BOISE STATE UNIVERSITY

COLLEGE OF ENGINEERING

IMPACT OF CLIMATE CONDITIONS ON THE USE OF INFRARED THERMOGRAPHY FOR THE INSPECTION OF COATED AND UNCOATED UNREINFORCED CONCRETE SAMPLES

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ABSTRACT

This project´s fundamental objective is to evaluate the ability of the infrared thermography technique under different climate conditions to detect and recognize anomalies, delamination and defects that cause deterioration on concrete surfaces both coated and uncoated.

The use of concrete as a construction material is very extended in today´s world and it is all-important the use of inspection techniques that allow proper monitoring and maintenance of concrete infrastructure in order to manage and administrate it´s useful life, through prevention and repair of damages. With the passage of time deterioration of this material exists, especially when their surfaces are visibly exposed to the actions of the environment and inclement weather. Therefore, Infrared Thermography has been presented as attractive alternative, facing other traditional methods.

However, its range of application on concrete elements has been focused from the beginning to the detection of very specific type of defects, except for recent years where it has been possible to observe some interesting developments. For this reason, it has become necessary to test IRT seeking its real potential under the conditions and situations more similar to those found in a field inspection.

In order to achieve this, the method of active infrared thermography has been used to test in our laboratory different cracked concrete samples during different climate conditions. This test recreates the different weather conditions that can occur in the field by developing a climate controlled system in the lab.

Finally, the analysis of the results has revealed that different climate conditions affect the reliability and performance of IRT for detecting surface defects on concrete structures. In addition, the fulfilment of concrete coatings´ function during different climate conditions was also studied. Large amount of test results have been collected and will be used in the future for improving the accuracy of the IRT technique.

1. INTRODUCTION

The concrete surfaces exposed to ambient have signs of deterioration, which have continuously evolved over the years. Because of this, it becomes necessary to have viable on-site techniques capable of evaluating the deterioration that has arised over the years. The infrared thermography technique (IRT) meets this requirement and moreover is easily operated which makes it a practical tool for the pursued application.

Although it is not a relatively new technique in this field of study, its reduced range of application in both building and civil engineering, makes complex the identification of deterioration processes in elements of concrete, especially because it is hard to obtain contrasted images and interpret them.

Nevertheless, its usefulness becomes relevant in many cases to manage maintenance and repair work. In this sense, we have seen the need to test IRT to evaluate its feasibility as a method of inspection and in situations that seek to simulate the common problems encountered during an inspection, such as different weather conditions (temperature, wind, humidity…).

The field of study of this project has been delimited to the application of IRT technique in different climate conditions to uncoated and coated concrete blocks without reinforcement which present cracks. For this, an experimental laboratory set-up has been created that will assess the capacity of exploration of IRT on different types of surfaces and different climate conditions.

This project has as main objective to verify the capacity of the technique of infrared thermography to detect and recognize defects under different climate conditions and to evaluate the performance of concrete coatings. Therefore, the potential of the technique as a non-destructive inspection method will be explored and the usefulness of concrete coatings will be analyzed.

2. CONTEXT

The durability and aging of the infrastructure are two of the concerns that constantly accompany the construction professionals. The performed work must be designed to conserve its resistance and last in time, but in order to achieve this, a series of maintenance actions are also required during its lifetime. Therefore, professionals must use tools, techniques and processes that allow reaching the required objectives, but at the same time it should be done in an efficient, fast and economical way.

In this aspect, non-destructive testing (NDT) is presented as one of the most interesting options to study, since they consist of a set of techniques capable of examining an element, through the use of several technologies, without affecting the future utility of that element. Infrared thermography belongs to this classification as one of the six basic categories that form the NDT. [7]

- Thermal and Infrared
- Sonic-Ultrasonic
- Mechanical-Optical
- Electromagnetic-Electric
- Penetration-Radiation
- Chemical-Analytical

In many cases these categories contain methods that are not completely non-destructive, but that when compared with other traditional methods whose techniques involve subtraction or destruction of a part of the element, they are included as NDT. However, IRT thermography is a remote sensing technique, so it does not need to be in contact with the element to analyze, and therefore its application does not absolutely compromise the structural integrity of the studied element. For this reason, infrared thermography is shown as a safe, fast and portable.

3. OBJECTIVES

The main objective of this project is to analyze a non- destructive test technique (NDT), the infrared thermography under different climate conditions and to analyze the usefulness of concrete coatings.

Therefore, the potential of this technique as a non-destructive inspection method will be explored, taking advantage of its main characteristics such as speed, portability and extensive recognition to examine large surfaces at once.

In order to analyze this technique two samples have been used. One of the samples is an uncoated concrete block and the other one is a coated sample.

The particular objectives of the project were:

- Learn about non-destructive tests
- Understand the basic principles and concepts of IRT
- Learn to use of a thermographic camera
- Do the set-up and procedure of the experimental test
- Analyze the thermographic images to evaluate if they are useful
- Improve the processing system of the records obtained by the infrared camera
- Identify the different variables and factors that intervene in a correct thermographic measurement and that allow boosting or reducing the detectability of defects and anomalies.

4. NON-DESTRUCTIVE TESTS

A Non Destructive Test (NDT) consists of the application of certain tests on an object, to verify its quality without modifying its properties and original state. These tests will allow the detection and evaluation of discontinuities or properties of materials without modifying their conditions of use or aptitude for service. [7]

NDTs are based on physical principles and the results are obtained from their application to evaluate certain characteristics of the inspected element. The results are not shown in absolute form, but they must be interpreted based on the indications of each method.

One of the techniques of non-destructive inspection that is of interest is based on infrared technology, which allows to capture the flow of energy emitted by a surface and transform it initially into an electrical signal and later into a digital image. The result of the transformation of infrared radiation into an image is known as a thermogram and software is used to obtain the temperature. [4]

5. CONCEPTS OF INFRARED THERMOGRAPHY

Infrared thermography (IRT) is composed of two concepts. On the one hand, the concept of thermography, which is defined as a technique to measure or record the temperature distribution over a surface, which means, thermography measures temperature variations; On the other hand, we have the concept of infrared (IR), which refers to wavelengths between 0.7 micrometers (μm) to 1000 μm of the electromagnetic spectrum [5].

Therefore, infrared thermography is the technique that measures the temperature differences in the infrared spectrum. This technique is based on the measurement of infrared radiation through the remote sensing. The radiation that a material emits is recorded without the need of being in contact with its surface.

However, in order to measure the different temperatures emitted by the material it is necessary a capture equipment that help to transform the infrared radiation, not visible, into radiations that can be represented in the visible spectrum, which are the ones that can be seen by the human eye. This is achieved through the use of devices capable of perceiving and measuring IR radiations, such as thermographic cameras, which manage to transform them into infrared images by associating thermal variations of temperatures with the colours of the visible spectrum.

In this sense, unlike the visible spectrum images, which are produced by reflection and reflectivity differences, IR images are produced by the phenomenon of the own emission of the material and by the variations of its emissivity.

This technique works thanks to the fact that the infrared camera allows us to measure the temperature of the concrete surface to be analyzed. If interior defects exist, there will be warmer points in the surface, since the heat transfer to the interior of the concrete specimen is interrupted, because those defects are filled with air or water, which have a lower thermal conductivity than the concrete. These surface temperature differences can be read with the IRT and defects can be detected.

6. HISTORY OF INFRARED THERMOGRAPHY

The infrared was discovered in the 1800s by the astronomer, and musician, German Friedrich Wilhelm Hershel. Hershel sent a ray of sunlight through a prism of glass to decompose it in its spectrum and measure the temperature of each of the colors. He found that the temperature of each color increased from the violet to the red part of the spectrum. But he also discovered that the temperature was increasing beyond the red, where the decomposition of the light from the solar ray was no longer visible. To his surprise, this region had the highest temperature of all.

The first thermal camera was developed for military applications in 1958. This technology was capable of producing a clear image in total darkness, thermographic technology offers the ability to see and detect threats in the darkest nights. The cameras thermal can see through the fog, the rain and the snow. They also have the ability to see through smoke, which increases your interest to military uses, since they are able to see through a fully covered battlefield of smoke.

The first infrared camera for commercial applications was developed in 1965 and since then, the first commercial suppliers of infrared camera together with the non-destructive testing conventions served to extend and consolidate this technique.

Finally, one of the last great advances in the technology of infrared cameras and infrared thermograph has been the appearance of microbolometers at the end of the 1980s. These have made it possible to eliminate the need to cool down the sensors with each measurement made, and therefore improve the mobility and portability of the camera during inspections.

7. THEORETICAL PROCEDURE OF A THERMOGRAPHIC TEST

As it has been observed in the previous topic, the equipment, applications, as well as the knowledge obtained about IRT thermography has been developed in a relatively fast time that goes back to little more than 200 years.

Therefore, as these technological advances have been integrated into the field inspections on buildings, there has been an increasing demand for methodologies and application procedures. In this aspect, a good thermographic procedure must follow a logical order of planning, preparation and execution.

The association of thermography of the United Kingdom proposes in its thermographic code of application for building, the following general procedure to carry out a Thermographic study. [8]

- Identification of a problem
- Problem classification
- Select IRT thermography technique to be used to diagnose the problem
- Develop the appropriate method
- Equipment and preparation
- Health and security
- Selection of adequate time for on-site inspection (weather conditions)
- Realization of the Essay
- Analysis of the results
- Report preparation

However, before undertaking a thermographic test, it is necessary to understand the principles that govern it. The thermographic test is based on the fact that variations in thermal properties of the bodies produce temperature differentials on its surface. In case of presenting an anomaly or defect, the temperature on that point will show a significant change in its value with respect to the values of temperature of points surrounding that defect. Therefore, these defects become visible for the thermal camera.

For these temperature variations to occur, it is necessary, then, that a heat flow through the body exists and varies the temperature. Usually, the sun fulfils this function when external inspections are made in the building. However, when inspections are performed in places without contact or influences of sunlight, another heating method should be used in order to produce that heat flow.

During the test, the professional performing of the inspection is must distinguish between real faults and other sources of temperature variation. Therefore, is very important to correctly select the type of thermography that is applied in each test, so to help to achieve the best results under the conditions that could arise.

8. CLASSIFICATION OF INFRARED THERMOGRAPHY

According to the classification of infrared thermography, there are two forms to measure the IR radiation of an element: by passive or by active IRT.

Active IRT thermography is the one that uses an external source of heat to give energy to the studied object, which causes an internal heat flow that has the purpose of obtaining significant temperature differences. These differences of temperature can potentially detect surface and subsurface defects, since the presence of these defects inside the object modifies its thermal diffusion, creating a contrast between the defects and the unaffected area around them.

Passive IRT is a simple form of measurement which does not require an excitation or external heating to cause in the studied element a flow of heat. In passive infrared thermography, unusual temperature profiles indicate a potential defect. Therefore, a point is taken as a reference, and if values are greater than this reference, those points are considered strong evidences of unusual behaviour in the element. [6]

9. DEFECTS AND DETECTABILITY WITH IRT

In measurements with infrared thermography, there are many factors that can cause an erroneous recording of temperature variations on the surfaces of the studied elements, which could strongly affect the detectability of the defects.

These are usually associated with common causes such as: variations in emissivity, reflections, by the curvature of the surface, angle or field of vision, problems from the camera, environmental interference (wind, light solar, humidity, among others), or the noise caused by radiations from the environment. [6]

Moreover, there are other important that also impact the detectability of anomalies and defects and it has to do with the technique that is used and with the defect itself. Therefore, there are physical variables that will affect the measurements such as:

- The size of the defect
- The nature of the defect
- The depth at which the defect is located
- The type of material
- The time that elapses from the moment excitation occurs until its visualization on active thermography.

10. THERMAL CAMERA

While a normal camera depends on the light to generate an image, a thermal camera, sometimes also called infrared camera, is able to capture minimum temperature differences and convert them into a clear thermal image where you could detect the most minimum details. Unlike other technologies, such as the light amplification, that a minimum amount of light is needed to generate an image, thermography can see in total darkness. [4]

A thermal camera records the intensity of the radiation in the infrared area of the electromagnetic spectrum and converts it into a visible image. The infrared energy that is radiated by an object is focused with the optical system of an infrared detector. The detector sends the data to the electronic sensor to process the image. After, the sensor transforms the data into an image, compatible with the viewer and displayed on a screen.

Infrared thermography transforms an infrared image into a radiometric image that allows reading the temperature values. Therefore, each pixel of the radiometric image is, in fact, a temperature measurement. In order to do achieve this, complex algorithms are incorporated into the infrared camera. The image is controlled by selecting the following parameters:

- Temperature range: The range sets the temperatures below and above which it cannot be measured. The smaller the range, the more accurate the measurement will be.

- Focus: The image must be correctly focused on the object from which we want to measure the temperature

- Thermal Contrast: it is the part of the temperature range that we are using. We can make the field wider or narrower. Many systems show 256 colors. This is for technical reasons, and also practical. The human eye is unable to differentiate more colors in the same image.

- Adjustment of emissivity: The thermographic camera automatically determines the emissivity of an observed surface. It is considered very important to obtain an accurate image

- Field Of View: It is the angle of vision that is obtained with the lens of the camera.

- Thermal sensitivity: It is the smallest temperature difference that a camera can detect.

- IR Resolution. Corresponds to the size of the camera's viewfinder and refers to the number of pixels that make up the obtained digital image.

- Spectral range. Refers to the type of infrared length used by the camera. In general, the far infrared band (between 7 -14 µm) is used.

11. PROCESSING OF THERMOGRAPHIC IMAGES

The processing or treatment of IR images has the possibility of improving considerably the quality of the thermograms, as well as the contrast of them, allowing the previously detected defects to be seen more clearly.

In this way the processing of images will seek to correct problems concerning the interpretation of signals by presence of noise, the reflectivity on the surface of the object due to the sources of excitation employed in active thermography, the existence of differences in emissivity in the specimen or material, among others.

Once the error to be corrected has been determined, a suitable method must be selected for the treatment of IR images. These methods are classified into three main phases: pre-processing, processing and post processing of IR images,

12. BENEFITS OF INFRARED THERMOGRAPHY

Infrared Thermography has many benefits and advantaged for the study of concrete infrastructure.

- The measurement is done remotely, it is without contact. This implies many advantages, two of them especially important. Firstly, it keeps the user out of danger. Secondly, thermography is not intrusive because it does not affect the inspected element in any way. Only radiation that comes out from the element is observed. This is a very important condition for many applications.

- ➢ It is two-dimensional. Direct comparison between areas of the same body is possible. We can measure the temperature in two points or in a hundred within the same image, and compare them. An image is perfect to get the initial idea of a situation. With an image, it is immediately determined where the problems are, or which points have a special interest. We do not know beforehand where the measurement should be made; it can be decided from the inspection of the image.

- ➢ It is a real time measurement, that is, it can be measured while the object is displayed on the camera's screen. If the object changes, the camera shows the change immediately, without inertia.

- ➢ It is multidisciplinary, not only they provide information about temperature, but they also talk about thermal patterns, behaviors, defects…

- ➢ Speed: Test can be completed in minutes without infrastructure closures.

13. INFRARED THERMOGRAPHY LAB TEST

13.1 INTRODUCTION

Lab scale concrete specimens were fabricated for these tests and they have been tested in a climate controlled testing system inside Boise State lab facilities using an infrared camera and thermocouples.

13.2 SPECIMENS

During this lab research three different specimens have been studied. Concrete blocks used in this test were fabricated in the HML lab of Boise State University with mix design calculations and all of them are unreinforced concrete samples. All the samples present a crack in order to simulate a defect. Samples are detailed in the following images.

13.2.1 UNCOATED CONCRETE SPECIMEN

Figure 1: Uncoated Concrete Specimen

This is a regular concrete sample with a crack and will be a studied specimen.

13.2.2 DECOCOAT COATED CONCRETE SPECIMEN

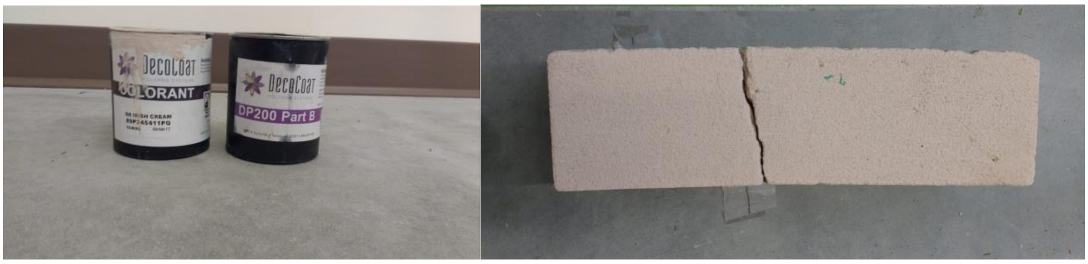


Figure 2: DecoCoat product and coated concrete block

In this case, we have a concrete specimen but DecoCoat SR Irish Cream product was applied on top of the concrete surface. According to the company this product uses special technology designed to cool high-traffic areas and reduce urban heat island effect and the temperature of asphalt surfaces while resisting UV damage and degradation of asphalt to create a more comfortable environment. [2]

DecoCoat product was applied following the instructions of the manufacturer. First of all, surface preparation was needed because dirt, debris, water and contaminants sitting on the surface affect adhesion of the coating. Therefore, surface was deeply cleaned using a broom. Regarding mixing, each mixed unit of DecoCoat Polymer Systems coating consists of a Part A and a Part B as it can be seen in the upper picture. The coating was applied in thin coats coat by roller. According to the manufacturer, typical pedestrian applications require 3 layers of coating. Vehicle applications require 4 layers or more depending on the amount of traffic.

13.3EQUIPMENT

The lab equipment used for the tests was the following:

- **Glass Container:** All the tests have been performed inside this container in order to keep required heat/wind/humidity conditions for our tests. The glass container dimensions are 48´´ Length, 13´´ Width and 20´´Height.

Figure 3: Glass container

- **Thermal camera:** FLIR model camera, model T430sc to capture image data. Object distance was set at 0 to 1 meter and atmospheric temperature was set at 20 degrees Celsius (similar to lab temperature). Relative humidity is considered around 50 percent and emissivity was set at default, that is, 0.95. The wavelength range of the camera is between 7 and 14 Microns. Integration time in the camera for our study is 12 milliseconds. [1]

- **FLIR ResearchIR Sowftware:** This software is a powerful and easy to-use thermal analysis software package for FLIR cameras. It provides camera control, highspeed data recording, image analysis, and data sharing. The ResearchIR software connects directly to FLIR Research and Science cameras via USB. [9]

Figure 4: FLIR camera and software (Images retrieved from www.flir.com)

- **Halogen lamp:** It was used for heating up the specimen which means we have an external source of heat which produces a heat flow. Threfore, active thermography is used for this test series.

Figure 5: Halogen lamp used (Image retrieved from www.evolux.cl)

- **Fan:** This element is used for simulating wind conditions that could take place in the field.

Figure 6: Fan installed on test

- **Humidifier:** This element was used for simulating humidity conditions that could take place in the field, for example on a rainy day. The humidity was being kept between 80-85%. In case the humidity exceeded 85% the humidifier was disconnected until it reached again the desired range.

Figure 7: Humidifier installed on test

- **Thermocouples:** Thermocouples measured the temperatures at different depths of the specimen. Three thermocouples were installed on each specimen before starting the test. The sensors are located 3 inch inside the specimen and each thermocouple is located at a different depth.

  - ✓ Thermocouple 1 was located at a depth of 2 inches from the top surface of the specimen.
  - ✓ Thermocouple 2 was located at a depth of 3 inches from the top surface of the specimen.
  - ✓ Thermocouple 3 is located at a depth of 4 inches from the top surface of the specimen.

Figure 8: Thermocouples on specimen

- **Rings:** Rings were used for locating the points where we want to measure the temperature on the Research IR software. First of all, circles with pencil were marked on the surface of the concrete where we want to measure. Then, rings are placed on those marks and cursors are adjusted on Research IR software. In total the temperature of 9 points of the concrete´s surface (9 cursors) are being measured.

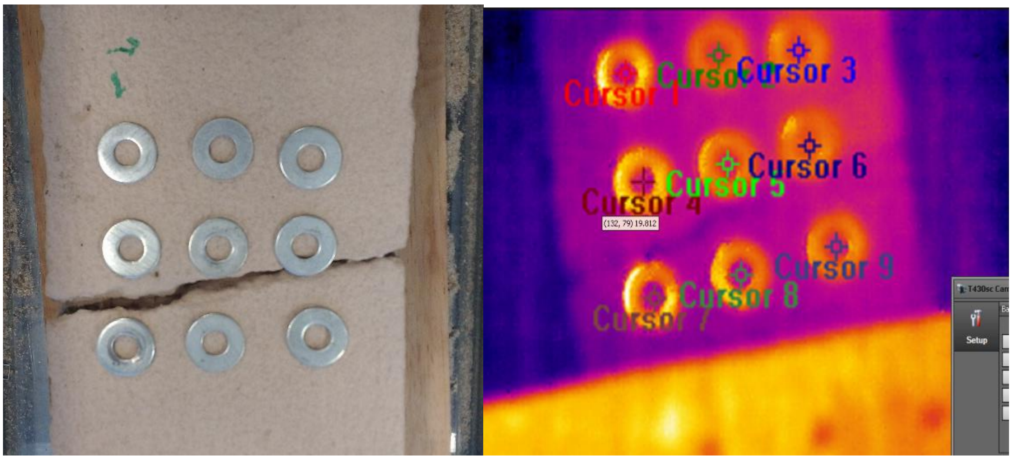


Figure 9: Rings for adjustment of cursors

- **Indoor Temperature and Humidity Monitor:** This device measures the temperature and humidity inside the glass container.

Regarding safety some equipment was implemented in order to avoid incidents or accidents. Oven gloves were used when manipulating the halogen lamp as the temperatures during the heating process are very high and there is a risk of getting hands burnt if protection is not used. Moreover, sunglasses were used when operating the halogen lamp to avoid bright light exposition which could be uncomfortable.

13.4 LAB TEST SET UP AND PROCEDURE

13.4.1 GENERAL SET UP AND PROCEDURE

Four type of test were made with each specimen: control, wind, covered humidity (Humidity V1) and uncovered humidity (Humidity V2). Before explaining the four type of tests, general set up and procedure will be described because it is the same for all type of tests.

First of all, equipment was set up inside the glass container as shown in Figure 10, except the halogen lamp which was be introduced after the specimen, as it is placed on top of it. Secondly, the specimen was prepared with the setup of the thermocouples as it was explained on the equipment section. After this, the specimen is introduced and then, the rings are placed on the marks to calibrate the cursors. When the cursors are correctly calibrated, the initial surface temperatures of those points are taken. Then, the test is ready to start and a type of test is carried out.

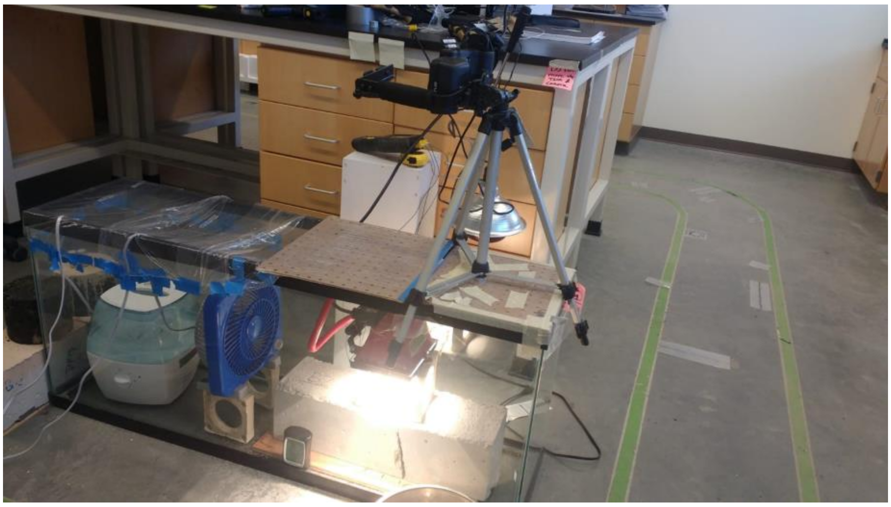


Figure 10: Test in process

Regarding variable readings, thermocouple temperatures, air temperature and humidity are noted down every ten minutes both during heating and cooling. However, there is an exception; in the first 10 minutes of heating and the first 10 minutes of cooling those variables are read every minute and this is because they will vary faster as a change has been introduced. All these variables are noted down on an Excel sheet.

13.4.2 CONTROL TEST

Control Test was carried out by heating the concrete block with a halogen lamp for two hours. When the heating period had concluded the halogen lamp was turned off and in that moment the IRT camera started recording the cooling process for a period of two hours. Control test aims to simulate a sunny day.

13.4.3 WIND TEST

Wind Test was carried out by heating the concrete block with an halogen lamp, but continuously being ventilated by a fan, both during heating and cooling. When the heating period had concluded (2 hours) the halogen lamp was turned off (but not the fan) and in that moment the IRT camera started recording the cooling process for a period of two hours. Wind test aims to simulate a windy day.

13.3.4 HUMIDITY TEST V1 (COVERED)

In this case, before the heating process started, the humidifier was turned on for one hour. After one hour of humidity the specimen was heated for two hours and when the heating period had concluded the halogen lamp was turned off. In that moment the IRT camera started recording the cooling process for a period of two hours. The humidity was being kept between 80-85% during the whole test. In case the humidity exceeded 85% the humidifier was disconnected until it reached again the desired range.

In this test, during the cooling process the camera did not continuously record the temperatures of the surface; it only recorded them every five minutes during the first ten minutes of cooling and then every 10 minutes the rest of the two hours of cooling. The glass container remained covered and occasionally was instantaneously uncovered to make a temperature reading. This means that high humidity was kept inside the glass container during cooling which is what we desired to simulate high humidity conditions. Humidity test aims to simulate a rainy day.

13.4.5 HUMIDITY TEST V2 (UNCOVERED)

In this case, before the heating process started, the humidifier was turned on for one hour. After one hour of humidity the specimen was heated for two hours and when the heating period had concluded the halogen lamp was turned off. In that moment the IRT camera started recording the cooling process for a period of two hours. The humidity was being kept between 80-85% during the whole test. In case the humidity exceeded 85% the humidifier was disconnected until it reached again the desired range.

In this test, during the cooling process the camera was continuously recording the temperatures of the surface; therefore the glass container had to remain uncovered, which means a constant loss of humidity. This was an undesired situation as high humidity is needed to simulate humidity conditions and to differ from the control test. This test did not have a high humidity like the other test, but it has an intermediate humidity. Humidity test aims to simulate a rainy day.

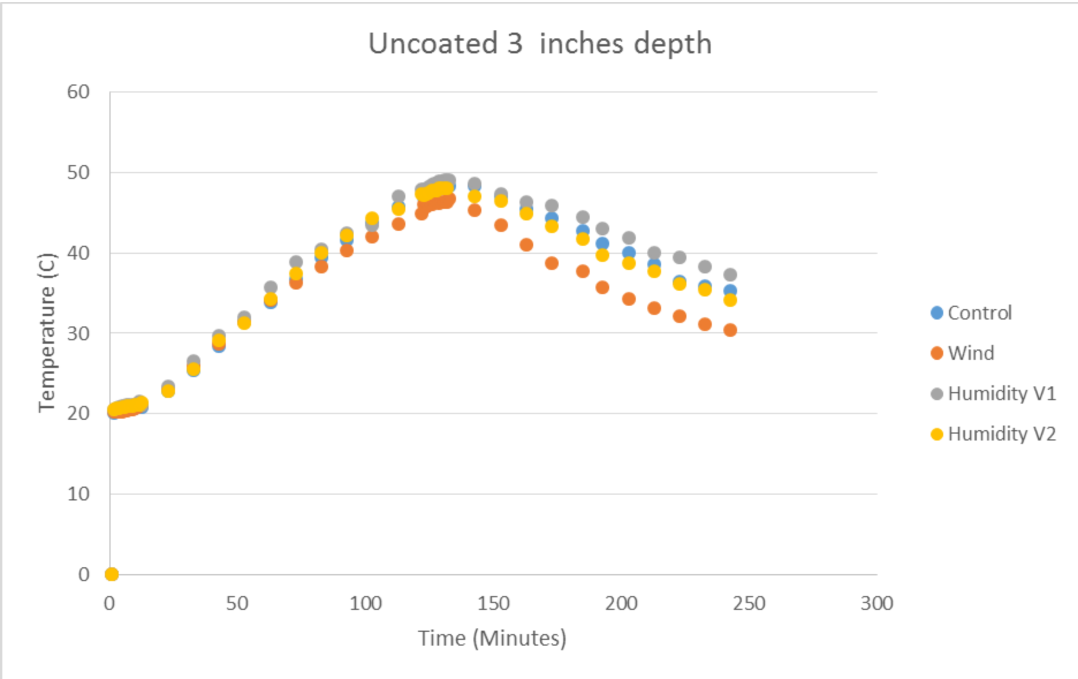
14. RESULTS

In this section data and measures obtained in the lab are plotted and analyzed in order to obtain results.

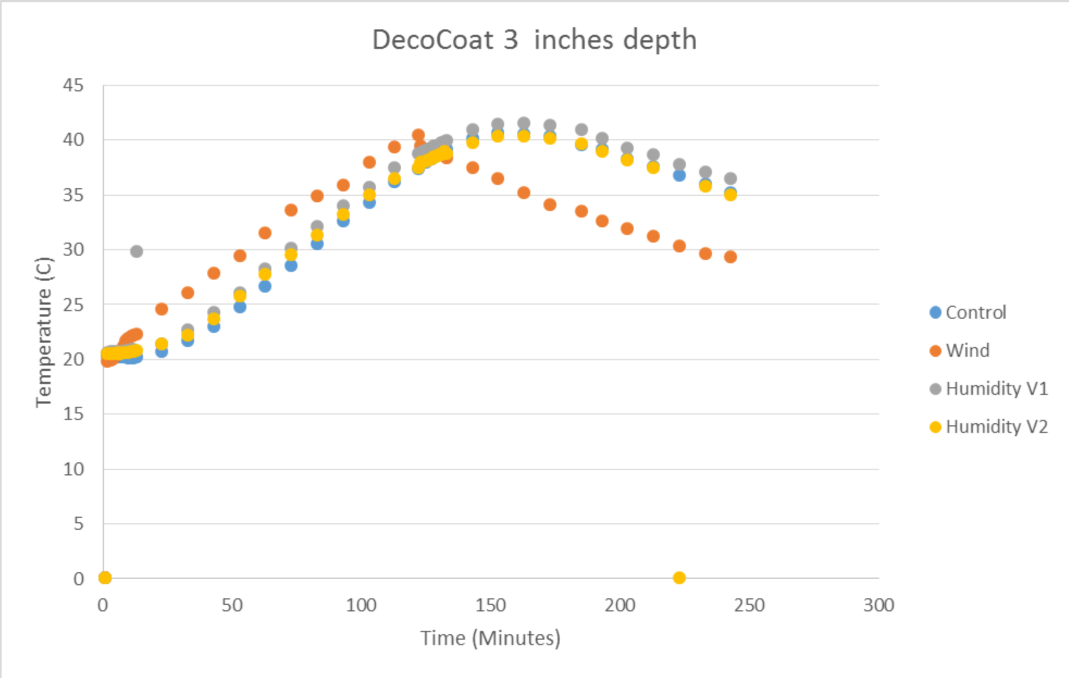
14.1 COMPARISONS BETWEEN DIFFERENT CLIMATE CONDITIONS

In this graphs the different climate conditions are analyzed. The four different colors represent the four different tests that have been carried out on each specimen. (See legend on the right side of graphs). In the graph both heating (120 minutes) and cooling are represented (120 minutes) and both stages are clearly defined by the slopes of the graphs.

Evaluating data for the three thermocouples would have been time-consuming and would overload this project. Therefore, all the data used for the graphs of this section has been taken from the readings of the thermocouple located at 3 inches depth, which is the one that is located in the middle, thus it can be more representative than the other ones. The aim of this very first section is not to compare data between the two different concrete samples, but to compare data between the different climate conditions (control, humid, humidity V1 and humidity V2). Future sections will compare the specimens.



Graph 1: Uncoated 3 inches depth



Graph 2: DecoCoat 3 inches depth

First of all, during cooling process the wind curve is the one that has the deepest slope of the four climate conditions for both graphs, which means that heat dissipation rate is higher than the other curves. This is due to the wind capacity to reduce the ambient temperature through ventilation, which causes faster heat dissipation in the crack, reducing its temperature much faster than the other test. This is because both systems (ambient and crack) are in thermal equilibrium, therefore if the ambient temperature is reduced, more heat from the crack will be released to the ambient causing a temperature reduction in the crack.

In humid conditions (humid test V1 and V2), during the cooling process the heat dissipation inside the crack is lower compared to the other tests, therefore it is observed in the graph that for the humidity tests the temperature during cooling keeps always higher than the other tests. This is very noticeable for Humidity V1. However, in the case of Humidity V2, the graph during cooling is almost similar to the control test, which means that the heat dissipation rate is very similar to the control test. This is due to the test procedure and the impossibility to maintain the desired humidity.

On the one hand, as it has been explained before, humidity V2 test remains uncovered during the whole cooling process in order to allow the camera to read surface temperature, which means a significant continuous loss of humidity. On the other hand, the test humidity V1 remains covered maintaining the desired humidity of 75-85%. This humidity difference of V1 and V2 will be greatly appreciated in the humidity graphs that will be presented later.

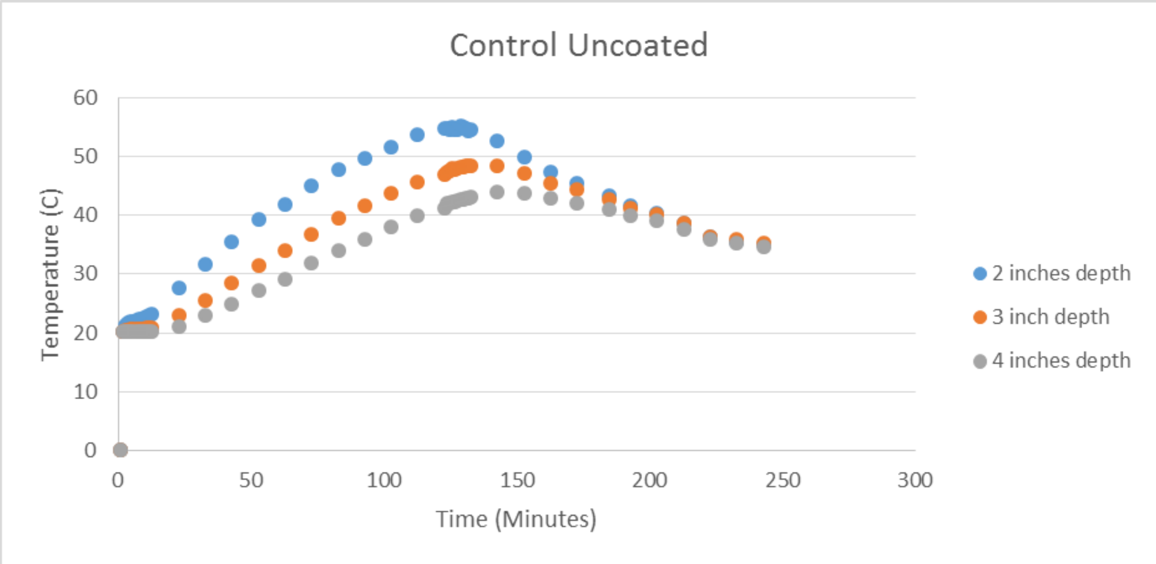
This low rate heat dissipation in high humidity conditions is produced because the differences of specific heat capacities between air and water. Whereas the specific heat capacity of air is 930 J/ kg C, the one of the water is 4186 J/ kg C, which is much higher. The specific heat is defined as the amount of heat that must be supplied to the mass unit of a thermodynamic substance or system to raise its temperature by one unit. Therefore, in the humid case inside the crack, the water content in the air is very high, which means, according to the previous definition more energy is needed to cool down the system.

Regarding the heating process, for the uncoated specimen the three curves seem very similar. However for the coated one, the wind test heats up faster than the other type of climate conditions and in a very linear way. This could be probably because in windy conditions the coating reduces the heat that is absorbed by the concrete, therefore more heat is retained in the crack which has no coating and can absorb heat more easily.

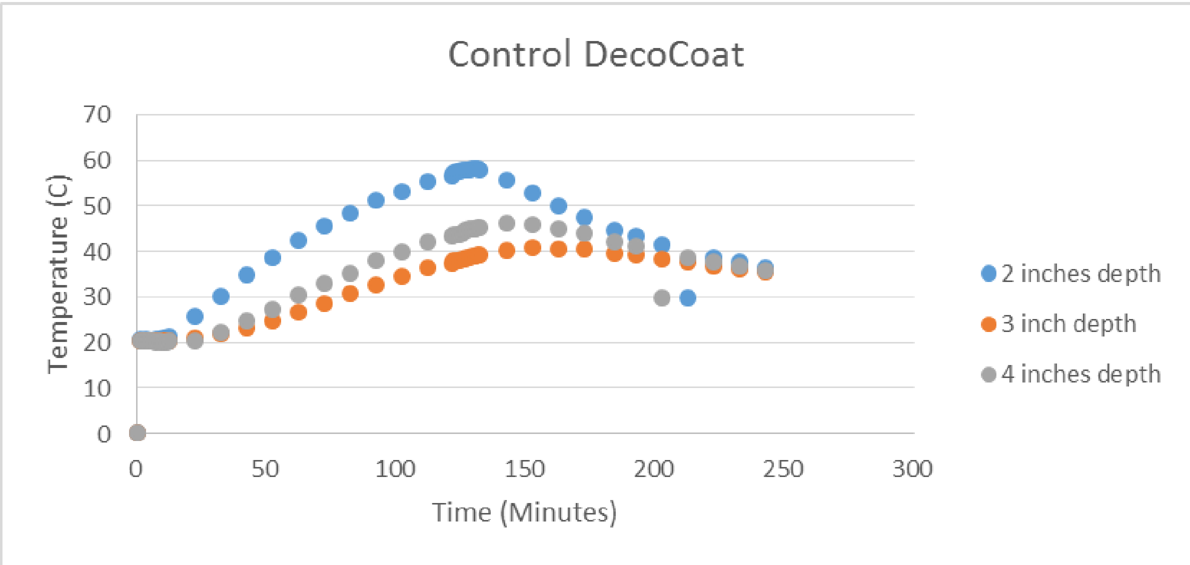
14.2 COMPARISONS BETWEEN DIFFERENT DEPTHS INSIDE THE CRACK

In this section a comparison between temperatures at different depths inside the crack is studied. As it has been mentioned earlier, the depth is measured from the top of the concrete block. The 2 inches depth is presented blue colour, the 3 inches depth in orange colour and 4 inches depth in grey (See legend). As the past section, in this section it is not intended yet to compare different type of specimens, it will be only compared how the experiment affects to the different depths of the concrete crack.

14.2.1 CONTROL



Graph 3: Control Uncoated



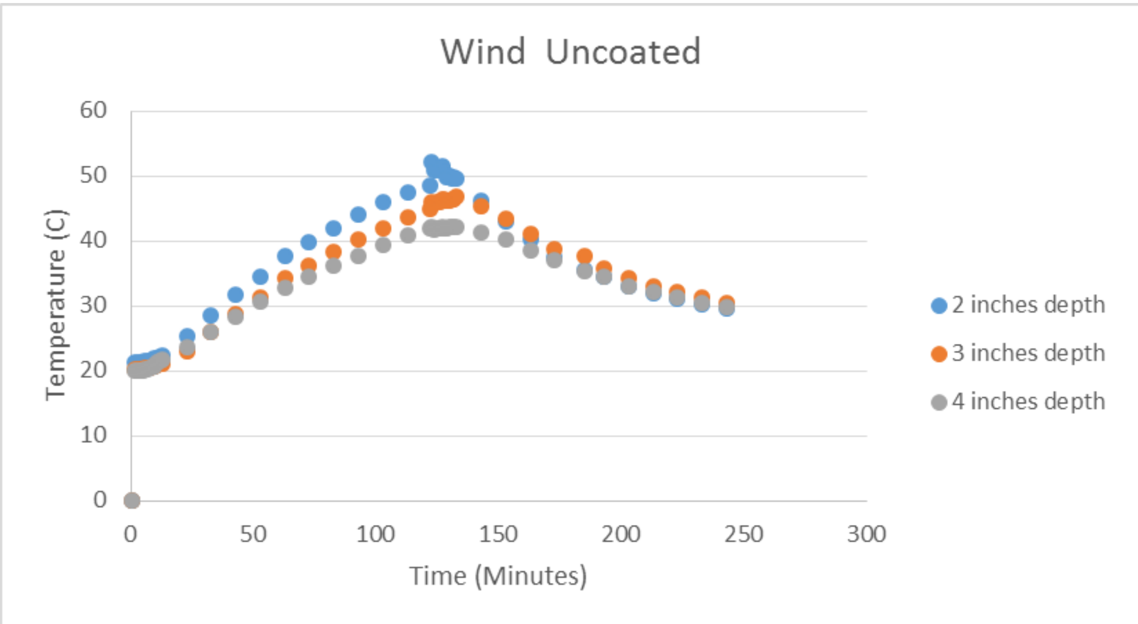
Graph 4: Control DecoCoat

In this graphs we can see the results of the control test. It can be observed in both graphs that during the heating process, the top edge of the crack (2 inches depth) has a higher temperature than the others (3 inches depth and 4 inches depth). The 2 inches curve has a more marked slope than the other two. This is because the thermocouple located at 2 inches depth is closer to the heating source than the other two thermocouples. By logic, it can be inferred that the thermocouple located the furthest from the heating source (4 inches depth) will have the lowest temperature during the whole heating process. This hypothesis is fulfilled by the uncoated specimen.

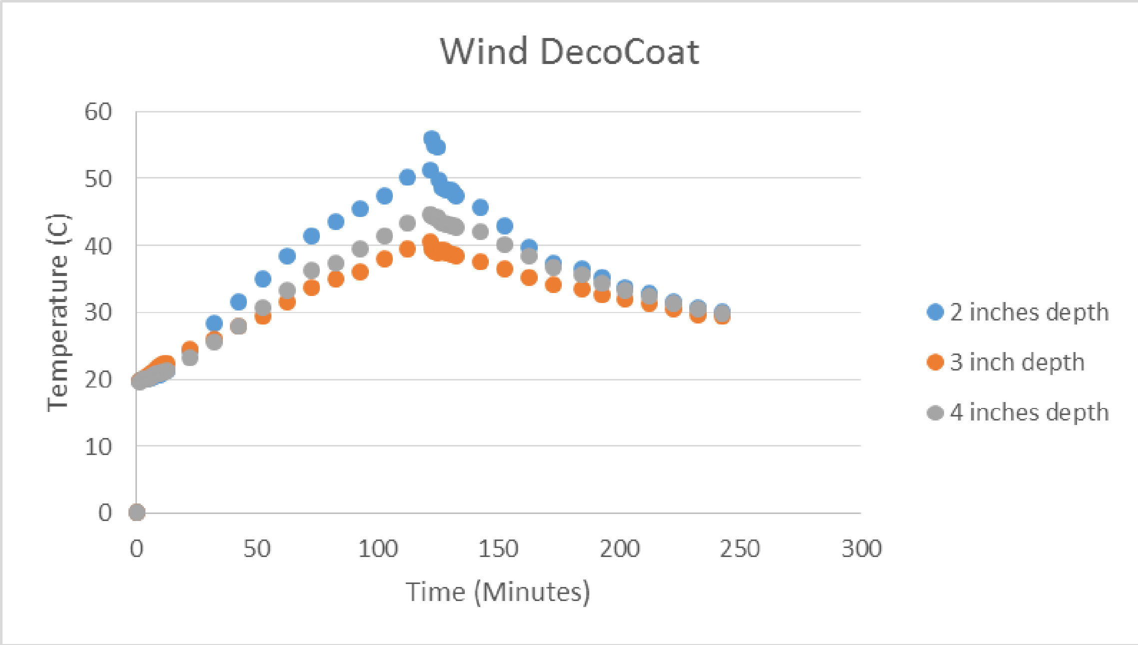
However, for the DecoCoat coating specimen, it can be seen in the graph that the one located in the middle (3 inches depth) is the one with the lower temperature during the entire heating process. This may not seem logical, but it is because the wall of the crack is not a smooth wall, but has protrusions (the aggregates). Just above the thermocouple located 3 inches deep, a piece of rock is found, which protects the sensor of that thermocouple from the heat source, and consequently a decrease in temperature is appreciated.

Regarding the cooling process, the thermocouple located at 2 inches depth has the fastest cooling speed. This is because this one is the closest to the concrete surface; therefore it can release heat to the ambient air in an easier way than the other ones.

14.2.2 WIND



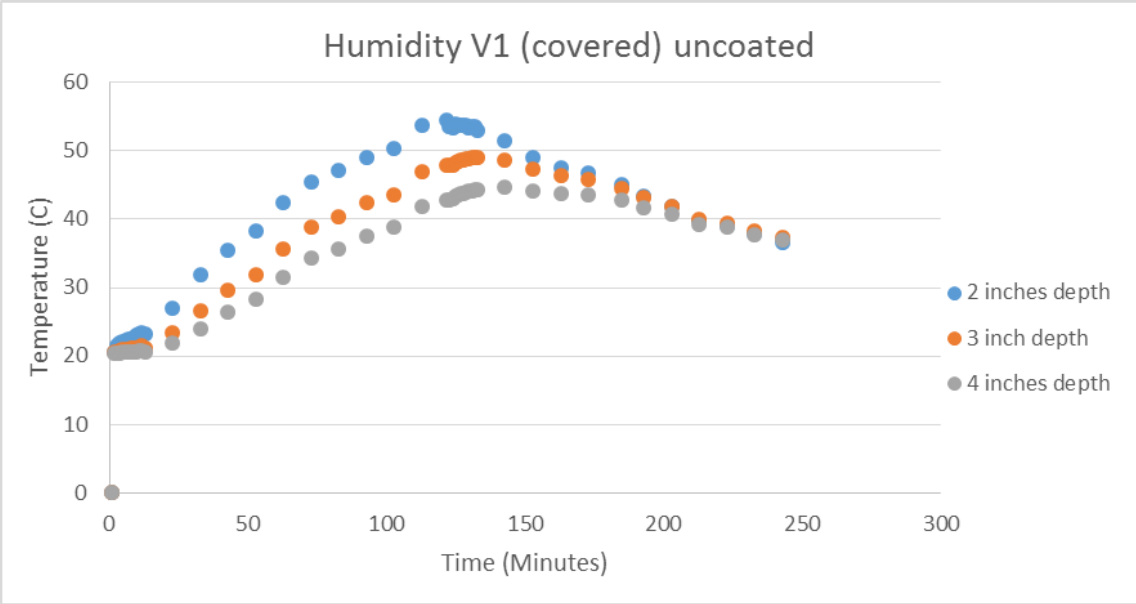
Graph 5: Wind Uncoated



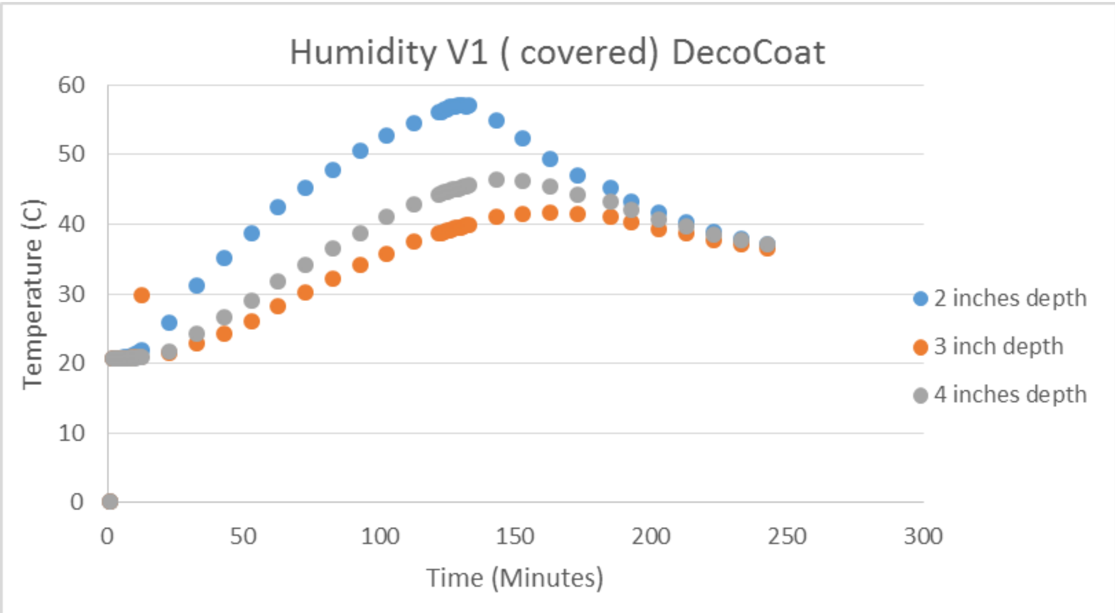
Graph 6: Wind DecoCoat

In this section the wind graphs are plotted. At first glance, it can be seen that during the heating process, now the difference between 2 inches curve and the other curves is not as noticeable as the control case. This means that, even being the closest thermocouple to the heat source, it is being continuously ventilated by the fan, which produces a remarkable decrease of temperature. This, along with an almost lack of ventilation for the thermocouples located at 3 and 4 inches depth make the three curves (2, 3, 4 inches) more similar to each other compared to the control case.

14.2.3 HUMIDITY



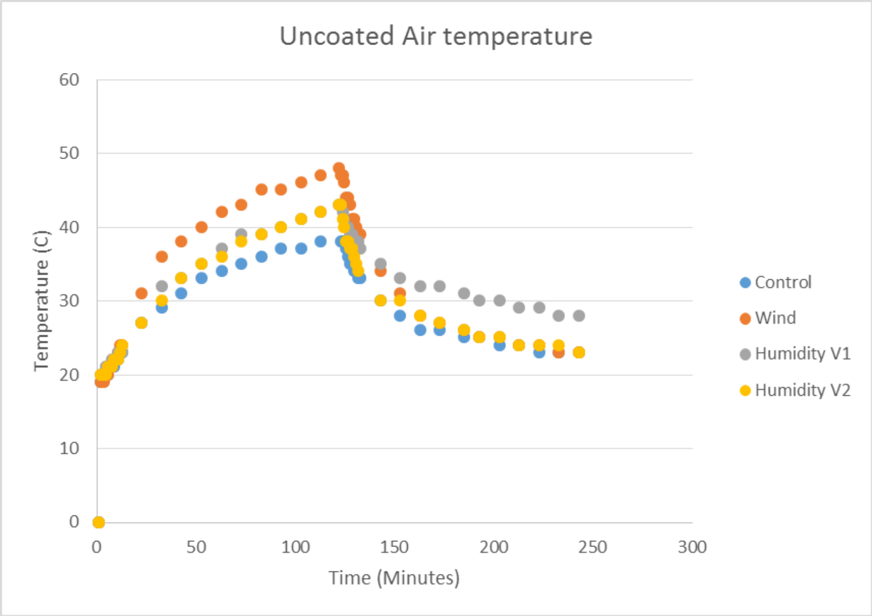
Graph 7: Humidity V1 Uncoated



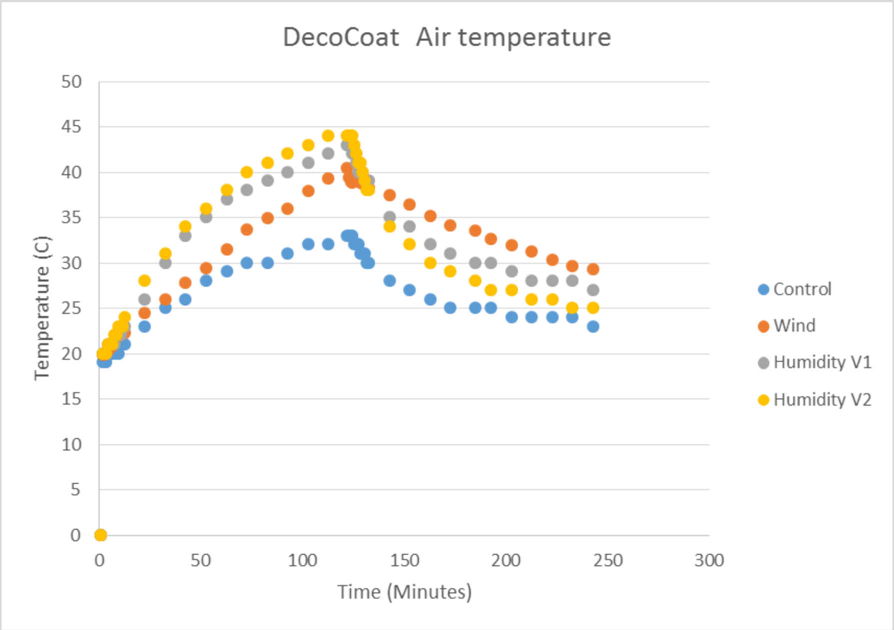
Graph 8: Humidity V2 DecoCoat

In this graphs we can see for the entire humidity test the comparisons for the thermocouples located at different depths. Only humidity V1 will be studied, where the humidity is kept high. From this graph it should be mentioned that for the coated specimen the 2 inches depth thermocouples has a significant higher temperature. This may be because the already explained reason. The coating reduces the heat absorption of the concrete and increases the heat of closest thermocouple from the surface, which is the 2 inches depth one.

14.2.4 AIR TEMPERATURE



Graph 9: Uncoated Air Temperature

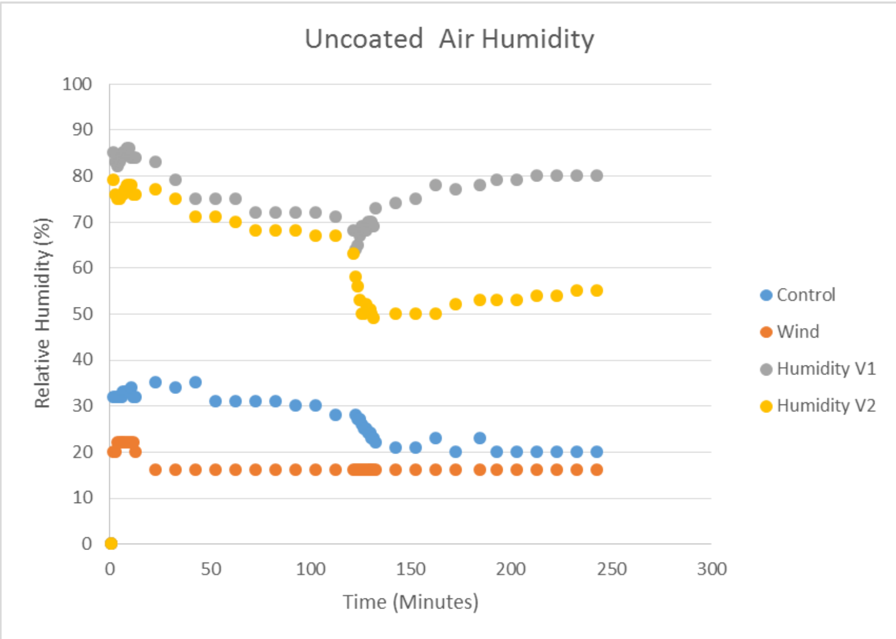


Graph 10: DecoCoat Air temperature

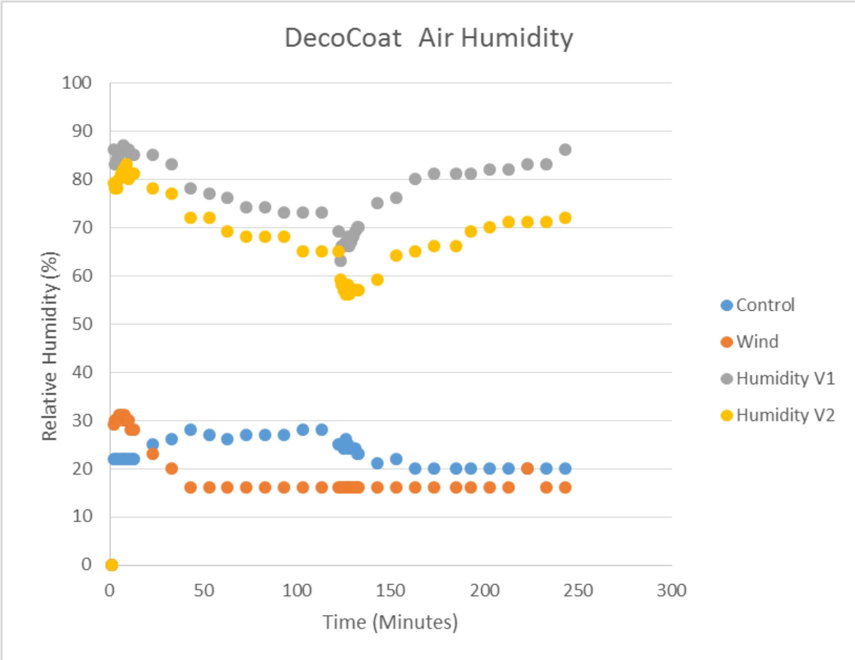
As it can be seen on the uncoated specimen graph during the cooling process, for humidity V1 (75-85% of relative humidity) the ambient air heat dissipation rate is slower. The slope of humidity V1 is less steep than the rest of the curves. As showed in the following graph, control and wind graphs have a humidity of around 20% during cooling, whereas humidity V2 is between 50-55%.

However, this does not seem to affect the ambient air temperature for humidity V2 during the cooling. Therefore, it seems that this slower heat dissipation rate of ambient air heat produce by high humidity is only given when the ambient humidity is exceeding a certain value around 70%.

14.2.5 AIR HUMIDITY



Graph 11: Uncoated Air Humidity



Graph 12: DecoCoat Air humidity

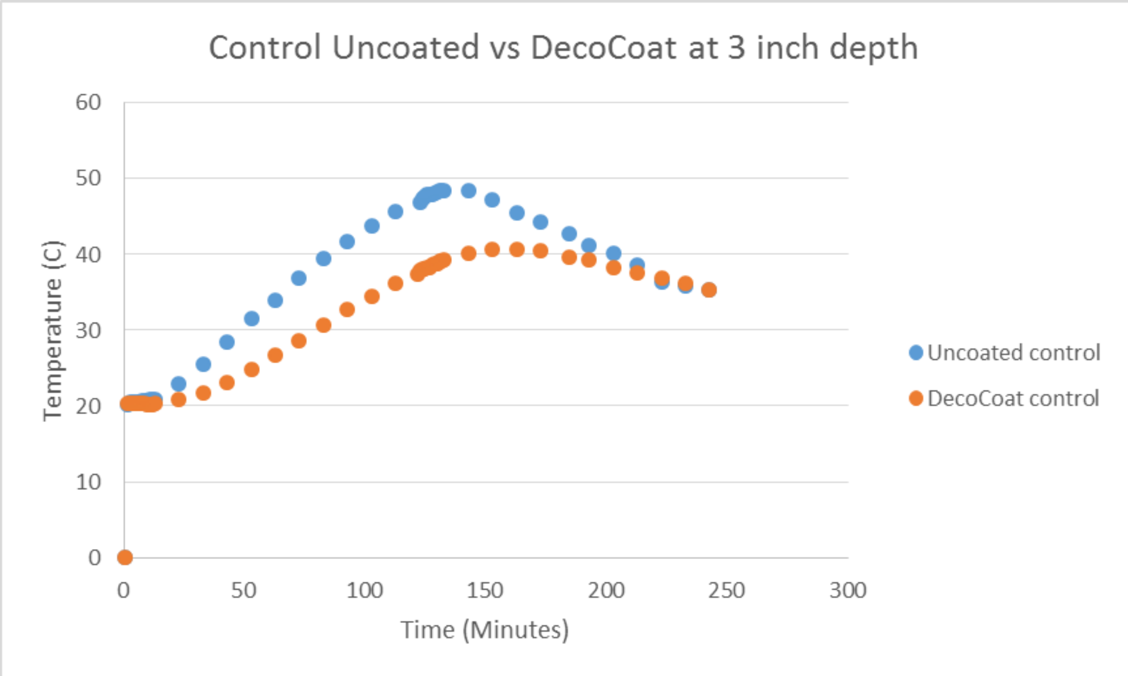
If we study now air humidity it should be mentioned that as it was said before there is a significant difference between both humidity versions during the cooling process. For both different samples humidity V1 has a high humidity whereas humidity V2 has an intermediate humidity. Regarding control and wind test, they have a similar humidity of around 20%. Wind test has a slightly less humidity than control one because the fan tends to dry and expel the humidity out of the system.

Now that this effect has been mentioned it should be added that at the beginning another climate condition was introduced. It consisted of a wind and humidity test using both the fan and humidifier at the same time. The purpose of this test series was to simulate a rainy and windy day. However, this test did not work as expected because the wind was expelling all the humidity and the results were the same as if the test that was performed was a wind test.

14.3 COMPARISON BETWEEN SPECIMENS

In this section we will compare the two specimens for each type of test; therefore we can analyze how the different specimens behave in the same climate conditions. Note that the uncoated curves will be presented in blue color and the coated ones in orange colour.

14.3.1 CONTROL TEST

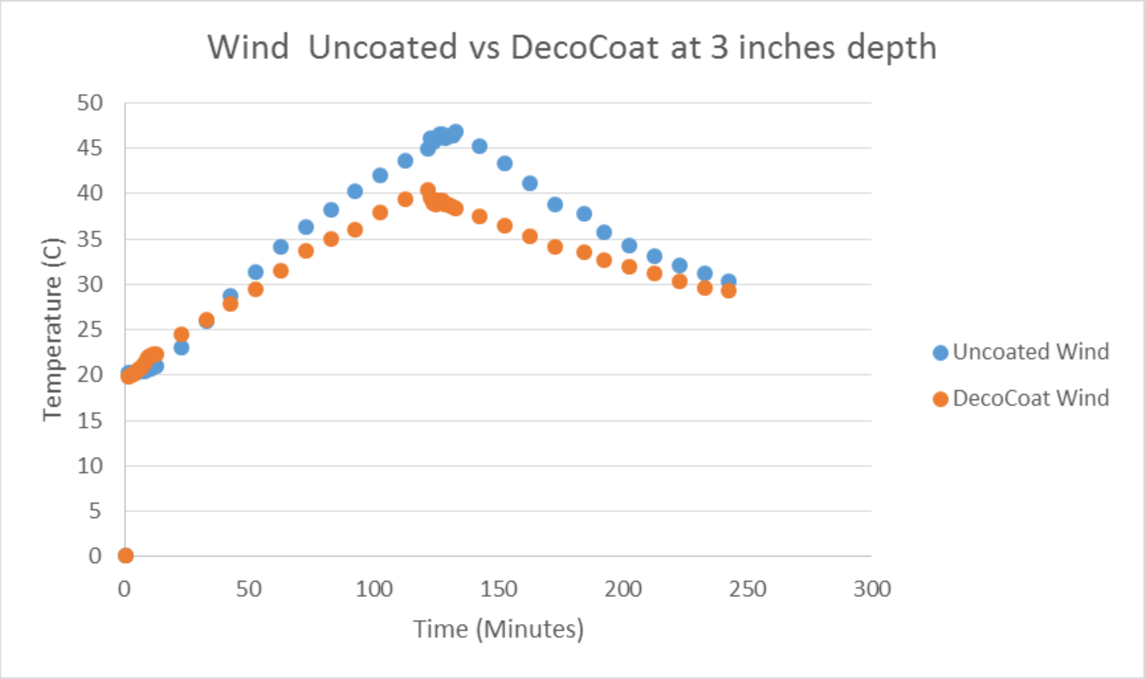


Graph 13: Control Uncoated vs. DecoCoat at 3 inches depth

The control graph is shown. We can observe that whereas for the uncoated specimen the maximum temperature that is reached at 3 inches depth is almost 50 °C, for the coated specimen it is around 40°C. Therefore, a high temperature difference exists during the whole heating process which makes bigger when time passes. This means that the coating reduces the temperature of the crack.

Besides, it should also be mentioned that the coated sample crack has a very low cooling rate compared to the fast cooling rate of the uncoated sample crack. The latter, even being 10°C higher at the end of the heating process, it reaches a slightly lower temperature than the coated specimen crack, which denotes a significant cooling rate. The final temperature for both is around 30°C.

14.3.2 WIND TEST



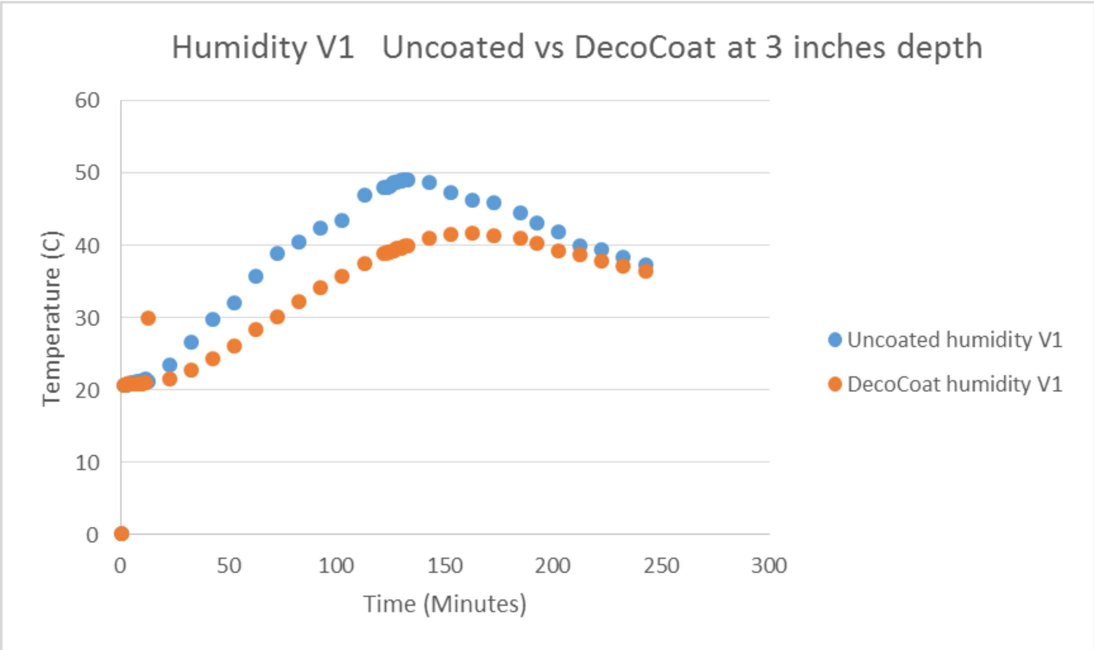
Graph 14: Wind Uncoated vs. DecoCoat at 3 inches depth

In this case the wind graph for the uncoated and coated block is shown. For the uncoated specimen crack, the highest temperature is around 47 °C, but for the coated one around 41 °C. In this case, the temperature difference between the two cracks is slightly lesser than before.

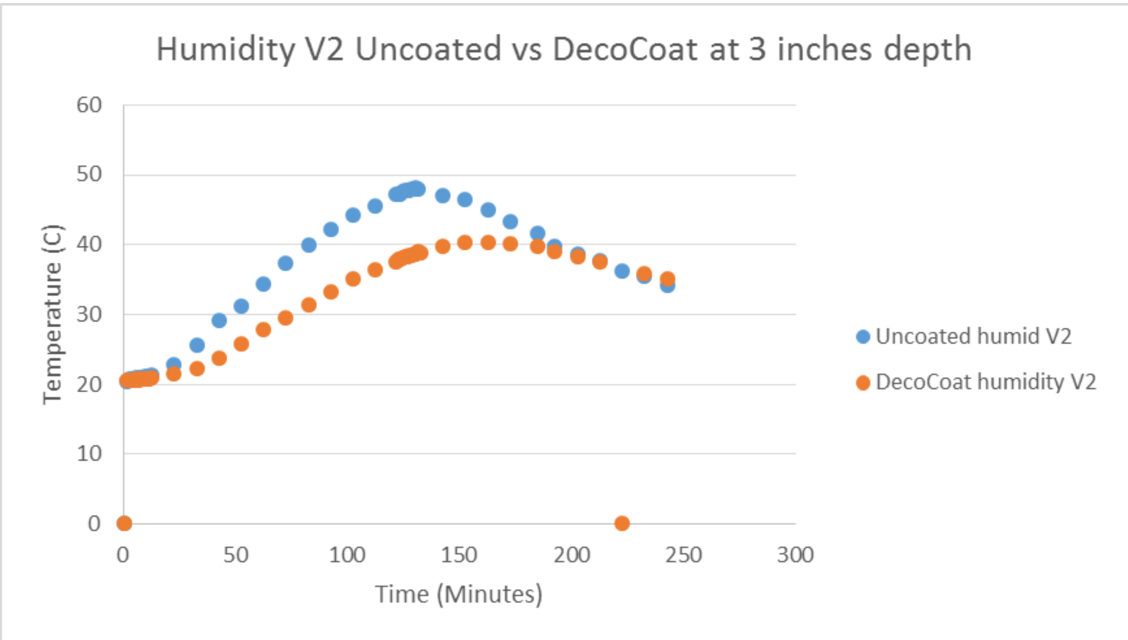
It could also be remarkable, that at the beginning of the heating process (for the first 30 minutes) the temperature of the coated sample crack is higher than the uncoated one, but after, the situation is brought back to the expected situation. This produces an intersection between the two curves during the heating process. This unusual initial behavior did not occur on the control graph and is probably related to the wind produced by the fan.

It could be due to the difference in the shape of the cracks of coated and uncoated blocks, which can allow more or less ventilation inside, thus increasing or decreasing temperature respectively. In this case it seems that the uncoated sample crack is slightly more ventilated than the coated one producing this anomaly. But it is not a representative behavior, because by continuing the process, we return to the expected situation.

14.3.3 HUMIDITY TEST



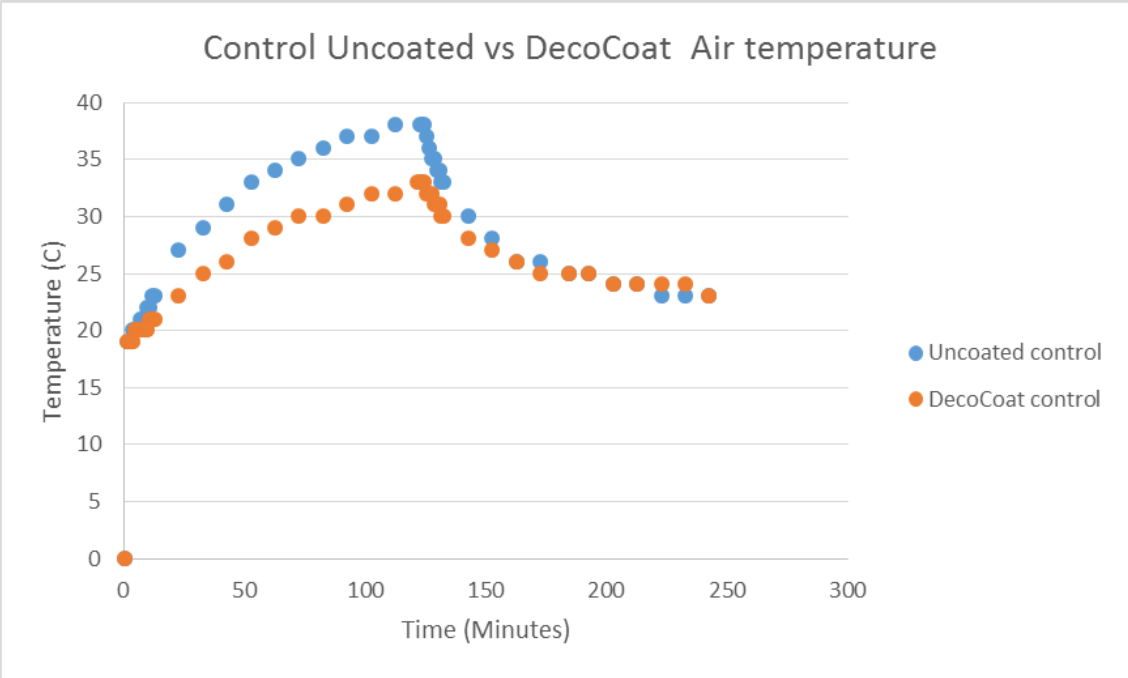
Graph 15: Humidity V1 Uncoated vs. DecoCoat at 3 inches depth



Graph 16: Humidity V2 Uncoated vs. DecoCoat at 3 inches depth

In these two graphs, we can see the comparison of the humidity test for both samples. We can see that the maximum temperature reached by the uncoated sample crack is around 50 °C and for the coated one is 40 °C. It can be observed that throughout the test, the behaviour of the curves is very similar to the explained for the control test.

14.3.4 CONTROL TEST AIR TEMPERATURE

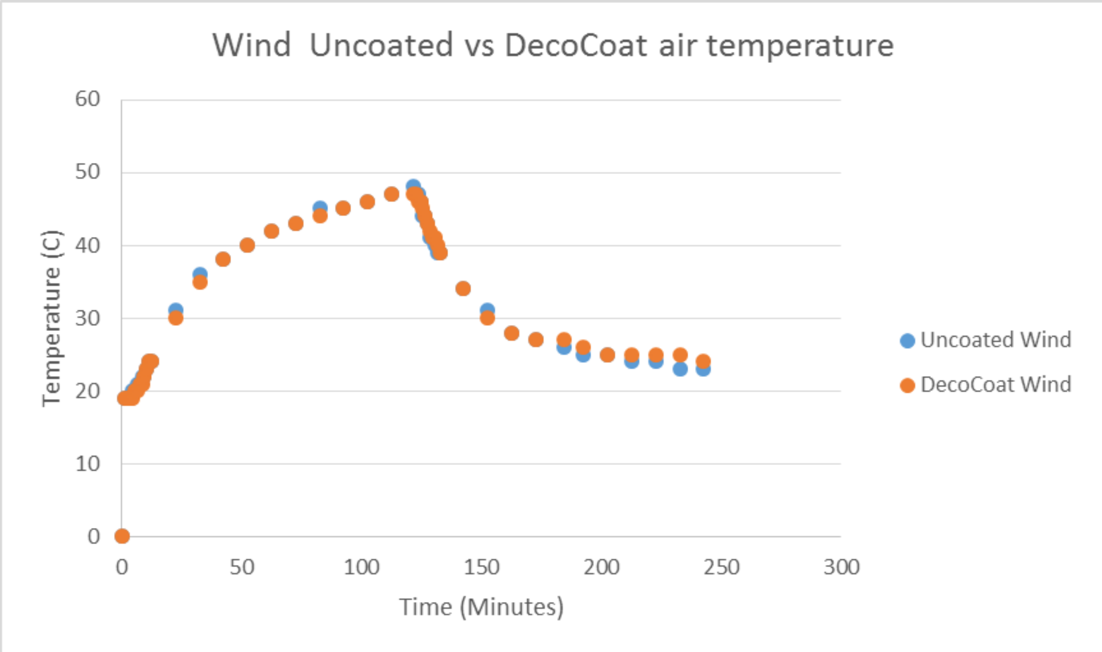


Graph 17: Control Uncoated vs. DecoCoat Air temperature

Regarding air temperature during the control test, it can be observed that during the heating process the air temperature is much higher for the uncoated experiment than for the coated one. The former generates a maximum air temperature of 38 °C, whereas the latter generates a maximum air temperature of 33°C.

As it was said by DecoCoat's manufacturer a reduction of the urban heat island effect exists by using this product, and a considerably air temperature reduction occurs (5°C). However, the uncoated experiment has a faster cooling rate and it reaches faster than the coated experiment to a lower temperature by the end of the test. This means that the coat does help to avoid reaching high temperatures but it has no effect on the cooling rate, thus it is not helpful for increasing the cooling speed.

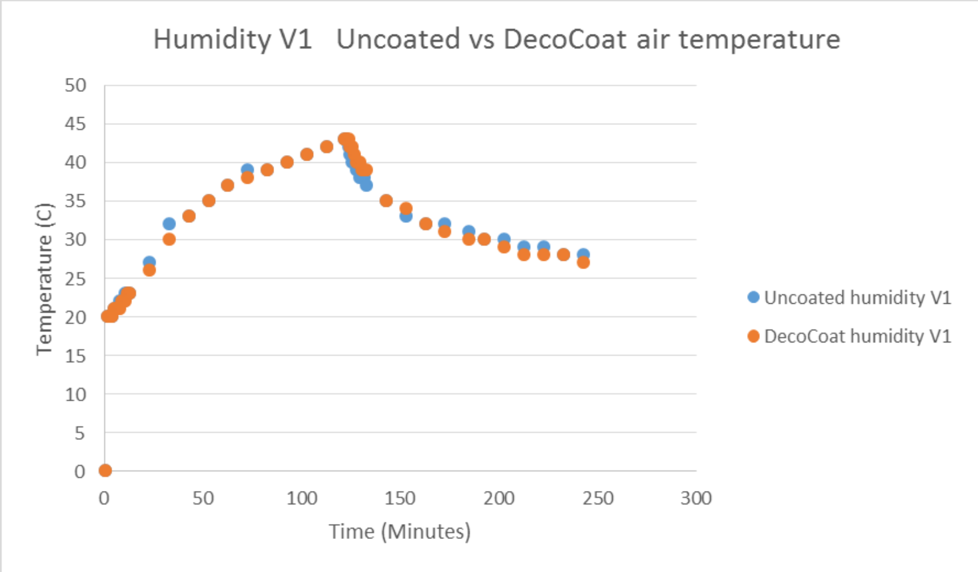
14.3.5 WIND TEST AIR TEMPERATURE



Graph 18: Wind Uncoated vs. DecoCoat Air temperature

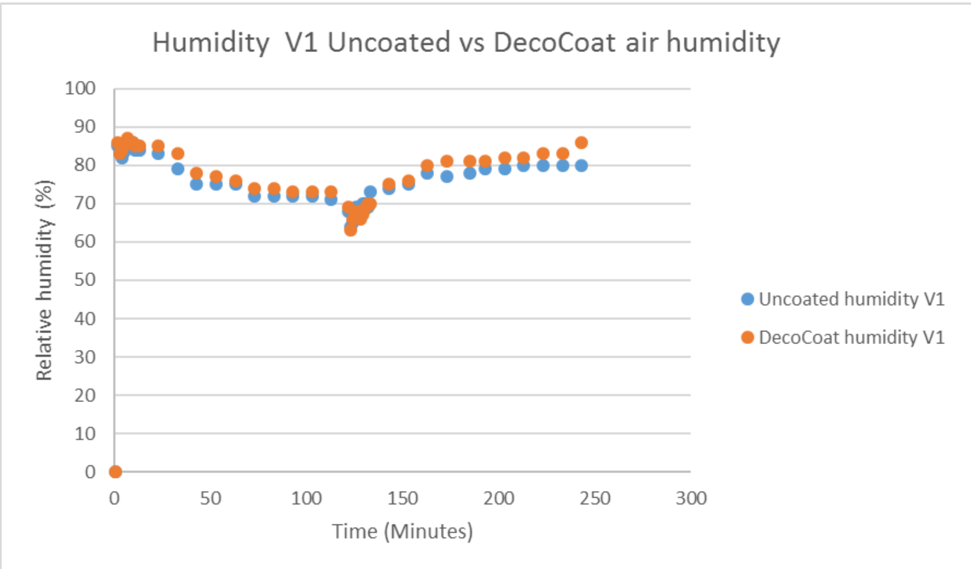
For the wind test, it can be appreciated that there are not significant differences between the air temperature for the coated and uncoated samples. If we extrapolate this result to the outdoors, it will mean that in windy days this type of coating will probably not be useful for reducing the ambient air temperature of the surrounding, thus it cannot prevent urban heat island effect.

14.3.6 HUMIDITY TEST AIR TEMPERATURE

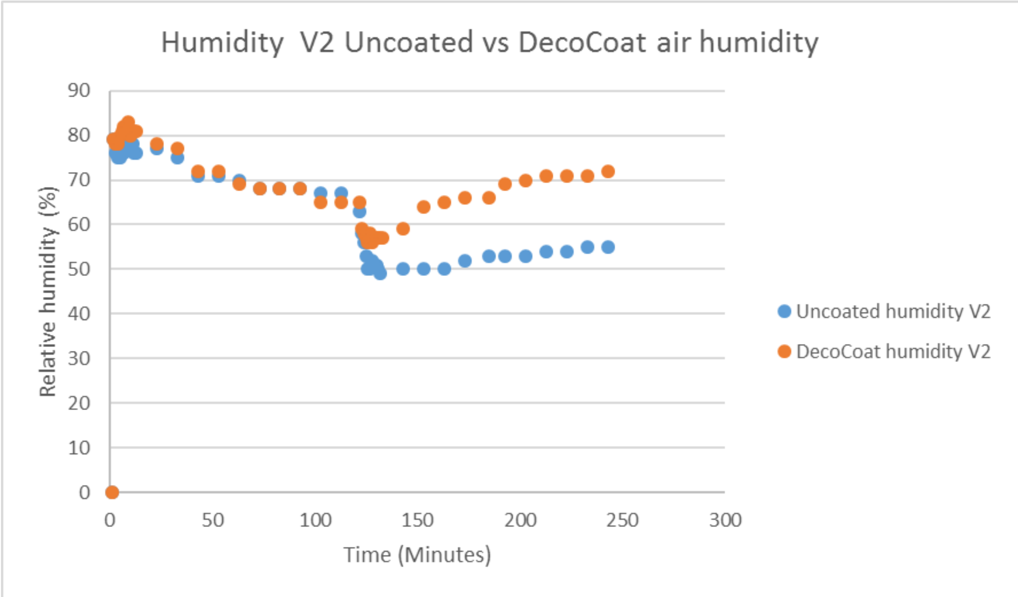


Graph 19: Humidity V1 Uncoated vs. DecoCoat Air temperature

If we analyze this graph we can observe that there are no significant differences between the air temperature of the uncoated and coated specimens. Observing these results, this coating is not very useful for high humidity days as it won't help reducing the air temperature.



Graph 20: Humidity V1 Uncoated vs. DecoCoat Air Humidity



Graph 21: Humidity V2 Uncoated vs. DecoCoat Air Humidity

It can be appreciated that for humidity V1 (high humidity test) no differences are appreciated on air humidity for both different samples. However, for humidity V2 (intermediate humidity test) the air humidity differences during the cooling process are very significant, about 15% more relative humidity for the DecoCoat specimen's ambient air humidity.

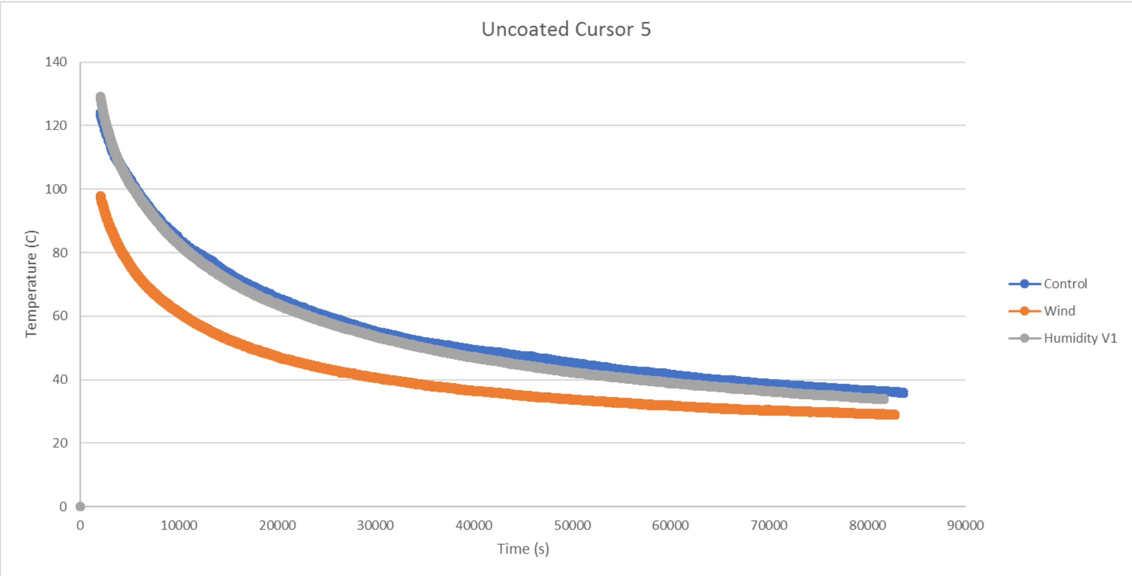
It seems that for intermediate humilities (about 50-70%) the concrete is able to absorb the humidity released by the humidifier, thus reduces the ambient air humidity. However, the DecoCoat coating acts as a barrier for humidity absorption of concrete, and this humidity is kept in the ambient increasing then the ambient air humidity.

In low humidity case, for example in the control test, there are no differences appreciated on air humidity of both different samples as there is no almost humidity that can be absorbed. On the other hand, in high humidity conditions and with the system being covered, even if the uncoated sample absorbs humidity, humidity is continuously being produced and there is a limit when the humidity absorption rate will be so low that becomes insignificant. Therefore, both graphs look very similar as we can see in Graph 20.

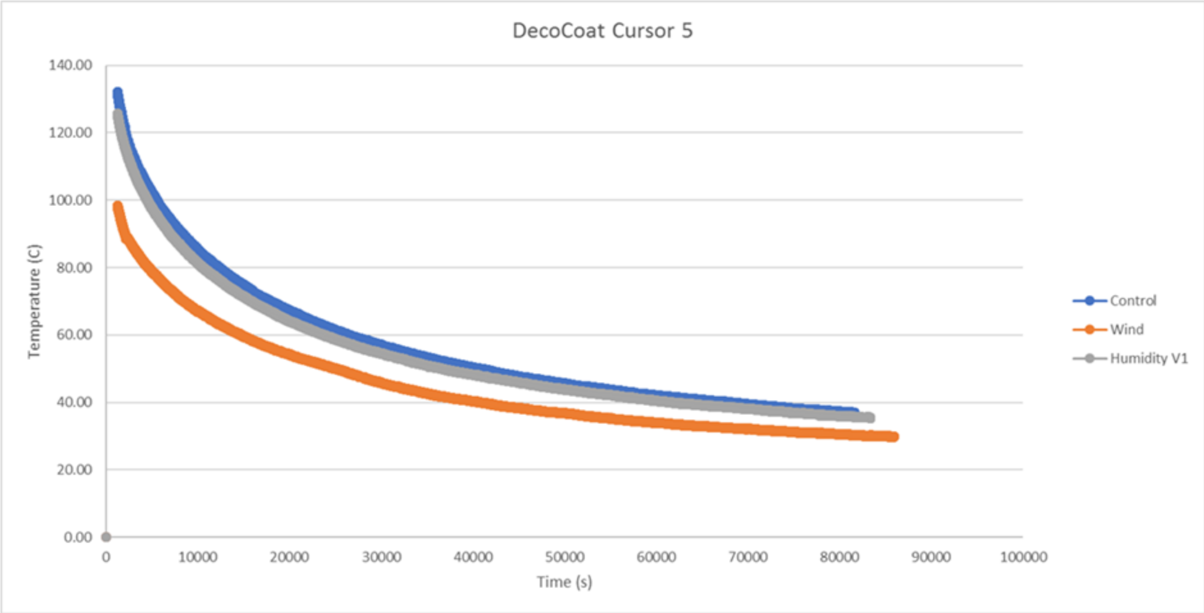
14.4 SURFACE TEMPERATURES FOR UNCOATED TEST

In this section the surface temperatures of the uncoated block will be studied. As it was explained before, this surface temperature is read by the infrared camera and of the nine temperature points that were measured, only cursor 5 will be measured which is situated in the middle of all measured points, thus it could be more representative (See Figure 9).

The following graphs are different from the previous ones, in the sense that the heating process is not being recorded, but only the cooling process. This is because during the heating process the heating source is between the camera and the surface of the block, thus an obstacle exists between the recording apparatus and the recorded surface, preventing the camera from reading the desired temperature.



Graph 22: Surface temperature: Uncoated cursor 5



Graph 23: Surface temperature: DecoCoat cursor 5

First of all, it can be seen that each curve starts in a different temperature on both graphs. This is because this initial point is the end of the heating process. Wind starts around a surface temperature of 100 °C, control around 125°C and humidity around 130°C.

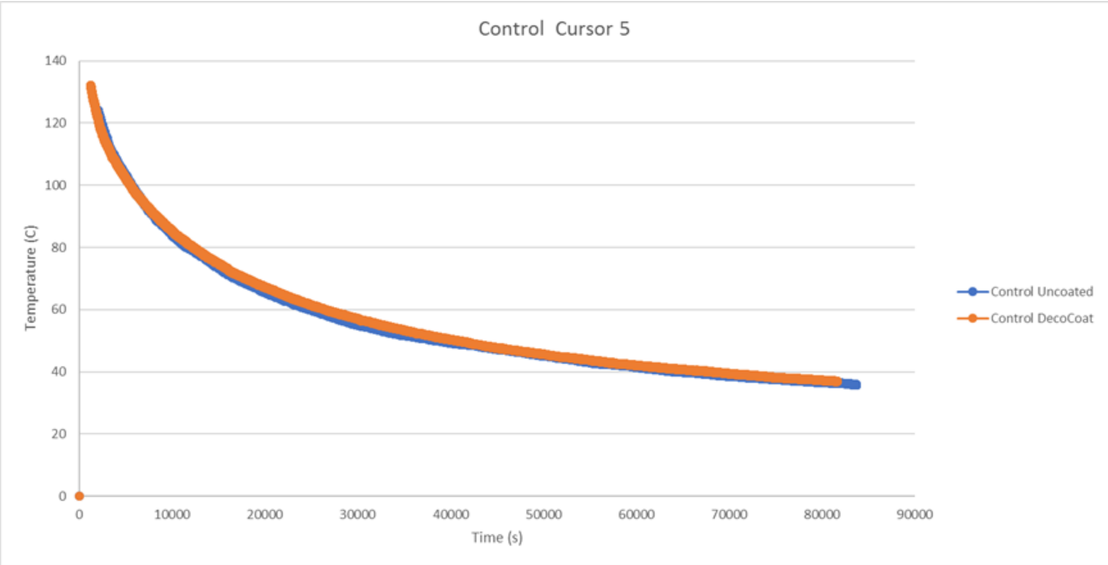
The cooling rate is very similar for control and humidity curves but the wind curve slightly differs from the other ones. It is displaced down because of its initial temperature, and also its cooling rate is a bit faster at the beginning of the cooling, but then it gets slower than the other curves.

Regarding the uncoated graph, probably if the recorded will have been longer, an intersection will occur. This means that generally speaking, for the whole cooling process the cooling rate is higher for the control and humidity. It can be proven because in the beginning we have a difference of 25 °C and in the end of the cooling process only a difference of about 10°C.

For the uncoated graph this intersection does not seem to occur, but also during the entire cooling process the cooling rate is higher for control and humidity curves.

14.5 COMPARISON OF SURFACE TEMPERATURES BETWEEN BOTH SPECIMENS

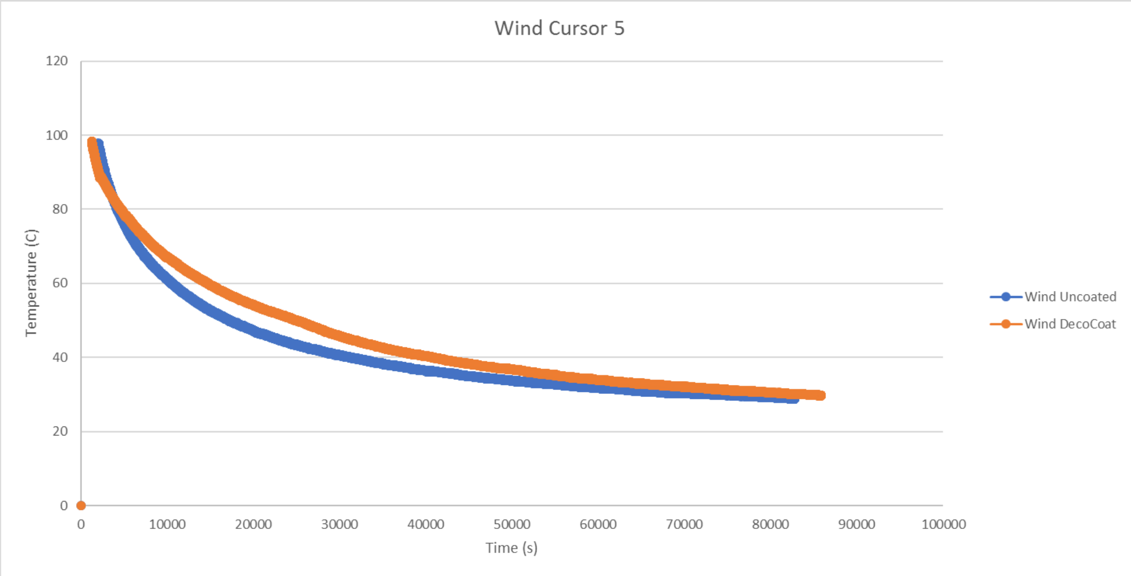
14.5.1 CONTROL



Graph 24: Surface temperature: Control cursor 5

Regarding the control test it can be seen that both curves have a very similar pattern and there are no differences between them. The only relevant difference is the initial surface temperature which is higher for the DecoCoat (136 °C) than for the uncoated (128°C). This means that the coating produces a higher surface temperature than the uncoated sample, about 8 °C more. This is not positive if we want to maintain the surface temperature as low as possible in order to extend the life cycle of the concrete.

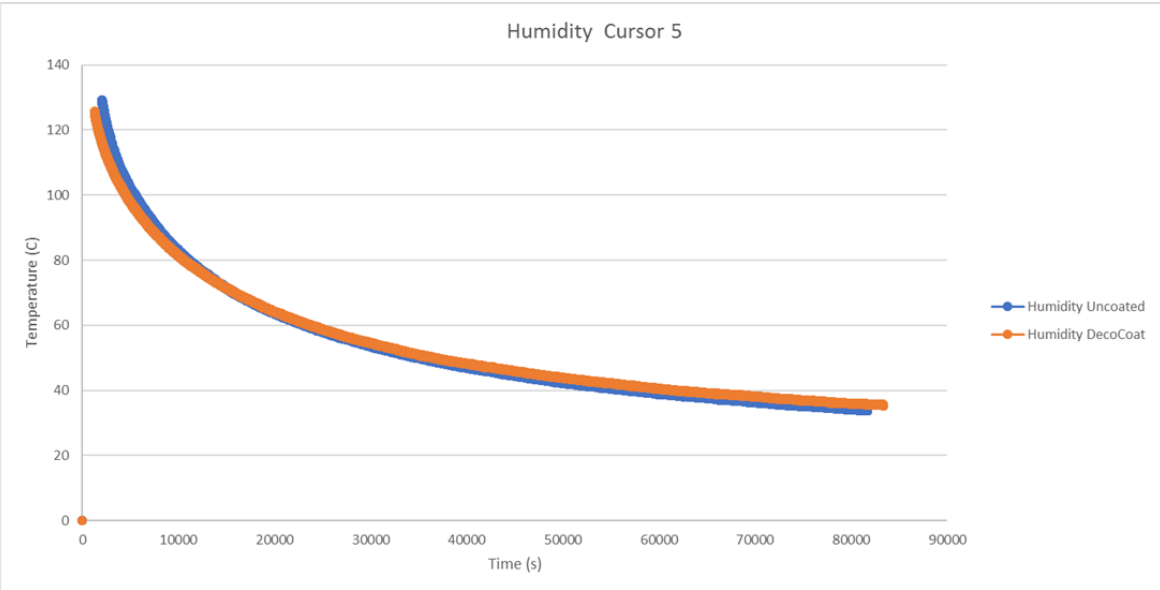
14.5.2 WIND



Graph 25: Surface temperature: Wind cursor 5

With reference to the wind graph it can be observed that in this case the initial surface temperature is the same for both samples (around 100°C). The cooling speed is faster for the uncoated sample

14.5.3 HUMIDITY



Graph 26: Surface temperature: Humidity cursor 5

For the humidity test of both specimens the curves look alike. Regarding the initial surface temperature, the one of the uncoated block is slightly higher, around 5°C. From this it can be deduced that in high humidity ambient the coated sample achieves a lower surface temperature.

15. CONCLUSION

- Windy days can be a potential problem when inspecting concrete blocks with IRT thermography. The wind capacity to reduce ambient temperature and surface temperature through ventilation causes faster heat dissipation inside the crack, which can complicate the ability of the IRT to distinguish temperature differences on the thermal images. Further studies will need to be done to confirm this hypothesis.

- In high humidity conditions, the heat dissipation rate is slower than the other climate conditions, due to the fact that moisture fills the cracks or voids rather than air, producing a change on the specific heat capacity. If we extrapolate this result to an outdoor IRT test performed on a building or bridge, it can be said that in high humidity weather, subsurface defects or cracks can be detected with IRT in a wider time range and the detectability of defects is increased. Further studies will need to be done to confirm this hypothesis.

- In all climate conditions, the coating reduces significantly the temperature of the crack which is a benefit for the life cycle of concrete, but the coating may complicate the subsurface defects detection by the IRT. This temperature reduction can reach up to 10 °C.

- Regarding crack temperature, the uncoated experiment has a faster cooling rate and it reaches faster than the coated experiment to a lower temperature by the end of the test. This means that the coat does help to reduce crack temperature by 10°C but it has no effect on the cooling rate, thus it is not helpful for increasing the cooling speed.

- As it was said by DecoCoat's manufacturer a reduction of the urban heat island effect exists by using this product and a considerably air temperature reduction occurs (around 5°C). However, this temperature reduction does only occur in the control test and not in the rest of the tests. Therefore, this coating is only effective for sunny days but that are not windy or with high humidity. In windy or high humidity conditions it seems that the coating does not reduce at all the ambient air temperature.

- Regarding air temperature, the uncoated experiment has a faster cooling rate and it reaches faster than the coated experiment to a lower temperature by the end of the test. This means that the coat does help to reduce air temperature by 5°C but it has no effect on the cooling rate, thus it is not helpful for increasing the cooling speed.

- For intermediate humidity conditions (50-70% relative humidity) the coat acts as a barrier for humidity absorption of concrete and this humidity is kept in the ambient increasing then the ambient air humidity. Therefore, the ambient humidity when the coated specimen is being tested is about 73%, whereas for the uncoated specimen it is about 55%, appreciating a significant air humidity difference. For high humidity conditions (70-90%) this difference is not appreciated, because even if the uncoated sample absorbs humidity, humidity is continuously being produced and there is a limit when the humidity absorption rate will be so low that becomes insignificant.

- Despite the coat being useful for reducing the air temperature, it does increase the concrete surface temperature in about 8°C in the control test and about 5°C in the humidity test. This is not positive if we want to maintain the surface temperature as low as possible, in order to extend the life cycle of the concrete. In the wind case, surface temperatures of both types of samples are the same.

- Regarding the different climate conditions, wind has a major effect than humidity level on the crack´s temperature and the surface temperature. Extrapolating to the outdoors this will mean that windy days have a bigger influence than rainy days in the parameters that have just been mentioned.

16. FUTURE STUDIES

Future studies will include experiments with other type of coatings that have been requested to different manufacturers. One sample has already been shipped to our lab, which is *Cool Coat Thermal Barrier Insulating Paint* from RainGuardPro manufacturer and this will used in future analysis, among other coatings. Further studies will also include phase change materials.

17. ACKNOWLEDGEMENTS

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