

THERMAL BRIDGES IN CONCRETE STRUCTURES: ANALYSIS OF THE CONDITIONS OF FILAMENTAL FUNGI DEVELOPMENT

PONTES TÉRMICAS EM ESTRUTURAS DE CONCRETO: ANÁLISE DAS CONDIÇÕES DE FORMAÇÃO DE FUNGOS FILAMENTOSOS

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Abstract

The importance of considering thermal bridges and their impacts on thermal transmittance calculation is an issue that has been discussed in cold season climate regions in Brazil. The presence of vulnerable points on the building envelope may affect thermal performance, besides the implications in the building walls and roofs' compositions, such as the filamentous fungi development. Internationally, it is observed the consideration of this theme in different rules and regulations. This study aims to discuss, through computer simulation, the need for Brazilian performance standards to consider the possibility of filamentous fungi formation in buildings with low and high thermal insulation. The analysis examines the thermo-hygrometric conditions near the building model's reinforced concrete structure where the thermal bridges occur and the surfaces of the vertical masonry enclosures for all facades. The results show a high probability of filamentous fungi growth in thermal bridges when the building is insulated, i.e., with low thermal transmittance. This study also points out that aspects related to the building's occupants, such as the control of natural humidity, can interfere with the indoor air's humidity level and, consequently, favor the formation of filamentous fungi.

Keywords: Thermal bridges. Filamentous fungi. Computer simulation.

Resumo

A importância de considerar as pontes térmicas e seus impactos no cálculo de transmitância térmica é um assunto que tem sido discutido em regiões de clima com estação fria no Brasil. A presença de pontos vulneráveis no envelope do edifício pode ter consequências no desempenho térmico, além de implicações nas composições de paredes e coberturas do edifício como, por exemplo, a formação de fungos filamentosos. Internacionalmente, observa-se a consideração desta temática em diferentes normas e regulamentos. Esse estudo tem por objetivo discutir, por intermédio de simulação computacional, a necessidade de as normas Brasileiras de desempenho considerarem a possibilidade de formação de fungos filamentosos nas edificações com baixo e elevado isolamento térmico. Na análise examinam-se as condições termo higrométricas próximas à estrutura de concreto armado do modelo da edificação onde ocorrem as pontes térmicas, e as superfícies dos fechamentos verticais de alvenaria, para todas as fachadas. Os resultados mostram que existe uma elevada probabilidade de crescimento dos fungos filamentosos nas pontes térmicas quando o edifício é mais isolado, ou seja, apresenta baixa transmitância térmica. Este estudo aponta também que aspectos relacionados aos ocupantes do edifício, como o controle da ventilação natural, podem interferir no nível de umidade do ar interno e, conseqüentemente, favorecer a formação de fungos filamentosos.

Palavras-chave: Pontes térmicas. Fungos filamentosos. Simulação computacional.

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Introdução

Due to the Brazilian energy sector crisis, which occurred in 2001, efficiency and optimization of energy use began to gain emphasis in the country. Therefore, performance and energy efficiency standards started to emerge. However, it is important to emphasize that the NBR 15.220 (2005) resulted from research that has been carried out since 1990 in Brazil.

In October 2001, Law 10.295 was published (BRAZIL, 2001), defining national policies on conservation and energy use. The first standard to evaluate the thermal performance in Brazil was published in 2005. The NBR 15.220 (ABNT, 2005) introduced recommendations on the thermal performance of single-family social housing applicable to the design phase. It established the Brazilian bioclimatic zoning, recommending constructive guidelines, and detailing passive thermal conditioning strategies for eight bioclimatic zones. Soon after, in 2008, the first version of NBR 15.575 (ABNT, 2013) was published, which evaluates, amongst other factors, the thermal performance of residential buildings and defines 13 aspects to be considered during the analysis of a residential building.

None of the Brazilian standards so far address thermal bridges or consider them in calculations of thermal transmittance. The existence of thermal bridges in a building can increase the enclosure's heat exchange and bring consequences for the building envelope. Among these consequences, we can mention increasing chances of filamentous fungi development and the direct interference of a building thermal comfort and energy consumption.

Several countries already consider the consequences of thermal bridges in buildings and have regulations to address the issue. EN ISO 14.683 (ISO, 2007) and EN ISO 10.211 (ISO, 1995) determine specific methods to calculate thermal bridges. The Portuguese Thermal Regulation (RCCTE) presents simplified methods to calculate thermal bridges. DIN 4103 (2013) is a German standard that addresses issues such as protection against moisture and the possibility of mold formation, and also presents calculation methods and construction guidelines. Argentine Standards IRAM 11.603 (IRAM, 2000) and IRAM 11.605 (IRAM, 1996) determine procedures to evaluate the risk of surface condensation and maximum thermal transmittance values for opaque closures.

Martin et al. (2011) emphasize the importance of calculating thermal bridges in heat transfer analysis in buildings, but the information is still limited and confusing. Most European Union countries use simplified methods to analyze thermal bridges, such as calculations in the stationary state, which would be insufficient, considering the importance of the building's inertia in energy demand.

One of the main consequences of thermal bridges in the building envelope, according to Evans and Schiller (2010), is the contribution to surface condensation. Condensation results directly in the formation of mold. In these cases, thermal bridges provide moisture condensation on the enclosure surfaces due to the surface temperature being lower than the dew point temperature. Regarding the influence of thermal bridges on the filamentous fungi development, Santos and Mendes (2014) state that the buildings' inner corners have less air circulation and higher relative humidity. This is due to the high hygrothermal capacity of the concrete from beams and pillars, where thermal bridges are located, there is a greater possibility of mold formation and structural damage.

According to Cunha, Vaupel, and Lüking (2008), buildings subject to low outdoor temperature conditions and low thermal resistance walls result in low indoor surfaces' low temperatures. When these factors are associated with inadequate occupant

behavior, especially in the ventilation aspect, it is inevitable to increase the indoor absolute humidity, generating high rates of relative humidity near the walls, which provides ideal areas for pathologies such as mold mildew.

Sedlbauer (2001) explains that although the quality of constructions has improved in recent decades, mainly through measures to reduce heat losses by ventilation and transmission, the number of microorganism building damage reports, especially by fungi, is increasing. One of the causes of mold and mildew increase in residential buildings is the combination of the sealing and insufficient ventilation. The work addresses the European context. Indoor air humidity increases, facilitating the formation of mold not only on the facades' inner surface but also on inner walls. Attention to the building envelope characteristics is essential for a healthy building. Through research and computer simulation, the authors prove the relation between thermal bridges and the possibility of filamentous fungi.

General considerations about thermal bridges

According to EN ISO 10.211-1 (ISO, 1995), thermal bridges constitute a part of the building envelope where thermal resistance is totally or partly modified by materials of different conductivity, change in the structure thickness or difference between outdoor and indoor structures, as in the wall/floor/ceiling connections.

Calculations of thermal bridges can be made using methods specified in regulations or by mathematical procedures, with specialized software. According to Oliveira (2013), there are automatic calculation software tools for thermal bridges. These are mainly based on introducing 2D or 3D geometric data of thermal bridges through a graphic interface. Some examples of software tools that work with 2D data are THERM®, BISCO®, PSI-THERM 2D® and TRISCO®, PSI-THERM 3D® that work with 3D data.

The impact of thermal bridges on energy consumption was analyzed by Cunha and Gioielli (2014). They observed the effect of thermal bridges of reinforced concrete structures on a hotel building's energy performance for Brazilian bioclimatic zones 1, 2, 3, and 4. The study concluded that in buildings with a window-to-wall ratio (WWR) of 30% to 45%, thermal bridges' existence implies a decrease in the consumption estimate. Depending on the bioclimatic zone, it can reach up to 10%. In the case of buildings with WWR of 60%, the failure to consider thermal bridges in the thermodynamic simulation can represent an increase of up to 4% on the consumption estimate, depending on the bioclimatic zone analyzed.

The study developed by Freitas and Cunha (2018) evaluated thermal bridges' impact on buildings' energy consumption in Brazilian bioclimatic zones 1, 2, and 3 (Brazilian coldest areas). Envelopes with different insulation levels and with different solar absorptions were evaluated. The study concluded that the outdoor surface color had the main influence on energy consumption fluctuation. In contrast, the thermal transmittance variation (U) of the building envelope had a minor influence. When the building energy model ignored the thermal bridges on vertical enclosures, energy consumption was lower in bioclimatic zones 1 and 2. In bioclimatic zone 3, the same situation resulted in higher consumption.

Levinskytė, Geležūnas, and Baniones (2016) developed an analysis of level "A" energy classification buildings in Lithuania and emphasized calculating linear transmission losses through thermal bridges. A semi-detached building was chosen to analyze the influence of thermal bridges through the THERM software. Two variations were examined - constructions without thermal bridge treatment and insulation and buildings with more effective thermal bridges' insulation solutions. Results showed that the most

substantial heat losses in the building occurred through walls and thermal bridges. Global heat losses reduced 10kWh/(m².year), about 20%, for the most energy-efficient construction and thermal bridges' treatment. The authors concluded that heat loss from a building designed with common thermal bridging solutions could be solved by increasing thermal insulation layers and using higher efficiency windows and doors. When a building was designed using effective solutions for linear thermal bridges, energy efficiency could be achieved with fewer insulation layers and doors and windows with inferior thermal behavior.

Freitas and Cunha (2018) analyzed the impact of thermal bridge modeling through computer simulation with EnergyPlus software in a residential building located in Southern Brazilian climate, considering two types of thermal insulation in the building and three scenarios. In the first one, thermal bridges were detailed on the envelope modeling through computer simulation, although the software could not effectively calculate thermal bridges' effect. In the second scenario, the traditional modeling used for computer simulation was considered, regardless of thermal bridges; and the third scenario acknowledged the calculation of thermal bridges according to EN ISO 10.211 (ISO, 1995), and the building thermal transmittance was altered as a function of thermal bridges. Results showed that the type of simulation modeling influenced the energy consumption results. Disregarding thermal bridges on the simulation (scenario 2) resulted in higher thermal comfort and lower energy consumption for the two types of insulation analyzed, leading to underestimating the building energy consumption and masking the thermal comfort results. The scenarios with thermal bridges presented higher energy consumption and inferior thermal comfort conditions.

Theodosiou and Papadopoulos (2008) carried out a computer simulation study on the impact of thermal bridges on typical Greek architecture buildings built with double-brick walls, which generally does not meet the performance regulations. The authors comment that, despite the thermal insulation required by the regulations, thermal bridges remain a weak point and conclude that the double-brick walls, which are widely used in Greece, are susceptible to thermal bridges. Considering that the buildings constructed in the last 20 years are partially insulated and do not consider calculating the actual thermal losses caused by thermal bridges, the thermal losses could be up to 35% higher than estimated without considering the thermal bridges. Even when using a better insulation system in buildings, heating expenses were 30% higher when calculated through the method that does not take thermal bridge calculations into account, showing that the legislative framework is insufficient, leading to a significant underestimation of the real power consumption.

General considerations about filamentous fungi

Guerra et al. (2012) suggest that the biodegenerative process known as mold is formed by filamentous fungi and characterized by the formation of stains due to the release of pigments or the presence of mycelium. It results from the formation of a mass of asexual spores, called "conidia". The "conidia" is dispersed by the air, water, insects, and other means, and when consolidated in a substrate, can germinate, generating new colonies.

Fungi are mainly terrestrial organisms that cannot produce their food (heterotrophic) and produce digestive enzymes that attack the material body to decompose organic matter. They are mostly, filamentous which are called "hyphae," and the organism's set of hyphae is known as "mycelium" (RAVEN; EICHHORN; EVERT, 2014).

According to Caneva, Nugari, and Salvadori (2000), physical or mechanical processes (disintegration or fracture) and chemical processes (decomposition) are the

mechanisms that can promote the biodegradation of materials. The agents responsible for degeneration, the type of substrate, and the environmental conditions will determine these processes' predominance. Biodegradation can occur in various kinds of materials and depend on the substrate characteristics, type of organism involved, and environmental conditions.

Sedlbauer (2001) states that ideal temperature and humidity conditions associated with nutrient availability and optimal pH factors may favor pathological manifestations related to filamentous fungi. According to Guerra (2012), the pH range between five and seven would be ideal for fungus growth; however, pHs between two and eleven are tolerated by a few species. Most species grow within a range of three to nine. Construction materials such as concrete have pH values higher than twelve. However, fungal growth on these materials cannot be extinguished since the relationship with the nutrients available will also influence these microorganisms' formation. Besides that, the fungus can change their direct environment's pH value by releasing several organic acids, making the extracellular space conducive to their development.

When the relative humidity of a building's inner wall surface is greater than or equal to 80% for six hours or more per day, mold may develop. The ideal air relative humidity for the development of mold is between 90% and 98%. However, some species, such as xerophile fungus, can grow under a relative air humidity range of up to 65% (KIEBL; SEDLBAUER, 2001). For Grunewald, Nicolai, and Zhang (2012), the microclimate near the inner walls' surface is related to heat production, user behavior, ventilation, and building envelope design, especially related to thermal bridge formation, humidity transport, and air changes per hour.

The temperature influences the air relative humidity level and the water content of the substrate in an essential way. Therefore, the environmental temperature reflects on the construction materials' moisture level. Warm environments have low relative humidity. When the surface temperature is lower than the dew point temperature, surface condensation may occur. Guerra (2012) emphasizes that moisture is the main factor for mold appearance, maintenance, and growth.

Sedlbauer et al. (2001) studied building materials' resistance to microorganism attacks. The authors concluded that controlling the environmental conditions, mainly humidity and temperature, are determinant factors to avoid a microbiological attack, but the materials' physical and chemical characteristics also influence.

Nowadays, lawsuits regarding constructions are usually linked to the appearance of mold in buildings since such pathology may be responsible for both the builder and the building's user. The adoption of construction techniques and the choice of materials, and the proper use of equipment are essential to provide a healthy building during its lifespan. Mold will only appear if its training conditions are met, being humidity the most relevant factor in forming fungi on walls (KIEBL; SEDLBAUER, 2001).

Cunha, Vaupel, and Lüking (2008) state that the damage caused by humidity and mold are already known. First and foremost, mold is formed by the following causes: insufficient insulation level and thermal bridges; high surface strength, for example, through shelves occupying the entire wall; high indoor humidity production; poor ventilation due to residents' behavior; and humidity in parts of the construction. However, Guerra et al. (2012) emphasize that mold is not generated only due to humidity or lack of ventilation since species are resistant to lower levels of moisture. Dirt particles, for example, may have organic nutrients, being enough to fuel their metabolism. Nascimento and Sinoto (2003) also point out that several materials and coatings used in constructions have organic compounds that can serve as a food source

for filamentous fungi. Certain layers may serve as direct sources of nutrients, while others can serve as a substrate.

Problems related to filamentous fungi go beyond damage to the building's envelope and affect users' health. Allergic diseases such as rhinitis and asthma can increase in environments contaminated by fungal spores, alive or dead, mainly when found in large amounts. (ALLSOPP; SEAL; SALVADORI, 2001)

Adan and Samson (2011) state that about 25% of the 27 EU countries' housing have problems with humidity and filamentous fungi growth. Approximately 4.6 million cases of diagnosis of asthma are attributed to exposure to environments contaminated by these microorganisms. According to the authors, indoor contamination should be considered as a vast and deep social problem.

Objective

This study aims to analyze, through computer simulation, the need for Brazilian Performance Standards to consider the probability of forming filamentous fungi in the envelope's inner surface of buildings with low and high thermal insulation.

Methodology

The research approach is quantitative and uses computer simulation. The method was divided into four steps (Figure 1). First, a literature review about thermal bridges and filamentous fungi was performed in the first step. In the second step, the building was modeled, and schedules were set for use and occupancy, lighting and equipment, materials, and natural ventilation. The third step consisted of analyzing the thermo hygrometric conditions on the envelope's inner surface and identifying the period of the year susceptible to the formation of filamentous fungi. Two building envelope conditions were tested: a highly insulated envelope and a poorly insulated envelope. The results were analyzed and discussed in the fourth step.

Case study

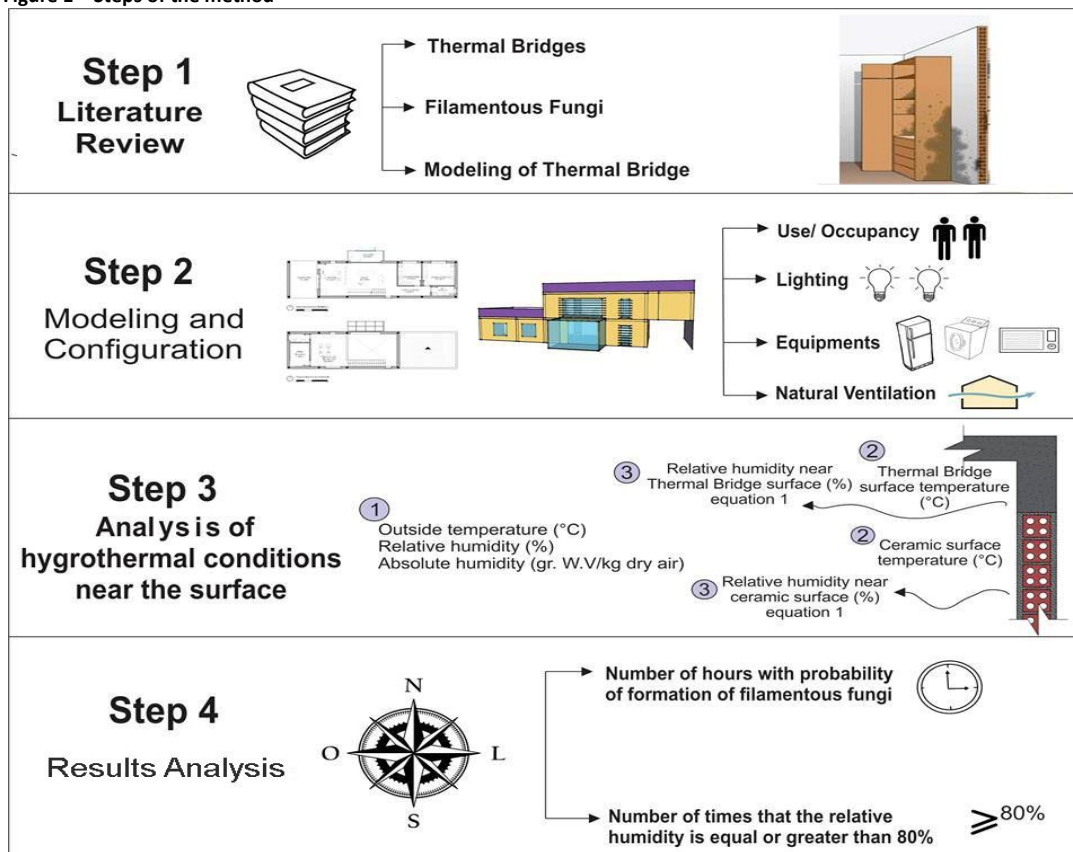
The residential building designed by Dalbem (2015) was used to develop the analysis (Figure 2). The building was designed to meet the Passive House criteria, but the walls' thermal transmittance was changed in this research.

The project uses passive strategies such as the East-West building axis to maximize solar gains in winter. It is distributed in 126.45m² of total area, divided into two floors. On the ground floor are the integrated kitchen and living room, solarium, two bedrooms, and bathroom. On the upper level are the work and technical areas and WC.

Building modeling and simulation

The building was modeled through the graphical interface for SketchUp 2015 called Legacy Open Studio 1.0.13 plugin. To configure different materials and compositions for thermal bridges and outdoor walls, the structure surfaces of the building were individually configured. The "New Construction Stub" command set the thermal bridge, allowing different configurations to be set for the rest of the building enclosure (Figure 2).

Figure 1 – Steps of the method



Source: the authors.

Figure 2 – Modeling architectural project for simulation



Source: Dalbem (2015).

The model settings were configured in the IDF editor of version 8.3 of EnergyPlus software. Occupancy and lighting schedules were configured according to the RTQ-R (Quality Technical Regulation for the energy efficiency level for residential buildings) (INMETRO, 2010). RTQ-R is a Brazilian residential building energy efficiency regulation. The lighting power density was set as 6 W/m² in the living room and 5 W/m² in the bedrooms.

The model was simulated for two cases, with two settings of materials, to analyze the probability of filamentous fungi formation in walls with or without insulation. In case 1, the thermal transmittance (U) of the envelope was set as 2.49 W/(m²K), which is the upper limit value to meet NBR 15.575 (2013) in colder zones. In case 2, the thermal transmittance (U) of the envelope was set as 0.39 W/(m²K), which corresponds to an insulated building. In both cases, the reinforced concrete structure was considered but

with different thicknesses. The roof was also the same for both cases, consisting of a 10 cm concrete slab, 5 cm air gap, and fiber-cement tiles.

Tables 1 and 2 below specify the materials used in computer simulations of the two cases.

Table 1 –Composition of the walls – Case 1

Case 1			
External Wall			
Layers	Thickness (m)	Thermal Conductivity λ (W/(mK))	Thermal Transmittance U (W/(m ² K))
External Plaster	0.025	1.15	2.49
Ceramic brick – 4 holes	0.095	0.90	
Internal Plaster	0.025	1.15	
Structure			
Layers	Thickness (m)	Thermal Conductivity λ (W/(mK))	Thermal Transmittance U (W/(m ² K))
External Plaster	0.025	1.15	3.06
Reinforced concrete	0.13	1.75	
Internal Plaster	0.025	1.15	

Source: the authors.

Table 2 –Composition of the walls – Case 2

Case 1			
External Wall			
Layers	Thickness (m)	Thermal Conductivity λ (W/(mK))	Thermal Transmittance U (W/(m ² K))
External Plaster	0.02	1.15	0.39
EPS	0.03	0.035	
Ceramic brick – 6 holes	0.10	0.90	
Air Gap	0.05	-	
Ceramic brick – 6 holes	0.10	0.90	
Internal Plaster	0.02	1.15	
Structure			
Layers	Thickness (m)	Thermal Conductivity λ (W/(mK))	Thermal Transmittance U (W/(m ² K))
External Plaster	0.02	1.15	2.52
Reinforced concrete	0.22	1.75	
Internal Plaster	0.02	1.15	

Source: the authors.

The building was configured as naturally ventilated and simulated using the AirFlowNetwork object in EnergyPlus. A 24-hour ventilation schedule was created with the window opening setpoint at the temperature of 25 °C, which means that when the indoor temperature is 25 °C and the outdoor temperature is at least 5 °C lower than the indoor temperature, the windows open.

The ground temperature was determined by the Slab tool, a program linked to EnergyPlus. A first simulation was performed to verify the average monthly indoor air temperatures, with the ground floor being considered adiabatic. Then, the Slab preprocessor was used to calculate and correct the average monthly indoor air temperatures.

Analysis

Simulations were performed for North, South, East, and West orientations for the two cases, using the weather file of Camaquã/RS, which is classified as bioclimatic zone 2 (ABNT, 2005). This zone is characterized by having high-temperature ranges throughout the year and extreme summer and winter (LEITZKE et al., 2018). Two thermal zones

located at opposite sides of the building were chosen to analyze each solar orientation's results.

Results for outdoor air temperature, indoor air temperature, indoor relative humidity, envelope inner wall surface temperature of the reinforced concrete structure (thermal bridge), and the masonry wall were requested yearly.

Indoor air temperature and relative humidity were evaluated considering the typical winter and summer days, which were obtained from the statistics data file of the weather file for a frequency of occurrence of 99.6% and 0.4%. The typical summer day corresponds to January 10 and the typical winter day corresponds to June 17.

Determination of the period of the year susceptible to the formation of filamentous fungi

Computer simulation results and the ASHRAE Psychrometric equations (ASHRAE, 2009) (Equation 1) were used to analyze the hygrometric conditions of the envelope inner wall surfaces.

Relative humidity near the surface calculated in Equation (1)

$$0.62198 \times ah \times 10000 \times [(0.00001255001965 \times (atnts + 273.15)^2 + (-0.01923595289) \times (atnts + 273.15) + 27.05101899 + (-6344.011577) \times (atnts + 273.15)^{-1}] \quad (1)$$

Where:

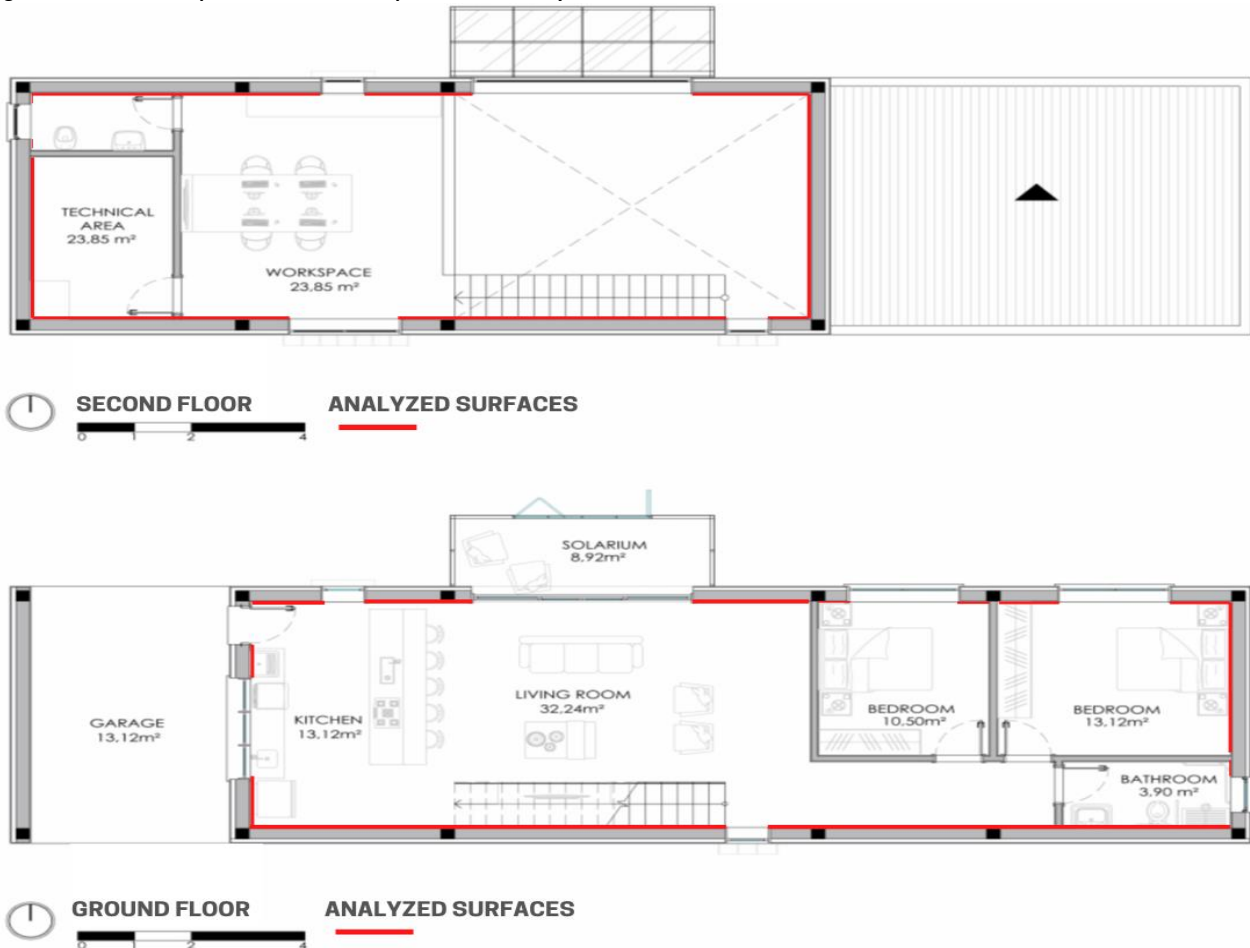
- ah=Absolute humidity;
- atnts=Air temperature near the surface.

The thermal zones absolute humidity was determined and, from that, the air relative humidity near the wall surface was also determined. The air relative humidity near the envelope's inner wall surface determines the probability of filamentous fungi formation throughout the year. When the air relative humidity was equal or higher than 80% for a period equal or longer than six hours, the period was considered susceptible for filamentous fungi development.

Results and discussion

Figure 3 indicates the surfaces analyzed by the study. Figures 4 and 5 show the possibility of filamentous fungi formation on the inner envelope wall surfaces for the ceramic brick surface and the reinforced concrete structure (thermal bridge) of each façade. The results correspond to the number of hours per year when the air relative humidity is equal to or higher than 80%. The number of times that the surface humidity was equal or higher than 80% for a period equal or longer than six hours.

Figure 3 – Ground floor plan and second floor plan with the analyzed surfaces



Source: Dalbem (2015)

Figure 4 – Probability of formation of filamentous fungi in simple walls

Simple Wall $U = 3.06 \text{ W/m}^2\text{K}$	West/South		West/North		East/South		East/North	
	Hour of the year with humidity above 80%		Hour of the year with humidity above 80%		Hour of the year with humidity above 80%		Hour of the year with humidity above 80%	
	Thermal Bridge	Ceramic Brick	Thermal Bridge	Ceramic Brick	Thermal Bridge	Ceramic Brick	Thermal Bridge	Ceramic Brick
	2.271h	2.917h	4.082h	4.702h	2.438h	3.557h	3.680h	4.548h
Simple Wall $U = 2.49 \text{ W/m}^2\text{K}$	Humidity $\geq 80\%$ for a period $\geq 6\text{h}$		Humidity $\geq 80\%$ for a period $\geq 6\text{h}$		Humidity $\geq 80\%$ for a period $\geq 6\text{h}$		Humidity $\geq 80\%$ for a period $\geq 6\text{h}$	
	Thermal Bridge	Ceramic Brick	Thermal Bridge	Ceramic Brick	Thermal Bridge	Ceramic Brick	Thermal Bridge	Ceramic Brick
	181 times	222 times	234 times	258 times	123 times	233 times	215 times	294 times
Simple Wall $U = 2.49 \text{ W/m}^2\text{K}$	North/West		North/East		South/West		South/East	
	Hour of the year with humidity above 80%		Hour of the year with humidity above 80%		Hour of the year with humidity above 80%		Hour of the year with humidity above 80%	
	Thermal Bridge	Ceramic Brick	Thermal Bridge	Ceramic Brick	Thermal Bridge	Ceramic Brick	Thermal Bridge	Ceramic Brick
	3.217h	4.161h	3.025h	3.847h	2.411h	2.856h	3.482h	3.998h
	Humidity $\geq 80\%$ for a period $\geq 6\text{h}$		Humidity $\geq 80\%$ for a period $\geq 6\text{h}$		Humidity $\geq 80\%$ for a period $\geq 6\text{h}$		Humidity $\geq 80\%$ for a period $\geq 6\text{h}$	
	Thermal Bridge	Ceramic Brick	Thermal Bridge	Ceramic Brick	Thermal Bridge	Ceramic Brick	Thermal Bridge	Ceramic Brick
	167 times	279 times	161 times	271 times	185 times	226 times	242 times	284 times

Source: the authors.

Figure 5 – Probability of formation of filamentous fungi in insulated walls

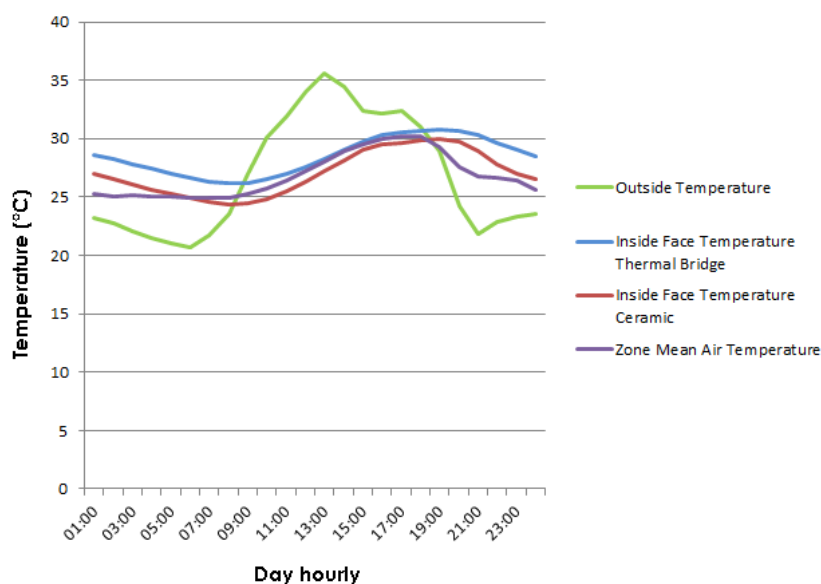


Source: the authors.

By varying the envelope thermal transmittance, we could verify that the probability of filamentous fungi formation on the thermal bridges was higher for the insulated case. There is a significant thermal transmittance difference between the reinforced concrete of the structure and the ceramic brick enclosure with insulation, resulting in a higher temperature difference near those surfaces. Meanwhile, in buildings with no insulation, the temperature and the relative humidity near the surfaces remained similar.

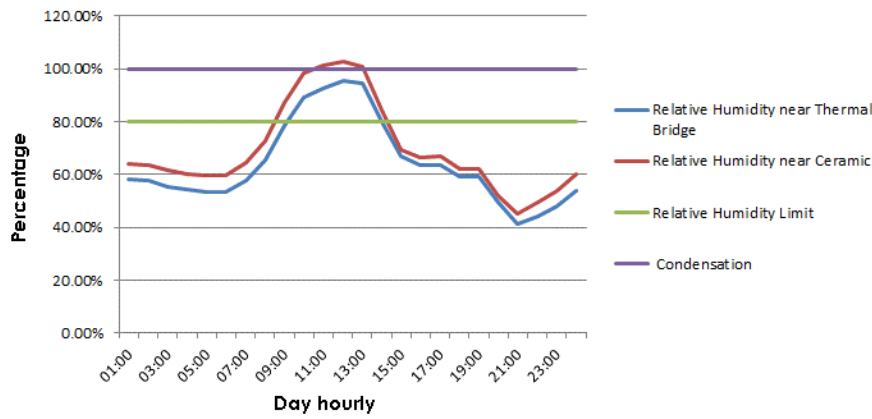
Figures 6, 7, 8, and 9 show the envelope inner wall surface temperature and humidity of the South-Eastern façade for the model with no insulation for summer and winter days.

Figure 6 – South-East façade: Temperatures – Summer day U = 2.49 W / (m²K)



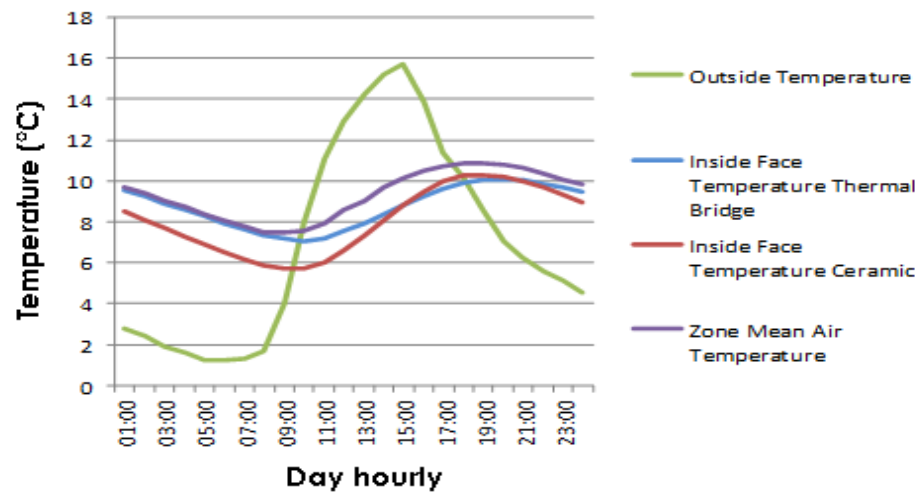
Source: the authors.

Figure 7 – South-East façade: Relative humidity near surfaces – Summer day U = 2.49 W / (m²K)



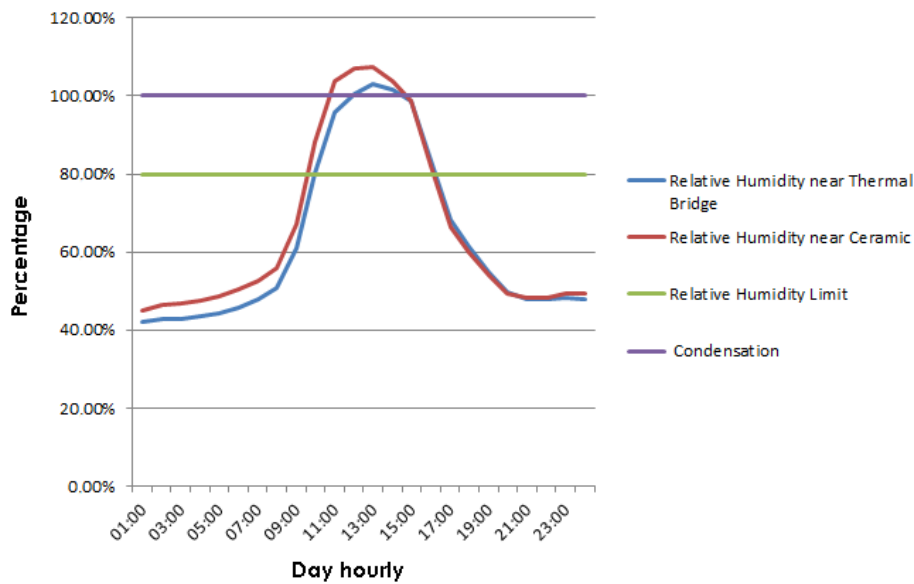
Source: the authors.

Figure 8 – South-East façade: Temperatures – Winter Day U = 2.49 W / (m²K)



Source: the authors.

Figure 9 – South-East façade: Relative humidity near surfaces – Winter day U = 2.49 W / (m²K)

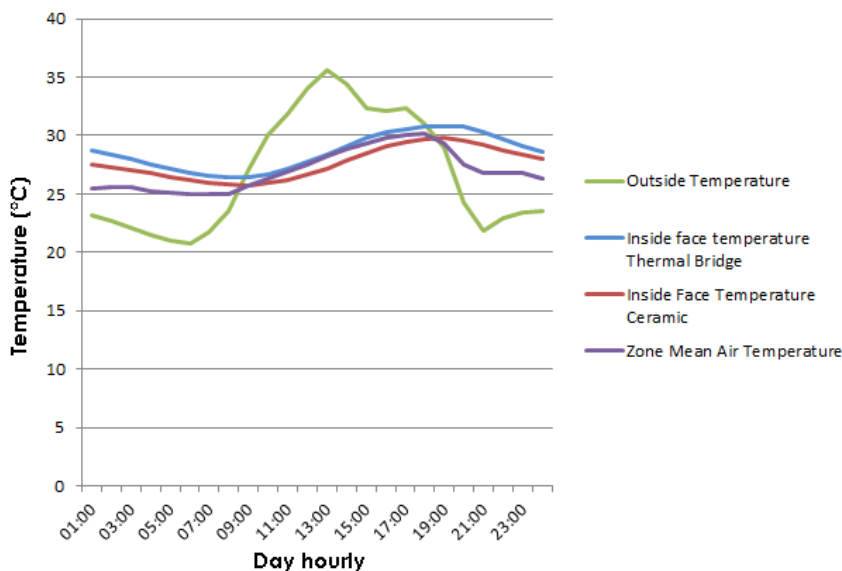


Source: the authors.

In the summer (Figure 6), the temperature near the thermal bridge's surface is higher than the temperature near the ceramic brick enclosure during the whole day, which will cause a higher relative humidity near the ceramic wall (Figure 7). In winter (Figure 8), the temperature near the thermal bridge is also higher, but only for the period from 3:00 p.m. to 5:00 p.m., which causes the air relative humidity curve (Figure 9) to be similar between the two surfaces.

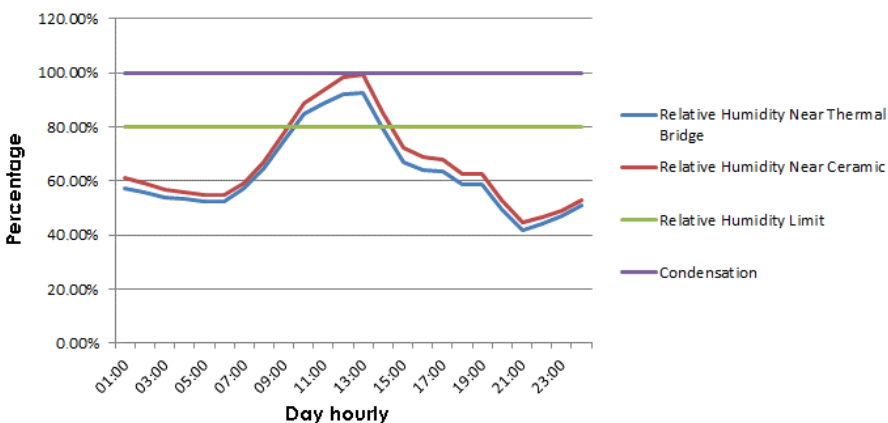
Figures 10, 11, 12, and 13 show the envelope inner wall surface temperature and humidity of the South-Eastern façade for the model with insulation for summer and winter days.

Figure 10 – South-East façade: Temperatures – Summer day U = 0.39 W / (m²K)



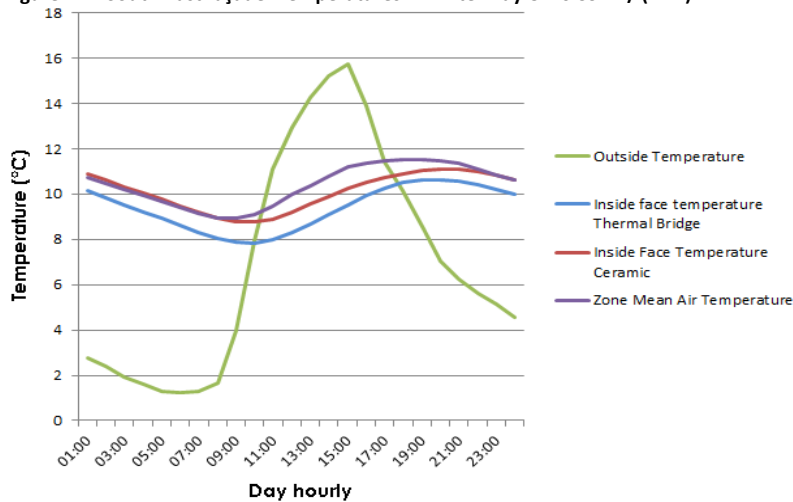
Source: the authors.

Figure 11 – South-East Façade: Relative Humidity near surfaces – Summer day U = 0.39 W / (m²K)



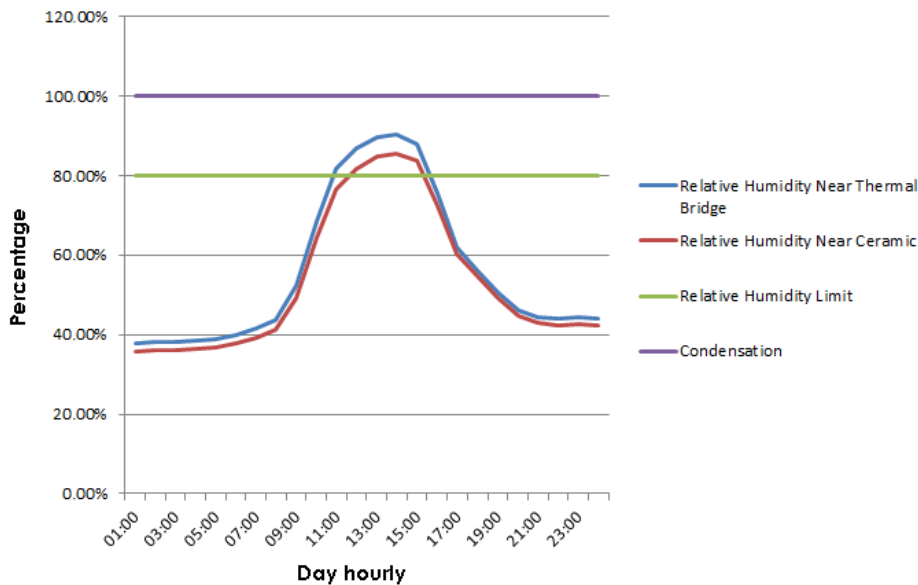
Source: the authors.

Figure 12 – South-East façade: Temperatures – Winter Day U = 0.39 W / (m²K)



Source: the authors.

Figure 13 – South-East façade: Relative Humidity near surfaces – Winter day U = 0.39 W / (m²K)

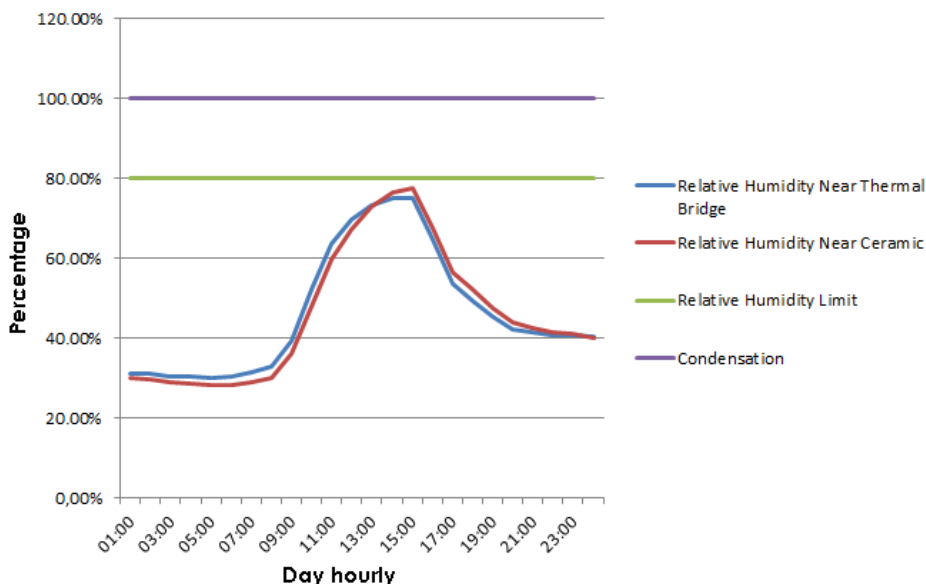


Source: the authors.

The insulated building behavior in summer was similar to the behavior of the building with no insulation. Besides the significant temperature difference near the thermal bridge's surface (Figure 10), it remained higher than near the ceramic brick surface, so the relative humidity near the ceramic wall was higher (Figure 11). In winter, the temperature near the ceramic brick surface (Figure 12) was higher than near the thermal bridge's surface, causing higher relative humidity near the structure (Figure 13). In the building with insulation, the air relative humidity near the surface of the thermal bridge was higher in the Eastern façade on both sides of the building most of the day.

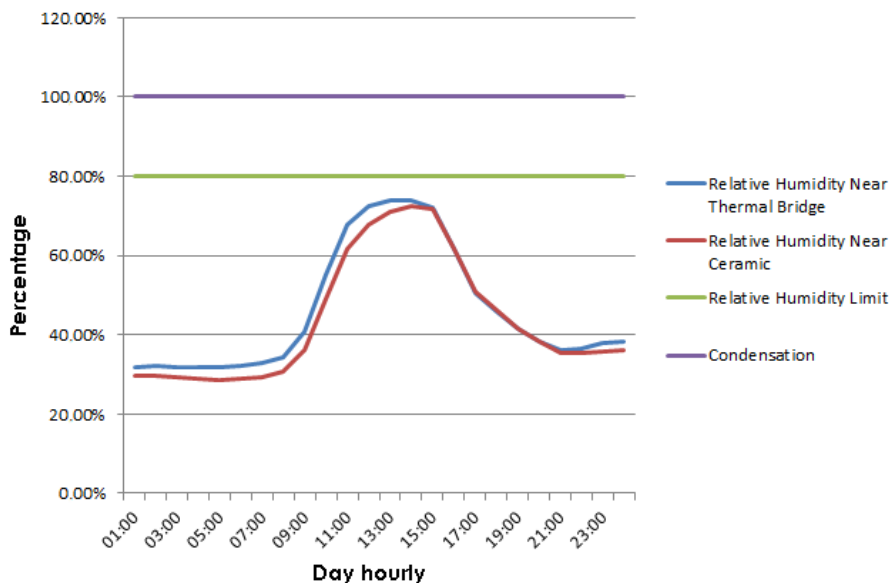
Figures 14 and 15 show the relative humidity of the East-South and East-North façades for the typical winter day.

Figure 14 – East-South façade: Relative humidity near surfaces – Winter Day U = 0.39 W / (m²K)



Source: the authors.

Figure 15 – East-North façade: Relative Humidity near surfaces – Winter Day U = 0.39 W / (m²K)



Source: the authors.

In summer, the model's East façade with no insulation presented different behavior compared to the other solutions. Since the reinforced concrete structure's thermal transmittance was higher than that of the insulated wall, the thermal bridge temperature was lower, increasing the relative humidity near the reinforced concrete structure's inner surface.

Conclusions

The study presented the probability of filamentous fungi formation on the envelope inner wall surface. Although air relative humidity was not the only factor that allowed the filamentous fungi formation, it was fundamental. Relative humidity favored fungi' appearance when air relative humidity was equal or greater than 80% for six or more hours. The high humidity level on the inner surfaces results from the low thermal

transmittance of the external walls. Without a thermal performance standard considering the mold growth risks, the problem will not be solved independently of the assumed strategy regarding the acclimatization of the internal environment.

Aspects related to building occupants, such as natural ventilation control, could interfere in the indoor air humidity level and consequently favor filamentous fungi. Aspects related to materials and construction techniques could also affect the establishment of filamentous fungi. Buildings with thermal insulation tend to present, in winter, filamentous fungi in its structural part, where thermal bridges occur. Buildings with no envelope thermal insulation tend to present filamentous fungi in the vertical enclosures that are not part of the structure.

Results showed the importance of considering and analyzing thermal bridges of reinforced concrete structures in calculations of thermal transmittance of walls. Their presence in the building composition can affect thermal comfort and energy consumption in buildings.

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