Chapter

The Importance of Emissivity on Monitoring and Conservation of Wooden Structures Using Infrared Thermography

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Abstract

Much of the built heritage is built of wooden structures. Due to the lack of maintenance, it is susceptible to biological attacks, such as fungi and wood destroying insects. Most of the methods used for its inspection and evaluation are intrusive. More friendly methods are required. Infrared thermography, being a non-destructive, contactless and versatile technique, can be a very useful tool in this field. However, the correct temperature measurement depends greatly on the emissivity value of the material. In this chapter, the emissivity values are presented and discussed for wood samples of *Pinus pinaster* species. In a qualitative analysis, this factor is not so important. Moreover, in a quantitative analysis for which the measured temperature value is relevant, it is crucial to know the emissivity value.

Keywords: emissivity, infrared thermography (IRT), wood, assessment of wooden heritage structures, heritage conservation, non-destructive testing, quantitative analysis, sustainability

1. Introduction

Throughout the world, wood is a universal material used since antiquity in infrastructures and structures. Like other building materials, wood develops pathologies that affect its durability and useful life expectancy. Humidity and temperature variations of indoor and outdoor environments are main factors that affect the biological degradation rate of wood. Wood deteriorates more rapidly in heat and humid than in cold and dry environments. Main organisms that degrade wood are fungi and insects, causing damage ranging from simple discolouration to complete deterioration; the damage can be possibly aesthetic or it can have disastrous consequences, such as the collapse of the structures. To prevent and control damage, it is crucial to evaluate the state of conservation of building elements. It includes the necessary non-destructive evaluation of its mechanical properties and conditions of wood [1]. Wooden structure monitoring is not necessarily expensive and prevents loses.

The early detection of anomalies allows avoiding aggravated damages in the structure that can lead to the inevitable replacement of structural elements. It is, therefore, relevant to prevent harm to people and property. It is essential that inspections of structures be carried out regularly in order to monitor the state of conservation.

The need to solve practical problems without destroying the integrity of the object under inspection has motivated the development of measurement techniques for assessing the physical properties of lumber. The earliest non-destructive assessment is a visual inspection; it is also widely used for wood product classification [2]. In general, the techniques currently used provide information at specific points. The whole is obtained by extrapolation, with a long series of studies. Often, the structure to be examined cannot be reached from the ground. They are time-consuming diagnostic methods that require the presence of teams of technicians. They are usually invasive because they require holes to be made which may also become access routes for pathogens. X-ray methods are also used and are therefore potentially harmful to health. The most frequent method with the best cost/benefit is the percussion of the wood using a blunt object; the analysis is based on the interpretation of the sound produced. The results, however, depend on the operator's experience and require direct contact with the area to be inspected, so it is necessary to mount scaffolds or staging when the elements under analysis are not reached from the ground. The interpretation of the information can be slow and difficult, depending on the variety and quantity of elements. This kind of inspection makes it difficult to record data to be compared to subsequent evaluations.

Thermography is a generic term for a variety of techniques used to visualise the temperature of object surface. Thermal imaging is the result of a complex interaction between the heating source, the material and its irregularities. In fact, the thermal properties of the materials are conditioned by the degree of their structural integrity; that is, when there are anomalies in the material structure, the heat flux changes. Then, thermography detects these changes. The surface thermal mapping results in the thermogram. The thermogram indicates the location where thermal heterogeneities exist. Therefore, it shows if a structure has damaged or defective parts. The thermogram displays the temperature variations using colour gradient.

Thermography is an *in situ* technique based on thermal image examination that can be applied to wood structures to find external signs which might indicate possible internal deterioration. This method is non-invasive and totally harmless to people. Being a non-destructive and non-contact technique, it can be a versatile tool, very useful for inspection. A portable infrared camera can be used to evaluate the structure in real time even when the structure cannot be accessed from the ground. Another advantage is that this technique allows the monitoring of disease progression. It makes possible to detect water content, state of deterioration, loss of density and anomalies. The assessment of the wood condition gives the information for maintenance and repairing.

In the science of wood, infrared thermography (IRT) is a relatively recent field of study [3]. The two main procedures are passive and active thermography. It is suitable for wood diagnose because it is a non-destructive and non-contact technique for recording the temperature of object surface, based on emitted radiation. The temperature values are mapped using false colour patterns.

In most of the instruments that use this technology, it is necessary to introduce an emissivity factor to calibrate the temperature measurement. The emissivity together with the reflected temperature allows the acquiring of data to produce the thermographic image [4]. The main issue is the determination of specific wood emissivity values.

1.1 Active and passive procedures

Maldague describes two thermographic procedures. In the active thermography, an energy stimulus is artificially produced on the object of study to cause an internal flow of heat on the surface to be inspected [5]. This flow can be triggered by different processes: simple thermal sources like lamps, heaters or flashes, hot air jets, ultrasonic pulses, infrared radiation, microwave, laser and among others. The generated heat flux is disturbed if there are defects or damages on or near the surface of the object of study. It causes discontinuities and thermal contrast. They are detected by analysing the thermograms obtained during the thermographic inspection. In the passive procedure, the thermal contrast is generated by natural sources such as sunlight [5–7].

1.2 Qualitative approach versus quantitative approach

The thermographic analysis can be qualitative and quantitative. Qualitative thermography focuses on the study of thermal patterns to reveal the existence and location of anomalies. Quantitative thermography uses temperature measurement as a criterion to determine the severity of an anomaly and to set repair priorities. Applying the qualitative approach, it is possible to determine the existence and location of a problem in the wood. The quantitative approach determines the severity of the problem; it can still help to determine when it should be repaired, by quantifying the temperature [6]. However, an accurate temperature measurement is strongly dependent on the value considered as a reference for the emissivity of the material.

The influence on temperature by the variation of the emissivity value can be observed in **Figure 1**. This figure shows the temperature reading in the thermographic camera as a function of the emissivity introduced in the equipment. When the calibration value of 0.89 (emissivity of the surface of the wood measured with the black tape method) is entered, the average value of the surface temperature is 43°C. However, if a different emissivity value is entered in the thermographic camera, the value of the temperature reading will deviate significantly from the actual value of the surface temperature. This error is all the greater the error in the emissivity value. For example, if an emissivity of 0.40 is introduced, we obtain a mean temperature value of 61°C, significantly different from the actual value of 43°C.

1.3 Factors affecting thermographic inspection

IRT is a measurement technique based on the detection of radiation in the infrared spectrum. In fact, all bodies above 0 Kelvin (absolute zero) emit this electromagnetic radiation. Electromagnetic radiation detection in the infrared (IR)

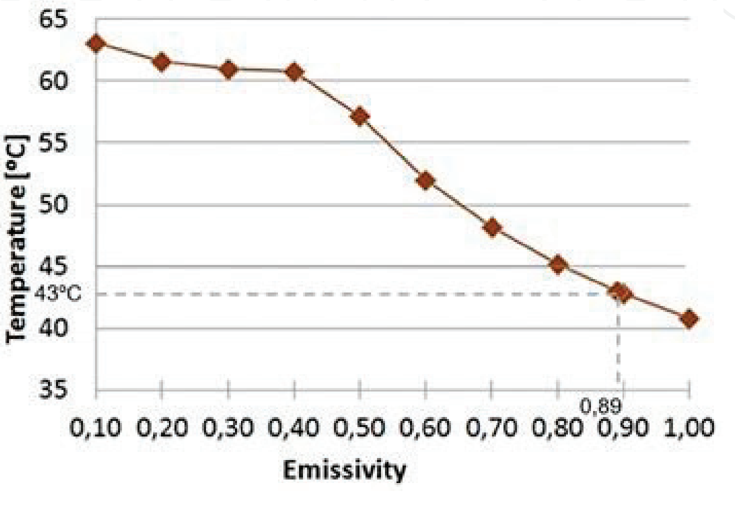

Figure 1.
Surface temperature of the wood sample as a function of the emissivity value.

spectrum is usually done between 2–5.6 μm and 8–14 μm. Both spectral bands are generally used due to their atmospheric malabsorption [5].

There are building materials with high emissivity in both spectral windows, as white marble. But there are other materials, such as wood, which have a wide range of emissivity due to the spectral window used in the observation [4]; therefore, it should be mentioned in each observation. Rice further states that the shorter wavelength spectral window (close to 0.7 μm) is desirable because the effective emissivity is higher and the effect of the surface characteristics is minimised [8]. Dewitt and Nutt (1988) in Rice highlight that the angle of observation in IRT is also determinant [8]. Radiation from a surface occurs in all directions, so the hemispherical term is often added. Mathematically, the solid angle on which the radiation measured is often referred to. However, in real surfaces, the radiation is not uniformly reflected in all directions. Then, the preferred method is to measure the normal or near normal radiation of the object surface. Fronapfel and Stolz conducted studies to determine the emissivity with different angles of observation where the emissivity variation can be observed [9]. This technique for building monitoring is expanded and has been used for more than 25 years in the diagnosis of any kind of buildings: historical, monuments and modern structures. Passive thermography is a qualitative method and is commonly used in the investigation of buildings. The purpose is to detect irregularities and malfunction. However, the lack of specific emissivity values of each material makes accurate temperature measuring impossible. In fact, there is not an infrared camera that reads directly dispensing this factor. All cameras interpret infrared radiation from the surface taking into account emissivity, reflectivity and, occasionally, the transmissivity of IR radiation. The transmissivity is only important for large distances between the camera lens and the object of study [10].

Figure 2 shows examples of the influence of homogeneous heating and adequate focusing in the determination of an accurate emissivity value [7]. Even with the correct emissivity value, incorrect focus or improper brightness and contrast may cause the observed surface temperature readings to be incorrect. For an accurate determination of the surface emissivity, it is necessary that the temperature of the surface is to be between 10 and 20°C above the ambient temperature. It is also important homogeneity in the heating process. **Figure 2** shows cases of thermograms where the heating was neither homogeneous, nor a correct adjustment in the focus, which led to the determination of incorrect values of emissivity and surface temperature.

1.4 Emissivity

Emissivity plays an essential role in thermography. Emissivity is used to characterise the optical properties of materials taking into account the amount of energy emitted compared to an ideal blackbody [10].

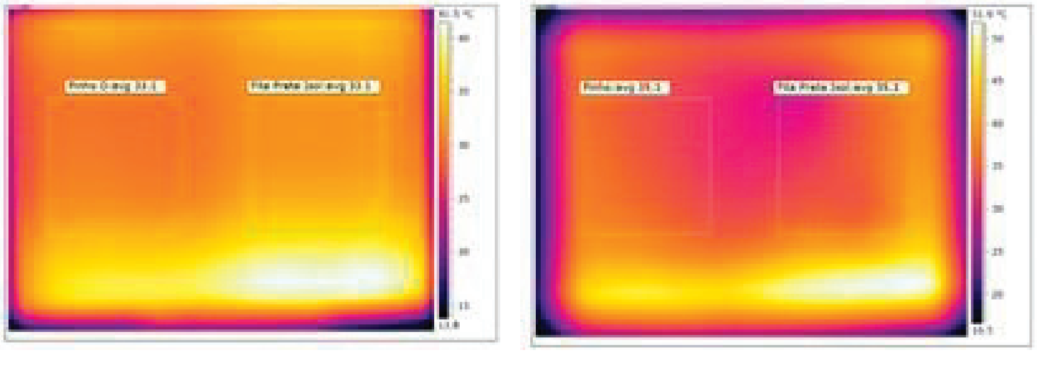

Figure 2.
Thermograms that show the heterogeneity of surface heating and inadequate focusing.

The emissivity scale goes from 0 (perfect mirror reflector) to 1 (perfect emitter black body). It depends on temperature, wavelength and surface conditions, such as roughness. Some authors also refer to the temperature reflected as being mainly dependent on the radiation coming from the surrounding environment as another factor that affects the accuracy of the temperature measured with infrared thermography [10, 11]. A surface with a low emissivity value, such as aluminium, steel, etc., acts as a mirror (high reflectance). However, these problems are usually solved using tapes or high emissivity paints [10].

Most of the materials used in buildings have high emissivity, generally above 0.8 [10].

IRT applied in building diagnostics can be used efficiently in the detection of heat loss, quality of thermal insulation in walls and roofs, thermal bridges, airflows and sources of moisture [6, 10, 12]. It also mentioned the capability of identifying structures, holes, cracks, material discrimination, analysing the state of mural paintings and the state of conservation of materials [13].

Avdelidis and Moropoulou determined emissivity values in historic buildings at different temperatures, applying infrared thermography of medium and long wavelength [10].

1.5 Thermography applied to wood structures

The literature describes the use of IR thermography for the evaluation of wood structures in historical buildings, such as the San Felipe Neri Oratory (Cadiz) [14] and a mosque in Ankara, Turkey [15].

Rosina and Robison describe that in Italy, IRT was used in different phases of building rehabilitation, from preliminary investigation to the rehabilitation process itself, as a final inspection instrument or as a part of the periodic observation and maintenance plan. This technique allows researchers to gather information about the location, shape, characteristics of the materials, and deterioration state of the elements and constructive systems. Taking into account the particular boundary conditions, the distribution of the surface temperature of the object of study allows the detection of discontinuities and changes in the structures of the buildings [6].

Studies on wood have confirmed the role of certain factors that affect its surface temperatures such as density, nodes, biological deterioration and cracks [16]. As referred above, the emissivity plays a crucial role in the thermography analysis. Lopez et al. determined the emissivity of wood samples using different species that were exposed to different temperature values. They propose an average emissivity value of 0.924 for temperature 22°C and spectral band 7.5–13 μm. They suggested that this value can be used for any type of wood, minimising the possibility of error in the determination of surface temperatures [17].

For an IR thermography test, it is necessary to have a thermal gradient to induce the thermal response of the surfaces. It is considered that 20°C is a satisfactory difference [18], while ASTM E1933-99a refers to a minimum of 10°C [19]. The ASTM E1933-99a standard is an existing normative that establishes procedures for the measurement and determination of emissivity of various materials using IR imaging systems [19].

Despite the theoretical and practical knowledge about this technique in several application areas, it has only recently been used for the diagnosis and evaluation of wood structures.

Thermography is used because the thermal conductivity and the resistivity of the materials are related to the degree of their integrity. That is, the structural anomalies cause a change in heat flow. Thermography indicates if a structure has damaged or defective regions; it shows the location of thermal heterogeneities. The thermograms display the different local temperatures using colour gradients; they are monochromatic scales, such as greyscale used at the beginning or the current polychromatic scales. In the thermograms of **Figures 3–5**, thermal heterogeneities can be observed denoting material cracks, both in the active and passive modes. Generally, in the passive mode, the cracks are noticed by lower temperatures, whereas in the active mode they are evidenced by higher temperatures [7].

Thus, **Figure 3** shows a thermogram obtained in the passive mode. It was taken from a wooden structure of a roof. A crack may be seen running longitudinally through the wooden beam. The crack is visible because thermal heterogeneity is visible in this part, that is, temperature values lower than the overall beam pattern, visible through darker shades. This information is obtained by comparison with the colour/temperature scale that is displayed on the right side of the thermogram.

Figure 4 shows a thermogram of the face of a sample of wood previously heated in an oven (active mode). This figure shows that in the active mode, cracks are evident because they exhibit thermal heterogeneities with temperature values higher than the general pattern of the observed object face. In this case, it is noticed by the lighter colours, unlike what happened in the passive mode of **Figure 3**.

Figure 5 shows the conventional photograph (visible wavelength) of a wood surface and its thermogram (infrared wavelength) in active thermographic mode. By the active procedure, this type of nodes and the cracks show colour heterogeneity in relation to the general pattern denoting higher temperature. The cracks of **Figure 5** although they are barely perceptible in the photograph are well seen in the thermogram.

Thermography also plays an important role in the inspection, assessment and monitoring of living wood structures, we mean trees. There are living wooden structures with relevant historical and cultural importance as the monumental trees and the notable ones. Thus, there are studies carried out about how to inspect, analyse and evaluate them to be safeguarded. Research on living wood structures has already been carried out in Italy. Since the 1980s, Giorgio Catena and Alexandra Catena have validated the usefulness of IR thermography technique [20]. In

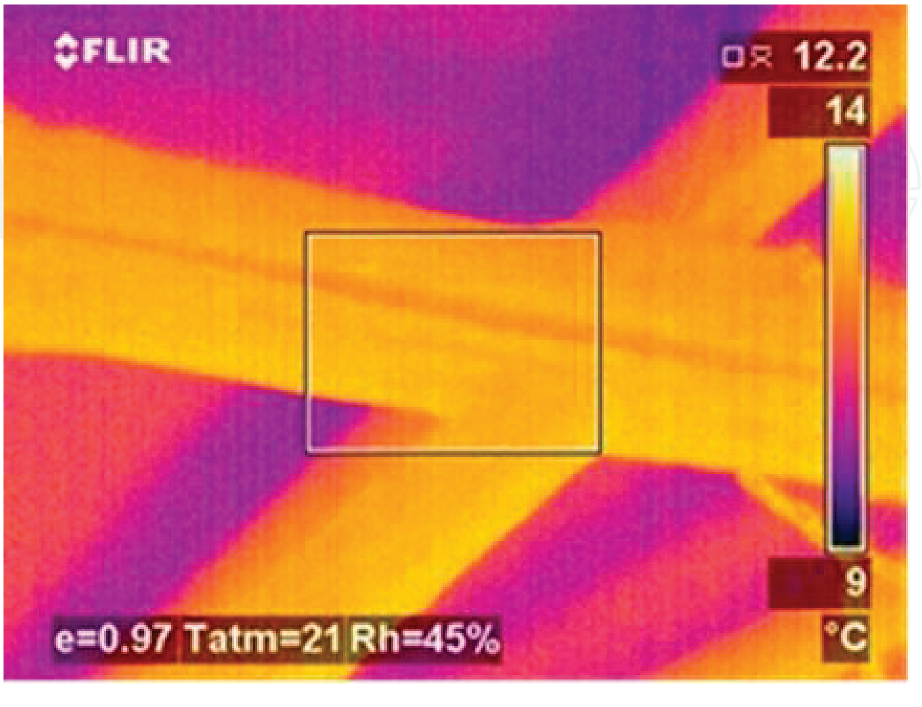

Figure 3.
Thermogram of old wooden structure: the crack is visible along the beam (passive method).

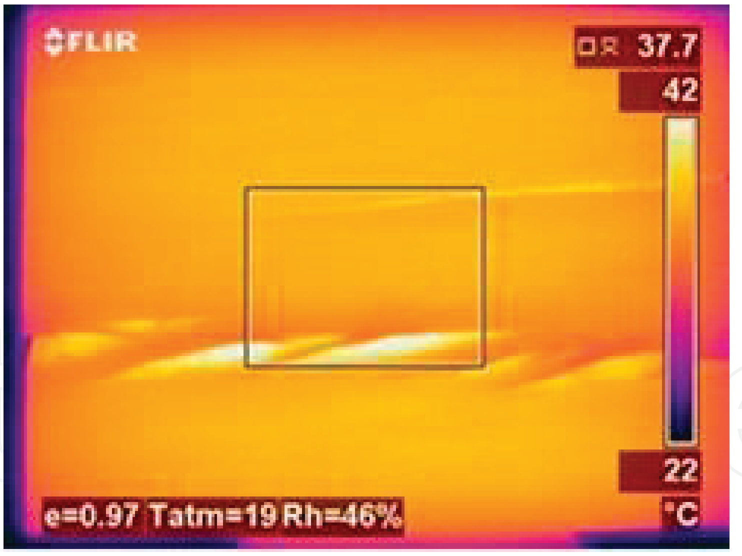

Figure 4.
Thermogram of a wood sample with visible cracks (active method).

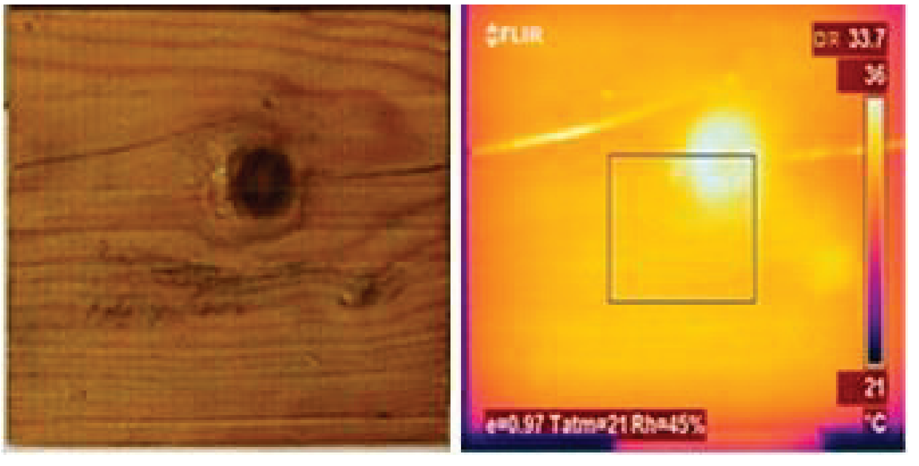

Figure 5.
Photograph and thermogram of pine sample (active mode). It shows cracks and knot.

England, Marcus Bellett-Travers applied the IR thermography to inspect, evaluate and minimise wood structure risk [21].

In Portugal, the TreeM Project aims to disseminate the possible uses of this technique [22, 23].

It is essential to safeguard, for as long as possible, the lives of these incredible living beings. Some trees are catalogued for conservation and protected by law due to their age, shape and size. Periodic inspections are also required in places of high risk of partial or total collapse. This is a mean to prevent losses to individuals and property.

2. IRT monitoring for the conservation of wood structures

IRT is a method of inspecting structures, whose data (thermograms and radiometric videos) require visual inspection with photographs in the visible range. Visual inspection is critical as certain heterogeneities detected by IRT may be non-significant, resulting only from, for example, dust. It should be noted that many of the present-day thermographic cameras already include a photographic camera in order to carry out the process in the same procedure, thus providing a photograph and a thermogram of the object with the same perspective.

The analysis of the information obtained provides elements for an evaluation of the structure, that is if the structure of wood presents or not anomalies (e.g., due to excess moisture, by the existence of fungi or by wood-decaying insects). This inspection shall be periodically repeated over the life of the structure so that the faults detected in the meantime are corrected in a timely manner. Thus, more radical and costly measures are avoided, extending the useful life of the structure.

The comparison of thermograms obtained over time is possible if a suitable value of emissivity of the surface of the wood studied is used. Some examples of the application of IRT in the detection of biodegradation are given by Grossman [24, 25]. A qualitative inspection requires the entering in the thermographic camera of a high emissivity value, since the wood is a material of low reflexivity and therefore with high emissivity. When inspecting the wood structure, non-conformities can be observed in the thermal pattern; they are identified by differences in the colour pattern in some places in relation to the whole.

In the case of quantitative analysis, it is relevant to know the concrete value of the temperature in order to have an idea of the severity of the damage detected. Therefore, a correct emissivity value is required, which is dependent on the environmental conditions of the place where the observation is being carried out. It is difficult to determine the correct emissivity value for an *in situ* given surface. This difficulty results from two fundamental aspects: (a) the difficulty in reaching the structure and (b) the difficulty in raising the temperature of the wood of at least 10°C [19] at 20°C [18] above ambient temperature because the higher the temperature differential, the greater the accuracy of the determined emissivity [19]. Thus, it is crucial to have tables of emissivity values for different types of wood to select the value that approximates the most to the real conditions. It would avoid the need of determining this value each time a study is carried out. Kang et al. emphasise the importance of tabulated emissivity values proposing a study with hundred species from Korea and Tropics [26].

The value of the emissivity is also a function of the density of the wood. If we use the same emissivity value, different temperatures will be seen in the wood. The deterioration causes a decrease in density. In the thermogram, this anomaly is detected through thermal heterogeneity indicating the points of deterioration.

Main advantage of IRT is that it indicates locations that require more detailed inspection and, if necessary, the application of other inspection techniques. The IRT does not replace the use of other techniques for evaluating structures, but provides information to apply other techniques only in concrete and localised points, avoiding their application in unnecessary areas. IRT inspections can be performed from the ground observing the structure as a whole. Thermograms and radiometric videos made with latest thermographic cameras produce records that can be compared with records of previous and future inspections.

3. Experimental work

3.1 Objectives of experimental work

The objective of the present study was to determine the emissivity values of two different samples of sawn wood with similar textures and colouration of the species *Pinus pinaster* Aiton (commonly known as brave pine or maritime pine). Although it is of same species, the two samples have different densities, since they come from two different locations with different climates—one from the region of Leiria (coast) and the other from the Serra da Estrela region (inland mountains). It is therefore intended to contribute to the need of tables of emissivity values for different wood species, in environmental conditions close to those *in situ* observed.

3.2 Instruments and materials

A Velleman DVM401 Digital Multifunction thermohygrometer was used to determine the environmental conditions. The thermographic machine used was the FLIR ThermaCAM B20 with 36 mm lens, field of view (FOV) of 22.6°, whose first three digits of the serial number are 234. The minimum focus distance is 0.3 m. For a length of 0.5 m between the machine lens and the sample surface, it has a 0.2 m horizontal field of view (HFOV), 0.15 m vertical field of view (VFOV) and 0.63 mm instantaneous field of view (IFOV). The thermographic camera works in the spectral band of 7.5–13 μm, with a thermal sensitivity of 0.10°C at 30°C and accuracy of ±2°C and ±2%. The focusing is performed manually. The detector type is an uncooled microbolometer focal plane array (FPA) with a resolution of 320 × 240 pixels. ThermaCAM QuickView 1.3 [27] and ThermaCAM Reporter 7.0 [28] were the software used. The determination of the emissivity was done applying the black tape method; it used black adhesive tape ISO Tape Tesa. A WTC binder oven was used to increase the temperature of the samples. The electronic balance used for weighing the samples has a 5 kg maximum capacity and accuracy of ±1 g. The fixation of the sample and the thermal camera was done using two tripods.

3.3 Samples

The wood samples were of the species *Pinus pinaster* Ait, commonly known as maritime pine or brave pine. This species is common in Portuguese territory. The two samples came from different locations, with different climates and consequently different densities. This species of wood was commonly used in Portugal. Currently, it is found in most part of the built heritage. Roofs, floors and walls components were built with the use of brave pine wood. Since the end of the 1990s, glued laminated products were produced in Portugal and with them other species were commercialised such as spruce tree. Pine became rarely used for construction.

The lumber samples are unfinished wood, as is often found in building structures. The dimensions of the samples are: 20 cm long along the fibres, 15 cm in the transverse dimension and 15 cm in thickness. These dimensions were defined to simulate a small section of a current beam and to minimise the effect of the environment on the surface of the object of study. **Table 4** shows the sample condition as density and water content. **Figure 6** shows the images of the two specimens.

3.4 Experimental methodology

Two studies were carried out, one for each sample. In each study, two trials were performed. A thermal differential of approximately 20°C was adopted, as suggested in the FLIR ThermaCAM B20 manual [18]. The experimental work was carried out in one laboratory of the Polytechnic Institute of Guarda (IPG). The values determined for the emissivity were compared to those found in the literature.

Since it used a thermal imaging camera and software from FLIR manufacturer, the methodology suggested in the Camera manual [18] also mentioned by Spencer et al. [29] and ASTM E1933-99a (Reapproved 2010) was applied [19]. Some adaptations for the determination of the Reflected Apparent Temperature (Reflective Method) and for the determination of the emissivity were introduced.

For each of the two samples, it was observed the face parallel to the wood fibres (20 × 15 cm) with fewer irregularities, avoiding cracks and knots. The determination of the emissivity was carried out according to the methodology of the black insulated electrical tape (i.e. a material with known emissivity value). Strips of black adhesive tape (with an emissivity of 0.970) [18, 27] were placed juxtaposed

Figure 6.
Samples of Pinus pinaster Aiton: from Leiria (coast)—left side and from Serra da Estrela (inland mountains)—right side.

Figure 7.
Laboratory experiments (general view).

in the direction perpendicular to the wood fibres so as to fill half the face of the sample, that is, 10 × 15 cm.

The samples were heated at least 20°C above the temperature of the space where the observations were made. Thus, to ensure thermal uniformity, the samples were placed in the oven at 60°C for 24 h. A type K thermocouple made it possible to verify the same temperature in the surface of the two zones, the area of the black ribbon and the area of exposed wood.

In **Figure 7**, we can observe how the thermograms of the wood samples were made.

The tests were performed with low light intensity (see **Table 1**) to avoid reflections. It was found that for a low light intensity, the reflected temperature was near the ambient temperature. The distance between the camera and the sample was 0.5 m. A tripod was used to fix the sample so that it was observed perpendicular to the plane of the surface. The laboratory conditions relevant to the machine calibration were monitored: ambient temperature, relative humidity and light intensity, as shown in **Table 1**.

Place	Room temperature (°C)	Relative humidity (%)	Reflected temperature (°C)	Light intensity (Lux)
IPG	21.0	45	21.5	2.85

Table 1.
Laboratory conditions.

Measures were taken at a sole point lead to unrepresentative temperature readings and should be avoided. Since wood is a very heterogeneous material, thermographic evaluations should be applied to a relatively large area of the sample.

The thermograms were analysed with the aid of ThermaCAM Reporter 7.0 software [28]. It was determined the emissivity value of the sample exposed surface. The value obtained corresponds to the emissivity of the analysed wood sample at ambient temperature. This procedure was repeated two times for each sample.

Each sample was weighed to determine the water content [Eq. (1)]. Each sample was weighed after the heating process, wet weight (W_{Wet}). The determination of the water content of the samples followed NP 614: 1973 [30]. The samples were heated at 100°C for 48 h. Successive weight measurements were performed until the weight remained constant, dry weight (W_{Dry}).

$$\text{Water content [\%]} = \left(\left(W_{Wet} - W_{Dry}\right)/W_{Dry}\right) \times 100 \tag{1}$$

4. Results and discussion

The thermogram in **Figure 8** is an example of the methodology followed to determine the sample emissivity.

Table 1 shows the environmental conditions of the laboratory while the thermograms were produced.

Tables 2 and **3** show the emissivity and the surface temperatures for each thermogram of both pine samples. The samples are from Leiria (coast) and Serra da Estrela (inland mountains).

Table 4 shows the average emissivity of both samples of wood of the species *Pinus pinaster* Ait.

The emissivity of each sample results from the average of the two tests performed in each. They are 0.864 for Leiria pine and 0.873 for Serra da Estrela pine. In each case, the emissivity and temperature values were determined by the average area of one square on the software used (100 × 100 pixels). The results are valid for the environmental conditions and the sample conditions described in the previous tables.

It should be highlighted that there is no significant range difference between the two samples: 0.018 for Leiria pine and 0.035 for Serra da Estrela pine. On the other hand, the emissivity values are in accordance with the bibliography consulted, that is, the highest values are around 0.9: 0.855–0.873 for Leiria pine; 0.855–0.890 for Serra da Estrela pine. As reported by Rice [8], manufacturers of IR temperature measuring equipment often recommend values between 0.94 and 0.95 for generic wood and conditions.

The manufacturer FLIR indicates for four samples of pine in the spectral window 8–14 μm values of emissivity, namely between 0.81 and 0.89. The spectral window 2–5 μm indicates values of emissivity between 0.67 and 0.75 [18]. Holst refers 0.85 for the emissivity of wood planed in the spectral window of 8–14 μm [31]. However, it is difficult to compare because emissivity values in the literature

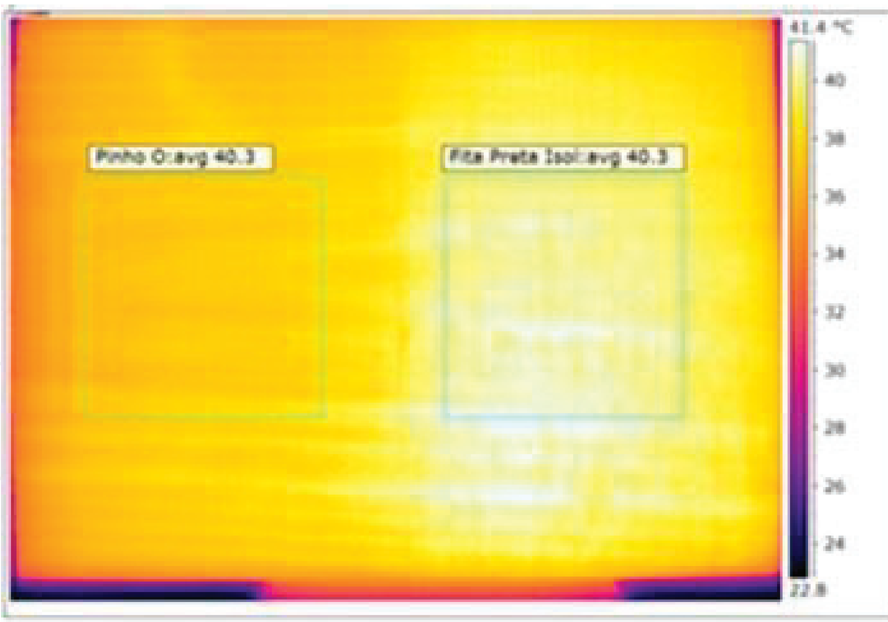

Figure 8.
Example of a thermogram obtained from one of the wood samples.

Place	Test number	Emissivity (ε)	Sample surface temperature (°C)
IPG	1	0.855	42.0
	2	0.873	43.4
	Average	**0.864**	**42.7**

Table 2.
Emissivity values—Leiria Pine sample.

Place	Test number	Emissivity (ε)	Sample surface temperature (°C)
IPG	1	0.855	47.1
	2	0.890	43.0
	Average	**0.873**	**45.3**

Table 3.
Emissivity values—Serra da Estrela Pine sample.

Samples	Number of tests	Volume (cm^3)	Dry weight (g)	Weight (g)	Water content (%)	Density
Leiria pine	2	4500	2507	2810	12.1	0.624
Serra da Estrela pine	2	4500	1869	2058	10.1	0.457

Table 4.
Samples conditions and emissivity.

refer to test conditions and experiments not fully described. The environmental characteristics to be described are ambient temperature and the relative humidity. The spectral observation window must be referred to. The conditions that refer to the sample itself, such as surface finishing, water content, density and the wood species itself, must also be mentioned.

The wood has values of emissivity, very dependent on the spectral window used.

When referring to emissivity of a natural material, such as wood, it is important to describe the set of factors conditioning the emissivity: the distance between the machine and the sample, observation angle, spectral window for observation, ambient temperature, and other ambient conditions such as relative humidity, light intensity, reflected temperature and sample surface temperature.

The difference between the sample surface temperature and the ambient temperature must be as constant as possible during the determination of the emissivity. According to the ASTM standard [19], the higher the difference the more rigorous will be the emissivity determination. The upper limit is the temperature value at which the physical properties of the object of study deteriorate.

The type of surface finishing, species identification (by scientific name), colour, sample water content and density should also be described. All these factors condition the emissivity measurement. On the other hand, only this way, by referring all the parameters, make it possible to obtain a comparative notion of the emissivity determined under different conditions. Therefore, more correctly will be the choice, for a real situation of surface temperature analysis with IR thermography technique. Even so, variations are expected in the resulting values because of both sets of environmental and sample parameters. In fact, when referring to sample parameters, there is a large variability among wood species, besides that, there is large variability along the tree itself from which the sample is taken (heartwood or sapwood). Even more, variation occurs depending upon the cutting technique (parallel or perpendicular direction to the fibre).

When reviewing the literature, it was not found systematised emissivity values under the same conditions, that is, for example, ambient temperature, spectral window and species under study. The literature on the subject is scarce and generally does not present all the relevant parameters to be taken into account for measurement.

In addition, it is not common the authors to describe the process applied to heat the surface of the sample although this is another factor that conditions the emissivity value [9]. It is relevant because not all types of heating are suitable for this purpose [18].

5. Conclusion

The aim of this research is to contribute to the obtainment of information relevant to the investigation of wooden building conservation. It was carried out under an experimental approach using pine wood of the *Pinus pinaster* species.

Emissivity values were obtained from two different samples of the same wood species. Emissivity values were obtained at an ambient temperature of 21.0°C, at a distance of 0.5 m. The sample dimensions of the observed face were 0.20 × 0.15 m to minimise errors from the surroundings. The spectral band used was the one the FLIR B20 thermographic camera provides, that is 7.5–13 μm. The samples did not have any type of finish. Lab conditions intended to reproduce the *in situ* conditions. The specimens studied, although of the same species, came from different climate zones and had different density values.

The emissivity values obtained are into the emissivity range suggested in the literature. However, it was not found literature that met the same conditions of observation regarding the species, ambient temperature, relative humidity and the spectral band used in this experimental work.

Experiments of this type are relevant since an incorrect emissivity measurement can lead to inaccurate results in the interpretation of the thermograms and hence to false conclusions.

The correct way to obtain temperature values at IR thermography systems is to establish the emissivity of the materials to be tested. Nevertheless, it is often not possible in the course of *in situ* investigations. In that case, samples of material should then be collected and tested in the laboratory, reproducing carefully the same environmental conditions as those found *in situ* to avoid distortions that may bias the results.

In the literature, we found few published works on emissivity values for wood materials. Thus, a listing of wood emissivity values at different ambient temperatures for buildings/timber structures is timely and relevant.

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Conflict of interest

The authors confirm that there are no conflicts of interest.

Notes/Thanks/Other declarations

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References

[1] Wyckhuyse A, Maldaque X. Wood inspection by infrared thermography. In: Proceedings of IVth IWASPNDE; 2002. Quebec, Canada

[2] Bucur V. Techniques for high resolution imaging of wood structure: A review. Measurement Science and Technology. 2003;**14**:R91-R98. DOI: 10.1088/0957-0233/14/12/R01

[3] Bucur V. Nondestructive Characterization and Imaging of Wood. New York: Springer; 2003. pp. 75-77. DOI: 10.1007/978-3-662-08986-6

[4] Ciocia C, Marinetti S. In-situ emissivity measurement of construction materials. In: Proceedings of 11th International Conference on Quantitative Infrared Thermography; 2012. Naples, Italy

[5] Maldague X. Nondestructive Evaluation of Materials by Infrared Thermography. London: Springer-Verlag; 1993. 139 p. DOI: 10.1007/978-1-4471-1995-1

[6] Rosina E, Robison E. The application of infrared thermography on wood-framed North American historic buildings. APT Bulletin. 2002;**4**:37-44

[7] Crisóstomo J. Contribuição para a Análise de Manifestações Patológicas em Madeira na Construção com Recurso à Termografia – Determinação da Emissividade de Algumas Espécies de Madeira Empregues em Portugal [thesis]. Castelo Branco: Superior School of Technology of the Polytechnic Institute of Castelo Branco; 2014

[8] Rice R. Emittance factors for infrared thermometers used for wood products. Wood and Fiber Science. 2004;**36**:520-526

[9] Fronapfel E, Stolz B. Emissivity Measurements of Common Construction Materials [Internet]. Available from: http://www.callsbsa.com/wp-content/uploads/2011/03/Emissivity-Measurements-of-Common-Construction-Materials.pdf [Accessed: January 21, 2013]

[10] Avdelidis N, Moropoulou A. Emissivity considerations in building thermography. Energy and Buildings. 2003;**35**:663-667. DOI: 10.1016/S0378-7788(02)00210-4

[11] Marinetti S, Sesaratto P. Emissivity estimation for accurate quantitative thermography. NDT and E International. 2012;**51**:127-134

[12] Wild W. Application of infrared thermography in civil engineering. In: Proceedings of 13th Estonian Academy of Sciences Engineering; 2007

[13] Lombillo I, Agudo E, Villegas L. Evaluación no Destructiva Del Patrimonio Construido: Inspección Visual, Técnicas Acústicas, Electromagnéticas y Tomográficas [Internet]. Available from: http://grupos.unican.es/gted/archivos/otros/ponencias/aend.pdf [Accessed: September 21, 2018]

[14] Linán C, Conde M, Rubio de Hita P, Gálvez F. Inspección mediante técnicas no destructivas de un edificio histórico: Oratorio San Felipe Neri (Cadiz). Informes de la Construcción. 2011;**63**:13-22. DOI: 10.3989/ic.10.032

[15] Kandemir-Yucel A, Tavukcuoglu A, Caner-Saltik E. In situ assessment of structural timber elements of a historic building by infrared thermography and ultrasonic velocity. Infrared Physics & Technology. 2007;**49**:243-248. DOI: 10.1016/j.infrared.2006.06.012

[16] Tanaka T, Divós F. Wood Inspection by Thermography [Internet]. Available from: https://www.ndt.net/article/v06n03/tanaka/tanaka.htm [Accessed: September 21, 2018]

[17] López G, Basterra L, Acuna L, Casado M. Determination of the emissivity of wood for inspection by infrared thermography. Journal of Nondestructive Evaluation. 2013;**32**(2):172-176. DOI: 10.1007/s10921-013-0170-3

[18] FLIR Systems. FLIR ThermaCAM B20 User's Manual. FLIR; 2006. 175-176 pp.; 209-210 pp

[19] ASTM E1933-99a (Reapproved 2010), Standard Test Methods for Measuring and Compensating for Emissivity Using Infrared Imaging Radiometers, American Society for Testing and Materials; West Conshohocken, USA; 2013

[20] Catena A, Catena G. Overview of thermal imaging for tree assessment. Arboricultural Journal. 2008;**30**:259-270. DOI: 10.1080/03071375.2008.9747505

[21] Bellett-Travers M, Morris S. The relationship between surface temperature and radial wood thickness of twelve trees harvested in notttinghamshire. Arboricultural Journal. 2010;**33**(1):15-26. DOI: 10.1080/03071375.2010.9747589

[22] Crisóstomo J, Pereira C, Roque E, Jorge L, Pitarma R. Considerações na observação do estado de salubridade de Árvores através da termografia por infravermelhos. In: Proceedings of the 1st Iberic Conference on Theoretical and Experimental Mechanics and Materials/11th National Congress on Experimental Mechanics; 4-7 November 2018; Porto. pp. 745-748

[23] Crisóstomo J, Pereira C, Roque E, Jorge L, Pitarma R. Análise da salubridade de Árvores através da termografia por infravermelhos. In: Proceedings of the 1st Iberic Conference on Theoretical and Experimental Mechanics and Materials/11th National Congress on Experimental Mechanics; 4-7 November 2018; Porto. pp. 749-758

[24] Grossman J. IR Thermography as a Tool for the Pest Management Professional. Miami, Florida: Hi-Tech Inspection Services, Inc. [Internet]; 2004. Available from: https://www.irinfo.org/articleofmonth/pdf/article_8_1_2004_grossman.pdf [Accessed: November 20, 2018]

[25] Grossman J. Trestles Anyone?: A Thermographic Nightmare, Miami, Florida, Hi-Tech Inspection Services, Inc. [Internet]. 2006. Available from: https://www.irinfo.org/articleofmonth/pdf/article_6_2006_grossman.pdf [Accessed: November 20, 2018]

[26] Kang W, Lee YH, Kang CW, Chung WY, Xu HL, Matsumura J. Using the inverse method to estimate the solar absorptivity and emissivity of wood exposed to the outdoor environment. Journal of the Faculty of Agriculture, Kyushu University. 2011;**56**(1):139-148

[27] FLIR Systems. FLIR ThermaCAM QuickView 1.3 Software User's Manual, FLIR; 2006

[28] FLIR Systems. FLIR ThermaCAM Reporter 7.0 Software User's Manual, FLIR; 2006

[29] Spencer M, Penn L, Nychka J, Boyer L, Liebertz J, Everdale L. Applying Infrared Thermography for the Purpose of Identifying Concealed Wood Framing Member Type and Subsurface Anomalies with Intended Application Towards Historic Structures [Internet]. Avalaible from: http://ncptt.nps.gov/wp-content/uploads/2008-06.pdf [Accessed: September 21, 2018]

[30] IPQ, NP 614: Madeiras – Determinação do Teor em Água; 1973

[31] Holst G. Common Sense Approach to Thermal Imaging. Washington: SPIE Optical Engineering Press; 2000. Monograph Vol. PM86