Detección de delaminaciones en puentes de concreto armado usando Termografía Infrarroja

Detection of Delaminations in Reinforced Concrete Bridges Using Infrared Thermography

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Abstract

The objective of this study is to evaluate the capability of infrared thermography for delamination detection in different types of concrete. This methodology was experimental, so two test concrete specimens with water/cement ratios (w/c) of 0.50 and 0.60 were prepared, and delaminations were simulated by inserting polystyrene plates (100 × 100 mm) with different thickness at different depths (25, 50 and 75 mm). The results show that the specimens with lower w/c ratio could detect defects more easily than the specimens with higher w/c ratio. The maximum depth of delamination detected was 50 mm with a minimum thickness of 3 mm. The results also show that morning hours are the best time for detection. However, night-time as an alternative period is presented. This technique is effective for superficial delamination detection, essentially for those elements exposed to sunlight during the day and high relative humidity in the night periods.

Keywords: *Non-destructive evaluation, infrared thermography, bridge inspection, concrete, delamination*

Resumen

El objetivo de este estudio es evaluar la capacidad de la termografía infrarroja para detectar la delaminación en diferentes tipos de concreto. Esta metodología es experimental por lo que se prepararon dos probetas de ensayo de hormigón, con razón agua/cemento de 0,50 y 0,60. Las delaminaciones se simularon insertando placas de poliestireno (100 x 100 mm) de diferente espesor a diversas profundidades (25, 50 y 75 mm). Los resultados señalan que la probeta de ensayo con menor razón a/c podría detectar los defectos más fácilmente que la con mayor razón a/c. La profundidad máxima de delaminación detectada fue de 50 mm con un espesor mínimo de 3 mm. Los resultados también señalan que las horas de la mañana son las mejores para realizar la detección; sin embargo, se presentan las horas nocturnas como periodo alternativo. Esta técnica es efectiva para la detección de la delaminación superficial, especialmente para aquellos elementos expuestos a la radiación solar durante el día y a una humedad relativa alta en los periodos nocturnos.

Palabras clave: Evaluación no destructiva, termografía infrarroja, inspección de puentes, concreto, delaminación

1. Introduction

Bridges are structures of great importance due to functions they accomplish. However, maintenance and inspection of these structures occur over long periods. This aspect may generate issues, since the detection of defects is not timely done, thus leaving the structure vulnerable to fast deterioration. Especially superstructure elements such as decks may be deteriorated due to direct exposure to environment aggressiveness and traffic loads that, in many cases, might be higher than projected (Vemuri y Atadero, 2017; Hiasa et al., 2017).

Bridge deterioration may occur by several mechanisms, steel corrosion mainly, which results in iron oxide accumulation, thus generating steel expansion and tensile radial stress in concrete causing cracking, delamination and spalling (Oh et al., 2013; Washer, 2012).

In most cases, bridge inspection is simply done by visual inspection or using destructive methods. However, these methods present several limitations and uncertainties for bridge assessment (Oh et al., 2013; Rehman et al., 2016). In order to reduce these issues, many non-destructive tests as Impact-Echo (IE), Infrared Thermography (IRT), Ground Penetrating Radar (GPR), Ultrasonic Pulse Velocity (UPV), among others, are used (Rehman et al., 2016). The applicability of these methods has been evaluated both in the laboratory and in the field (Yehia et al., 2017). Nevertheless, many techniques do not have specific standards for inspection and require direct contact with the structure, in addition to a complex data analysis (Oh et al., 2013; Watase et al., 2015).

Infrared thermography has many advantages over other non-destructive methods, since it may be used remotely avoiding direct contact; it can analyze areas and provide a better overview of structure conditions; results are immediate, among others. In case of inspection for reinforced concrete bridges, its specific use is related to delamination detection as a product of corrosion in reinforced concrete (Hiasa et al., 2017; AASHTO, 2011; Aggelis et al., 2010); however, it does not provide information on defects depth and it is highly influenced by environmental conditions (Yehia et al., 2007; Washer et al., 2010).

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Concrete quality may also become an influential factor for inspection with infrared thermography because, according to design requirements and specific load conditions, bridges are constructed with different material portions and, in some cases, with the use of various chemical additives (Farrag et al., 2016). In this sense, the objective of this study is to evaluate the technique of infrared thermography for detection of corrosion products, specifically delaminations, taking into account concrete of different water/cement ratios (w/c) and specific environmental conditions of the study site.

2. Literature review

Infrared thermography is a non-destructive test that measures the infrared radiation emitted by any object surface, converting it into an electrical signal to be processed and creating thermal images known as thermograms. Every material emits infrared radiation when their temperature is above absolute zero (Bagavathiappan et al., 2013).

There are two manners of applying infrared thermography that vary according to heating source: active and passive. The first manner requires external heat sources to create thermal gradients in concrete. In the second way, stimulus is created by environmental conditions, without external sources. Each form has specific applications; however, bridge inspection is most of times carried out passively (Oh et al., 2013; Bagavathiappan et al., 2013; Rocha & Póvas, 2017). In this sense, standard D4788-03 (ASTM 2013), establishes a method under passive application and recommends a minimum of 3 hours of direct sunlight for inspection purposes.

The concept of thermography application is based on the fact that delaminations and defects inside concrete interrupt heat flow in this material. During daytime, when concrete is exposed to the sun and environmental conditions, areas above delaminations and voids are heated faster than concrete areas without defects since these do not allow heat transfer because delaminations and voids are usually filled with air or water that has a different thermal capacity than concrete. These defects have high temperatures in these sectors during the day and as lower temperatures at night in relation to concrete without internal defects, thus forming thermal differentials (Washer, 2012; Vaghefi, 2012; ASTM, 2013).

According to literature, detection limits for delaminations on w/c ratio and depth have not been clearly established. Yehia et al. (2007) found voids and delaminations at 40 mm deep in concrete with 28 MPa compressive strength, whereas Kee et al. (2012) found delaminations at 50 mm in concrete with the same strength. Maierhofer et al. (2007) found voids at 60 mm deep in 48 MPa concrete by using active thermography. Washer et al. (2010) were able to clearly detect defects 75 mm deep in 27.6 MPa concrete. Alfredo-Cruz et al. (2015) found delaminations at 50 mm deep in 38 MPa concrete with 0.35 w/c ratio, but defects found at 75 mm deep were not very visible. Farrag et al. (2016) found delaminations and voids at 100 mm deep by using 50 MPa compressive strength concrete. Uncertainty regarding detection capability of infrared thermography may be due to the fact that studies were carried out in different places with particular conditions (Hiasa et al., 2016), besides various characteristics of concrete used.

3. Materials and experimental program

This experimental program is based on test specimen molding in order to simulate bridge element surfaces exposed to the sun and, therefore, evaluate technique capability to detect delaminations at different depths and in different concrete types. For this reason, two specimens of different w/c ratios, 0.6 (CS1) and 0.5 (CS2), and a 1:2.8:2.6 (cement: gravel: sand) trace were molded. Cement used was CPII Z-32 and the maximum gravel diameter was 19 mm.

Test specimen dimensions were 500 × 500 × 100 mm. In order to simulate delaminations in concrete, polystyrene plates of 100 × 100 mm in different thickness were placed at different depths and positions as specified in table 1 and figure 1.

Table 1. *Detail of the artificial delaminations*

Delamination	Concrete specimen 1		Concrete specimen 2	
	Depth (mm)	Thickness (mm)	Depth (mm)	Thickness (mm)
D1	25	3	25	3
D2	25	6	25	6
D3	25	12	25	12
D4	50	3	50	3
D5	50	6	50	6
D6	50	12	50	12
D7	50	3	75	3
D8	50	6	75	6
D9	50	12	75	12

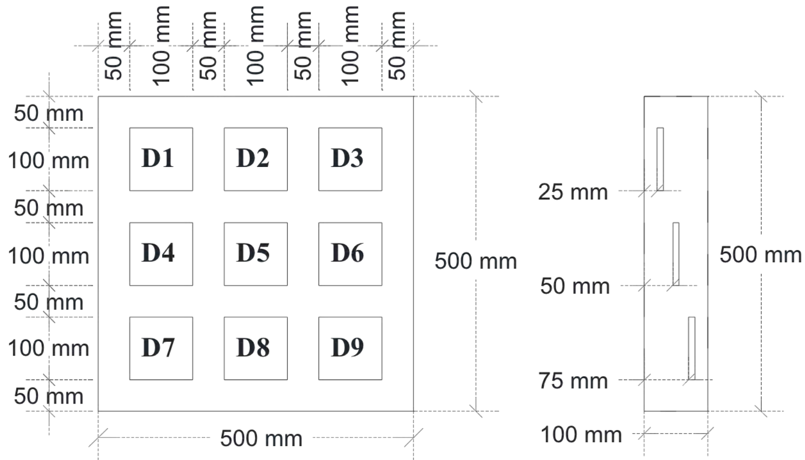

Figure 1. *Position of the delaminations in the concrete specimens*

A FLIR E60 thermographic camera was used for this study, whose characteristics are presented in FLIR (2013).

After a 28-day concrete curing period, the specimens were taken outside, to an area that allowed solar radiation throughout the day, without any shadow interference. The camera was placed one meter away from the specimens. Thermograms were collected every 30 minutes from 7:00 a.m. to 9:00 p.m. in order to observe concrete surface temperature throughout the day. Although some researchers give recommendations about data collection time for sun exposure conditions (Kee et al., 2012; Washer et al., 2010), there is no definite period, since many investigations are contradictory on this point. Therefore, taking measurements as long as possible in order to obtain the best inspection time for the chosen study site, Recife City - PE, was decided.

The monitoring was conducted during 18 days in the month of May, 2017, without rain or cloudy conditions. Using a thermohygrometer, the ambient temperature and relative humidity readings were taken.

Cylindrical specimens of 10 cm diameter and 20 cm height were also molded for each water/cement ratio to determine the 28-day compressive strength of the concrete, using the procedure established by standard NBR 5739 (ABNT, 2007). Table 2 shows the results of the compressive strength tests on the cylindrical specimens.

Tabla 2. *Compressive strength of cylindrical concrete specimens*

Property	***CS1***	***CS2***
w/c Ratio	*0,6*	*0,5*
28-days compressive strenght (MPa)	*25,3*	*32,1*
Average density (kg/m^3)	*2198*	*2394*

For result analysis, a thermal gradient or differential temperature, *ΔT*, defined by equation (1) was used.

$$\Delta T = TD - TC \quad (1)$$

Where TD = temperature of the delamination; and TC = temperature of the intact concrete.

4. Results and discussion

During test time, data reproducibility could be verified, since they exhibit the same behavior throughout the day. Therefore, the results that could generalize this behavior were presented. figures 2-7 show the thermograms taken at different times of day. Dark colors represent low temperatures and light colors represent high temperatures.

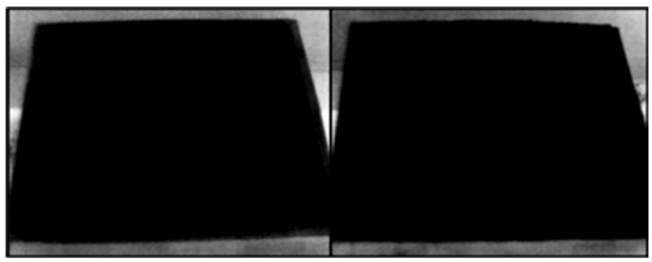

Figure 2. *Thermograms at 7 a.m.: a) CS1 and b) CS2*

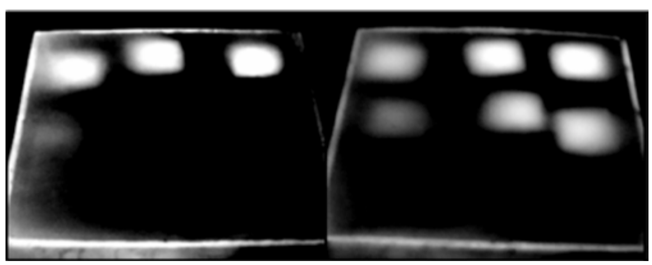

Figure 3. *Thermograms at 10 a.m.: a) CS1 and b) CS2*

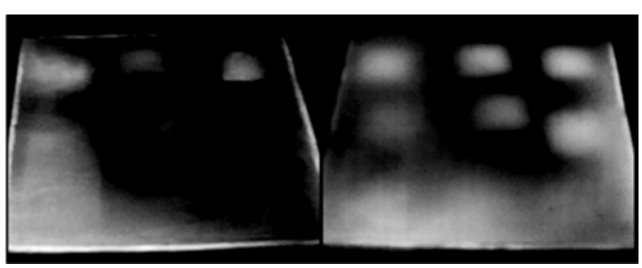

Figure 4. *Thermograms at 12 p.m.: a) CS1 and b) CS2*

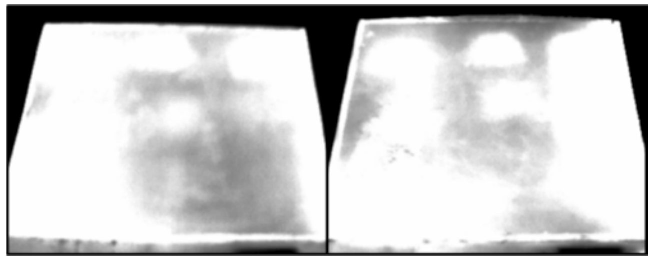

Figure 5. *Thermograms at 14 p.m.: a) CS1 and b) CS2*

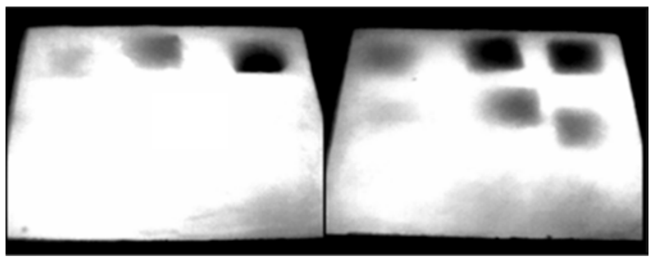

Figure 6. *Thermograms at 18 p.m.: a) CS1 and b) CS2*

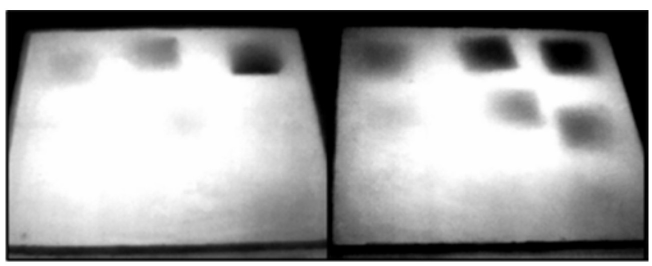

Figure 7. *Thermograms at 21 p.m.: a) CS1 and b) CS2*

It is observed that in CS1 only the delaminations up to 25 mm deep and in CS2 the delaminations up to 50 mm deep can be detected. In the morning, the delaminations are detected as hot areas opposite to afternoon and night hours, where they are perceived as cold areas, in relation to the intact concrete. The most superficial delaminations, 25 mm deep, are detected most of the day, due to their rapid heat absorption, since concrete layer is thin. The heat is concentrated in a small area, which allows fast heating and cooling.

4.1 Delamination temperature

Figure 8 shows behavior of the delaminations at 25 mm deep and the concrete surface without any delamination in CS1. It may be noted that the delaminations rapidly increase their temperature during early morning hours. However, this behavior reverses in the afternoon and evening, when defect temperatures fall. Figure 9 shows the behavior of the delaminations temperature at 25 mm and 50 mm depth at CS2, observing the same behavior at CS1; the delaminations show higher temperatures in the morning and in the early afternoon, but at night, they become cold.

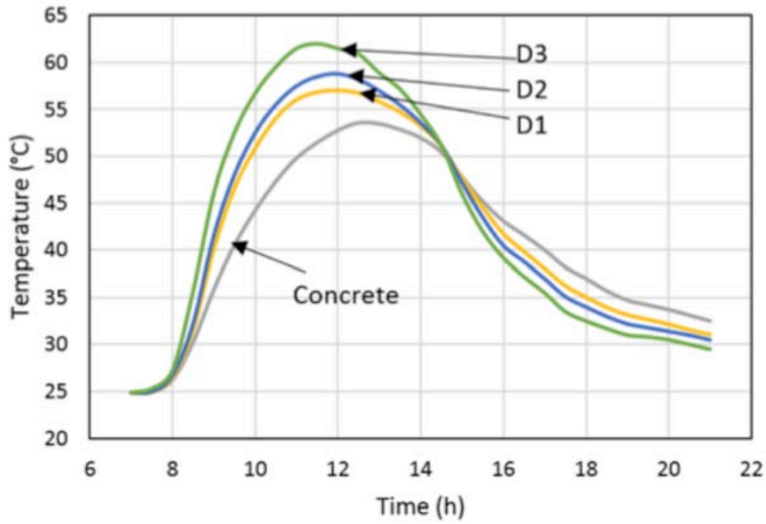

Figure 8. *Behavior of the delaminations and the intact concrete temperatures – CS1*

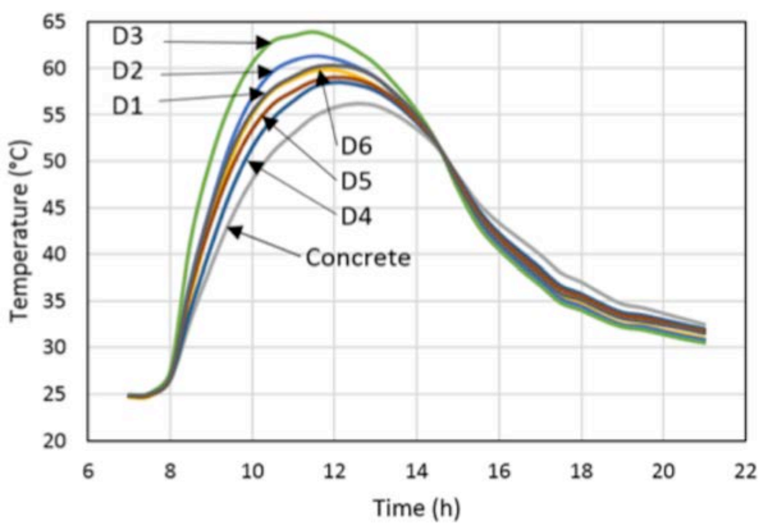

Figure 9. *Behavior of the delaminations and the intact concrete temperatures – CS2*

Figures 8 and 9 show two periods: heating and cooling. The first, from 7 a.m. and the second starting at noon, with a change in thermal contrast at approximately at 2:30 p.m.

In both test specimens, the maximum temperature values for the delaminations and the concrete are present around 10 a.m. and noon. During this time, the temperature of the intact concrete is lower than the temperature of delaminations, thus creating positive thermal contrasts. From 4 p.m., the concrete becomes hotter than the delaminations, thus creating negative thermal contrasts.

According to figures 8 and 9, the thickness of the delamination affects the temperatures presented, because the greater the delamination thickness, the hotter it is in relation to the others with the same depth, like D3 at 25mm deep in CS1, and D3 and D6 at 25 and 50 mm deep, respectively in CS2. This is because the delamination allows a limited heat transfer, a greater thickness represents a greater difficulty regarding heat transfer to the concrete below the delamination, retaining greater amount of heat for the above areas, being captured by the camera as hot areas.

At night, when behavior is reversed, the concrete gets cooler in these areas, and when the solar energy is not present, the areas tend to balance with the environment. The most superficial delaminations balance faster than the deepest ones because they have smaller concrete layers.

4.2 Relative humidity and ambient temperature

Figures 10 and 11 show the thermal contrast between the areas above delaminations and the temperature of the intact concrete, regarding the environmental conditions recorded: ambient temperature and relative humidity.

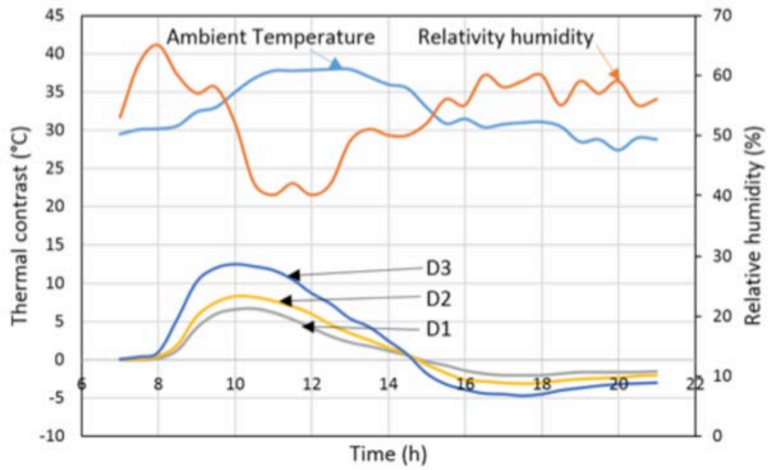

***Figure 10.** CS1 Thermal Contrasts*

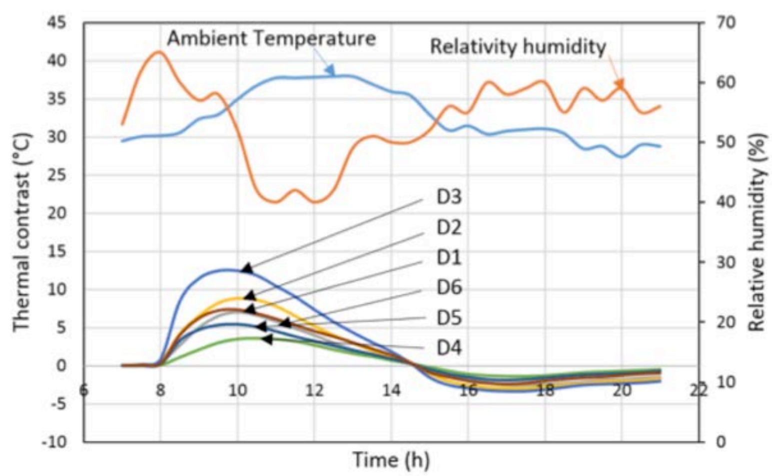

***Figure 11.** CS2 Thermal Contrasts*

In both test specimens, the greatest contrasts produced at the same time as the ambient temperature increases and the relative humidity decreases were observed. The maximum contrast values occur when the ambient temperature is high and the relative humidity is low. This period occurs from 9 a.m. to 1 p.m., representing an appropriate inspection period, since the delaminations are perceived as positive thermal contrasts, as seen in figures 3 and 4. However, in previous period, the delaminations are not detected (figure 2). In the afternoon, as the ambient temperature decreases, the relative humidity increases; the thermal contrast reverses from 2 to 3 p.m. and the delaminations are not clearly detected in the thermograms taken (figure 5). After 3 p.m., the detection is done through negative thermal contrasts (figures 6 and 7), when the ambient temperature is low and the relative humidity high. Nevertheless, these values are low compared to those in the morning.

This behavior may be explained considering that the concrete specimens are exposed to sunlight and the environment during the day, which develops a heating process by radiation and convection, respectively. However, solar radiation has greater influence in this process, rapidly increasing the concrete temperature. The presence of defects or delaminations in the concrete prevents heating in the areas below thus, retaining heat. Therefore, the most superficial defects heat up faster than deepest ones.

At night, when the solar energy is not present, heat transfer takes place mainly by the convection mechanism between the heated concrete during the day and the ambient temperature that presents lower values. The concrete loses heat until it balances its temperature with the environment. The most superficial delaminations tend to balance faster than the deepest ones because they have smaller concrete layers.

The relative humidity plays an important role during the cooling process. Washer et al. (2010) indicate that moist air creates a more efficient convective heat transfer between concrete and ambient temperature, since the moist air penetrates more quickly into the concrete than dry air. In this case, the thermal contrasts are developed in the nocturnal period with high values of relative humidity, thus helping in the process of thermal equilibrium.

4.3 w/c ratio

The thermograms (figures 2-7) show that in CS1 only the delaminations at 25 mm deep are distinguished, and in CS2, up to 50 mm deep. This represents a detection of 33% in CS1 (3/9) and 67% in CS2 (6/9).

This difference in delamination detection is attributed mainly to the w/c ratio, since it was the only different characteristic in test specimen molding (CS2 with a 0.5 w/c ratio and CS1 with a 0.6 w/c ratio). Properties such as porosity and density affect concrete thermal conductivity and affect the results for infrared thermography (Farrag et al., 2016; Al-Hadharmi et al., 2012).]. In this case, CS1 has a lower density than CS2, thus presenting greater porosity and heterogeneity, which limits the heat flux through the concrete and reduces the thermal contrast formations on its surface, only being detectable up to 25 mm deep.

According to these results, the greatest detection range in delamination depth was at CS2, up to 50 mm, with 32 MPa compressive strength, whereas CS1 was only 25 MPa. These values are direct con-sequence of w/c ratio (Mehta & Monteiro, 2013 Figure 12 shows the relation between delamination depth detected and compressive strength by a comparison against other investigation results (Kee et al., 2012; Farrag et al., 2016; Yehia et al., 2007; Maierhofer et al., 2007; Alfredo-Cruz et al., 2015), observing a trend of the greater concrete compressive strength, the greater detection depth for delaminations.

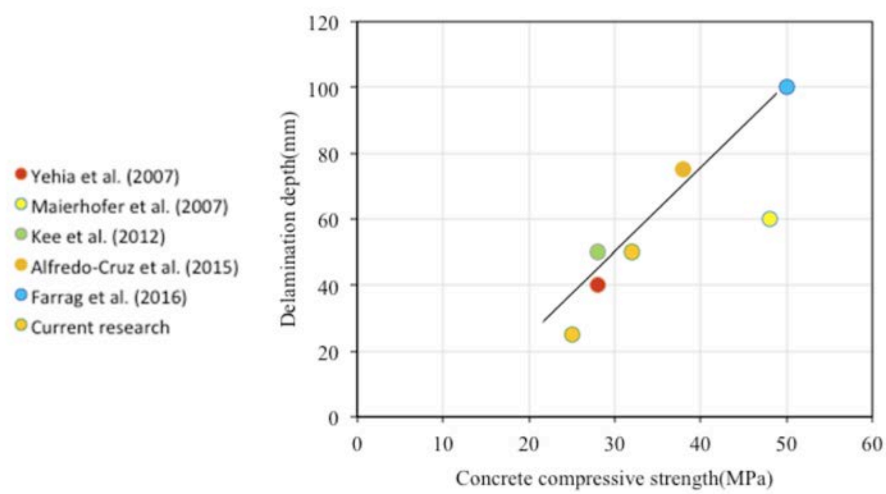

Figure 12. *Delamination depth by thermography and concrete compressive strength relation*

Washer (2012) establishes that simulated delaminations represent an ideal behavior model and that thermal contrast values would be much higher compared to real delaminations. However, the detection of differences and thermal changes during the day by thermographic cameras represents good accuracy and reliability for delamination detection.

This technique provides information on internal defects by measuring radiation emitted by concrete surface. However, the information is mainly focused on defect location and issue area at appropriate times, but it does not provide information on the nature of delaminations, which in *many cases are related to corrosion, as well as failures in construction process, which may apply in such cases.*

5. Conclusion

This document presented results for delamination detection with infrared thermography in bridge elements with different w/c ratios that have direct contact with solar radiation. These results are based on the use of specimens and an 18-day inspection period.

The results show that inspection is efficient on surface defect detection for concrete, but there are periods of time where inspection is ineffective, essentially during heating and cooling periods, where the thermal contrasts show minimum values.

The w/c ratio and its influence on concrete density and compressive strength affect the results. Concrete with lower w/c ratio had the best results for delamination detection , unlike the test body with higher w/c ratio, where detection was limited, showing that the better concrete quality is, the better results are obtained.

Infrared thermography is an important tool for inspection of concrete structures, especially bridges, where delaminations may appear and are difficult to access. However, the test is strongly influenced by environmental conditions and there may be some limitations on detecting deep defects and in low quality concrete.

Combination with other tests may help in a better characterization of these defects, besides complementing information. Recent advances in camera technology, inspection procedures, and data analysis provide greater reliability on delamination detection.

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