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Thermal resistance and conductivity of recycled construction and demolition waste (RCDW) concrete blocks

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Abstract

In Brazil, studies to reuse construction and demolition waste are a special issue because a large amount of this material has been delivered to the public landfills and in illegal places. Some researchers have suggested reusing this material in building elements, such as bricks or blocks. It is possible to find a lot of researches in physical/mechanical characterization, while little effort has been made to characterize recycled construction and demolition waste blocks (RCDW) for their thermal properties. The aim of this work was to characterize the RCDW thermal resistance and conductivity in order to provide subsidies for a building's thermal performance analysis. The hot-box method was adapted, together with measuring techniques with a heat-flow meter to determine the RCDW thermal properties. The results indicated that the RCDW block overall thermal resistance and thermal conductivity in the solid region was within the intervals of $0.33 \leq R_I \leq 0.41 m^2 K W^{-1}$ and $0.60 \leq \lambda \leq 0.78 W m^{-1} K^{-1}$, respectively. The lower resistance and conductivity values are justified by the presence of aggregate with a lower density and lower thermal conductivity than the natural aggregate.

Keywords: hot-box method, sustainable materials, thermal properties.

1. Introduction

A large amount of construction and demolition (C&D) waste (known as C&D materials or C&D debris) are generated in cities around the world. C&D wastes, such as bricks, ceramic bricks, concrete, soil, wood, among others, are produced when new structures are built, when existing structures are renovated or demolished, and when the land is prepared or excavated (ABNT, 2004). Construction and demolition waste management has been a major issue worldwide due to the high level of construction activity in economically advanced countries and in emerging economies such as Brazil and China (Agamuthu, 2008). In Brazil, one third of this material is delivered to the public landfills, while the rest is generally disposed of in illegal places (Leite *et al.*, 2011).

The inert fraction of demolition waste, usually derived from concrete, bricks and tiles, is well suited to be recycled as a substitute for coarse aggregate. It has a great potential to be reused in building elements, like bricks, blocks, and in road construction, for bases and sub-bases (Leite *et al.*, 2011; Soutsos *et al.,* 2011). Some researchers have verified that the replacement of the course and fine natural aggregates, by recycled aggregates at the levels of 25 and 50%, have little effect on the compressive strength, although higher levels of replacement reduced the compressive strength (Soutsos *et al.*, 2011; Leiva, *et al.*, 2013). So, the aggregate derived from recycled construction and demolition waste (RCDW) is an attractive alternative material to be utilized in new constructions. In the references, it is possible to find a lot of research in physical and mechanical characterization of these materials but little effort has been made in characterizing the thermal properties of RCDW blocks (thermal resistance/transmittance and conductibility) which are very important for building thermal performance.

The heat is transferred to the inside or outside of the building by conduction, radiation and convection. It can be reduced through thermal insulation by appropriate construction techniques and choice of materials. The thermal insulation, usually known as building envelope, is determined by the walls' and roof's thermal resistance (R-value) and affects the total energy consumption of heating and cooling systems and thermal comfort for their occupants. In a building that has a high R-value provides more effective insulation than a building with low R-value, resisting the flow of heat or cold and reducing the thermal exchange. Others factors, like windows and door (fenestration), affects the final thermal resistance of the building envelope, modifying its final insulation (Incropera, 2007).

The thermal resistance property is directly dependent on the material type, thickness and density of each layer present in the wall and roof composition. For most wall and roof patterns, the theoretical thermal resistance can be obtained in manufacturer catalogs or can be estimated by procedures established in standard codes (ISO 6946, 1997; ABNT, 2003). In the calculation model, it is usually necessary to previously know the geometrical, density and conductibility of the wall or roof components. The R-values obtained are especially used in the building design. However, theoretical values differ from the R-value determined by in-situ methods. Uncertainties in material properties, in mathematical model, in the modification of the final thickness layers during the wall/roof execution process, among others, cause differences between the models. The calculation model cannot be applied in cases in which these previous properties are unknown, specially the thermal conductivity coefficient. This usually happens in blocks in which the aggregate was obtained from RCDW. It is usual to make physical and mechanical characterization of RCDW blocks, restricting the determination of R-values by in situ tests.

Literature presents two methods to determine the in situ thermal insulation of buildings: steady-state and transient (dynamic) measurement techniques (Incropera, 2007). The steady-state measurement technique is based on a one-dimensional heat flow approach and requires a temperature gradient over a known thickness of the sample. The temperature must be established in order to control the heat flow between the two sides of the tested element. The R-value can easily be obtained by measuring the gradient temperature together with direct heat-flux through the sample. Three main techniques are applied: the guarded hot-plate, the hot-box technique and the heat-flow meter.

The hot-box, applied in this study, consists of a five-sided box mounted in the warm side of the room with the open side enclosing the test sample. The heat input to the box is controlled so that the temperature in the box is the same as in the surrounding warm room (ABNT, 1980; ISO 8990, 1994). However the heat-flow meter method is usually applied to test the insulation parameters of building envelopes in situ because of its lightweight components and matching parts (ISO 8301, 1991; ISO 9869, 1994). However, with in situ thermal analyses, the experimental determination of the thermal resistance of walls always presents practical problems, especially, in finding the steady state conditions across it. It is practically impossible to control the thermal transient because of the daily variation of climatic conditions. Another possibility is to make prototype experiments, but the costs are high because it is necessary to manufacture the prototype, transport it and install it in the laboratory. Because of the differences in the prototype wall fabrication and the in situ thermal analyses of the walls, along with the differences in the experimental conditions (one is made under a laboratory-controlled climate and the other placed within a natural actual climate), the thermal resistance of the wall determined in situ might present a significant deviation from the resistance determined from the prototype. The difference between experimental results and theoretical values is greater when compared to the hot-box technique (more accurate) because thermal properties are dependent on climatic effects including humidity and solar radiation, among others (Peng and Wu, 2008; Luo *et al.*, 2011).

As RCDW blocks can be considered new or alternative material to be used in new constructions, in situ thermal experiments should be discarded in order not to compromise the building thermal performance. The prototype experiment should also be abandoned because of the necessity of the large amount of samples that have to be manufactured, which involves high initial costs in the experiment. Therefore, the hot-box technique seems to be the best choice.

This paper aimed to characterize the thermal resistance and thermal conductivity of RCDW blocks. To do this, the hot-box chamber adapted, along with measuring techniques from the heat-flow meter to perform the thermal insulation by RCDW blocks. These properties are very important for performing a building's thermal energy simulation and are not presented in the Brazilian Code NBR 15220 (ABNT, 2003). Notwithstanding, this search complements a previous study denominated "Constructive Techniques with Sustainable Practices" developed by Santos *et al.* (2013).

2. Materials and methods

2.1 Materials

The construction and demolition (C&D) waste utilized in this work was initially pre-screened, classified and underwent manual triage. It was defined as just mortar, concrete and clay brick for its composition. The selected material underwent crushing and screening processes, whereby three types of recycled aggregates were obtained, which were classified according to the particle sizes (or sieve size): 4.74 (#4), 2.0 (#10), 0.425 (#40) and 0.075 (#200)mm. Samples were screened out in the initial stage using a #4 sieve. Recycled Fine Particles (RFP) were classified by the particle size smaller than the mesh of #4 sieve and Recycled Coarse Particles (RCP) remaining in the sieve (Figure 1a). In the concrete preparation, only the fraction passing the #4 sieve was used and that remaining in the mesh #200 sieve (RFP), plus Pozzolanic Portland Cement (PC IV 32).

After RCDW classification into different particle sizes, the Theoretical Experimental Packaging adapted by Costa (2006) was performed. Mixed were three size fractions in different percentages, in order to determine the combination for a higher bulk density and lower voids in the concrete mixture. The best combination was determined in the mixture proportion of 15/47/38 (powder/ sand/ fine gravel in percentage), which led to a concrete mix of 1:9 (1:1.35:4.23:3.42). The amount of water in every trace was determined by a tactile-visual test in order to observe the formation of a homogeneous and cohesive mixture on hand. The water /cement ratio (w/c) equal to 1.32 was found. The pastes with fine and coarse aggregates needed additional water due to their high porosity and low specific gravity which increase the water/solid ratio (Leiva *et al.*, 2013).

Figure 1
(a) Classified construction and demolition waste and (b) RCDW Blocks (250x125x75mm).

2.2 Blocks Manufacturing

The block's composition was obtained by completely replacing the fine aggregate with recycled FP. The dry components (cement and recycled powder, sand and fine gravel) were placed in a planetary mixer until a homogeneous combination was obtained. Water was then added to obtain a homogeneous paste. The formed paste was placed into molds for manufactured samples of various shapes and sizes to be used in the physical, mechanical and thermal tests (Figure 1b). Samples were taken out of the molds 24 hours after casting and cured in a water tank at 25°C for 28 days. The compressive strength tests were performed at ages 7 and 28 days (ABNT, 1995). The compressive strength was superior to 4MPa, and the bricks were classified as Class B for structural use in wall elements just above the ground level. The physical tests indicated that there was saturated specific mass, dry specific mass, voids ratio and water absorption by dipping was 1.6gcm^{-3}, 1.48gcm^{-3}, 26.75% and 12.5%, respectively (Santos *et al.*, 2013).

2.3 Chambers Manufacturing

The RCDW thermal resistance test followed the adapted hot-box technique, according to NBR 6488 (ABNT, 1980). The heat flux between hot and cold box was estimated using a thermal fluximeter (ISO 9869, 1994). The first chamber (denominated "hot chamber") was composed of a sandwich panel made of MDF wood boards (16mm), EPS boards (50 mm) and thin aluminum foil to isolate it from the exterior climate. One infrared lamp (250W) was positioned inside the chamber for an internal heat source and a dimmer dispositive was utilized to adjust the infrared light level.

The second chamber (denominated "ambient chamber") was composed of just EPS boards (25mm) to help stabilize the external temperature, making the heat fluxes less dependent on external weather conditions and improving the thermal steady-state conditions between the two chambers. It is not a cold chamber because refrigeration was not used to cool the air inside the ambient as prescribed by Brazilian code NBR 6488 (ABNT, 1980). This chamber was just kept at room temperature with the objective of isolating the sample from direct climatic conditions. The samples were attached in the chamber in order to be exposed to the hot air generated by the heat/radiation emitted from the infrared light and were protected from direct radiation. They were heated indirectly by hot air circulation inside the chamber with the help of three fans.

2.4. System Test

To estimate the heat flux between the hot and ambient chambers, the heat-flux meter technique (ISO 9869, 1994) was used. The walls to be tested were instrumented by thermistor NTC with 10k sensors (accuracy of ±0.25°C) for the surface temperature measurement. Two sensors were installed in the central position of the wall sample, facing the interior of the hot chamber. The sensors were adequately protected from the movement of hot air inside the hot chamber (Figure 2a) and fixed with adhesive tape. Another two sensors were fixed on the exterior center of the sample's wall,

Figure 2
(a) Internal and (b) external temperature and heat flux sensor in the RCDW wall.

facing the ambient chamber. They were positioned between the heat-flux sensors (near the circular plate), installed in the vertical position and fixed adhesive tape, to avoid direct contact with the air. A heat-flux sensor, model HFP01 manufactured by Hukseflux (accuracy of 5% on sample wall), was fixed to

the exterior face of the sample's wall between the two temperature sensors to measure the heat-flux. It was fixed using adhesive tape in all its contours (Figure 2b) and its central position was facing the opposite direction of the interior temperature sensor. A good thermal contact between all sensors and the sample wall

surface was ensured. All the sensors were connected to a data logger to perform the automatic readings. A sample rate measurement of 5 minutes was chosen to be adequate, taking into account the variation velocity of the environmental parameters measured. All the equipment was previously calibrated.

2.5 Test wall thermal resistance calculation

Measurement analysis was carried out with the progressive mean method as stipulated by ISO 9869 (1994). R-value

can be calculated by Equation 1, where T_{si} is the internal temperature, T_{se} is the external temperature, q is heat flow between

the two sides of the tested element and j represents each measurement made during the element test.

$$R_n = \frac{\sum_{j=1}^{n}(Tsij - Tsej)}{\sum_{j=1}^{n}q_j} \qquad (1)$$

The R_n calculation for each measurement is made in succession, starting from the first. The calculated value converges asymptotically to the real value (especially thermal steady-state conditions). The R-value of sample's wall was evaluated using the mean of temperatures and heat-flow rates, at least in a period of temperature wave

(such as 1 day, 24h) instead of the immediate data.

To verify the adaptation of the hot-box method, a material with thermal resistance known previously (Wood Wool Cement Board - WWCB) was tested and the results were very close to its theoretical thermal resistance.

With the chamber tested, two

RCDW sample walls with dimensions of 0.50x0.375x0.125m (Figure 2) were tested in the solid face and in the region where there was an air gap. The air gaps were closed on the upper surface of the blocks aiming to adequately represent the behavior of the wall in service. The measurements were carried out during at least 72h (3 days).

2.6. Error Analysis

The uncertainty of the R-value estimate was derived from the individual measurement uncertainties and the Standard Deviation (S.D.) of the average value. This is necessary because each of the measured parameters (heat flux, internal and external temperature) has an associated uncertainty due to the sensor itself and be-

cause of the logging system (Baker, 2011). The error determination of each variable measured on the R-value was estimated with each measured parameter disturbed by its error. The instrument's calibration error declared by the manufacturers was assumed. The overall uncertainty on the R-value estimation (δR_n) can be calcu-

lated as the Root Mean Square (RMS) value of the deviations of each error case from the base case plus the S.D. of the R_n average period considered (Equation 2), where R_{err_Tsi}, R_{err_Tse} and R_{err_Q}, are the R-values calculated by applying the errors due to internal/ external temperature and heat flux.

$$\delta R_n = \sqrt{\left[\left(R_n - R_{err\_Tsi}\right)^2 + \left(R_n - R_{err\_Tse}\right)^2 + \left(R_n - R_{err\_Q}\right)^2 + S.D.^2\right]} \qquad (2)$$

As the R-value calculated converges asymptotically to the final value of R_n and as we were only interested in the final average value, the combined uncertainty was evaluated only in the period

of the last temperature wave experiment (last 24hours). The measurement of the statistical uncertainty (expanded uncertainty) can be taken into account assuming a coverage factor (k) equal to

2, which is the typical value in this kind of measurements. This coverage factor leads to a confidence level of approximately 95% (Baker, 2011). The final R-value can be expressed by Equation 3.

$$R = R_n \pm k.\delta R_n \qquad (3)$$

3. Results and discussion

The first test was conducted in the block's solid face. The test was carried out during three and a half days as presented in the Figure 3. It is possible to notice that the calculated value converges asymptotically with the real value, as desired. The surface

temperature difference between the two faces of the sample (~13.4°C) was not high because RCDW blocks are not considered good isolators (Table 1). The mean heat flux through the block was 76Wm^{-2}. R_n oscillates until it settles and the oscillation has low amplitude

because of the good constancy of the temperature difference established, remaining near 6.35% (Figure 3a). The R-value estimated and the error analysis is presented in the Table 1, and the mean R1-values and the test uncertainties were 0.18m^{2}KW^{-1}±0.02m^{2}KW^{-1}.

Sensor position		(a) Solid face	(b) Face with air void
Variables average values (24hours)	Difference temperature	13.41°C	12.81°C
	Internal Surface Temperature	55.88°C	55.33°C
	External Surface Temperature	42.47°C	42.53°C
	Heat flux	76.35 Wm^{-2}	66.93Wm^{-2}
	Average Rn-value	0.18m^{2}KW^{-1}	0.19m^{2}KW^{-1}
	Overall uncertainty δRn	0.01m^{2}KW^{-1}	0.01m^{2}KW^{-1}
Error analysis	R_{err_Tsi} (sensor error 0.25°C)	0.18 m^{2}KW^{-1}	0.2 m^{2}KW^{-1}
	R_{err_Tse} (sensor error 0.25°C)	0.18 m^{2}KW^{-1}	0.2 m^{2}KW^{-1}
	R_{err_Q} (5% heat flux)	0.18 m^{2}KW^{-1}	0.2 m^{2}KW^{-1}
	standard derivation (S.D.)	0.004m^{2}KW^{-1}	0.002m^{2}KW^{-1}
	Percentage error	6.35%	6.05%

Table 1
R$_n$ value estimation of RCDW wall 1: (a) in the solid face and (b) in the face with air void.

Figure 3
Internal and external surface temperature in the wall experiment and thermal resistance in (a) solid surface and (b) in the face with air void.
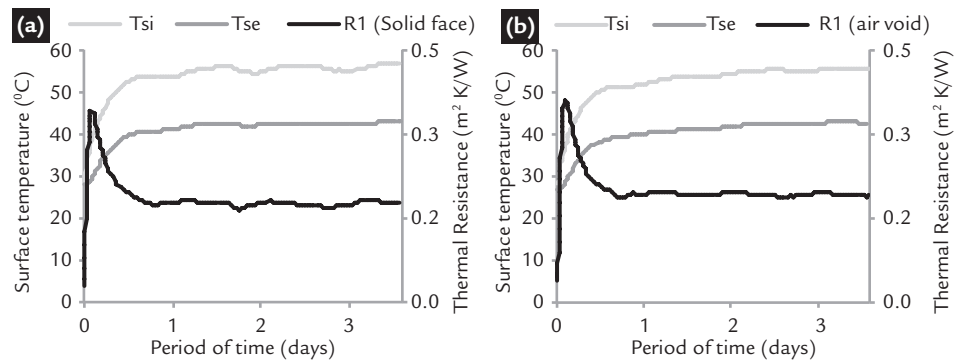
Another test was performed with the sensor installed in the face of the sample where there is a presence of an internal air void (Figure 3b). The internal and external surface temperatures were similar to that observed in the first test (Table 1), but the heat flux was 9.5Wm^{-2} lower than the heat flux observed in the solid region of the wall. The behavior was attributed to the presence of the unventilated air layer within the wall (thickness layer higher than 25mm) which has a similar thermal resistance design value to that of the concrete blocks made of RCDW (R$_{airlayer}$=0.18m^{2}KW^{-1}) (ISO 6946, 2008; ABNT, 2003). The estimated R1-value and the error analysis is presented in the Table 1 and the mean R1-values and the uncertainties for the measurement test was 0.19m^{2}KW^{-1}±0.02m^{2}KW^{-1}.

The experiments were repeated in one more RCDW sample. The results were similar to the first with small differences in the internal and external temperature and in heat flux through the wall. The mean R2-values were similar and the uncertainties for the measurement experiments in solid and in internal air void position were 0.19m^{2}KW^{-1}±0.02m^{2}KW^{-1}

and 0.21m^{2}KW^{-1}±0.02m^{2}KW^{-1}, respectively. The observed differences were only 0.02m^{2}KW^{-1} between the experiments. For a concrete with density between 1600-2100kgm^{-3} (density near the RCDW blocks), the thermal conductivity was equal to 1.40Wm^{-1}K^{-1} (ABNT, 2003), and thermal resistance was equal to 0.09m^{2}KW^{-1}. This value is lower than the RCDW blocks in the solid region.

The overall thermal resistance of the block was calculated weighing the thermal resistance obtained in the two experiments in the solid and air void region by its respective areas in the cross section of the block (ABNT, 2003). The R1-value and R2-value of overall thermal resistance were 0.18m^{2}KW^{-1}±0.02m^{2}KW^{-1} and 0.20m^{2}KW^{-1}±0.02m^{2}KW^{-1}. The confidence interval was set at 0.16≤RT≤0.22m^{2}KW^{-1}. The total thermal resistance was determined using the procedures established by NBR 15220 (ABNT, 2003), by adding the internal and external surface resistances to the overall thermal resistance of the block, which led to 0.35m^{2}KW^{-1}±0.02m^{2}KW^{-1} and 0.37m^{2}KW^{-1}±0.02m^{2}KW^{-1}, respectively. The confidence interval was set at

0.33≤RT≤0.39m^{2}KW^{-1}.

The RCDW concrete conductivity (inferior, mean and superior λ-value) was determined by dividing the block thickness by its thermal resistance in the solid region. Following this procedure for the first and the second experiment, the confidence interval was set at 0.60≤λ≤0.78Wm^{-1}K^{-1}. It is expected that RCDW concrete would display lower values of thermal conductivity than the conventional concrete not only due to the presence of aggregate with a lower density and lower thermal conductivity (like ceramic brick and gypsum) than the natural aggregate, but also due to the higher porosity observed in mixture. Leiva *et al.* (2012) tested RCWD and conventional concrete blocks and determined 0.66Wm^{-1}K^{-1} and 1.63Wm^{-1}K^{-1} of thermal conductivity, respectively.

The total thermal resistance of the RCDW wall was inferior to the usual Brazilian construction wall made of external and internal mortar and ceramics blocks with internal voids (thermal resistance varying from 0.4 to 0.45m^{2}KW^{-1}). NBR 15220 (ABNT, 2003) divided Brazil into eight bioclimatic regions and depending on

the building's region of installation, it stated that for exterior walls with absorptance superior 0.6, the walls must have a total transmittance lower than 2.50Wm⁻²K⁻¹ in order to avoid excessive heat gain. The transmittance of the RCDW wall can be obtained inverting the total thermal resistance determined (U=1/R = 2.57 and 3.03Wm⁻²K⁻¹). RCDW blocks are made of cement and their final color is clay. Thus, the absorptance is higher than 0.6. Thereby, RCDW walls were not indicated to be used in some Brazilian bioclimatic regions. It was suggested that the external wall be painted with light colors (absorptance lower than 0.6) to attend the Brazilian code. Another possibility was to introduce internal/external mortar (0.025m) in the RCDW wall to reduce the thermal resistance to 0.4m²KW⁻¹, a value close to the usual Brazilian wall.

4. Conclusions

The adapted methodology was able to determine the thermal resistance of an RCDW wall and the following conclusions can be stated:

(a) The block's overall thermal resistance was set at $0.33 \leq RT \leq 0.39 m^2 KW^{-1}$, inferior to traditional ceramic blocks with mortar, utilized in Brazilian construction walls; (b) The RCDW concrete thermal conductivity varies from $0.60 \leq \lambda \leq 0.78 Wm^{-1}K^{-1}$, which is lower than the 1.40 Wm-1K⁻¹ presented in NBR 15220 (ABNT, 2003) because recycled material has lower thermal conductivity than natural aggregate; (c) It was necessary to paint the external wall with light colors to attend the thermal transmittance stipulated in the Brazilian code; this procedure makes it possible to use RCDW blocks as a building component; therefore, it is an alternative material to reduce the delivery of construction and demolition waste to the public landfills and to illegal places; (d) The chamber utilized helped to improve building thermal performance because it allowed modifications to be introduced in the building design phase; it permits the determination of the R-value of a building envelope with material that will be used in the region of implantation, which leads to a more realistic thermal insulation for the building envelope than values stipulated in codes; and (e) In contrast, the chamber has the disadvantages of measuring thermal properties under laboratory-controlled climate.

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