group based on depths and surface conditions. Therefore, the k-means clustering method [47] was applied to process the delamination data of different surface materials and depths in Figure 11a, where k is set as 1. Here, k represents the centroids of each delamination data cluster, the data sets' central positions, as shown in Figure 11b, and the points with the same color and shape as in Figure 11a.

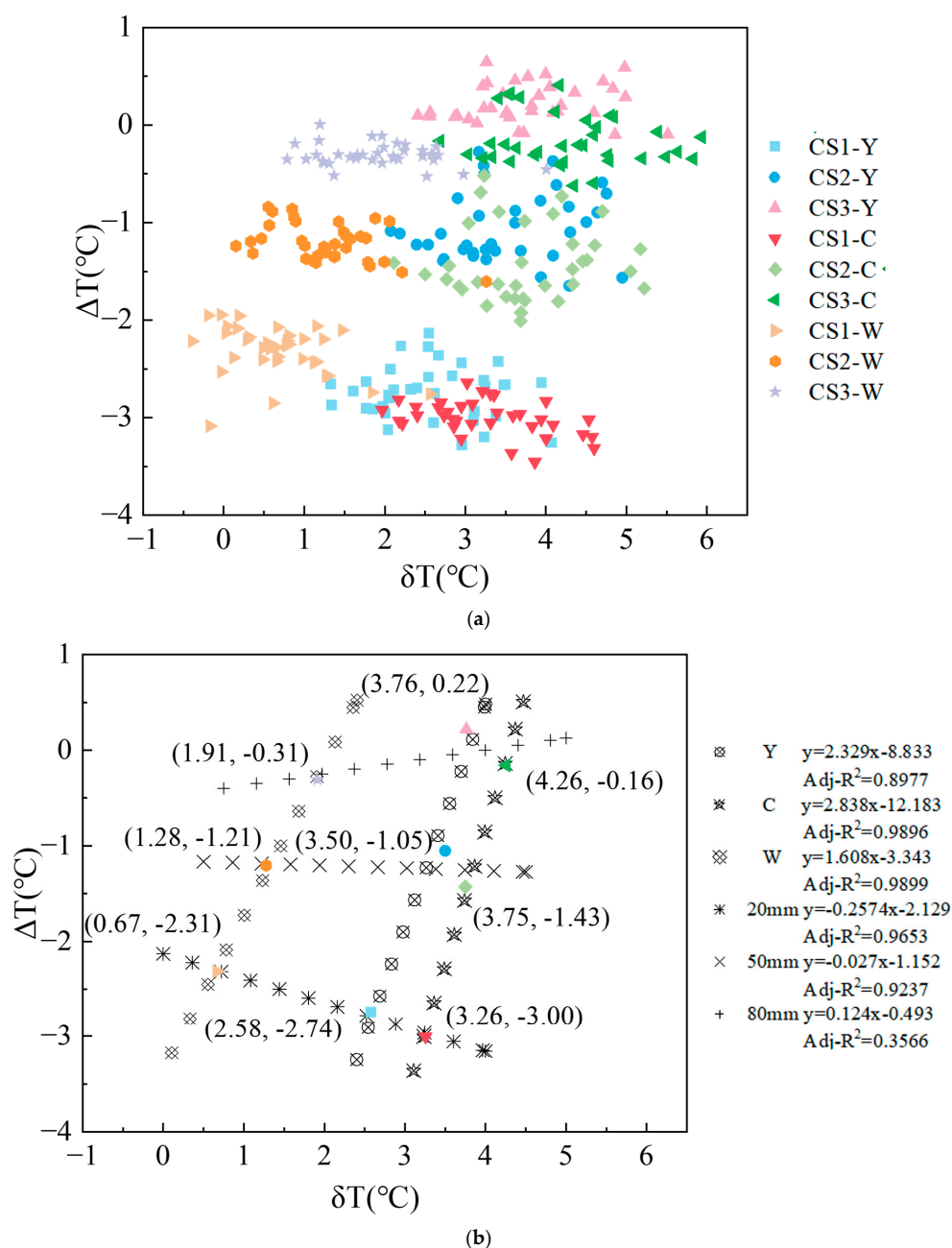


Figure 11. Zone I: the Map of thermal contrast (ΔT) and temperature difference between non-delaminated area and air (δT): (a) scatter plots of different delaminations and (b) fitting curves by depth or surface material.

The centroids were linearly fitted according to the same depth, resulting in three depth lines, as shown by the 20 mm, 50 mm, and 80 mm lines in Figure 11b. The value of ΔT is discussed based on its magnitude, without discussing its positive or negative sign. Across surface variations, the ΔT for a 20 mm depth delamination increases from 2.31 to 3.0, with an increase in δT from 0.67 to 3.26. Meanwhile, the linear correlation of the adjusted R^2 is strong (0.9653). For 50 mm depth delamination, ΔT remains almost unchanged (1.21, 1.05, and 1.43) with the increase in δT (from 1.28 to 3.75). Meanwhile, the linear correlation of the adjusted R^2 is strong (0.9237). For 80 mm depth delamination, ΔT remains almost unchanged (0.31, 0.22, 0.16) with the increase in δT (from 1.28 to 3.75), but the linear correlation of the Adj- R^2 is weak (0.3566). The results show that shallow delamination developed thermal contrast (ΔT) more sensitive to the variation in surface absorptivity than the deeper delamination in this period. This finding indicates that when the surface absorptivity is given, the range of thermal contrast could be determined for shallow and middle depths delamination.

The centroids were linearly fitted to the same surface, resulting in three surface lines, as shown by the C, Y, and W lines in Figure 11b. The value of ΔT is discussed based on its magnitude, without discussing its positive or negative sign. For delamination under a concrete surface, ΔT decreases from 3.00 to 0.16 as depth changes, with δT increasing from 3.26 to 4.26, and the linear correlation is strong with an adjusted R^2 of 0.9896. For delamination under a yellow paint surface, ΔT decreases from 2.74 to 0.22, with δT increasing from 2.58 to 3.76, and the linear correlation is strong with an adjusted R^2 of 0.8977. For delamination under a white paint surface, ΔT decreases from 2.31 to 0.31 as δT increases from 0.67 to 1.91, and the linear correlation is strong with an adjusted R^2 of 0.9899. The results indicate that the thermal contrast (ΔT) is more sensitive to depth changes under concrete surfaces while less so under lighter-colored surfaces. This finding suggests that, given a specific depth, the thermal contrast range can be determined for concrete and other colored surfaces.

In summary, δT , depth, and surface material all influence the determination of ΔT . At the same depth or the same surface material, this study can determine ΔT uniquely through δT . However, there may be misjudgments when depth and surface material are considered simultaneously. For example, under the same δT , delaminations may coincide in concrete at a depth of 20 mm and under yellow paint at a depth of 50 mm, illustrating a limitation of this model. And during this period, delaminations with a depth of 80 mm have ΔT values ranging from -0.5°C to 0.5°C . According to the threshold set in this study, delaminations within this range are considered ineffective for detection within Zone I, while other delaminations can be detected effectively.

3.4.2. Zone II (Approximately from 23:00 to 07:00 the Next Day)

As shown in Figure 12, the plot depicts the temperature difference between the non-delaminated area and the air (δT) and thermal contrast (ΔT) in Zone II. Linear fittings were performed for each delamination, resulting in nine curves. Additionally, linear fittings were conducted for the delaminations at the same depth, producing three overall depth-related curves, totaling twelve. At the same depth, the slopes of each delamination curve are very similar (20 mm: -0.191 , -0.278 , -0.259 ; 50 mm: -0.122 , -0.091 , -0.117 ; 80 mm: -0.063 , -0.026 , -0.026), and the slopes of the delamination curves at the same depth are close to those of the corresponding overall curves. These results indicate that different absorptivities have little to no impact on delamination detection. However, at different depths, the slopes of the overall curves decrease as the depth increases.

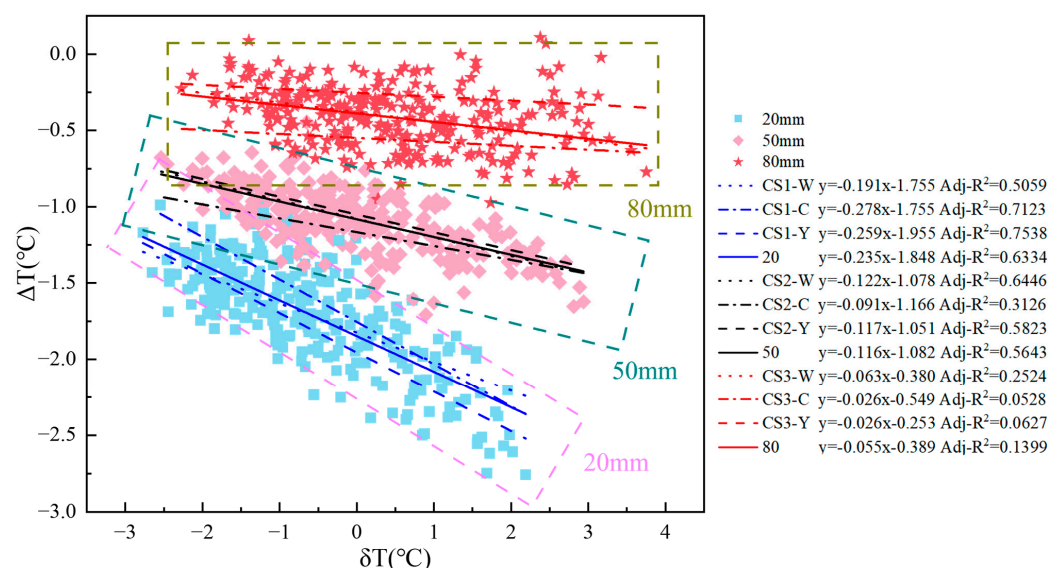


Figure 12. Zone II: the map of thermal contrast (ΔT) and temperature difference between non-delaminated area and air (δT).

As shown in Table 6, the variance analysis [48] was conducted on ΔT with the same depth and different surface treatment methods, and their correlation coefficients p were all less than 0.05, indicating a significant correlation between data with the same depth but different absorptivities. Under the same depth, the mean values (20 mm: -1.77 , -1.65 , -1.66 ; 50 mm: -1.04 , -1.20 , -1.02 ; 80 mm: -0.27 , -0.58 , -0.38) and median values (20 mm: -1.70 , -1.59 , -1.60 ; 50 mm: -1.04 , -1.19 , -0.99 ; 80 mm: -0.27 , -0.58 , -0.37) are relatively close, which further confirms their strong correlation. Indeed, the scatter plots for each surface material are very close, and except for the 80 mm delamination, ΔT increases with increasing δT . The results show that during this period, ΔT is unrelated to surface absorptivity but is related to depth and surface emissivity. This finding indicates that when depth and δT are determined, the range of ΔT can be determined.

Table 6. Correlation analysis of ΔT between different delamination layers.

Delamination Type	Mean ($^{\circ}\text{C}$)	Median ($^{\circ}\text{C}$)	Variance	p -Value
CS1-Y	-1.77	-1.70	0.121	2.9×10^{-2}
CS1-C	-1.65	-1.59	0.158	
CS1-W	-1.66	-1.60	0.084	
CS2-Y	-1.04	-1.04	0.037	8.57×10^{-11}
CS2-C	-1.20	-1.19	0.049	
CS2-W	-1.02	-0.99	0.026	
CS3-Y	-0.27	-0.27	0.025	2.25×10^{-34}
CS3-C	-0.58	-0.58	0.025	
CS3-W	-0.38	-0.37	0.021	

Under the same surface material, significant differences exist in the mean and median values for the same surface material at different depths. It shows that the skewness of their scatter plots gradually decreases with increasing depth, indicating that heat conduction within the delaminated areas of the concrete specimen is restricted to varying degrees with depth. Therefore, deeper delamination results in less restricted heat conduction, leading to closer temperatures between the delaminated and non-delaminated areas.

This study shows that changes in surface properties have little impact on the infrared detection of delamination in concrete structures during Zone II. In contrast, delamination depth still has a significant negative impact on detection. During this period, the ΔT of the painted delaminations with a depth of 80 mm ranged from $-0.5\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$. However, some un-delaminated concrete delaminations without treatment had values greater than $0.5\text{ }^{\circ}\text{C}$. According to the threshold set in this study, delaminations falling within this range could not be effectively detected in Zone II, while all other delaminations could be detected. This study did not consider the size of the delaminations, which poses certain limitations. In their studies, researchers [22–24,49] have suggested that even relatively deep delaminations of sufficient size could be detected. Meanwhile, when δT is positive, this study can uniquely determine the depth or ΔT through δT alone.

3.4.3. Zone III (Approximately 7:00–17:00)

As shown in Figure 13, the plot depicts the temperature difference between the non-delaminated areas and the air (δT) and thermal contrast (ΔT) in Zone III. When the sun appears, the ambient temperature gradually rises. Although the temperature of the specimen also gradually increases, when the specimen's temperature is higher than the ambient temperature, the specimen radiates energy to the outside. This results in different ΔT values at the same δT , forming a behavior similar to a hysteresis curve. It was observed that the scatter plot resembles a hysteresis model. By using the hysteresis model, the relevant hysteresis curves were fitted accordingly [50]. The hysteresis curve rises rapidly to its maximum value at the same depth. Then, it slowly decreases to a specific value before rapidly dropping to its minimum value. It finally returns slowly to the origin, as shown in the upper half of Figure 13c. The degree of expansion of the hysteresis curve increases with the absorption rate, with the curves for the 20 mm deep delamination particularly noticeable. For instance, the ΔT for CS1-C rapidly rises from $0\text{ }^{\circ}\text{C}$ to around $8\text{ }^{\circ}\text{C}$, then decreases to about $6.5\text{ }^{\circ}\text{C}$ before sharply dropping to around $-1.5\text{ }^{\circ}\text{C}$ and finally returning to the origin. Similarly, the ΔT for CS1-Y quickly climbs from $0\text{ }^{\circ}\text{C}$ to about $5\text{ }^{\circ}\text{C}$, decreases to around $4\text{ }^{\circ}\text{C}$, then drops to around $-1\text{ }^{\circ}\text{C}$, and returns to the origin. For CS1-W, the ΔT rises swiftly from $0\text{ }^{\circ}\text{C}$ to approximately $3.5\text{ }^{\circ}\text{C}$, then decreases to about $3\text{ }^{\circ}\text{C}$, drops to around $-0.5\text{ }^{\circ}\text{C}$, and finally returns to the origin. This phenomenon could be because surfaces with higher absorption rates have a greater ability to absorb solar radiation, accumulating more heat. Additionally, due to the restriction of heat transfer in the delaminated areas, the temperature in the delaminated regions tends to be higher than that in the non-delaminated regions.

For the same surface material, the expansion of the hysteresis curve decreases with increasing depth. This is particularly evident for different depths of delamination on untreated concrete surfaces, as shown in the bottom of Figure 13c. For CS1-C, ΔT rapidly rises from $0\text{ }^{\circ}\text{C}$ to about $8\text{ }^{\circ}\text{C}$, then drops to around $6.5\text{ }^{\circ}\text{C}$ before quickly falling to approximately $-1.5\text{ }^{\circ}\text{C}$ and finally returning to the origin. For CS2-C, ΔT rises rapidly from $0\text{ }^{\circ}\text{C}$ to about $4\text{ }^{\circ}\text{C}$, then gradually rises to around $4.5\text{ }^{\circ}\text{C}$ before returning to the origin. For CS3-C, ΔT rises rapidly from around $-0.5\text{ }^{\circ}\text{C}$ to about $1.7\text{ }^{\circ}\text{C}$ before gradually returning to the origin. This phenomenon could be because the heat conduction inside the concrete specimen is restricted in the delaminated regions. The degree of restriction varies with depth, meaning that deeper delaminations experience less restriction. As a result, the temperature difference between the delaminated and non-delaminated regions decreases as the depth increases. Therefore, this study concludes that in Zone III, both surface property variations and delamination depth negatively impact the detection of subsurface delamination in concrete.

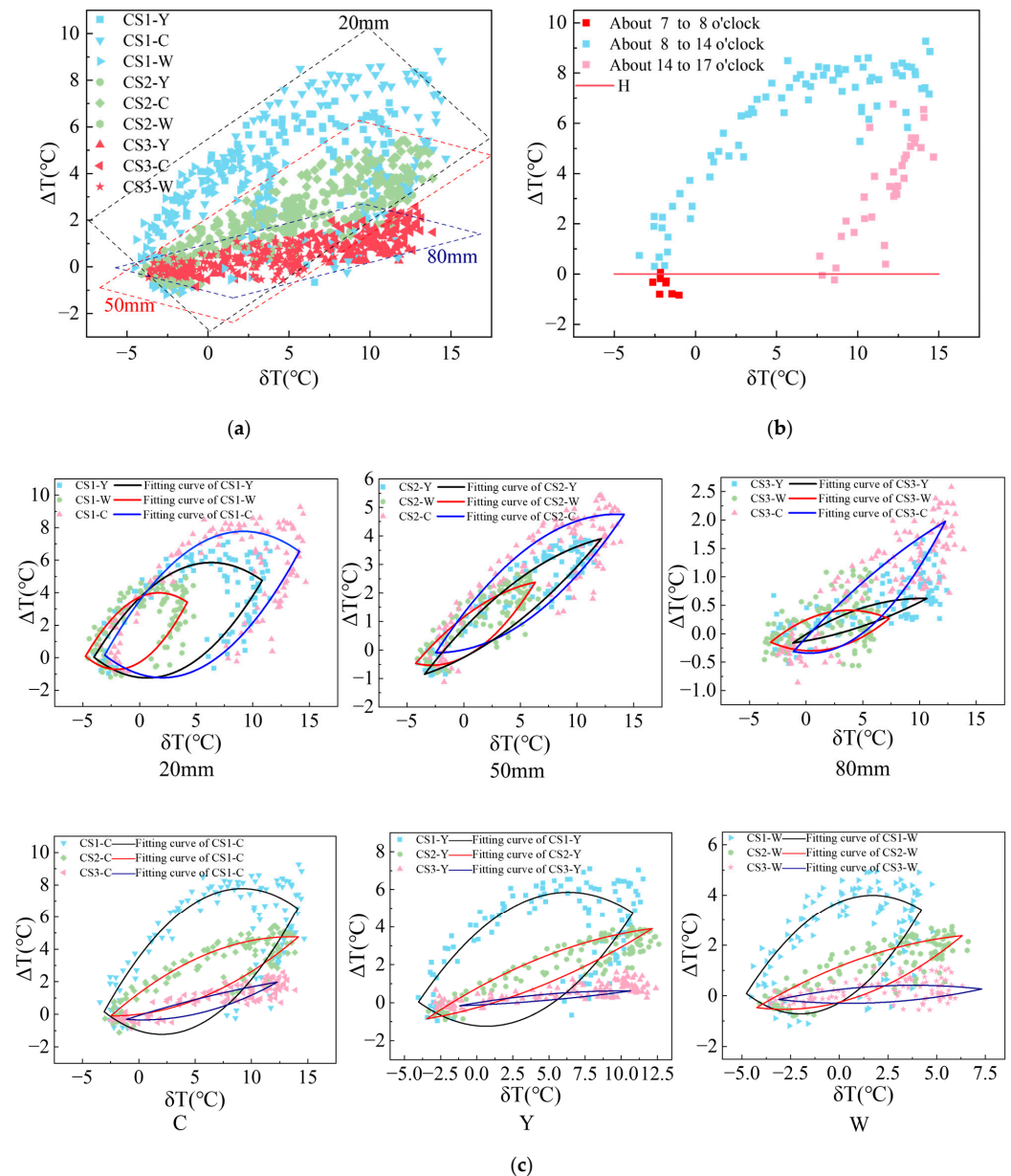


Figure 13. Zone III: (a) the map of thermal contrast (ΔT) and temperature difference between non-delaminated area and air (δT); (b) segment the CS1-C in Figure a by time for reference; and (c) hysteresis curve graph for the same depth or the same surface material.

From 7 to 8 o'clock, it is difficult to determine the delamination depth. However, from 8 to 14 o'clock, this study suggests that the delamination depth can be preliminarily determined using ΔT and δT and further refined based on the detection time. Similarly, the period from 14 to 17 o'clock is similar to the period from 8 to 14 o'clock. According to the threshold set in this study, delaminations at depths other than 80 mm can generally be effectively detected during this period. However, 80 mm deep delaminations require sufficiently large δT values to be detectable.

4. Conclusions

This study conducted experimental research and data analysis to reveal the effects of surface absorptivity and depth on the infrared delamination detection of concrete structures under natural environmental conditions. According to the findings, the ΔT curve can be divided into three characteristic zones based on its variation pattern based on the daily solar

loading cycle. In Zone I, linear fitting of the centroids obtained from k-means clustering can distinguish the ΔT distribution under different absorptivities and depths. In Zone II, δT and depth can be used to determine the range of ΔT , and variance analysis indicates that the impact of absorptivity on detection is negligible during this period. Zone III has a hysteresis effect between ΔT and δT , where depth and absorptivity influence the hysteresis loop, effectively impacting ΔT . The shallower the depth, the larger the hysteresis loop; the more significant the absorptivity, the larger the hysteresis loop.

In summary, this study has found that depth has a negative impact on infrared detection of concrete delamination, while absorptivity has a positive impact on detection. For delamination with different depths and the same absorptivity, the effectiveness of infrared detection decreases with increasing depth, such as delamination under the surface of concrete, whose maximum ΔT values are 9.40 °C (20 mm), 5.54 °C (50 mm), and 2.63 °C (80 mm), respectively. For delamination with the same depth but different absorptivity, as the absorptivity increases, the effectiveness of infrared detection also increases. For example, for delamination with a depth of 20 mm, their maximum ΔT values are 5.15 °C (absorptivity of 0.369), 7.35 °C (absorptivity of 0.538), and 9.40 °C (absorptivity of 0.652), respectively. And the larger the δT , the easier it is to detect delamination. For infrared delamination detection of concrete structures with different surface colors (cool colors), this study provides a reference for further quantifying and assessing concrete delamination using δT among colors with similar absorptivity. This approach is particularly useful for regions with latitudes and climate conditions similar to those of Chongqing.

Although this study has revealed the effects of absorptivity and depth on the infrared detection of concrete structure delamination, the impact of delamination size, the region where the concrete structure is located, and the environment (climate, season) on infrared detection of delamination remains unclear, and the detectable limit of delamination depth is also yet to be determined. These will be the directions for future research.

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