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# Measurement of thermal conductivity in lightweight concrete produced with ground stone residue

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**ABSTRACT**
With the advancement of concrete production technologies, such as the development of additives, use of different aggregates, dosing methods, mixing and application equipment, they have contributed to the emergence of concrete with special characteristics, as is the case with light concrete. Given the above, this research continues the experimental studies of structural lightweight concrete with expanded clay (coarse aggregate) developed by Lucas and Azambuja (2020). This research presents the results of mechanical properties at older ages, 28 days 214 days for Trait 1 (AN100%) and Trait 2 (AB20%) compared to the results of 7 days of age, however, the main contribution was the measurement of thermal conductivity with construction of a low-cost prototype in accordance with NBR 15220-4:2005, using the protected hot plate method. The results showed compressive strength values of a minimum of 17,8 MPa at 7 days of age and a maximum of 28,6 MPa at 214 days, values above 17 MPa established by NBR NM 35:1995 at 28 days, as well as the tensile strength by diametrical compression, which also presented values that served as a basis for framing concrete as lightweight and structural. The evaluation of thermal conductivity was performed using a hot plate, in which the results were satisfactory between 0,44 and 0,71 W/(m.k), appropriate values to answer the question of thermal performance, thus as well as complying with the established by ABNT NBR 15220-2:2008.

**KEYWORDS:** Lightweight concrete. Expanded Clay. Crushing Sand.

## 1. INTRODUCTION

According to ACI 213R-87, lightweight concretes can be manufactured through the partial or total replacement of conventional aggregates and must have a specific mass in the hardened state between 1.400 to 2.000 kg/m$^3$. The main characteristic of lightweight concrete is its reduced density compared to conventional concrete. The thermal and acoustic performance of lightweight concretes is influenced by the lightweight aggregates used in their production (ANGELIN *et al*., 2017); (DÍAZ *et al*., 2010).

This article continues the research carried out by Lucas and Azambuja (2020) who evaluated the mechanical properties of lightweight concrete produced with expanded clay with partial replacement of 20% of natural sand by crushing sand, with a plasticizer additive. In which two traits were produced, the first Trait 1 reference (AN100%) and the second Trait 2 with the replacement of 20% of natural sand by crushing sand (AB20%). 7-day-old specimens were evaluated. At this age, the results showed that the replacement of 20% of natural sand by crushing sand caused a 6% reduction in tensile strength by diametrical compression and a 9% increase in compressive strength compared to Trait 1 that does not contain sand of crushing. The specific mass values in the hardened state were for Trait 1 and Trait 2 of 1.612 kg/m$^3$ and 1.570 kg/m$^3$ respectively. However, Trait 2 with crushed sand showed adequate results for the production of lightweight concrete with axial compressive strength of 19,5MPa at 7 days of age, higher than the minimum value of 17MPa, at 28 days, established for structural lightweight concretes in NBR NM 35, 1995.

The lightweight concrete produced by Lucas and Azambuja (2020) fulfills the ACI 213R-87 requirements for the specific mass parameter in the hardened state. However, there is a need to investigate its mechanical properties at more advanced ages, in addition to measuring its thermal conductivity. These data can contribute to scientific knowledge about the lightweight concrete produced.

Thermal conductivity is a measure characterized by the ability of a material to conduct a certain amount of heat through a unit thickness, due to a temperature gradient, under certain conditions. Previous studies indicate that the specific mass, the shape of the aggregates and the moisture content determine the properties of concrete and influence its thermal conductivity (MYDIN; WANG, 2011; SERRI *et al*., 2014).

In this scenario, the construction industry has been developing more and more studies regarding the thermal properties of the materials used in the preparation of concrete. The thermal performance standards aim to improve the quality needed in cementitious elements in accordance with what is established for the evaluation of these properties (DÍAZ *et al*., 2010; ANGELIN, 2014).

According to Sacht *et al*. (2010), when evaluating the conductivity of lightweight concrete using the parallel hot wire method, thermal conductivity and specific mass values ranging from 1,8 W/(m.k) to 0,54 W/(m.k) and 2.364 kg /$m^3$ to 1.216 kg/$m^3$, respectively. Recent studies by Angelin (2014) also refer that ABNT NBR 15220:2005 describes the performance of thermal conductivity tests through the protected hot plate method, reaching thermal conductivity values and specific mass of 0,61 W/(m.k) and 1.687 kg/$m^3$, respectively.

AHMAD and CHEN (2019) evaluated the thermal properties of lightweight foamed concrete produced with the addition of expanded clay and silica fume, through the parallel hot wire, reaching maximum values of thermal conductivity and specific mass of 0,92 W/(m.k) and 1.578 kg/$m^3$ respectively.

ABNT NBR 15220-2:2008, in its item B.3, establishes the thermal conductivity values, as well as the relationship of these values according to the specific mass, as transcribed in Table 1.

**Table 1: Thermal properties of lightweight concretes**

| Especific mass (kg/$m^3$) | Thermal Conductivity W/(m.k) |
|---|---|
| 2.200 – 2.400 | 1,75 |
| 1.600 – 1.800 | 1,05 |
| 1.400 – 1.600 | 0,85 |
| 1.200 – 1.400 | 0,70 |
| 1.000 – 1.200 | 0,46 |

Source: ABNT NBR (2008)

Given the above, this research continues the experimental studies of structural lightweight concrete with expanded clay (coarse aggregate) developed by Lucas and Azambuja (2020). This survey presents mechanical properties results at older ages, 28 days and 7 months (214 days) for Trait 1 (AN100%) and Trait 2 (AB20%) compared to the results of 7 days of age, however, the main contribution was the measurement of thermal conductivity with the construction of a low-cost prototype in accordance with NBR 15220-4:2005, using the protected hot plate method.

## 2. OBJECTIVES

This research continues experimental studies for the evaluation of mechanical properties of lightweight concrete, currently at more advanced ages, and develops, in particular, a low-cost prototype for measuring thermal conductivity using the protected hot plate method.

## 3. METHODOLOGY

The method used in the production of lightweight structural concrete in this research was in accordance with the requirements of the IPT/USP (Institute for Technological Research) and the ABCP method (Brazilian Association of Portland Cement). The dosage and tests were carried out at the Civil Construction Laboratory of UNESP/FEB/DEC. The tests performed were on concrete in the fresh state (slump test) and in the hardened state (diametral tensile strength, axial compression strength and measurement of thermal conductivity) based on the Brazilian standards described below.

The determination of tensile strength values by diametrical compression followed the requirements of ABNT NBR 7222:2011 and axial compression strength according to ABNT NBR 5739:2007, in six cylindrical specimens of 100mm in diameter and 200mm in height for each trait studied, at the ages of 28 days and 214 days (7 months). It is important to highlight that the concrete dosage took place on September 25, 2020, at that time, referring to the studies carried out by Lucas and Azambuja (2020) in sufficient numbers of specimens for a future evaluation at more advanced ages. In this study, the tests to evaluate the mechanical properties took place on April 26, 2021, the reason for the 214 days.

The thermal conductivity was evaluated according to the requirements of ABNT NBR 15220-4:2005, in two identical concrete specimens with dimensions of 320mm x 320mm wide, with a thickness of 50mm, at 28 days of age, for the traits T1 (AN100%) and T2 (AB20%).

### 3.1 MATERIALS

The following materials were used for the dosage of lightweight concrete: Portland cement CPII-F-32, fine aggregates (natural sand and crushing sand), expanded clay (coarse aggregate) and plasticizer additive in two different mixes: T1 (AN100%) of 1:0, 47:1, 25:0.38 and T2 (AB20%) of 1:0, 59:0, 42:1, 25:0.45. It was used in the plasticizer additive dosage in the proportion of 1.5% in relation to the cement weight (Lucas and Azambuja, 2020).

To measure the thermal conductivity, the recommendations prescribed in NBR 15220-4:2005 were used. The determination of thermal conductivity by this method involves measuring the average temperature gradient established over the specimen, from a certain heat flux and under steady state conditions. It establishes that the hot plate can be square with a side of at least 200mm, still, the ratio between the width of the guard ring and the dimension of the hot plate must be between 1:4 and 1:6.

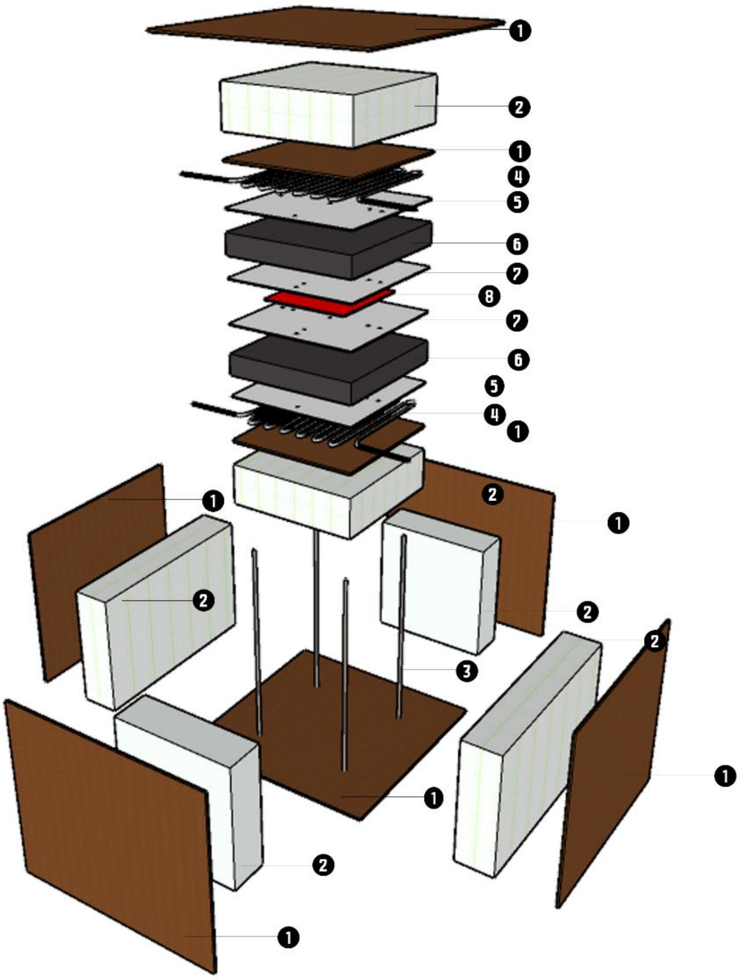
Based on the data indicated in the normative text, a study of the technical feasibility of building a low-cost prototype for measuring thermal conductivity in the laboratory was started. For this it was necessary to find the essential inputs for the elaboration of the prototype, such as: heating plate, temperature sensor, thermal insulator and data reading system.

After research, it was defined that the heated table used in 3D printers that serve as a heated base for the creation of parts through the filaments expelled by the extruder nozzle, MK2B PCB heated table, with dimensions 210mm x 210mm, for meeting the requirements established by NBR 15220-4:2005.

The dimension of the specimens, for measuring the thermal conductivity, was defined respecting the ratio between the guard ring width and the heated table. Therefore, 320mm x 320mm specimens were manufactured, with thicknesses of 50mm.

In Figure 1, a mounting scheme of the prototype and its parts is presented.

**Figure 1: Scheme of the set for measuring thermal conductivity.**




1- Plasticized plywood boards
2- Expanded polystyrene (insulating base)
3- Locking force (threaded bars)
4- Aluminum coils
5- Aluminum plate (sensor arrangement on the cold plate)
6- Bodies of evidence (concrete)
7- Aluminum plate (sensor arrangement on hot plate)
8- Heating plate (MK2B PCB)
Source: THE AUTHORS (2021)

As illustrated in Figure 1, two identical lightweight concrete specimens with flat and parallel surfaces are arranged horizontally on each side of the CENTRAL HOT PLATE [(comprised by the mounting: Aluminum plate + Heating plate (MK2B PCB) + Aluminum plate)] and placed between the two isothermal cold plates [(they are formed by the set: Aluminum plate + aluminum coils)]

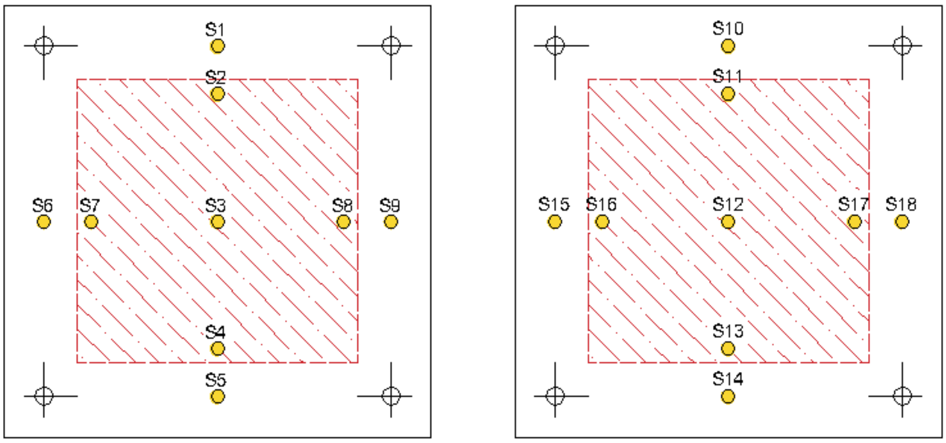
For temperature measurement, as established in ABNT NBR 15220-4:2005, thermocouple sensors are placed on the hot plates and on the cold plates. DS18B20 temperature sensors, produced by the company Dallas, were used for measuring temperatures between -55 ºC and 125 ºC, with an accuracy of about 0.5ºC in the range of -10 ºC and +85 ºC. The programmable resolution is from 9 to 12 bits.

According to the manufacturer, the sensor connects to another device through onewire communication, which means that various data can be transmitted through a single connector identified by the acronym DQ. Two other sensor connectors are used for power supply which are ground (GND) and 5V (VCC). It is recommended to use a 4.7 kΩ resistor connection between the 5V power supply and the DQ pin.

This sensor is peculiar because it is possible to connect several DS18B20 sensors to the connector (single cable), because each sensor contains a unique 64-bit code that identifies which one of them the signal comes from.

On the hot plates the temperature sensors were positioned as shown in Figure 2.

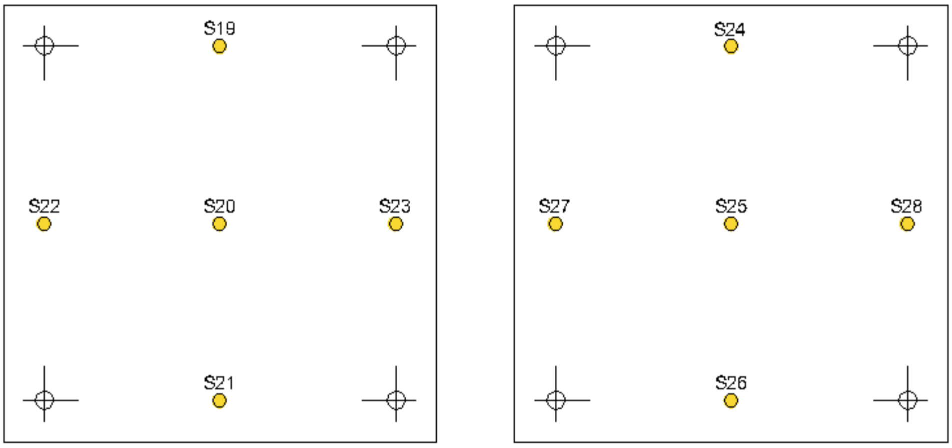
**Figure 2: Arrangement of temperature sensors on the hot plate.**




Source: THE AUTHORS (2021)

The number and arrangement of sensors placed on the surfaces of each plate are identical to those used in the central section of the hot plate (Figure 3). To place the sensors, small holes and slots were made on the surface of the board to pass the cables connected to the temperature sensors, after which all the slots were filled with thermal paste.

**Figure 3: Arrangement of sensors on the cold plate**

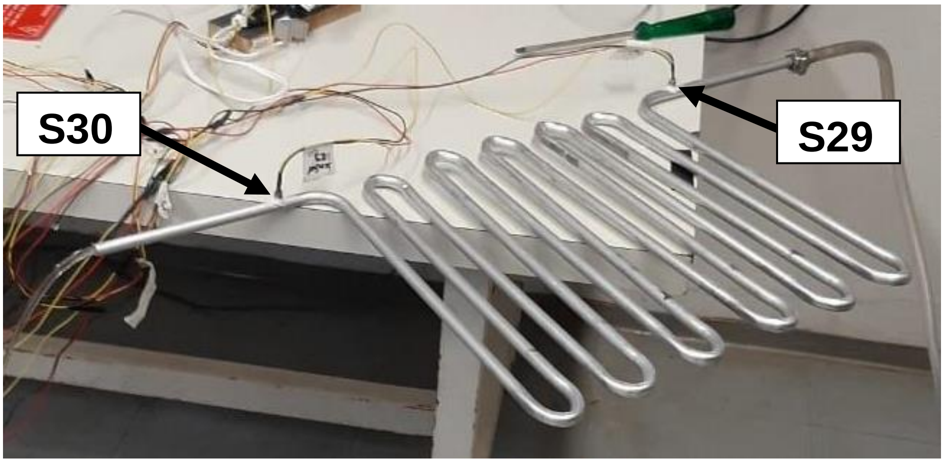



Source: THE AUTHORS (2021)

To pass the cooling fluid on the cold plate, an aluminum coil was used (Figure 4), for water inlet and outlet. This coil was constructed by bending the aluminum tube with heating by a blowtorch and using a tube bender and clamps and/or clamps. Care must be taken in this operation to avoid piping rupture.

Two temperature sensors were placed on the coil to read the water inlet and outlet, where S29 is the water inlet and S30 the outlet.

**Figure 4**: Coil for water inlet and outlet




Source: THE AUTHORS (2021)

The equipment was insulated along its entire length with expanded polystyrene, EPS (Expanded Polystyrene), 10 cm thick, to avoid temperature changes with the external environment, as shown in Figure 5, as recommended by NBR 15220:2005.

**Figure 5:** Prototype for measuring thermal conductivity.

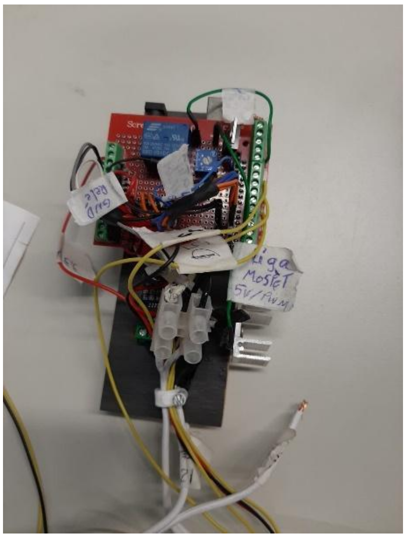
Source: THE AUTHORS (2021)

For the temperature reading it is necessary to use Dallas sensors connected to an Arduino UNO microcontroller board (Figure 6) based on the ATmega328 chip. This board has 14 digital I/O pins, 6 digital inputs, a 16 MHz oscillator crystal, a USB connection, power connector, ICSP bus and a reset button (RODRIGO, 2017).

The programming that is included in the Arduino UNO was developed, enabling the realization of temperature measurements with the Dallas DS18B20 sensor.

The two libraries (Onewire and Dallas Temperature) were inserted, allowing the interaction between the DS18B20 sensor with the Arduino UNO.

**Figure 6:** Arduino UNO board



Source: THE AUTHORS (2021)

**Figure 7**: Electric source

Source: THE AUTHORS (2021)

Because it is the mounting of equipment that involves programming and electronic systems, such as the languages used for sensor recognition.

The main inputs of the prototype for measuring thermal conductivity, assembled in the laboratory, and their unit prices, quoted on May 19, 2021, are presented in Table 2:

**Table 2: Cost of main inputs**

| Main inputs | Quantities | R$ (unit) | Cost (R$) |
|---|---|---|---|
| Plastic Plywood 25mm 2.20x1.10 Black | 1 | 175,00 | 175,00 |
| Expanded Polystyrene (EPS) 100cm x 50cm x 10cm | 2 | 30,00 | 60,00 |
| 3/8 Threaded Bars Zinc plated 1 meter + 2 Nuts and 2 Washers | 4 | 10,00 | 40,00 |
| 1/2"x1/16" Aluminum Round Tube (6 meters) for coil | 1 | 15,00 | 15,00 |
| Aluminum plates (320mmx320mmx6.35mm) | 4 | 82,50 | 330,00 |
| Heating plate (MK2B PCB) | 1 | 66,00 | 66,00 |
| Dallas DS18B20 Temperature Sensors | 32 | 10,00 | 320,00 |
| Cable Manga 4 Ways (50 meters) | 1 | 50,00 | 50,00 |
| Arduino board | 1 | 90,00 | 90,00 |
| Power Source (12V) | 1 | 154,00 | 154,00 |
| **Total** | | | 1.300,00 |

Source: THE AUTHORS (2021)

The equipment mounting was adjusted to avoid temperature measurement errors due to external or internal factors not foreseen in its development.

The thermal conductivity evaluation was carried out on two identical concrete specimens, polished with an electric grinder with grinding wheel (weight 120), at 28 days of age, for the T1 ($AN_{100\%}$) e $T_2$ ($AB_{20\%}$). Figure 8 illustrates a polished specimen with dimensions of 320mm x 320mm and 50mm thick.

**Figure 8:** Polished concrete scpecimen

Source: THE AUTHORS (2021)

To measure the thermal conductivity, a symmetric device was built using a central heating plate and two heatsinks at the other ends. To determine the thermal conductivity, it is necessary to identify the heat ow crossing the block and the temperatures at its end, so that it must be determined with the following expression:

$$k_a = L_a \frac{q''}{T_q - T_f} = L_a \frac{(q/A)}{T_q - T_f}$$

In which:

ka is the thermal conductivity of the sample

La is the thickness of the concrete

q″ = q/A is the heat ow crossing the sample

Tq e Tf are the measurements of the temperatures on the hot and cold plates, respectively.

## 4. RESULTS AND DISCUSSIONS

Next, the results of tensile strength by diametrical compression, axial compression strength and thermal conductivity of lightweight concrete produced with basaltic stone residue are presented.

### 4.1. Diametric compression tensile strength

Diametric compression tensile strength results were determined at the ages of 28 days and 7 months (214 days). Table 3 presents the results of traits 1 and 2. It is noteworthy that the results at the age of 7 days are presented according to Lucas and Azambuja (2020).

**Table 3: Determination of Tensile Strength by Diametric Compression**

| | $T_1$ (AN100%) | | | $T_2$ (AB20%) | | |
|---|---|---|---|---|---|---|
| | 7 days[1] $f_{c0,7d}$ (MPa) | 28 days [2] $f_{c0,28d}$ (MPa) | 214 days [2] $f_{c0,214d}$ (MPa) | 7 days [1] $f_{c0,7d}$ (MPa) | 28 days [2] $f_{c0,28d}$ (MPa) | 214 days [2] $f_{c,0214d}$ (MPa) |
| **Average** | **1,86** | **2,16** | **2,50** | **1,71** | **2,13** | **2,60** |
| Standard Deviation (S) | 4,7 | 2,8 | 5,27 | 1,6 | 2,2 | 4,25 |
| Coefficient (%) | 25,3 | 13,3 | 21,07 | 9,3 | 10,1 | 16,08 |
| Minimum value | 13,5 | 17,1 | 15,16 | 14,6 | 19,0 | 20,74 |
| Maximum value | 25 | 25,2 | 29,26 | 19,2 | 25,1 | 31,09 |

Source: [1]Lucas e Azambuja (2020); [2]THE AUTHORS (2021)

As can be seen in the two studies, the values achieved both at 28 days and at 214 days were greater than 2 MPa, the minimum tensile strength established by ABNT NBR 7222:2011. As it can be seen that between T1(AN100%) and T2(AB20%) there are no significant differences in the results of tensile strength, this means that the influence of 20% sand crushing showed to be efficient.

### 4.2. Axial compression strength

Axial compressive strength results were determined at the ages of 28 and 7 months (214 days). Table 4 presents the results of axial compressive strength and compressive strength characteristic of the studied traits. It is noteworthy that the results are presented at the age of 7 days according to Lucas and Azambuja (2020).

**Table 4: Determination of Axial Compressive Strength**

| | $T_1$ (AN100%) | | | $T_2$ (AB20%) | | |
|---|---|---|---|---|---|---|
| | 7 days[1] $f_{c,7d}$ (MPa) | 28 days[2] $f_{c,28d}$ (MPa) | 214 days[2] $f_{c,214d}$ (MPa) | 7 days[1] $f_{c,7d}$ (MPa) | 28 days[2] $f_{c,28d}$ (MPa) | 214 days[2] $f_{c,214d}$ (MPa) |
| **Average** | **23,1** | **25,5** | **31,3** | **22,5** | **24,3** | **27,3** |
| Standard Deviation (S) | 3,2 | 1,5 | 1,6 | 1,8 | 1,9 | 1,9 |
| Coefficient (%) | 14,1 | 6,1 | 5,2 | 7,9 | 7,8 | 7,1 |
| Minimum value | 19,4 | 23,1 | 29,5 | 20,8 | 21,1 | 25,3 |
| Maximum value | 26,5 | 27,6 | 33,3 | 25,3 | 26 | 29,3 |
| | Characteristic axial compression strength - $f_{ck}$ (MPa) | | | | | |
| | **17,8** | **23** | **28,6** | **19,5** | **21,1** | **23,8** |

Source: [1] Lucas e Azambuja (2020); [2]AUTORES (2021)

The characteristic axial compressive strength, shown in Table 4, was determined by the following expression:

$$f_{ck} = f_{cm} - 1{,}65SD$$

In which:

$f_{ck}$ is the characteristic compressive strength

$f_{cm}$ is the average compressive strength

**SD** is the standard deviation

NBR NM 35 (1995), item 4.3.1.1. sets the minimum value of 17 MPa for axial compressive strength at 28 days. It is observed that Traits T1 (AN100%) and T2 (AB20%) obtained results superior to those recommended by the normative text.

It can be seen that there was a reduction in strength by 16% between T1(AN100%) and T2(AB20%), however this is due to the difference between the specific mass, which means that the higher the specific mass of the concrete, greater will be its strength, an aspect observed by several researchers such as Shafigh et al (2018), with values of compressive strength and specific mass of 22 to 27 MPa and 1.640 to 1.770 kg/m³ respectively, Moravia *et al.* (2010) in which obtained values of compressive strength and specific mass of 17,6 to 33 MPa and 1.571 to 1.652 kg/m³ respectively, and Oliveira *et al.* (2011) with resistance and specific mass ranging from 17,7 to 22,4 MPa and 1.267 to 1.442 kg/m³ respectively.

## 4.3. Thermal Conductivity

The results achieved for thermal conductivity are presented in Table 5, as well as their respective specific masses.

**Table 5: Thermal conductivity result and specific mass**

| Traits | Thermal Conductivity (W/m.k) | Especific mass (kg/m³) |
|---|---|---|
| **$T_1$ (AN100%)** | 0,71 | 1.612 |
| **$T_2$ (AB20%)** | 0,44 | 1.570 |

Source: THE AUTHORS (2021)

NBR 15220-2:2008, in its item B.3., indicates for light concrete with specific mass between 1,600 to 1.800 kg/m³ the conductivity of 1,05 W/(m.k) and with specific mass between

1.400 to 1.600 kg/m$^3$ the thermal conductivity of 0,85 W/(m.k). The concretes presented acceptable thermal conductivity values for being inferior to the parameters established by the standard. For T1 (AN100%) the thermal conductivity was 33% lower than that established by the standard, while for T2 it was 49%.

NBR 15220-2: 2008, in its item B.3., indicates for light concrete with specific mass between 1.600 to 1.800 kg/m$^3$ the conductivity of 1,05 W/(m.k) and with specific mass between 1.400 to 1.600 kg/m$^3$ the thermal conductivity of 0,85 W/(m.k). The concretes presented acceptable thermal conductivity values for being less than the parameters established by the standard. For T1 (AN100%) the thermal conductivity was 33% lower than that established by the standard, while for T2 it was 49%.

## 5. CONCLUSION

This article, as mentioned above, continued the experimental studies of structural lightweight concrete with expanded clay (coarse aggregate) elaborated by Lucas and Azambuja (2020). The results showed that the replacement of natural sand by 20% of crushing sand caused a significant reduction in compressive strength of approximately 16%. Although there is this reduction in compressive strength, crushing sand showed satisfactory results for the production of structural lightweight concrete, as the compressive strength values for all traits at all ages of concrete exceed the minimum value of 17 MPa at 28 days, established by NBR NM 35:1995.

It was observed that the specific mass of T2 (AB20%) is lower than that of T1 (AN100%), providing a lower thermal conductivity result. The concretes presented acceptable thermal conductivity values between 0,44 and 0,71 W/(m.k), appropriate values to answer the question of thermal performance, as well as complying with the established by ABNT NBR 15220-2:2008.

## 6. ACKNOWLEDGMENT

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