PAN
ARCHIVES OF ACOUSTICS
Vol. **44**, No. 1, pp. 99–104 (2019)
DOI: 10.24425/aoa.2019.126356

Sound Insulation of Dwellings Façades – the Case of Santiago de Chile

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(*received March 28, 2017; accepted October 23, 2018*)

The increment in the number of automobiles and the densification of the city has increased noise pollution rates. In addition, the lack of regulation in Chile regarding the acoustic insulation of façades is a problem of a growing concern. The main objective of the present study was to obtain a model of the Sound Insulation of housing, façades, stratified in Santiago, Chile, based on constructive variables. It is expected to serve as a basis for one future regulation for acoustic façades of houses. In the present study, tests based on the international ISO 140-5 standard were carried out *in situ*. An estimation model of the Standardized Level Difference $D_{ls,2m,nT,w} + C$, was obtained based on the opening/façade proportion, and the type of glass used for the windows.

Keywords: sound reduction index; construction quality; acoustic insulation; façade.

1. Introduction

Façades are constructive elements of residential buildings that protect us from the harmful effects of noise pollution from exterior sources. Noise pollution threatens people's health (WHO, 1999) and has emerged as one of the main sources of residential complaints (WHO, 2011). In urban zones, the main sources of noise are associated with the transportation of people and goods, widely emphasizing road traffic in noise pollution (MMA, 2011). The annoyance within homes – due to outside noise – is not only related to the acoustic insulation of the façade, but also to certain attitudes of its residents: perception of danger associated with the sound source, awareness of noise prevention, general sensitivity to noise, assessment of the importance attached to the noise source, and the degree of non-acoustic nuisance regarding the sound source (FIELDS, 1993). In recent years there has been an increase in the urban population, where cities are saturated with tall buildings and the amount of automobiles has increased; including public, freight, and private transport (SILVA *et al.*, 2014). Using the Chilean case as an example, between 2009–2013, there was a 36% increase in the amount of automobiles (INE, 2014).

The increase in traffic noise sources in Chile represents a growing pressure, both for the availability of routes and as a factor of environmental noise. In Chile, the mandatory Acoustic Regulation is currently legally valid through the General Ordinance of Urban Development and Construction (MINVU, 2004), which sets minimum values of airborne sound insulation and the impact between housing units. It is important to mention that the regulation does not include the acoustic insulation of façades.

The acoustic behaviour of a façade depends on multiple factors, ranging from the type of windows and doors (and the proportion of surface of these elements on the total surface of the facade), the quality and condition of the seals, the presence of fissures and cracks and the quality of the installation in general terms (Meza, 2007). Ventilation regulations are also a relevant factor (De Rozas *et al.*, 2006).

Chilean authorities are currently discussing the possibility of modifying the sound insulation requirements in buildings, incorporating a minimum value of airborne sound insulation of façades. To achieve this, it will be necessary to understand the acoustic behaviour of predominant building types in Chile and characterize the environmental noise in the vicinity of houses. In Chile there is no established connection between how buildings are constructed and the degree of acoustic comfort needed, depending on the level of environmental noise.

The main objective of the present study was to obtain a model of the Sound Reduction Index of housing façades, stratified by construction quality in Santiago, Chile.

2. Methods

2.1. Scope and sample selection

This was a descriptive and analytical type study and was carried out in the Chilean Metropolitan Region. We used a non-experimental and transverse research design. The sample was directed and not random, and was made up of 120 homes distributed in 31 communities.

2.2. Procedure of field measurements

The airborne sound insulation of façades was measured together with a visual inspection to verify the existence of constructive faults in the facades. People with formal studies in construction recorded these measurements through visual observations.

The tests were carried out according to the method described in the international ISO 140-5 standard. The standardized level difference was measured according to (ISO, 1998):

$$D_{ls,2m,nT} = L_{1,2m} - L_2 + 10\lg\left(\frac{T}{T_0}\right), \text{ [dB]}, \qquad (1)$$

where $L_{1,2m}$ is the equivalent sound pressure level 2 m in front of the façade averaged over the façade surface; L_2 is the equivalent sound pressure level in the receiving room averaged over the room; T is the reverberation time averaged in the receiving room; and $T_0 = 0.5$ s is the reference reverberation time. Two sound source positions and two microphone positions were used. For the measurement of the receiving room five microphone positions were used. The single value (weighted in dBA) $D_{ls,2m,nT,w}$ for pink noise was obtained according to ISO 717-1 standard (ISO, 2013), which is compatible with Chilean standards (MINVU, 2004).

2.3. Equipment

A hand-held Analyzer type 2270 averaging integrator, sound level meter, was used for the sound pressure level measurements, with a microphone, model 4189 1/2″ Free Field. Verification of the sound level meter calibration was performed before and after each test, using a calibrator Type 4231. For pink noise emission in front of the façade, an active speaker 15″ (1100 W_{rms}) was used. To measure the reverberation time, the impulse method was used, using a 9 mm caliber starter pistol with a spherical diffuser for better omnidirectional radiation (Farina, 2001).

2.4. Housing taxonomy

To determine a quality label for the façade of the dwelling, the method of accounting for constructive defects (n) was used by way of visual inspection. To sort the samples into five intervals facade quality, the following definitions were used: from "A" which is the end that represents the best condition of acoustic insulation ($n < 2$) and "E" which represents the worst condition of acoustic insulation ($n > 15$). Point "C" represents the mid-point between "A" and "E", while point "B" represents the mid-point between "A" and "C". Similarly point "D" represents the mid-point between "C" and "E". The study was carried out in the Chilean Metropolitan Region, as this is where the largest concentration of people exposed to high noise levels are located (MMA, 2011).

2.5. Statistical model of linear regression

A multiple linear regression model was applied using the stepwise selection method, in order to estimate the single insulation index $D_{ls,2m,nT,w}$, both backward and forward, separately for the significance level of coefficients and for the log-likelihood ratio test (LR test). The values used as selection criteria for explanatory variables in the model were 0.05 for entry and 0.045 for elimination. For the full model, seven different forms were considered, from the inclusion of all possible explanatory variables to only those formed by relationships between original variables. The model that had a greater explanatory power and better adjustment was selected. For this we considered the adjusted coefficient of determination Raj2, as well as Akaike Information Criterion (AIC) and, Bayesian Information Criterion (BIC) indices and the variance of the residuals (Weisberg, 2005; Kleinbaum, 2008; Montgomery, 2003).

3. Results and discussion

3.1. Construction quality of façades

The main deficiencies found in the present study corresponded to: fissures, microfissures, misalignment, and door and window frames. The deficiencies found in the assessed houses were very similar to those found in other studies. Ali and Wen (2011) reported that the most frequent defects found in the construction of façades were cracks, peeled paint, chipping, unevenness, hollowness and humidity. On the other hand, Chew *et al.* (2000) found that for exposed brickwork façades in tropical climates, the main defects found were: cracks, humidity and biological growth. Eschenasy (2012) compiled the main defects of façades in New York City, mentioning – in their very detailed glossary – that in brickwork façades one can frequently find: fissures, cracks and abrasions. Regarding the elements of the façades, this study identifies the deterioration of door and window joint seals as the main defects.

3.2. Airborne sound insulation

The overall results obtained are shown in Table 1. The average Sound Reduction Index over the 120 façades was $D_{ls,2m,nT,w} + C$ = 21.6 dBA ± 2.2 dB of expanded uncertainty (Machimbarrena, 2015). Figure 1 shows a box-plot diagram of the D index for the different categories of observed housing quality. Only the excellent category shows a significant difference with the two lower categories.

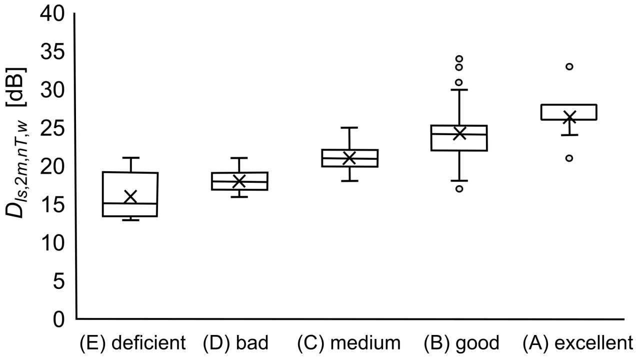


Fig. 1. Behaviour (Box-plot) of the sound reduction index obtained for each of the five categories (x: mean; box limits: quartiles Q1, Q2 and Q3; circles: outliers).

3.3. Comparison with other studies

In a study carried out in Italy by the *Istituto per le Tecnologie della Costruzione* ITC (Scamoni, Scrosati, 2014; Masovic, 2012) 334 façades were measured. The different characteristics and typologies of façades and the influence of acoustic and

Table 1. Description of the registered variables in the database (n = 120).

Variable	Average	Median	Standard deviation	Minimum	Maximum
Insulation with pink noise spectral correction [dBA]	21.6	22.0	3.4	12	32
Façade surface area [m^2]	10.64	9.22	5.46	2.02	41.08
Surface area of windows in façade [m^2]	3.22	2.62	2.27	0.63	16.35
Surface area of doors in façade [m^2]	0.68	0.00	1.04	0.00	7.42
Volume [m^3]	47.47	42.84	23.99	12.53	127.12
Windows/façade surface proportion	0.323	0.294	0.188	0.042	1.000
Doors/façade surface proportion	0.079	0.00	0.123	0.000	0.826
Openings/façade surface proportion	0.395	0.367	0.196	0.000	1.000
Façade/volume surface proportion	0.240	0.232	0.091	0.028	0.610
Age, in years	30.0	24.5	21.60	1.0	97.0
Materiality	brickwork	brickwork	reinforced concrete	light partition	adobe
	56 (47%)	11 (9%)	24 (20%)	24 (20%)	5 (4%)
Type of glass	simple	thermo panel			
	108 (90%)	12 (10%)			
Construction quality	E	D	C	B	A
	5 (4%)	10 (8%)	35 (29%)	59 (49%)	11 (9%)
Presence of doors	without doors	with doors			
	75 (63%)	45 (38%)			
Type of road facing façade	avenue	street	passageway		
	23 (19%)	63 (53%)	34 (28%)		

non-acoustic parameters were studied, both in Italy and France. They found an average $D_{2m,nT,w}$ (100–3150 Hz) equal to 38.3 dB with a SD = 4.4 dB for façades mainly constructed with bricks. The typology included façades with balconies, corner façades (with and without balconies) and flat façades. In this study the analysis of statistical significance was carried out. The descriptor that showed greater significance was the volume/window proportion (p-value = 0.0309), concluding that the percentage of façade glazing and the insulation properties of the window ($R_{w,\text{glass}}$) predominate the global insulation properties of the façade. The study did not include façades with doors. For its part, a comprehensive study of acoustic insulation of façades carried out by the Division of Acoustics of Belgian Building Research Institute (Ingelaere *et al.*, 2005), commissioned by the Flemish government, evaluated the extra cost of housing in a future scenario due to the increased acoustic demands of façades. Ten types of façades with different types of exterior noise were studied. Measurements showed that $D_{2m,nT,w}+C(C_{tr})$ are mostly found between 25 and 35 dBA (Vermeir *et al.*, 2004). It concluded that a future regulation cannot demand a $D_{2m,nT,w}+C_{tr}$ value of less than 30 dBA as a requirement. Moreover, an increase in the requirement will necessarily modify the V/Sup. Window ratio. In another study, tests were carried out on typical houses in Italy, obtaining $D_{2m,n,w}+C$ values between 34 and 37 dBA (Buratti *et al.*, 2014). In addition, using data obtained in a study carried out by the Universidad Politécnica de Madrid, where 26 housing façades were measured using the loudspeaker method, an average of $D_{2m,nT,w}+C$ equal to 29 dBA was obtained (Díaz, Pedrero, 2000). Furthermore, a study carried out in Korea (Kim, 2007), whose objective was to study the unique index of airborne sound insulation also using the loudspeaker method, found that the façades of apartments with balconies have $D_{2m,nT,w}+C$ index values ranging from 21 to 28 dBA. Moreover, in Spain, a campaign of measurements carried out in Malaga and Alicante, with over 1200 measurements, reported that 68.4% of the samples showed a $D_{ls,2m,nT,w}+C$ of less than 28 dBA (Meza, 2007).

Figure 2 shows a comparison of the results (in dB) obtained in the studies carried out in Spain and Italy. Clearly, the results obtained in Santiago appear to be much lower than the two reference cases considered. Most probably – and the reason for the need for deeper study – the lack of certification of labour quality in Chile is the main variable that would explain these results.

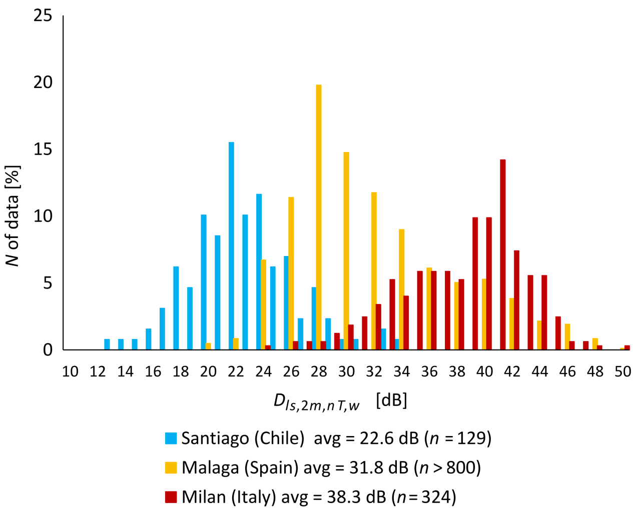


Fig. 2. Comparison of $D_{ls,2m,nT,w}$ obtained in Santiago (Chile), Malaga (Spain) and Milan (Italy).

3.4. Regression model for insulation

The selected model incorporates the openings/façade surface proportion, the type of glass and the construction quality of the façade as explanatory variables of $D_{ls,2m,nT,w}+C$. The results are shown in Table 1. Although in agreement with the results obtained by Scamoni and Scrosati (2014) that the connection between the windows and façades is one of the most important factors that affects the degree of acous-

Table 2. Regression model for $D_{ls,2m,nT,w}+C$.

Variable	Estimated coefficient	Standard error	p-value	Model diagnostic indices
Intercept	15.32	0.894	< 0.01	R^2 = 0.7315 R^2_{aj} = 0.7172 AIC = 488.84 BIC = 508.35 Residues: $\overline{X}$ = $6.60\cdot10^{-9}$ s = 1.76 Heterocedasticity test*: p = 0.1897 Normality test**: p = 0.6722
Door sill/façade surface ratio	–2.39	0.869	< 0.01	
Type of glass (0 – normal, 1 –thermo panel)	4.81	0.574	< 0.01	
Construction quality				
D	2.63	0.994	< 0.01	
C	5.73	0.869	< 0.01	
B	7.87	0.841	< 0.01	
A	10.90	0.976	< 0.01	

* Breusch-Pagan/Cook Weisberg test.

** Shapiro-Wilk test.

tic insulation, this was not significant as an explanatory variable of $D_{ls,2m,nT,w} + C$. However, the opening/façade proportion was significant.

An additional average insulation of 4.81 dBA was observed due to the use of thermo panels (double glazing), while maintaining the other characteristics of the façade constant.

An interesting finding was that the estimated increase in insulation, controlling for other covariables, was almost constant between two consecutive categories of construction quality (2.18 dBA on average).

The regression equations obtained are the following:

- double glazing

$$D_{ls,2m,nT,w} + C = 15.32 - 2.39x_1 + 4.81 + x_2, \tag{2}$$

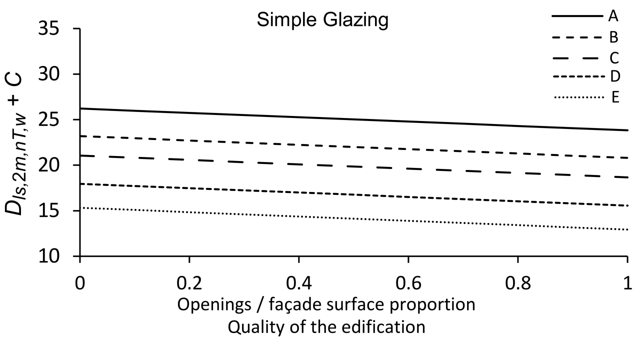
- simple glazing

$$D_{ls,2m,nT,w} + C = 15.32 - 2.39x_1 + x_2, \tag{3}$$

where $x_2 = \{10.9, 7.87, 5.73, 2.63, 0\}$ for $\{A, B, C, D, E\}$ construction quality index respectively.

Figures 3a, 3b show the estimated sound insulation for different façade configurations based on the opening/façade surface proportion, where we can clearly see the positive effect that the thermo panel windows and the quality of construction have.

a)



b)

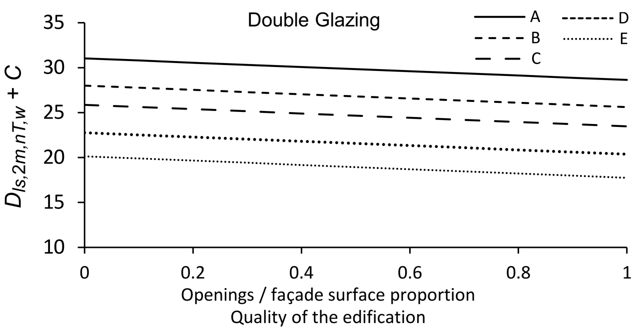


Fig. 3. Estimated insulation for different façade configurations: a) window with simple glazing, b) double glazing window.

As shown in Fig. 4, a significant difference between façades with double glass and single glass windows was not obtained. In addition to the limitations mentioned above, it was not possible to test apartments on the top floor of buildings in the present study. Finally, we were faced with the difficulty of characterizing houses due to the custom in Chile of making irregular modifications so as to avoid paying higher taxes. On the other hand, the prediction models do not consider a correction factor that incorporates the effect of certified labour in the final acoustic quality.

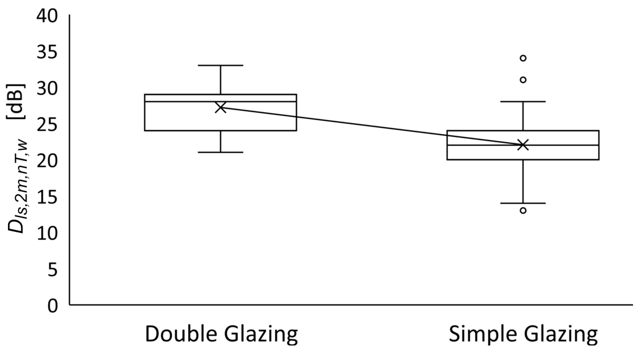


Fig. 4. Box-plot of the distribution of $D_{ls,2m,nT,w}$ level difference (dB) for façades with single versus double glazed windows.

4. Conclusions

The main conclusions of this study are as follows.

According to the obtained model, on average, the insulation decreased by 2.4 dBA between a façade without openings and a façade with 100% openings, considering the other variables as constant. Moreover, façades with thermo panel windows exceed windows with simple glass by 4.8 dBA on average. For its part, houses of "excellent" quality exceed those of "deficient" quality by an average of 10.9 dBA.

Additionally, to obtain a higher difference in levels, the following conditions must be met:

1) good condition of the façade,
2) good quality of the terminations, and
3) low window/wall surface proportion.

The results of this study reveal the importance of considering the connection between the glazed and blind elements in the architectural design of the façade. The creation of a guideline would allow for the comparison of the acoustic effectiveness of façades by only knowing the materiality. Using a sample that considers a wider territorial area could develop this study more deeply, taking into account that Chile has different climatic zones that demand different degrees of thermal insulation. This is also likely to affect the acoustic insulation values of façades. This would be relevant for the implementation of regulations that make acoustic insulation of façades compulsory, where it would be necessary to consider the established materials for each climatic zone of housing locations.

Acknowledgments

This project has been possible thanks to the FONDECYT Project ID 11121636. The authors would like to thank the students from the Escuela de Construcción Civil of the Pontificia Universidad Católica de Chile for their help with the experimental work. The authors also wish to thank Dr. Guillermo Rey Gozalo and Dr. Chris Feuillade for reviewing the manuscript and for his valuable suggestions.

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