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THERMO-ENERGETIC PERFORMANCE OF INSULATED CONCRETE FORMS: IMPROVEMENTS IN LOW-INCOME HOUSES IN THE CLIMATE OF SÃO PAULO

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ABSTRACT

Insulated concrete form (ICF) is an evolving construction system that could offer desired advantages in civil construction. The purpose of this study was to evaluate the thermo-energetic behavior of the ICF for use in low-income housing under climate conditions of São Paulo city – Brazilian bioclimatic zone 3. By using the Brazilian Technical Regulation of Quality for the Energy Efficiency Level of Residential Buildings (RTQ-R), the performance of the envelope of a single-family dwelling was analyzed by comparing the ICF system with materials conventionally used in walls. The analysis showed that ICF allow more energy efficient dwellings than masonry in ceramic or concrete bricks. The innovative construction system offers better conditions for summer and winter analysis. Compared to the bricks used in Brazilian civil construction and considering low solar absorptance in envelope, the ICF can offer a superior performance in 6.4% for summer and 15.9% for winter. With high solar absorptance envelope, the ICF can offer superior performance in 11.5% for summer and 20.8% for winter. The results demonstrate the good performance of the technique and suggest its application to obtain energy efficient buildings that contribute to sustainability.

KEYWORDS: Construction materials and components, Energy efficiency in buildings, Expanded polystyrene, ICF system, RTQ-R.

DESEMPENHO TERMOENERGÉTICO DO SISTEMA *INSULATED CONCRETE FORMS*: MELHORIAS EM CASAS POPULARES NO CLIMA DE SÃO PAULO

RESUMO

Insulated Concrete Forms (ICF) é um sistema construtivo em desenvolvimento, que pode oferecer benefícios almejados na construção civil. O objetivo deste estudo foi avaliar o comportamento termoenergético do ICF para o uso em habitações populares, considerando as condições climáticas da cidade de São Paulo – zona bioclimática 3. Utilizando o Regulamento Técnico da Qualidade para o Nível de Eficiência Energética de Edificações Residenciais (RTQ-R), analisou-se o desempenho da envoltória de uma habitação unifamiliar, comparando-se o sistema ICF com técnicas tradicionais no Brasil. A análise comprovou que o ICF permite habitações com maior eficiência energética do que a alvenaria em tijolos cerâmicos ou de concreto. O sistema construtivo inovador proporcionou resultados melhores para as análises da envoltória nas condições de verão e de inverno. Em comparação com os blocos tradicionais utilizados na construção civil brasileira e considerando baixa absortância solar na envoltória, o ICF acarretou um desempenho superior em 6,4% para o verão e 15,9% para o inverno. Com alta absortância solar no envelope, o ICF proporcionou um desempenho superior em 11,5% para o verão e 20,8% para o inverno. Os resultados deste estudo demonstram o bom desempenho do sistema construtivo ICF e sugerem a sua aplicação para se obter edificações energeticamente eficientes e que contribuem para a sustentabilidade.

PALAVRAS-CHAVE: Eficiência energética em edificações, Sistema construtivo ICF, Materiais e componentes de construção, Poliestireno expandido, RTQ-R.

1 INTRODUCTION

Energy demand in Brazilian buildings has grown exponentially in the last decades and, according to Brasil (2016), the perspective is of a growing expansion of the number of buildings. Currently, there are approximately 63 million residential buildings and it is estimated that 13 million more will be built in the next 10 years. There is a deficit of more than 6 million dwellings in Brazil (Fundação João Pinheiro, 2018). Adding to the fact that the construction sector is expecting accelerated growth, the prospect of a relevant growth of energy demand in this group of consumers in the long term is signaled. Research shows that by 2050 energy consumption in the residential sector could more than double (Brasil, 2016).

Electricity consumption in Brazil is high because heat waves throughout the country influence the growth of air conditioners use. Thus, from an irregular rainfall regime, resulting from constant climate change, in 2014 the capacity of hydroelectric plants to supply electricity to the country was questioned (Cerqueira *et al*., 2015). According to Brasil (2019), nearly 51% of the electricity required in the country is used in buildings. Additionally, the data show that residential buildings consume about 25% of total electric demand. Studies developed by the Brazilian Energy Research Company (Brasil, 2016) characterized the expectation of electric energy consumption by classes of consumer equipment up to 2050. It was observed that the consumption with air conditioning, related to inefficient envelopment, tends to remain the most representative type of electricity consuming. A thermally efficient envelope can be characterized as one that provides indoor thermal comfort with the lowest energy consumption for artificial conditioning (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2007; Barrios, Huelsz, Rojas, Ochoa & Marincic, 2012). According to Zhu, Hurt, Correia and Boehm (2009), Batista, La Rovere and Aguiar (2011) and Lopes, Romeu, Azenha and Ferreira (2018), the building envelope comprises the most important system in the energy assessment since it separates the external and internal environments. Thus, much of the consumption with environmental conditioning could be avoided if the buildings were designed in such a way as to ensure comfort to users even on the hottest days of the year.

In Brazil, the classification of energy efficiency of residential buildings as per the Brazilian Labelling Program [PBE] is regulated by the Technical Regulation of Quality for the Energy Efficiency Level of Residential Buildings [RTQ-R] (Instituto Nacional de Metrologia, Qualidade e Tecnologia [INMETRO], 2012) that classify the buildings from more efficient levels (level A) to less efficient (level E). The regulation establishes, for example, requirements, scoring criteria and methods of thermo-energic analysis of building envelope. The housing envelope should be analyzed from three criteria: efficiency in summer, when naturally ventilated; efficiency in winter, when heated artificially; and efficiency when artificially cooled, the latter being only informative.

Recent research has been making use of the RTQ-R as a criterion for the performance of conventional and innovative building systems for residential buildings. In this context, the studies of Amorin and Vieira (2016), Bortone, Zara, Giglio and Yokota (2018), Invidiata, Souza, Melo, Fossati, and Lamberts (2016), Rocha, Barros, Leite and Petreche (2016), and Zara, Santos and Giglio (2018) can be cited.

The Architecture, Engineering and Construction [AEC] industry has several construction systems for housing. However, in Brazil, more traditional systems, such as conventional ceramic brick masonry and structural concrete brick masonry, are those that have greater use (Marinoski, 2011; Molina & Calil Júnior, 2010; Nichele, 2014; Pereira, 2018). On the other hand, several researches (Bodach & Hamhaber, 2010; Bortone *et al*., 2018; Marafon, Laco, Sanches, Leão, & Borges Leão, 2014; Moreno, Morais & Souza, 2017; Sorgato, Melo, Marinoski & Lamberts, 2014; Zara *et al*., 2018) prove that these constructive systems have low thermal performance for different Brazilian climates and often do not meet the NBR 15575 (Associação Brasileira de Normas Técnicas [ABNT], 2013) standard.

Alternative building techniques that prioritize the issues of environmental preservation, comfort, or even the agility and economic viability of the material, should be studied (Al Sehaimi, Koskela & Tzortzopoulos, 2013; Birkeland, 2012). In this context, the Insulated Concrete Forms [ICF] construction system is an alternative. The technique uses expanded polystyrene [EPS] as forms. After assembly, the forms are filled with reinforced concrete, forming the structural and sealing walls of the building.

The ICF promises important benefits for the AEC industry, combining agility, durability, energy efficiency and thermal comfort (Petrie *et al*., 2002; Kosny *et al*., 2002; Solomon & Hemalatha, 2020). Petrie *et al*. (2002) and Kosny *et al*. (2002) demonstrate the superiority of thermo-energetic behavior in residential buildings built with the ICF system in the United States. In the study by Petrie *et al*. (2002) it was observed that a house in ICF consumes from 7.5% to 9.2% less energy than a typical American wood frame house. In addition, the results of Kosny *et al*. (2002) have shown that, in some United States locations, heating and cooling energy demands for buildings with massive walls with relatively high thermal resistance (ICF) may be lower than those in similar buildings constructed using low thermal resistance walls. The numerical values showed that the change in the thermal resistance of the wall can influence between 5 and 8% the energy consumption in buildings and that the ICF is a suitable practice for such improvement (Kosny *et al*., 2002). Solomon and Hemalatha (2020) analyzed the structural and thermal performance of the ICF; in the experiments the ICF composition showed a plastic deformation 78 times higher than concrete plain. In addition, the ICF achieved thermal resistance of 5.22 m^2K/w, a value 7.9 times higher than concrete plain. The properties of the innovative construction system show that the ICF helps in the sustainable building construction with high thermal insulation and better structural strengths (Solomon & Hemalatha, 2020).

The ICF construction system has a high development propensity in the Brazilian AEC industry. However, because it is a relatively new vertical sealing technology in the country, there is a lack of studies that show the energy efficiency of the system. Therefore, it is necessary to carry out studies, which seeks to analyze sealing materials and relate them to the reduction of electric energy consumption in a dwelling. In this paper, a study of the ICF is carried out comparing it with the sealing systems conventionally used in the construction of low-income houses, emphasizing the climate of Sao Paulo. The results of this study report information that contributes to the development of the innovative construction system in Brazil.

2 METHOD

In the present paper, by using the RTQ-R method (INMETRO, 2012) the thermo-energetic performance of residential buildings is analyzed according to the material used for walls. The methodology is based on studies that analyzed the thermo-energetic behavior of residential buildings by the method of the Brazilian regulation of labelling.

This chapter presents the object of study, the stages of research development and procedures for determining the energy efficiency of the construction technologies considered.

2.1 Object of study

The building object of study consists of a single-family dwelling with design proposed by Caixa Econômica Federal (2007), based on the federal government's *Minha Casa Minha Vida* housing program. Through this program, more than three million homes have already been built (Paulsen & Sposto, 2013). The building chosen is a detached one-story house in contact with the ground. The house was analyzed as shown in Figure 1. The dwelling is composed of a living room, a kitchen, two bedrooms and a bathroom, with a total area of 42 m². The height of the ceiling is 2.80 m.

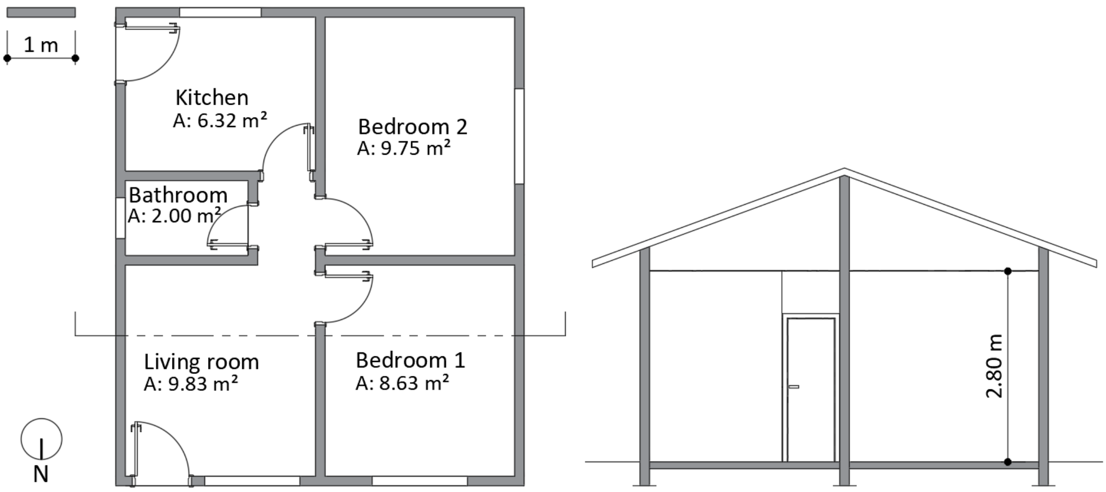


Figure 1: Floorplan and section of the single-family detached house

In this type of housing, the external and internal walls are usually made of ceramic or concrete bricks with 9.0 cm thick and a layer of mortar of 2.5 cm thick on each side. The roof is made of a wooden structure (non-ventilated attic) with a ceramic tile surface. The ceiling is a suspended structure of PVC lining or reinforced concrete slab. The floor is made of a 5.0 cm thick concrete layer covered with ceramic tiles. The windows consist of aluminum frames with two sliding panels and simple clear glass 3 mm thick, without shading elements. The solar absorptance of the roof corresponds to the natural color of the tile (75%) and the solar absorptance of the walls usually varies from 20% to 75%.

In order to represent different vertical sealing materials applied and present the performance of the ICF, the house was analyzed considering the application of ceramic bricks of 9.0 cm and 14.0 cm, concrete bricks of 9.0 cm and 14.0 cm, and ICF with EPS formwork of 14.0 cm thick. Also, in order to identify the best thermo-energetic performance of the building, 19 cases with different combinations of components and absorptance of the envelope were elaborated. Variations in walls and roofs are listed in Table 1 and the 19 cases evaluated are shown in Table 2.

Table 1: Variations in roofs and walls

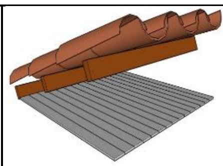
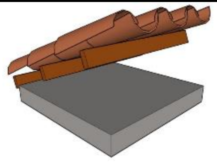
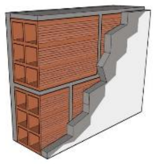
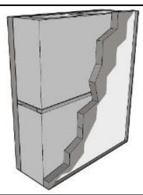
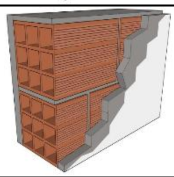
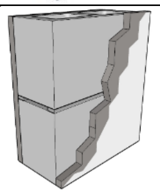
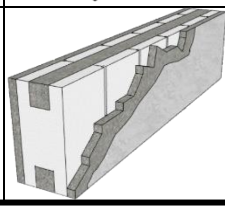
Code		Specification		Thermal transmittance [W/(m²•K)]	Thermal capacity [kJ/(m²•K)]
Roof	R1	Ceramic tile, wood structure and PVC lining		1.75	21
	R2	Ceramic tile, wood structure and reinforced concrete slab		2.05	238
Wall	W1	9.0 cm ceramic brick with 2.5 cm plaster on each face		2.46	150
	W2	9.0 cm concrete brick with 2.5 cm plaster on each face		2.78	209
	W3	14.0 cm ceramic brick with 2.5 cm plaster on each face		1.85	161
	W4	14.0 cm concrete brick with 2.5 cm plaster on each face		2.69	272
	ICF	ICF 14.0 cm with 2.5 cm plaster on each face		0.41	194

Table 2: Specifications of the 19 cases analyzed

Cases	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
Wall code	W1	W1	W2	W2	W3	W3	W4	W4	ICF	ICF	W3	ICF	W1	W2	W3	W4	ICF	W3	ICF
Wall absorpt.	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	50%	50%	20%	20%	20%	20%	20%	20%	20%
Roof code	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R2	R2	R1	R1	R1	R1	R1	R2	R2

Roof absorpt.	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	20%	20%	20%	20%	20%	20%	20%

2.2 Climate conditions

The Brazilian territory is divided into eight bioclimatic zones, where Z1 is the coldest zone and Z8 is the hottest one (ABNT, 2005). The bioclimatic zone 3 [Z3] is characterized by regions with a softer climate, with dry and cold winters and humid and hot summers (Ferreira, Souza & Assis, 2014).

In order to evaluate the thermo-energetic performance of the house (Figure 1), according to the different cases of involvement proposed in Table 2, the Z3 was chosen, covering much of the southern and southeastern region of the country. Most of the Brazilian population is concentrated in these regions (Instituto Brasileiro de Geografia e Estatística, 2018). Additionally, the Z3 covers important cities in Brazil, such as São Paulo, Belo Horizonte, Florianópolis and Porto Alegre. In this study, São Paulo (Figure 2) was chosen as the representative city for the application of the RTQ-R method.

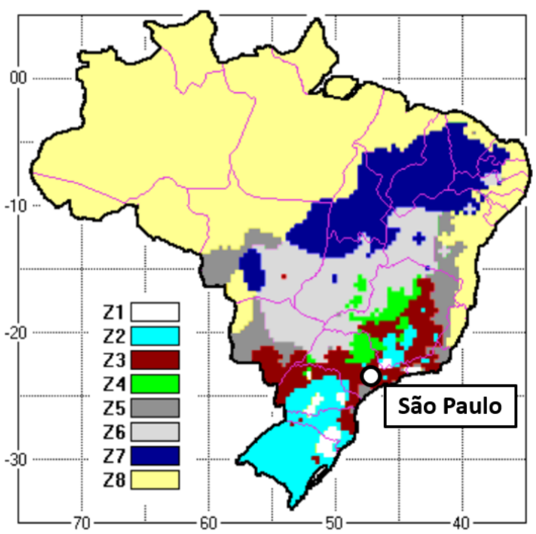


Figure 2: Map of Brazil with bioclimatic zoning and the location of the São Paulo city

2.3 Use of the RTQ-R

The RTQ-R prescriptive method evaluates the envelope through prerequisites, tables, equations, and performance indicators, providing a score indicating the partial efficiency level of each long permanence room (living rooms and bedrooms) and total according to the bioclimatic zone in which the building is located. Alternative to the prescriptive method, there is the simulation method, which compares the results obtained in computational simulations with reference values pre-established in RTQ-R to determine the level of energy efficiency of the evaluated building. However, the prescriptive method is mostly used in Brazilian housing labelling (INMETRO, 2019).

In the RTQ-R prescriptive method the following variables are considered to evaluation: solar orientation and area of openings, contact of the building with the ground, solar exposure of the roof, area of external and internal walls, useful area of rooms, ceiling height, thermal transmittance of walls and roofs, thermal capacity of walls and roofs, percentage of openings for ventilation and natural lighting and presence of shading elements in openings.

The evaluation of the envelope, using the RTQ-R (INMETRO, 2012), is elaborated from an indicator of degree-hour for cooling [DHC], when naturally ventilated, and indicators of annual relative energy consumption per square meter for heating [RCH] and cooling [RCC], obtained according to linear equations by inserting parameters related to the physical characteristics and thermal properties of the building envelope. The efficiency parameters have the following characteristics: DHC (measured in °Ch) represents the annual sum of degrees hour for the base temperature of 26 °C for cooling; RCH (measured in kWh/m²/year) represents the annual consumption for environmental heating during the period from 9.00 p.m. to 8.00 a.m., every day of the year, with maintenance of the temperature at 22 °C; e RCC (measured in kWh/m²/year) represents the annual consumption for environmental cooling during the period from 9.00 p.m. to 8.00 a.m., every day of the year, with maintenance of the temperature at 24 °C, the latter being only informative and not entering into the performance weighting of the envelope.

It was analyzed the envelope of summer and winter and when artificially cooled, corresponding to DHC, RCH and RCC, respectively. The electronic worksheet (INMETRO, 2017) provided by PBE was used for the calculations proposed by the Brazilian regulation RTQ-R (INMETRO, 2012). Based on the DHC, RCH and RCC indicators obtained, the thermal performance of each long permanence room was determined by means of its numerical equivalent for natural ventilation [$NumEqRoomEnv_{NatV}$], heating [$NumEqRoomEnv_{H}$] and cooling [$EqNumRoomEnv_{C}$] according to the RTQ-R reference values shown in Table 3.

Table 3: Reference values for bioclimatic zone 3 for the energy efficiency levels of the envelope of each long permanence room

Level	NumEqRoomEnv	DHC [°Ch]	RCH [kWh/m²/year]	RCC [kWh/m²/year]
A	5	DHC ≤ 822	RCH ≤ 6.429	RCC ≤ 6.890
B	4	822 < DHC ≤ 1643	6.429 < RCH ≤ 12.858	6.890 < RCC ≤ 12.284
C	3	1643 < DHC ≤ 2465	12.858 < RCH ≤ 19.287	12.284 < RCC ≤ 17.677
D	2	2465 < DHC ≤ 3286	19.287 < RCH ≤ 25.716	17.677 < RCC ≤ 23.071
E	1	DHC > 3286	25.716 > RCH	RCC > 23.071

According to RTQ-R (INMETRO, 2012), in order to obtain an overall performance indicator of the housing envelope, the numerical equivalents of each long permanence room were weighted by using Equations 1, 2 and 3.

$$NumEqEnv_{NatV} = \sum \frac{NumEqRoomEnv_{NatVi} \times ARoom_i}{TA} \quad (1)$$

$$NumEqEnv_{H} = \sum \frac{NumEqRoomEnv_{Hi} \times ARoom_i}{TA} \quad (2)$$

$$NumEqEnv_{C} = \sum \frac{NumEqRoomEnv_{Ci} \times ARoom_i}{TA} \quad (3)$$

Where:

$NumEqEnv_{NatV}$ is the numerical equivalent of the housing envelope for natural ventilation;

$NumEqEnv_{H}$ is the numerical equivalent of the housing envelope for heating;

$NumEqEnv_{C}$ is the numerical equivalent of the housing envelope for cooling;

$NumEqRoomEnv_{NatVi}$ is the numerical equivalent of the envelope of each room of the housing for natural ventilation;

$NumEqRoomEnv_{Hi}$ is the numerical equivalent of the envelope of each room of the housing for heating;

$NumEqRoomEnv_{Ci}$ is numerical equivalent of the envelope of each room of the housing for cooling;

$ARoom_{i}$ is the area of each room of long permanence of the housing;

TA is the total area of the long permanence rooms of the housing.

Finally, the numerical equivalent of the housing envelope [NumEqEnv] was determined through an equation that correlates the importance of the level of energy efficiency for cooling [$NumEqEnv_{NatV}$] and heating [$NumEqEnv_{H}$] for bioclimatic zone 3, according to Equation 4. The numerical equivalent of the envelope for cooling consumption [$NumEqEnv_{C}$] is informative only and is not considered in the calculation of the numerical equivalent of the housing envelope. The efficiency of the housing envelope is classified by means of Table 4.

$$NumEqEnv = 0.64 \times NumEqEnv_{NatV} + 0.36 \times NumEqEnv_{H} \quad (4)$$

Table 4: Energy efficiency levels according to numerical equivalents

Level	NumEqEnv
A	4.5 ≤ EqNumEnv
B	3.5 ≤ EqNumEnv < 4.5
C	2.5 ≤ EqNumEnv < 3.5
D	1.5 ≤ EqNumEnv < 2.5
E	EqNumEnv < 1.5

3 RESULTS AND ANALYSIS

The results of the analysis of energy efficiency levels of the building envelope are presented according to the Brazilian regulation RTQ-R (INMETRO, 2012). This way the following sections show the analysis for the summer situation, when naturally ventilated; the analysis for the winter situation, when artificially heated; the analysis for the summer situation, when artificially cooled; and the analysis of the weighted envelope for the summer (when naturally ventilated) and winter.

3.1 Summer situation (naturally ventilated building)

Figure 3 shows the performance results for summer with the efficiency level limits for the degree-hours for cooling indicator.

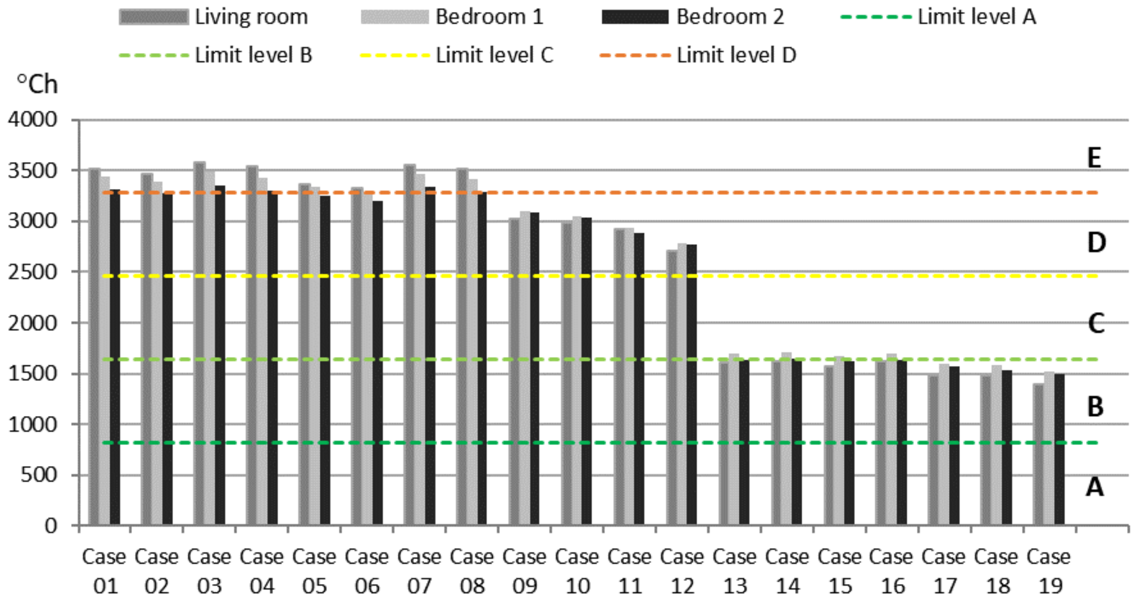


Figure 3: Degree-hours for cooling (DHC) indicators for each case

It can be observed that case 03 was the one that presented the worst performance among the 19 cases evaluated. In this situation, the envelope had walls in concrete bricks 9 cm with external painting of high solar absorptance (75%) and roofing with PVC lining and natural-colored ceramic tile – high solar absorptance (75%).

The case 01 presents similar configuration to case 03, being the masonry composed, however, by ceramic bricks. For this situation, where the difference is only the sealing material, a reduction of 151 °Ch (1.5%) is observed. The ICF under the same conditions as cases 01 and 03 is represented by case 09, where a reduction of 1202 °Ch (11.5%) was obtained. It should be noted, however, that the vertical closure in ICF has a final thickness of 19 cm in view of the 14 cm of the walls of concrete bricks and ceramic bricks of cases 01 and 03. This situation features a geometric divergence that could generate a gap that reasonably compromises the comparison between these three cases, considering possible differences in building areas.

Therefore, in order to have equivalent situations of geometry and envelope parameters and effectively characterize the performance of the construction systems, there are cases in which ceramic bricks and concrete bricks are used also with 14 cm – thickness equal to that of the ICF forms – creating closures with 19 cm. In equal situations of geometry and solar absorptance, the cases 05, 07 and 09 represent, respectively, the ceramic brick, concrete brick and ICF. Among the three, the one that presented the best behavior was case 09, consisting of walls in ICF. In this comparison, a reduction of 739 °Ch (7.4%) was obtained in relation to case 05 and 1144 °Ch (11%) in relation to case 07.

Another configuration that deserves to be highlighted among those that present high solar absorptance in walls and roof is that of case 10. As in case 09, previously reported, the envelope has walls in ICF with solar absorptance 75% in the whole envelope. Therefore, what distinguishes cases 09 and 10 is the building lining. In the first case the lining is PVC type, with 1 cm thickness, whereas the second is solid slab with 10 cm. The GHR indicators show that the slab lining contributes to an improvement in the thermal performance of the building due to its greater thermal capacity. Case 10 indicates a reduction of 139 °Ch (1.5%) compared to case 09.

Cases 01 to 10 present high solar absorptance both in walls and roof. Faced with this worst situation, the only building system that achieved level D of energy efficiency was the ICF. All other cases have reached level E. Cases 11 and 12, on the other hand, are situations that characterize a medium color tone (solar absorptance 50%) for walls and natural color (solar absorptance 75%) for ceramic roofing. In these configurations, the 14 cm ceramic brick (conventional constructive system with better performance among those evaluated) and the ICF are described. Again, it was possible to verify the superiority of the thermal performance of the ICF, comparing the GHR indicators. In this comparison the innovative construction system provided a reduction of 496 °Ch (5.7%).

Cases 13 to 19 describe situations with low solar thermal absorptance (20%) for walls and roofing. Cases 13 to 17 depict all five wall compositions considered and with PVC lining. In these conditions, the ICF provided a reduction in the DHC indicator of 288 °Ch (5.8%), 319 °Ch (6.4%), 203 °Ch (4.2%) and 294 °Ch (5.9%) in relation to the 9 cm ceramic brick, 9 cm concrete brick, 14 cm ceramic brick and 14 cm concrete brick, respectively. The last two cases, 18 and 19, present the two best results obtained: one of them corresponds to the conventional ceramic brick system of 14 cm and the other to the ICF system. The better behavior of the EPS material this time resulted in a reduction of 202 °Ch (4.4%) compared to the ceramic brick of the same thickness.

3.2 Winter situation (artificially heated building)

Figure 4 indicates the performance results for winter, through the relative energy consumption, delimited by the level of energy efficiency.

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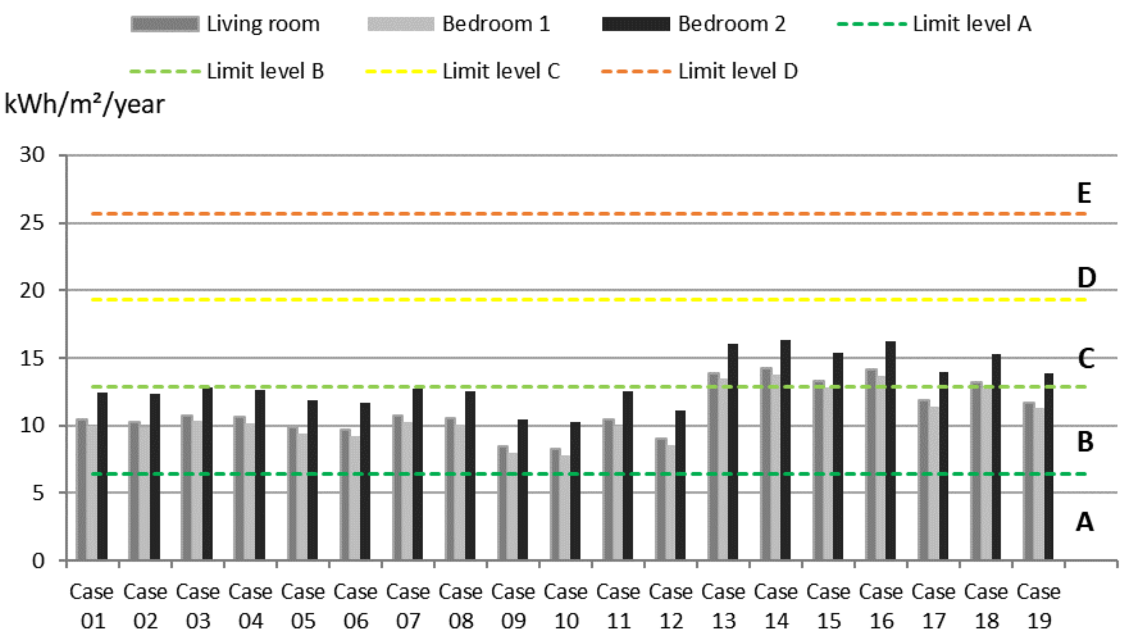

Figure 4: Relative energy consumption for heating (RCH) for each case

For cases 01 and 03, in which the variable is only the sealing material, it is again observed that the performance of the concrete brick is lower than that of the ceramic brick. The relative consumption for the situation with ceramic brick is 0.958 kWh/m²/year (2.8%) more economical than the concrete brick. The ICF material, under the same wrapping conditions as cases 01 and 03, is represented by case 09, in which there is a reduction of 6,085 kWh/m²/year (18.5%) and 7,042 kWh/m²/year (20.8%) of consumption for these cases, respectively. There is, however, a difference between the wall thicknesses that traditionally is 14.0 cm against the 19.0 cm of the ICF method.

In equal conditions of wall thickness, situations 05, 07, and 09 can be compared. In this evaluation the ICF provides a reduction in the relative consumption indicator for heating in the building of 4,237 kWh/m²/year (13.7%) on the ceramic brick and 6,783 kWh/m²/year (20.2%) on the concrete brick. It is evident the influence of the use of an insulating material that results in low transmittance to the envelope, improving its thermal performance.

In the configurations of cases 11 and 12, the 14.0 cm ceramic brick (conventional constructive system of better performance among those evaluated) and the ICF block studied are shown. The better thermal performance of the ICF, this time, provides a reduction of 4,273 kWh/m²/year (13%).

In situations 13 to 19, the walls and roof have low solar absorption (20%). Considering the comparison of cases 13 to 17, the ICF material provided a reduction in the consumption indicator for heating of 6.083 (14%), 7.042 (15.9%), 4.272 (10.3%) and 6.782 (15.4%) kWh/m²/year in relation to the 9.0 cm ceramic brick, 9.0 cm concrete brick, 14.0 cm ceramic brick and, 14.0 cm concrete brick, respectively. In other words, all cases in ICF showed superior performance.

3.3 Summer situation (artificially cooled building)

Figure 5 shows the performance results of the housing when artificially cooled, through the relative energy consumption indicator for cooling. The behavior of the building for artificial cooling situation is not considered in obtaining the score according to the level of efficiency of the envelope, however, the informative indicator is fundamental for a better analysis of the performance of the building envelope, besides being mandatory its presentation on the energy efficiency label. The RTQ-R (INMETRO, 2012) establishes that only the bedrooms should have this condition analyzed.

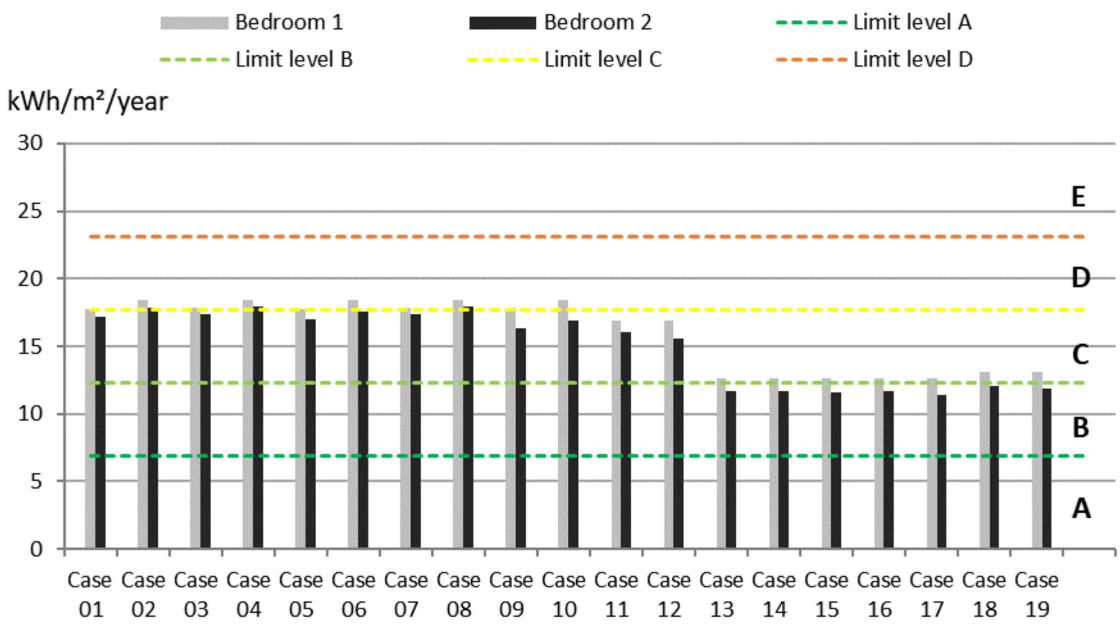

Figure 5: Relative energy consumption for cooling (RCC) for each case

The worst case that can be observed corresponds to number 08, a situation where the envelope has the highest thermal capacity. In this situation, the envelope presents walls with concrete bricks of 14.0 cm with external painting of dark color of high solar absorption (75%) and covering with ceiling in concrete slab and ceramic tile of natural color (75%). Under the same conditions, the ICF (case 10) contributes to a reduction of 1.039 kWh/m²/year (2.9%) in consumption.

Among the configurations that have high solar absorption in the entire envelope and PVC ceiling, comparing the results of conventional walls with ICF seals, the results are as follows: the sealing with EPS formwork (case 09) resulted in a reduction in the cooling indicator of 0.862 (2.5%), 1.039 (3%), 0.605 (1.7%) and 1.041 (3%) kWh/m²/year in relation to the 9.0 cm ceramic brick, 9.0 cm concrete brick, 14.0 cm ceramic brick, and 14.0 cm concrete brick, respectively. It is observed again the influence of the thermal capacity of the walls on the results, since the greatest differences occurred for the cases constituted of walls with concrete bricks.

In another combination, admitting walls with medium color (50%) and roofing with slab lining with natural colored roof (75%), cases 11 and 12 consist of the ceramic brick closures 14.0 cm and ICF, respectively. The analyses indicate similar consumption, but with a small saving of 0.395 kWh/m²/year (1.2%) provided by the ICF system in relation to the ceramic brick.

In the last scenario, in which it is considered the application of color with low solar absorption (20%) in the walls and coverings with PVC lining, there are cases 13 to 17. Situations 13, 14, 15 and 16 show very similar results, with differences about 1%. Taking the ICF as the most efficient and comparing with these cases there are savings of 0.21 (0.9%), 0.284 (1.2%), 0.146 (0.6%) and 0.314 (1.3%) kWh/m²/year. The differences are minimal, but still demonstrate the best performance of the ICF system also for the situation of mechanical cooling of the built environment.

Finally, cases 18 and 19 present higher consumption compared to previous cases of equivalent absorptance since they have a reinforced concrete slab ceiling, which increases the thermal capacity (heat storage) of the envelope.

3.4 Energy efficiency level of the building envelope

Table 5 shows the final energy efficiency levels for the housing envelope. It is noteworthy that the results are obtained by weighting the performance (DHC and RCH) of each long permanence room and its respective areas, according to RTQ-R (INMETRO, 2012).

Table 5: Energy efficiency levels according to numerical equivalents

Envelope analysis	Case 01	Case 02	Case 03	Case 04	Case 05	Case 06	Case 07	Case 08	Case 09	Case 10	Case 11	Case 12	Case 13	Case 14	Case 15	Case 16	Case 17	Case 18	Case 19
Natural ventilation	E	E	E	E	E	D	E	E	D	D	D	D	B	B	B	B	B	B	B
	1.00	1.35	1.00	1.00	1.35	1.65	1.00	1.00	2.00	2.00	2.00	2.00	3.69	3.69	3.69	3.69	4.00	4.00	4.00
Heating	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	B	C	B
	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.31	3.00	3.65	3.31	3.65
Cooling	C	D	C	D	C	C	C	D	C	C	C	C	B	B	B	B	B	B	B
	2.53	2.00	2.53	2.00	2.53	2.53	2.53	2.00	2.53	2.53	3.00	3.00	3.53	3.53	3.53	3.53	3.53	3.53	3.53
Final efficiency	D	D	D	D	D	D	D	D	D	D	D	D	C	C	B	C	B	B	B
	1.72	1.94	1.72	1.72	1.94	2.14	1.72	1.72	2.36	2.36	2.36	2.36	3.44	3.44	3.55	3.44	3.88	3.75	3.88

Among the configurations that have high solar absorption in the envelope (cases 01 to 10), the ICF presents better rates than all other construction systems. For the numerical equivalent of the envelope in summer situation (natural ventilation), case 06 was the only one composed of conventional masonry system (14.0 cm ceramic brick) that obtained a level D score, equal to that of the ICF (with difference in numerical value), for natural ventilation of the rooms. However, the final efficiency of the ICF was still higher than the reported case. For the worst performance situations, such as cases 01 and 03, the EPS blocks filled with reinforced concrete showed great superiority in the final score of the housing envelope.

Cases 11 and 12, which have a medium color on walls and dark color on the roof, show equal scores among themselves and between cases 09 and 10, also composed of ICF wall, but with dark color throughout the envelope. With that, it is observed that the slight improvement presented in the previous graphs, generated by the lower solar absorption of the walls and the fact that the buildings have PVC ceiling panels or reinforced concrete slabs, do not result in changes in the numerical equivalents of the envelope.

Analyzing now the situations in which low solar absorptance (white paint) was used in the entire envelope, as expected, the level of efficiency increased in all the construction systems analyzed. Cases 13 and 14, for example, which have an equivalent configuration to cases 01 and 03, had their overall envelope score significantly increased. Cases 15 and 16, which are like situations 05 and 07, but with a clear envelope, showed a general envelope performance being 83% and 91.7% more efficient. For the configuration composed of walls in ICF, analyzing the situations 09 and 17, it is observed that the application of light colors in the envelope provides an improvement of 64.4% in the energy efficiency score of the building envelope studied. Comparing the final numerical equivalent of the envelope of cases 13, 14, 16, and 17, with low solar absorption, the ICF system provides a score 12.5% higher than the walls of 9.0 cm ceramic brick and 9.0 cm or 14.0 cm concrete brick. When comparing the scores of the envelopes 15 and 17, the ICF results in a score 9% higher than when using a 14 cm ceramic brick.

Evaluating, finally, cases 18 and 19, which configure the conventional and innovative building systems with better results, it can be seen again the superior thermal behavior of the ICF. In this comparison, case 19 shows an overall envelope efficiency level 3.5% higher than case 18. Another evaluation can be made by the individual levels of the envelope, when only the ICF reaches level B in all conditions and the 14 cm ceramic brick is limited to the C score for the winter envelope.

4 CONCLUSIONS

In view of the lack of studies regarding the thermo-energetic performance of the ICF system in Brazil, compared to conventional masonry systems, it was possible to estimate the potential for thermo-energetic improvement of low-income houses that make use of this innovative construction system.

For summer conditions (natural ventilation), already admitting the use of light colors in the envelope as a strategy for better performance of the house, the ICF system can offer an average thermal performance of 6.4% higher than that obtained with conventional façades of ceramic or concrete bricks more used in Brazilian civil construction. In a more demanding situation, with dark colors, the ICF shows even greater benefit. It provides an 11.5% better performance than the closures commonly used in the Brazilian industry.

By evaluating the performance for winter (relative consumption for heating), with white walls, the ICF technology can offer an average saving of 15.9% in relative consumption for heating. When the exterior colors are dark, the ICF has even more advantage: it can offer an average saving of 20.8% in consumption with heating air conditioning.

Emphasizing, finally, the performance for mechanical refrigeration (relative consumption for cooling), the ICF system showed that it can offer, when dark colors are used in the envelope, on average 2.5% more savings with air conditioning than the most usual masonry compositions in Brazil. When white colors are used in the envelope of the building, the ICF offers thermal performance 1.2% higher than conventional façades.

In summary, as expected due to its low thermal transmittance, the ICF obtained the best performance in the different conditions evaluated according to the RTQ-R. The innovative construction system presented the highest overall score of the envelope and the highest score in the conditions of summer, winter and when the building is artificially cooled. Additionally, it was the only level B construction system in envelope energy efficiency for all envelope evaluations considered by the RTQ-R in bioclimatic zone 3.

The results obtained are attractive and promising. Due to the good thermal performance in summer conditions, better results are estimated for warmer climates. There is a need for further studies on the ICF construction system in other bioclimatic zones and in other situations, such as analysis of its structural performance, for example.

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