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Effective absorption of architectural ETFE membranes in the lab

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Abstract

In this paper the determination of the sound absorption characteristics of architectural ETFE (Ethylene tetrafluoro ethylene) membranes by an adapted ISO354 [1] measurement method is reported. Despite the large-scale deployment of these systems in the built environment, little work has been published on this matter. Architectural ETFE membranes and cushions, which are often based on a multilayer foil structure, are gaining popularity amongst architects and designers. As the sustainability topic evolved from an elusive goal to a stringent requirement, over the past decades, designers have been seeking for new material solutions. ETFE membranes fits this paradigm. These lightweight membranes allow for a more efficient structural design that leads to a reduction of material use for structural purposes. ETFE foils themselves require less energy for production and transportation than glass panes [2]. The lightweight nature of the membranes results in acoustic transparency at low frequencies. In a typical setting where the membranes are used in a roof or wall structure, this behaviour leads to low frequency acoustic waves not being reflected. From a room acoustic perspective, the high one-way transmission to the outdoor world can be seen an "effective absorption" by the membrane. By the reducing effect on the sound pressure level and reverberation time, this is highly beneficial for the indoor acoustic comfort.

In terms of determination of this "effective absorption" in a reverberant chamber, this acoustic transparency poses a challenge: acoustic waves that pass the membrane, reflect on the hard wall or floor behind it, and re-enter the room after having been partially absorbed. This situation is quite different from the one where ETFE membranes are encompassing the building interior, in which the part of the acoustic wave energy that passes the membrane does not re-enter the room. This complication was solved by mounting the ETFE membrane on a frame and place it on a box filled with mineral wool, so that the box space under the membrane acted as an acoustic sink, mimicking an outdoor (100% absorbing) environment. Despite the small size of the sample, reliable values were found for the frequency dependence of the "effective absorption", and implemented in the framework of simulations, auralizations and measurement interpretation of real spaces based on ETFE membranes and cushions.

Keywords: ETFE, room acoustics, cushions, absorption, ISO354

1 Introduction

ETFE membranes are thin extruded films that are often used in architectural projects. In medium to large sized projects, the membranes are used as an alternative to glass panes as a separation between outside and inside. While the membranes are often used to form air-inflated cushions in buildings, in this paper single layer membranes are examined exclusively. The surface area of these constructions often exceeds 1000 m^2. ETFE membranes/cushions are usually applied as roof structures in shopping malls, public transit terminals and hotel lobbies. Due to the design flexibility of these structures, the shapes and sizes of individual cushions and entire constructions vary widely.

2 Conceptual approach: room acoustics

The room acoustic behaviour of ETFE membranes is unconventional for a building material [3]. The acoustic transparency of the ETFE membranes is high in the low frequencies and low in high frequencies. The transparency contributes to a high “effective absorption” (in room acoustic modelling) at low frequencies.

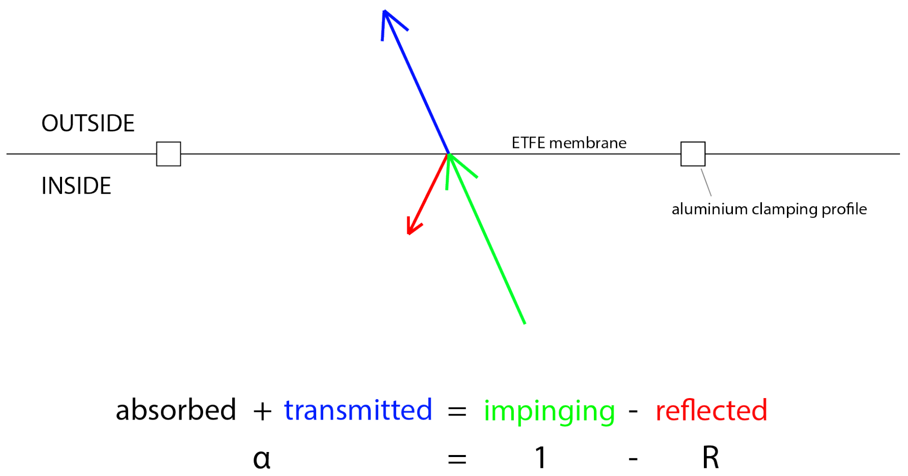

Figure 1. Transmission and reflection of an ETFE membrane. At low frequencies, most of the energy is transmitted. In the setting where the membrane is encompassing a building interior, from a room acoustic point of view, this transmitted energy can be considered as “absorbed”. At high frequencies, membranes are quite reflective.

3 Experimental approach

The effective absorption was measured using the conventional ISO354 method in the reverberation chamber. However, the transparency of ETFE membranes made it challenging to accurately measure their effective absorption. For this measurement campaign, two 2.08 m^2 aluminium frames with tightened ETFE membranes were available. The surface tension was comparable with the one in architectural projects.

Since it was expected to measure a relatively large absorption in the low frequencies, a 60 cm thick layer of glass wool was placed in a 61 cm high MDF box under the transparent ETFE membrane (pictured in Figure 2). The 60 cm of glass wool effectively mimics an outdoor environment that doesn't reflect any sound energy (transmitted through the membrane). A measurement was performed to check this assumption and the results will be discussed later on in this paper (setup "C").

Figure 2. Basic experimental setup in the reverberation chamber (A): a 61cm high wooden box filled with 60cm of mineral wool is used to absorb the acoustic energy that is transmitted through the membrane.

The wooden box was made such that the frame fitted flush on the box. The walls of the wooden box were sufficiently thick (according to the mounting type A description in ISO354).

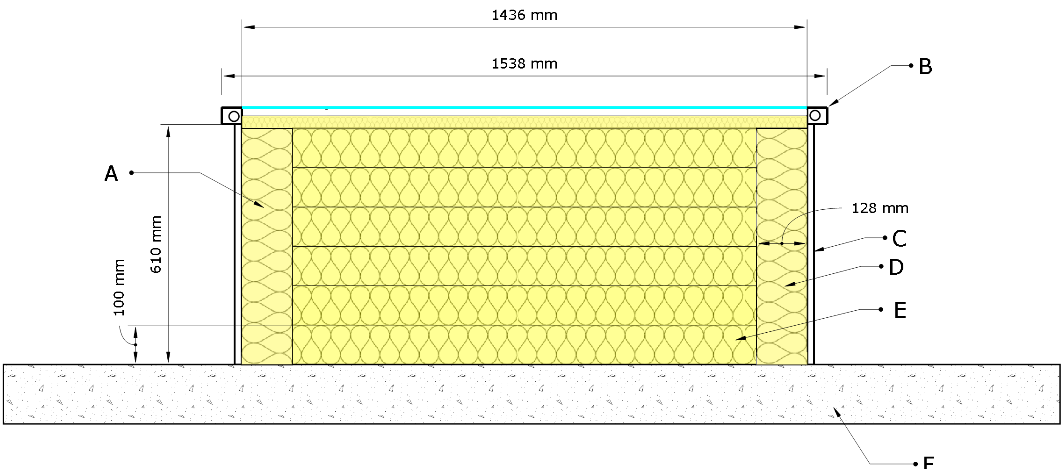

Figure 3. cross-section of the box. A: Compacted foam mats, B: Aluminium frame, C: MDF panels 18 mm thick, D: rolled up foam mats, E: glass wool panels 100 mm thick, F: laboratory floor (concrete)

While the reverberant room is suitable for ISO354 measurements, the sample surface size (2.08 m²) is below the required size (10-12m^2). Therefore, to validate the first measurement, the second ETFE frame was used to double the surface area of the test sample. A second box was constructed, the result is shown in Figure 4.

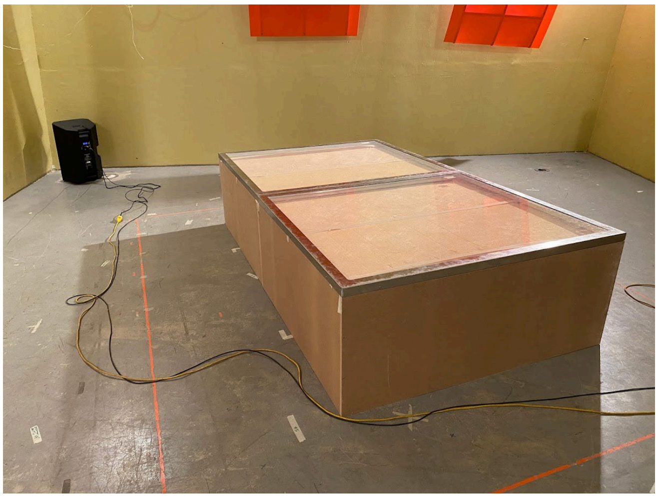

Figure 4. Supplementary measurement configuration with two boxes, each filled with glass wool absorption, both covered with an ETFE frame. This configuration was constructed to increase the absorption behind the ETFE structure of interest (to simulate open air), and thus to enhance the accuracy of the measurement (B).

4 Calculation

Reverberation time was measured by using the interrupted noise method. The samples were positioned in the middle of the room. The sample absorption information was extracted from two sets of measurements: a reference measurement 1 with the room and empty box (in the analysis, the small absorption of the inner box surfaces was negligible), and a measurement 2 with the sample covering the mineral wool filled box. For each set, 8 microphone positions and 3/4 speaker positions were used. Three speaker positions were used with sample and four without sample. The sound production and signal acquisition were controlled remotely, and the temperature and humidity were closely monitored and averaged over time.

The effective absorbing surface of the mineral wool backed ETFE was determined in the standard way:

$$A_T = 55.3V\left(\frac{1}{c_2 T_{30,2}} - \frac{1}{c_1 T_{30,1}}\right) - 4V(m_2 - m_1) \quad (1)$$

where c_1 and c_2 (m/s) are the values of the speed of sound in air during the measurements 1 and 2 at temperatures T_1 and T_2 respectively. $T_{30,1}$ and $T_{30,2}$ (s) are the reverberation times per third octave band in the empty reverberation chamber with empty box and with sample respectively. m_1 and m_2 [1/m] are the frequency and humidity dependent power attenuation coefficients according to ISO 9613-1 [3]. V=197m^3 is the room volume.

The effective absorption coefficient was determined as:

$$\alpha_s = \frac{A_T}{S} \quad (2)$$

where: S (m^2) is the surface area of the test sample (2.08m^2).

5 Results

Figure 5 shows that in the model prediction of the reference situation with the empty box in the room, an absorption peak occurs in the frequency range in the 125 and 160 Hz third octave bands. This peak corresponds with a resonance due to standing waves in the box that are most likely not present when the box is filled with glass wool. This peak, shown in Figure 5, corresponds with the half-wavelength of the standing waves in the box (1.53m => 223 Hz/2 = 111 Hz, 1.35m => 253 Hz/2 = 126 Hz). For further processing, it was manually removed by interpolating between the absorption values of the adjacent 1/3 octave bands. A simple linear interpolation was performed between the values obtained for 100 Hz and 200 Hz to neutralize this effect.

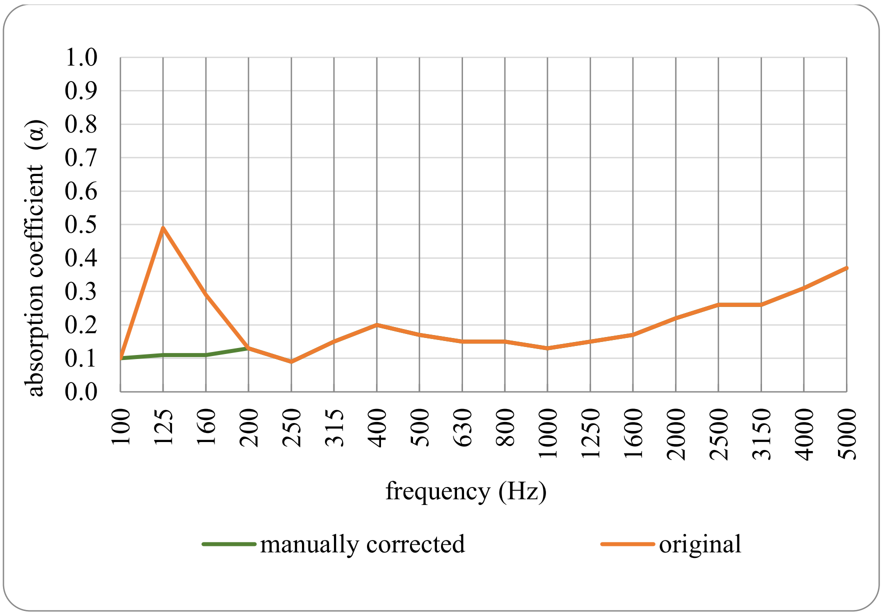

Figure 5. Absorption coefficient of the reference scenario, the empty wooden frame (box)

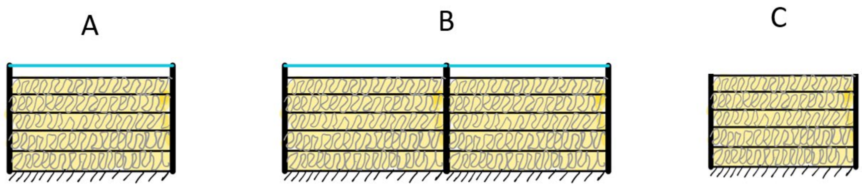

Figure 6. schematic configuration of the 2 measurement configurations A and B, with respectively one (A) and two (B) glass wool filled boxes covered by an ETFE membrane. (C) corresponds to a glass wool filled box without an ETFE membrane or aluminium frame on top. The yellow areas indicate the presence of a 60cm thick layer of glass wool. The blue lines indicate a 250 µm layer of ETFE. Between the membrane and the upper surface of the mineral wool, there was 3-4 cm of air.

In the two measured configurations “A” and “B” (Figure 6), there were respectively one and two boxes, with 2.08 and 4.16 m² of ETFE in the room; the area of the aluminium test frames was neglected in the analysis. The two results for the absorption spectrum in Figure 6 are very similar, with a somewhat higher deviation below 160 Hz, which can be attributed to effects of the above-mentioned resonance.

To check the assumption of broad band total absorption in the observed frequency range by the 60 cm of glass wool, setup ”C” was also measured individually (with the empty box as a reference, box with absorption but no ETFE). In Figure 6 the high absorption of this thick layer of glass wool is displayed, it hovers around 1 in all measured frequencies. This confirms the hypothesis of very high broad band absorption of the thick layer of glass wool.

To further validate the experimental results, an analytical model for the absorption was used to determine the random incidence absorption on the 2.08 m^2 ETFE membrane. The analytical model was implemented in Odeon(R) and was based on the transfer matrix method [4]. Figure 6 shows that the model result corresponds quite well with the experimental absorption spectra, with a limited excess absorption of about 0.05-0.1 across the whole spectrum.

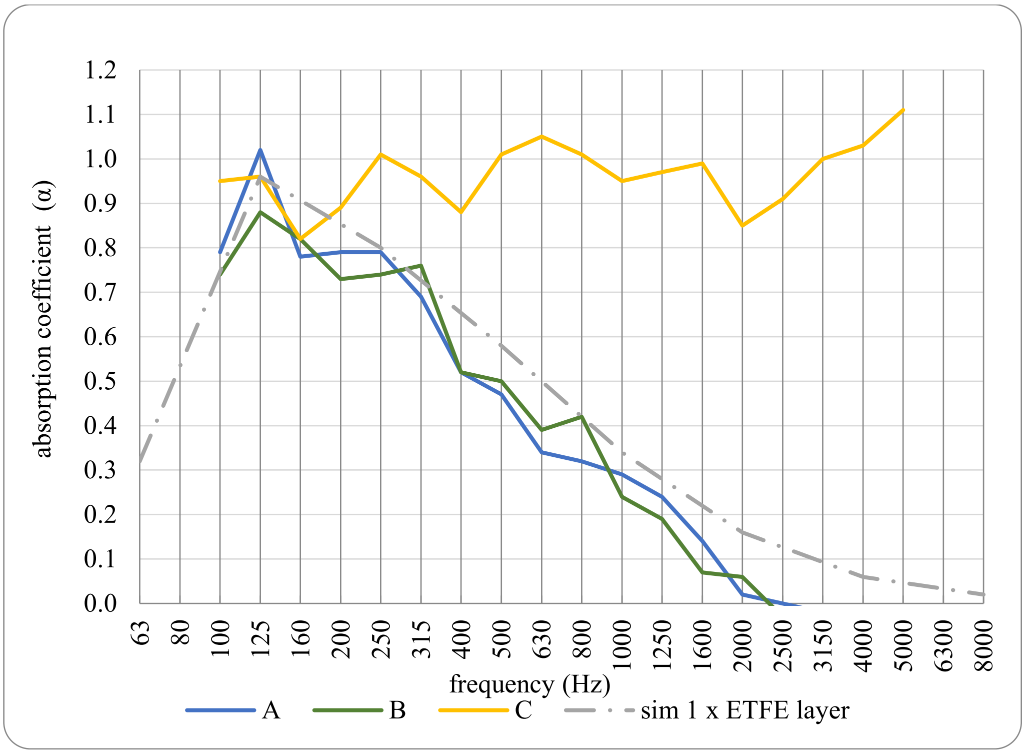

Figure 7: spectra of the absorption coefficient for the measured configurations, in the three configurations (full lines), together with a simulated spectrum (dash-dot line) of the absorption of one ETFE covered, glass wool filled box.

Table 1: Relative standard deviation of the reverberation times used for absorption coefficient determination (in %).

measurement	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
A	0.16	0.19	0.09	0.10	0.06	0.05	0.04	0.04	0.04	0.03	0.04	0.03	0.02	0.03	0.03	0.02	0.03	0.03
B	0.16	0.16	0.08	0.07	0.07	0.08	0.07	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.03
C	0.15	0.17	0.12	0.09	0.08	0.07	0.07	0.04	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.03	0.03	0.01
empty box	0.16	0.16	0.08	0.07	0.07	0.08	0.07	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.03

Finally, all relative standard deviations of the reverberation time measurements are shown in Table 1 (calculated according to ISO354). Outliers are removed manually but a minimum of 18 individual measurement points were used. The variability of the reverberation time is relatively high in the low frequencies but similar for all measurements in each third-octave band.

6 Conclusion

In spite of its small surface area, the spectra of the absorption coefficient of a flat ETFE membrane of about 2 m^2, determined experimentally using a modified ISO354 method, by using one and two samples, correspond quite well with each other and with the spectrum calculated by the transfer matrix method. The result, which was obtained by placing the ETFE membrane on top of a strongly absorbing mineral wool filled box, confirms that ETFE membranes are transparent at low frequencies and reflective at high frequencies. Further research is ongoing to determine the absorption coefficient of the more complex multi-layered ETFE cushions.

7 References

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