Acoustical and thermal performance of multilayer closing panels used in steel-structured buildings

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Abstract

This article provides an evaluation of the acoustical and thermal performance of some closing systems by referencing materials such as cement plates, plasterboard walls, precast concrete panels and expanded polystyrene. Reverberation time is calculated by applying an empirical formula, which uses temperature and relative air humidity values obtained from simulations that were conducted using the computational simulation program ESP-r (Energy Simulation Program-research). The internal temperature presented by the ESP-r is an indicator of thermal performance. Using a simplified graphic method, the acoustical performance is also evaluated by estimating the loss of sound transmission that occurs through the closing panels. Combinations of these panels, which form multilayer panels mediated by a layer of air and with or without insulating material between them, are applied. The results show that multilayered closing systems, when filled with insulating material, are an efficient solution than can provide adequate acoustical and thermal performance.

Keywords: building acoustics. steel-structured buildings. closing panels. acoustical and thermal performance.

1. Introduction

Steel structure construction has proven to be a comprehensive aspect in the development of civil construction, particularly in projects that can provide adequate global efficiency. However, the rapid assembly of metallic structures in construction systems requires the application of closure systems that follow philosophies similar to those of prefabrication and speedy construction. As such, the use of industrial closing systems is presented as a rational solution. In the Brazilian construction market, several pre-fabricated panels are available. A global analysis of thermal and acoustical performance prevents future interventions in the construction (SALES, 2001).

The use of multilayer closing systems, systems composed of two panels mediated by a layer of air and insulating material, can result in superior acoustical performance. High-quality performance is linked to an increase in noise transmission loss without requiring high cost or significant material accumulation. Thus, sound transmission loss through a wall, and reverberation time within an environment because of existing people, air and surfaces may be acoustical performance indicators of locks. However, these closing systems have low thermal inertia, which may compromise their thermal performance and require an integrated study of their thermal and acoustical performance (BIES; HANSEN, 2003; RIBAS; SOUZA, 2011).

The purpose of this paper is to conduct a thermal and acoustical evaluation of the performance of some multilayer closing systems that are used in the construction of steel structures in Brazil. Examples of these systems include cement plates, plasterboard walls, precast concrete panels and expanded polystyrene. The study has been performed on composed panels (multilayer system) with and without insulating material. An estimation was conducted to determine the sound transmission loss (TL), which occurs through the closings, and reverberation time (RT) and temperature (T_i), which occur in the environment.

2. Materials and methods

An estimation of TL is made through a simplified graphical method presented by Sharp (1973) and analyzed by Bies and Hansen (2003) and Bistafa (2006). The RT is calculated from an empirical formulation devised by Citherlet (2001), which uses simulated values for temperature and relative air humidity obtained through the computational program ESP-r (Energy Simulation Program – research). The RT is calculated by using the building model. The geometric edifice model is generated in three dimensions. It is based on thermal zones and the building is characterized by its architectonical variables, constructive materials and correspondent layers.

2.1. Sound transmission loss (*TL*)

The loss in sound transmission (*TL*), which occurs when sound arrives at the other side of a wall with a lower intensity than the original sound is a characteristic of sound insulation and the closure may indicate its acoustical performance (BIES; HANSEN, 2003; BISTAFA, 2006). Gerges (2000) presents Eq. (1) for the calculation of the *TL*, called *mass law*:

$$TL = 20\log (f \cdot M) - 47.4 \quad (dB) \tag{1}$$

where *f* is the frequency of the incident wave (Hz) and *M* is the surface density of the wall material (kg/m²).

In a single wall, the sound transmission loss is influenced by the frequency of the incident sound (*f*) exhibiting different resonance and vibration behavior, depending on the wall's mass and stiffness. The *TL* of simple isotropic panels (solid and homogeneous) can be obtained from experimentational or standard essays or can also be estimated as a function of critical frequency, f_c, Eq. (2), by applying the simplified graphical method to one idealized model composed of one panel with dimensions *a*, *b* and *h*, bending stiffness (B_s), Eq. (2), and module of elasticity (*E*), as shown in the Figs. 1 and 2. This method considers the simply supported panel, which limits its applicability (BISTAFA, 2006).
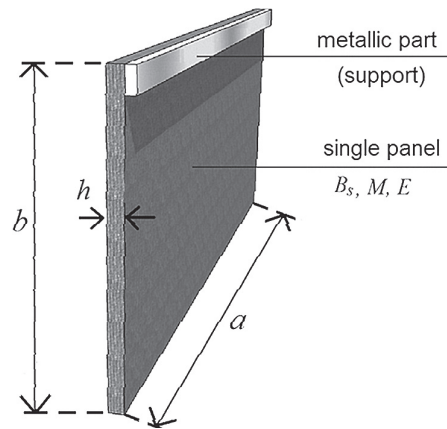

Figure 1
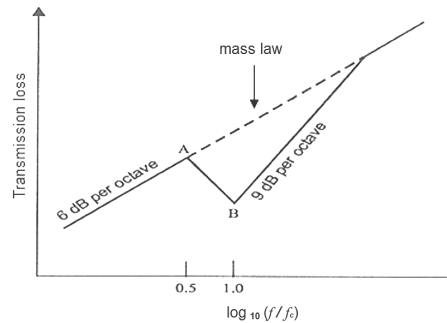Idealized model of an
isotropic simply supported panel.

Figure 2
Estimation of the *TL* through simple
isotropic panels (BIES; HANSEN, 2003).

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{M}{B_s}} \quad (Hz) \quad \text{and} \quad B_s = \frac{Eh^3}{12} \quad (N.m) \tag{2}$$

where *c* is the speed of sound wave in air (m/s); *M* is the surface density of the material panel (kg/m²); B_s is the panel's bending stiffness (N.m), given by Eq (2), *E* is the module of elasticity of the material (N/m²) and *h* is the thickness of the panel (m).

The points A and B in Fig. 3 have coordinates (0.5 f_c; TL_A) and (f_c; TL_B), respectively, calculated by Eq. (3).

$$TL_A = 20\log (f_c \cdot M) - 54 \quad (dB) \quad \text{and} \quad TL_B = 20\log (f_c \cdot M) + 10\log\eta - 45 \quad (dB) \tag{3}$$

where η is internal damping factor of the panel (non-dimensional). After the point B and f_c, the TL is given by Eq. (4), valid for $f > f_c$, applied until the frequency to which the *TL* is calculated by the *mass law*, Eq. (1).

$$TL = 20\log(f \cdot M) + 10\log\left(\eta\frac{f}{f_c}\right) - 45 \quad (dB) \tag{4}$$

Closing systems with double walls may produce more sound insulation than those produced by systems with simple walls, provided the walls are of the same thickness, Fig.3. Due to the complexity of the sound energy transmission between the panels, the acoustical insulation is not equivalent to the sum of the individual acoustical insulation values. Bies and Hansen (2003) and Bistafa (2006) present a simplified graphical method to estimate the *TL* of doubled walls. The

method, which is based on Sharp's analysis (1973), considers that panel fixation is determinant on the efficiency of their sound transmission (GERGES, 2000; HASSAN, 2009).

The panels can be fixed to the same scantling or metallic profile through resilient bars in an effort to reduce the mechanical vibrations. There are two common approaches to fixing the panels that result in four possible combinations. When the panel is fixed directly to the scantling or metallic profile, one line of contact is created between these two elements to create the *fixation in line*. The spacing among the scantlings or profiles (*b*), Eq. (8), should be uniform. The four possible combinations of fixation are line-line, line-punctual, punctual-line, and punctual-punctual. In the case of fixation in line or punctual fixation, the simplified graphical method is applied when the panels are fixed to the same scantling or metallic profile. Through formulation, the coordinates of the points A, B and C are determined through estimation of the coordinates from point A' (Fig. 4). The formulation applied through the simplified graphical method to determine the *TL* curve, based on line-line fixation, is shown in Table 1, Eq. (5) to (10). In the formulation, number 1 is associated with the panel that generates the smallest f_c, and number 2 is associated with the remaining panel (BIES; HANSEN, 2003; BISTAFA, 2006).
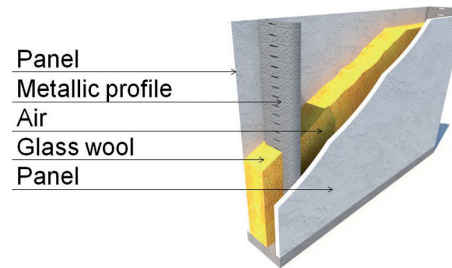

Figure 3
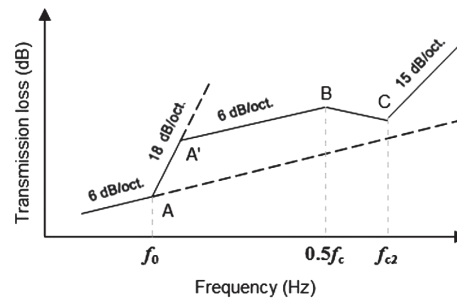Diagram of the closing systems: with absorber material.

Figure 4
Estimation of *TL* through double walls (BIES; HANSEN, 2003; BISTAFA, 2006).

Table 1
Coordinates of the points A, B and C to line-line fixation.

Point/co-ordinates	Equations	
A $(f_0; TL_A)$	$f_0 = 80\left(\dfrac{M_1 + M_2}{dM_1M_2}\right)^{1/2}$	(5)
	$TL_A = 20\log(M_1 + M_2) + 20\log f_0 - 48$	(6)
B $(0.5 f_{c1}; TL_B)$	a) when there is no sound-absorbing material in the gap, TL_B is equal to TL_{B1}:	
	$TL_{B1} = TL_A + 20\log\left(\dfrac{fc_1}{f_0}\right) - 6$	(7)
	b) when there is sound-absorbing material in the gap, TL_B is givem by the largest value between TL_{B1} and TL_{B2}, and TL_{B2} is:	
	$TL_{B2} = 20\log M_1 + 10\log b + 30\log f_{c2} + 20\log\left[1 + \dfrac{M_2 f_{c1}^{1/2}}{M_1 f_{c2}^{1/2}}\right] - 77$	(8)
C $(f_{c2}; TL_C)$	1. for $f_{c2} \neq f_{c1}$: $TLc = TL_B + 10\log\eta_2 + 6$	(9)
	2. for $f_{c2} = f_{c1}$: $TLc = TL_B + 10\log\eta_2 + 5\log\eta_1 + 6$	(10)

where f_0 is the lowest frequency of resonance from the set mass-air-mass (Hz); TL_i is the transmission loss at the point i (dB); d is the spacing among the panels or deepening of the cavity (m); M_i is the surface density of the panel i (kg/m²); f_{ci} is the critical frequency of the panel i (Hz), seen in Eq. (2); b is the spacing among scantlings in the fixation in line (m); and η_i is the internal damping factor of the panel material i.

2.2 Reverberation time (*RT*)

The *RT* can indicate the acoustical performance of a closing and it depends on the frequency of emission, the capacity of the surrounding material to absorb this frequency, the volume of the present air and the spectrum of the sound frequencies. It is characterized by the absorption due to the closing (wrapper), the furniture, the persons and the existing air in the room (BIES; HANSEN, 2003; HASSAN, 2009; MAEKAWA; RINDEL; LORD, 2011).

To obtain the time of reverberation, the capacity of the sound insulation from the closing systems and the capacity of the applied materials in the interior of the

building, which absorbs the internal noise, is required. Sabine defined the *RT* by the Eq. (11), in 1896 (CITHERLET, 2001; BISTAFA, 2006).

$$RT = 0.161 \cdot \frac{V}{A_f^t} \qquad (s) \qquad (11)$$

where *V* is the volume of the room (m³); *f* is the considered frequency (Hz); and A_f^t is the total area equivalent to the room to the frequency *f* (m²). The total area equivalent (A_f^t) is defined by the sum shown in Eq. (12) (CITHERLET, 2001; HASSAN, 2009; KNUDSEN; HARRIS, 1978).

$$A_f^t = A_f^{fech} + A_f^{obj+pes} + A_f^{ar} = \sum_i^{fech}\left(S_i.\alpha_{i,f}^{Sab}\right) + \sum_j^{obj}(N_j \cdot A_{j,f}^{obj}) + \sum_k^{pes}(P_k \cdot A_{k,f}^{pess}) + 4mV \qquad (m^2) \qquad (12)$$

where A_f^{fech} is the area of equivalent absorption of the closing in the interior of the room (m² Sabine); $A_f^{obj+pes}$ is the absorption equivalent of the objects and persons in the interior of the room (m²); A_f^{ar} is the equivalent absorption due to the air in the interior of the room (m²) should be considered at frequencies equal or above 1000 Hz ; S_i is the area of the internal surface i of the room (m²); $\alpha_{i,f}^{Sab}$ is the Sabine's coefficient of absorption of surface *i* in the frequency *f*; N_j is the number of occurrences of the object like *j*, $A_{j,f}^{obj}$ is the equivalent area of absorption of the object j in the frequency *f* (m²); P_k is the number of occurrences of the person *k*; and $A_{k,f}^{pes}$ is the equivalent area of absorption of the person *k* in the frequency *f* (m²); *m* is the coefficient of the sound absorption of the air (m⁻¹); *V* is the volume of the room (m³).

2.3 Acoustical and thermal performance

Quantify acoustical performance is an essential step to improve the isolation of an environment. So standards are designed to establish reference values that aim to provide sound insulation to the environment ideal for the activity there developed (BIES; HANSEN, 2003; DUARTE; MOORHOUSE; VIVEIROS, 2012).

The reverberation time should be based on the use of the room, as inadequate values may disrupt the intelligibility or quality of speech. The higher the volume in the room and the greater number of low-absorbing materials used, the higher will be the duration of the reverberation. If the reverberation continues in the environment for a significant length of time, it may overcompensate the position of syllabi and/or musical notes; if it disappears altogether, some sound sources may not be perceived at all (MAEKAWA; RINDEL; LORD, 2011).

Because spaces where speech and verbal communication is anticipated (classrooms, conference spaces and theatres) require smaller reverberation times, ideally, the reflected sound decreases rapidly to prevent interference with direct sound and does not reduce its intelligibility. For a small room, a reverberation time of 0.5 s is adequate. However, a longer time is necessary for concert halls because the reverberation until a certain point is required to ensure that acoustical quality in orchestral music is not compromised (MEHTA; JOHNSON; ROCAFORT, 1999; BISTAFA, 2006).

According to the Brazilian Standard NBR 15575 (ABNT, 2013), a closing system must have appropriate acoustical insulation to aerial external noises, by impacts and among environments. The minimum thermal performance in summer in Brazil is verified when $T_{i,max} \leq T_{e,max}$, where $T_{i,max}$, is the maximum value of the air temperature registered in the edifice (°C) and $T_{e,max}$, is the maximum value of the external air temperature registered.

3. Results

3.1 Estimate of the *TL*

An estimation of the *TL* is made for multilayer closing systems, which consist of combinations of cement plates (PLC), plasterboard walls (GEA), precast concrete panels (PMC) and expanded polystyrene (EPS), with or without sound absorber material in the panel air cavity. Glass wool (LVI) is preferred. The acoustical features of the panel materials are shown in the Table 2.

Material	E (N/m²)	ρ (kg/m³)	η	B_s (N.m)	f_c (Hz)
PLC (10)	1.2×10^8	1330	0.005	83	21158
GEA (12.5)	2.0×10^9	750	0.006	339	3113
PMC (75)	2.3×10^{10}	2400	0.020	842285	274
EPS (100)	2.5×10^6	960	0.005	210	12670

Table 2
Acoustic features of the panel materials.

The dimension *b* is assumed equal to 0.60 m and the fixation is line-line. One of the closing systems is fictitious, for example, the use of the plasterboard as an external closing. However, it is applied to the simulations for comparison with other situations.

The *EPS* panel is formed with mortar that is 22.5 mm thick and *EPS* that is 55 mm thick and mortar that is 22.5 mm thick.

3.2 The thermal simulation and the calculation of the *RT*

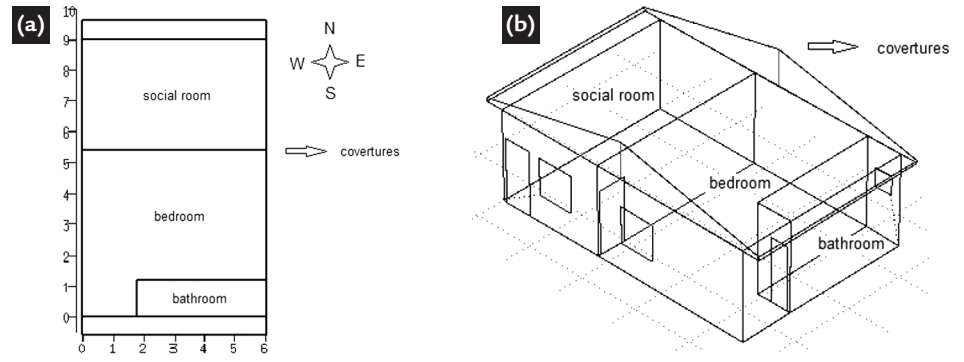The time value of the temperature (T_i) and the relative humidity of the air (h_r) are obtained through nu-

merical simulation. The building, with an area of 54 m², is divided into four thermal zones (social room, bedroom, bathroom and covertures), ceiling height of 3.00 m and total height of 4.20 m, Fig. 5.

Figure 5
Basic plant (a) and perspective (b) of the building, generated by ESP-r.

For the configuration of each space, the internal and external closings are varied during the simulations, the materials in Table 3 are applied and the compositions of the other closing materials and the thickness are: the ground: ceramic material (10), mortar (20) and concrete base (80); the cement slab: cellular autoclaved (CCA) (140), composed by one concrete layer (20), CCA (100) and total internal redressing in mortar (20); covertures: ceramic tile (10); windows: common transparent glass (4); external door: wood with medium specific mass (25); internal door: compensated wood (25); closing of bath: wall (105) composed by PLC(10)-air(75)-

PLC(10) and ceramics (10).

The presence of persons, lamps turned on and equipment gaining casual heat (sensible and latent) was not considered. For air flow, a rate of renewal equal to 3 ren/h is adopted (ABNT, 2013). For the characterization of the weather conditions, the weather zoning presented by the Brazilian Standard NBR 15220 (ABNT, 2005) was adopted. Data for one typical summer day from zone three were used (13/01/2000) with the city of Belo Horizonte used as a reference (latitude – 19.85 and longitude – 43.9). Other data utilized in the simulations (medium values) are the following: variation of sun radiation

incident for a horizontal plan (RS) equal 97.71 W/m², dry bulb temperature (TBS) equal 24.47 °C, sun radiation incident for a normal direction (RS_{Total}) equal 299.08 W/m², predominant wind speed and direction equal 1.68 m/s e 77.5° (time sense from North), and relative air humidity (h_r) equal 63.13 %.

The variation of the TL and of the RT, as a function of frequency and at 14:30 when the temperature reaches 27.5 °C, for the social room, is illustrated by curves in Fig. 6 to 11. The variation of the T_i and of the RT, as a function of time and at a frequency of 1000 Hz, is shown in the curves in Fig. 12 to 17.

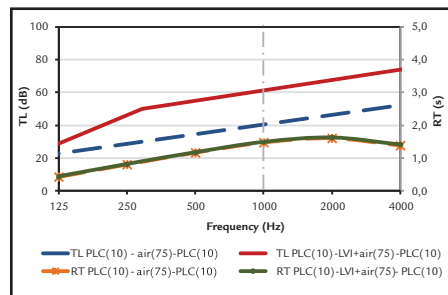Figure 6
TL and *RT* as a function of frequency - PLC.

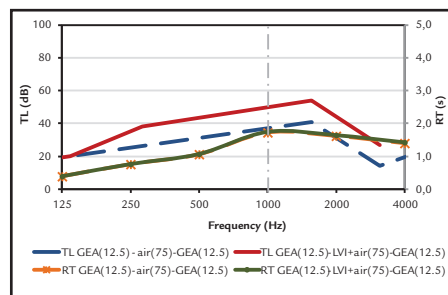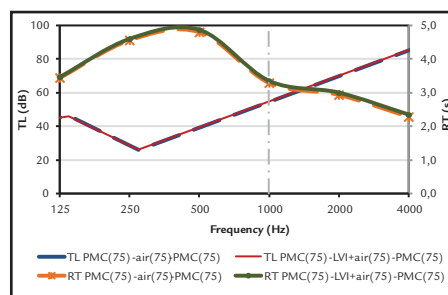Figure 7
TL and *RT* as a function of frequency - GEA.

Figure 8
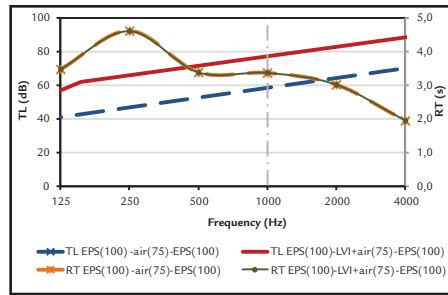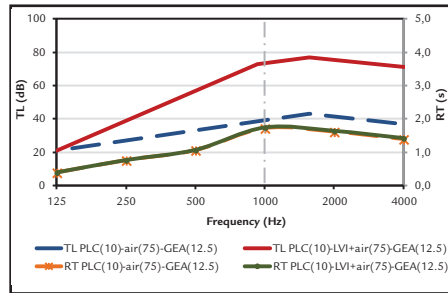*TL* and *RT* as a function of frequency - PMC.

Figure 9
TL and *RT* as a function of frequency - EPS.

Figure 10
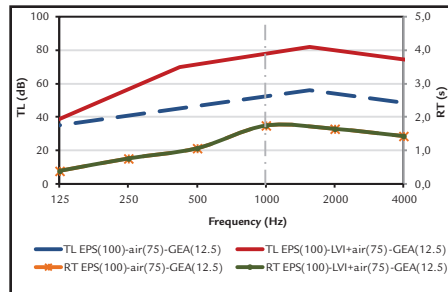*TL* and *RT* as a function of frequency - PLC-GEA.

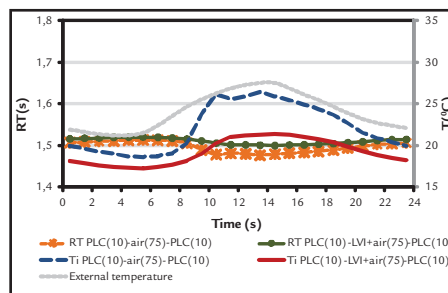Figure 11
TL and *RT* as a function of frequency - EPS-GEA.
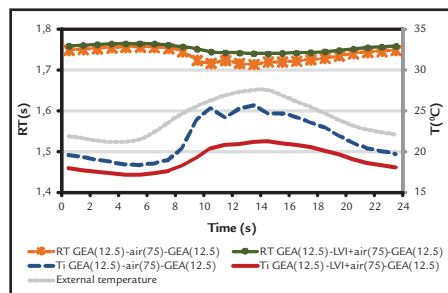

Figure 12
RT and T_i as a function of time (1000 Hz)-PLC.

Figure 13
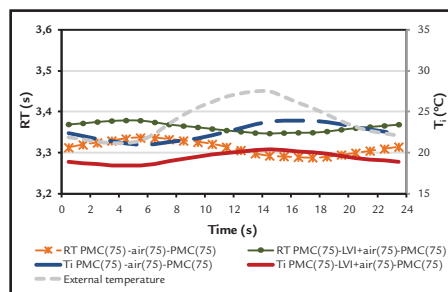*RT* and T_i as a function of time (1000 Hz)-GEA.

Figure 14
RT and T_i as a function of time (1000 Hz)- PMC.

Figure 15
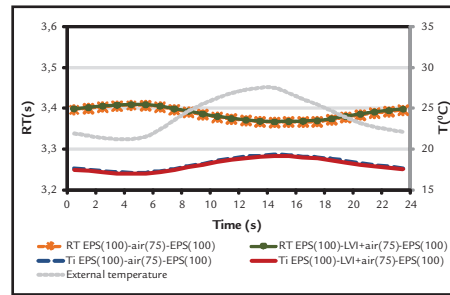*RT* and *T_i* as a function of time (1000 Hz)-EPS.

Figure 16
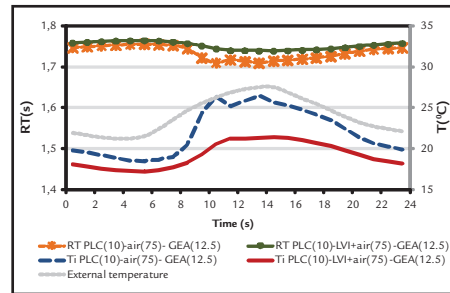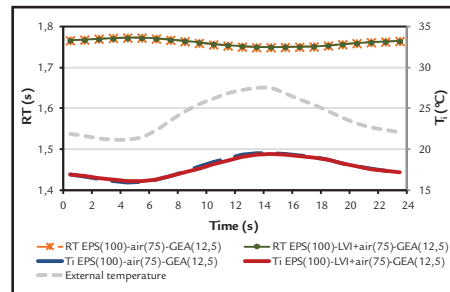*RT* and *T_i* as a function of time (1000 Hz)- PLC-GEA.

Figure17
RT and *T_i* as a function of time - (1000 Hz)-EPS-GEA

4. Analysis and conclusion

The use of an insulating material in a closing system has the potential to cause an increase in the *TL* and a decrease in the *T_i*; however, results indicate that it does not exert a substantial influence on the *RT*. In the frequency range considered here, the *TL* is higher for the PLC(10)-LVI+air(75)-GEA(12.5) when considering the closings in PLC and GEA and for the EPS(100)-LVI+air(75)-EPS(100) in the other closings. The closings in PLC and EPS exhibit the *mass law* behavior for a wide range of frequency. The other closings exhibit behaviors in the regions controlled by resonance and coincidence.

When considering the 1000 Hz in the social room wall, each of the analyzed closings conform to the criterion recommended by the Brazilian Standard NBR 15575 (ABNT, 2013) of a *TL* greater than 35 dB. The fulfilled closings with LVI resulted in better performance, and the lowest values of TL were observed at GEA(12.5)-LVI+air(75)-GEA(12.5), Fig. 6 to 11.

In the reference building model, with an equivalent frequency (1000 Hz), the PLC presents the higher coefficient of sound absorption. To this frequency, the closings resulted in values of *RT* greater than the recommended value of 0.5 s for a small room designated for speech (Fig. 6 to 11). Note that the presence of persons and furniture are not being considered as housing; this omission creates the tendency to reduce the area of sound absorption inside the space, which increases the *RT* value. When comparing the performance of the closings in reference to the *RT*, it is observed that the closings constituted by PLC, GEA,

PLC-GEA and EPS-GEA show a smaller RT than others.

With respect to thermal performance, all the analyzed closings meet the criterion recommended by Brazilian Standard NBR 15575 (ABNT, 2013) of $T_{i,max} \leq T_{e,max}$. The T_i is smaller for the closings formed by EPS and EPS-GEA, but the *RT* is higher. Considering the *RT* and T_i, the PMC(75)-LVI+air(75)-PMC demonstrates superior performance (Fig. 12 to 17).

From the depicted results, the double closing system PLC(10)-LVI+air(75)-PLC(10) displays great acoustical and thermal performance. This study has illustrated that when choosing the most appropriate closing system for a building, it is necessary to perform a comparison between the results of the analyses in the frequency range of interest.

Acknowledgments

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