STAR (Sustainable Thermal and Acoustic self-made solutions for buildings refurbishment in disadvantaged social contexts by Reusing poor materials)

M2: Report assessing the thermal and acoustic properties of the materials

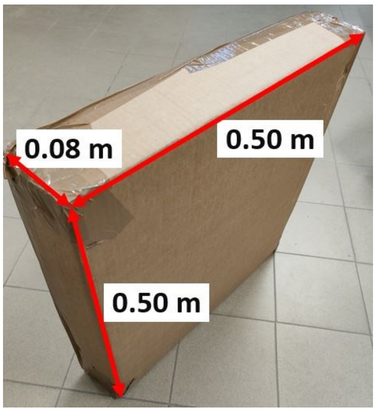
1. Introduction

This report outlines the methodology and results of tests conducted on reusable materials. The tests were carried out to evaluate thermal conductivity, acoustic properties, and fire resistance.

The selected materials for testing include surgical masks, panels made from natural fibers, and panels made from recycled fabric fibers. Additional tests are currently being conducted on structures made from reused textile materials. The types of samples analyzed (**Figure 1**) can be categorized into:

- Home-made panels, i.e. carton boxed filled with surgical masks (T1)
- Industrially assembled panels made from natural fibrous materials (T2)
- Industrially assembled panels made from reused materials (textile materials) (T3).

The following sections will specifically present the methodology and instrumentation used for thermal analysis (Section 2), acoustic analysis (**Section 3**), and fire resistance analysis (Section 4).



(a)


(b)

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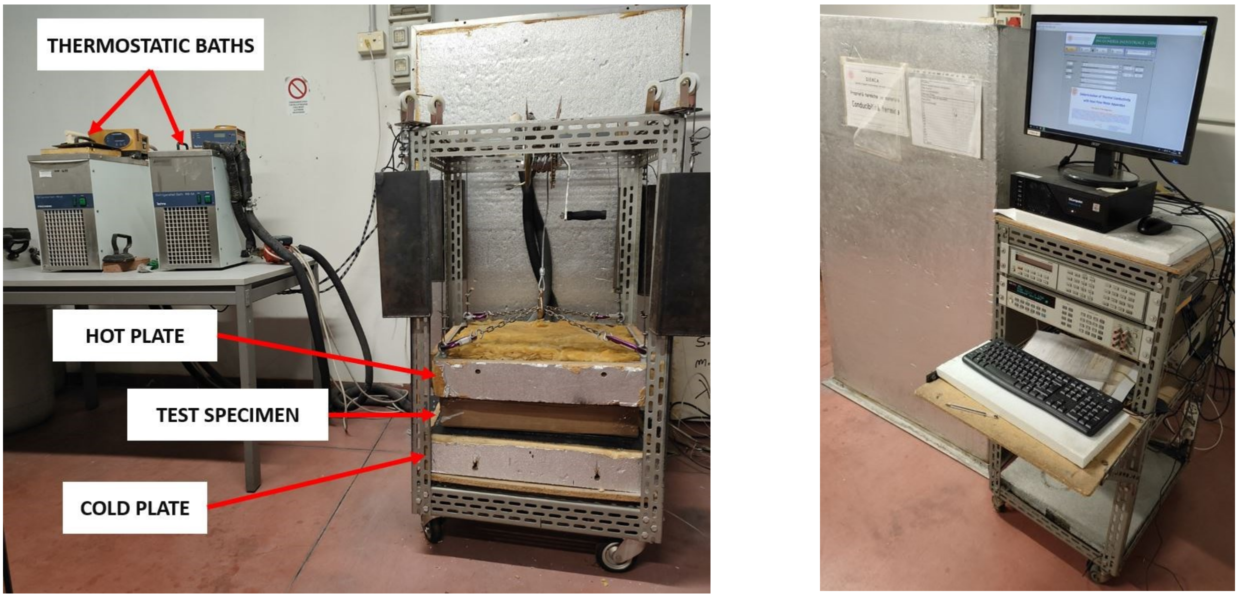
(c) (d)

Figure 1 – Principal specimens investigated: (a) and (b) carton box filled with surgical face masks; (c) panels made of natural fibrous material and (d) panels made of reused textile materials.

2. Thermal conductivity tests

Thermal conductivity tests were conducted at the University of Bologna, Italy, and the Ecam Ricert Institute in Monte di Malo—Vicenza, Italy. The initial tests utilized a home-made heat flow meter designed to analyze materials with thermal conductivities less than 5 W/(mK), adhering to the ISO 8301 [**1**] standard. Meanwhile, the apparatus used in the second location was a commercial guarded hot plate (model Lambda Meter EP500) manufactured by Lambda Messtechnik GmbH in Dresden, Germany, in accordance with EN 1946-2 [**2**] standard. It should be noted that most tests were conducted at the University of Bologna using the apparatus shown in **Figure 2**; however, some tests were carried out in Vicenza solely to cross-check the results.



(**a**) (**b**)

Figure 2 – View of the home – made thermal conductivity apparatus: in (**a**) is shown the test specimen placed between the hot and cold plate, while in (**b**) is shown the data acquisition system (switch, ice reference point and multimeter).

The experimental setup to measure conductivity involves placing the sample, sized 0.50 x 0.50 x 0.07 m, between two plates, one hot and one cold, maintained at a constant temperature by conditioned water from two thermostatic baths. The conductivity test involves recording temperatures and the heat flow across the sample using heat flux meters. Thermal conductivity (λ, W/(mK)) is calculated according to the UNI EN 12667 [**3**] standard using the following formula:

$$\lambda = fed\frac{1}{\Delta T}, \tag{1}$$

where d (m) is the average specimen thickness, e (mV) is the output from the heat flow meter, f (W/(mV m^2)) is the calibration factor of the heat flow meter, and ΔT (K) represents the temperature difference between the two plates. Additionally, the test is conducted in a quasi-steady state, i.e., temperature and heat flow measurements are collected when the system reaches thermodynamic stability, which is determined when the variation in heat flow is less than 0.5 %.

For the first type of panels (T1), multiple tests were conducted by varying the density (ρ) of masks in the sample, altering their arrangement, and using a polyurethane matrix to enhance the panel's long-term stability. Moreover, the effect of a sanitization process and of a flame-retardant application was investigated. The results from these variations are presented in **Table 1** and **Figure 3**.

Table 1 – Thermal conductivity test performed on the T1 panels. Where there are multiple conductivity values, they refer to tests conducted twice on the same test specimen.

Test specimen	ρ (kg/m^3)	λ (W/(m K))
Masks in an ordered arrangement	60	0.046
Masks in an ordered arrangement	90	0.039
Masks in a disordered arrangement	90	0.042
Crumped masks	30	0.072 – 0.064
Crumped masks	40	0.055 – 0.059
Crumped masks	50	0.051 – 0.052
Crumped masks	60	0.047 – 0.047
Crumped masks	76	0.052 – 0.052
Shredded masks (0.355 kg) in polyurethane foam (44 %) without nose clip-on	54	0.048
Shredded masks (0.59 kg) in polyurethane foam (21 %) without nose clip-on	63	0.041
Sanitized crumped masks	60	0.066
Sanitized crumped masks	70	0.060
Sanitized crumped masks	75	0.059
Sanitized crumped masks	80	0.054
Sanitized crumped masks	90	0.050

Sanitized + flame retardant crumped masks	60	0.053
Sanitized + flame retardant crumped masks	70	0.050
Sanitized + flame retardant crumped masks	75	0.059
Sanitized + flame retardant crumped masks	80	0.044
Sanitized + flame retardant crumped masks	90	0.052

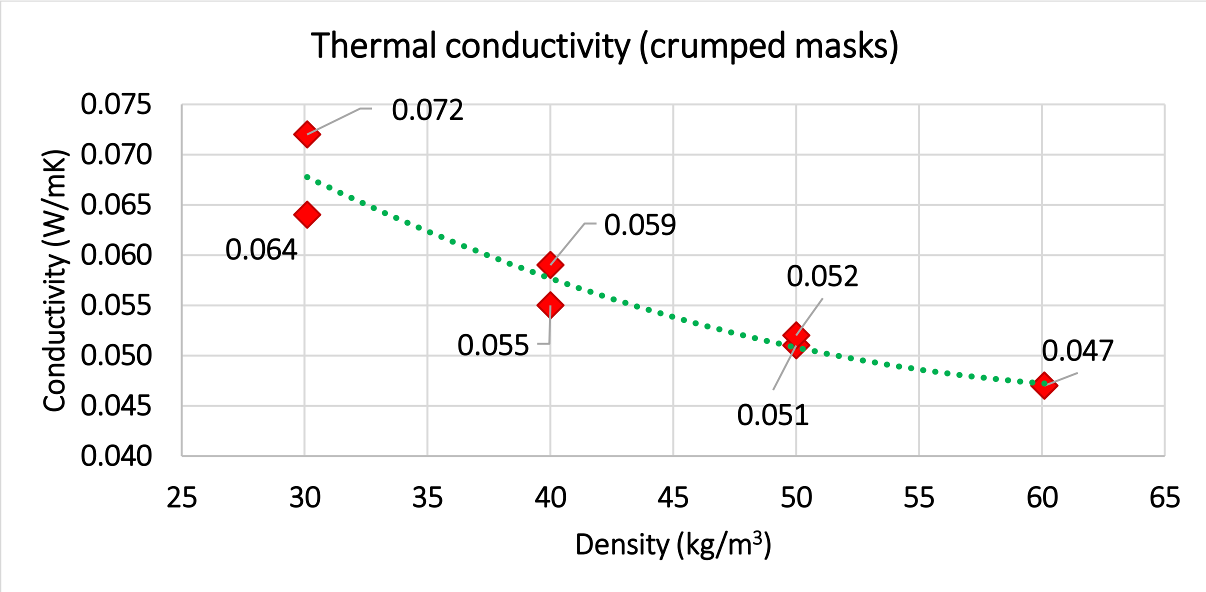


Figure 3 – Trend of the thermal conductivity vs density for crumped masks; the red points refer to experimental text performed, while the green dashed line refers to a second order correlation.

Focusing on **Table 1**, it can be observed that the thermal conductivity values vary significantly depending on the type of sample or the arrangement of the masks within the sample. Specifically, for a fixed density (90 kg/m³), the conductivity is 0.039 W/(m K) for masks arranged in an ordered manner, compared to 0.042 W/(m K) for masks arranged randomly (an increase of 7.7 % in conductivity). This phenomenon is likely due to the formation of larger and more irregular air pockets, which can trigger convective motions. This aspect also explains why conductivity decreases as the density increases: for masks arranged randomly at different densities, the conductivity decreases with increasing density (**Table 1** and **Figure 3**), following approximately a second-order relationship (eq. 2).

$$\lambda(\rho) = 2 \cdot 10^{-5}\rho^2 - 0.0022\rho + 0.1183 \qquad (2)$$

Additionally, it was observed that conductivity tests performed on the same sample tend to yield the same value only at higher densities. For example, with a 30 kg/m³ sample, two tests were performed where the only difference was the rearrangement of the masks inside the panel (visible in **Figure 1**(**a**)), resulting in conductivity values of 0.064 and 0.072 W/(m K). However, for the 60 kg/m³ sample, both tests yielded the same conductivity value of 0.047 W/(m K). The effect of adding polyurethane foam alongside the masks was also investigated, aiming to provide a stable structure over time and prevent the masks from settling at the bottom due to gravity. The results showed that the inclusion of the foam did not lead to significant improvements in conductivity, assuming equal sample density. Further tests were conducted after a high-temperature sanitization process in a dishwasher (since the project envisions the use of insulation materials that can ideally be assembled by users themselves) and after treatment with a commercially available fire retardant. The results, shown in **Table 1**, indicate a deterioration in performance compared to the untreated insulating panels (with the same panel type and density). This is likely due to the residual moisture content after the treatments.

Additionally, for completeness, vapor permeability measurements were taken, showing that surgical masks are highly permeable to vapor, similar to the characteristics of other commercial fibrous insulators like rock wool.

Thermal conductivity measurements were subsequently performed on panels (in this case, industrially produced) made from both recycled and natural materials (**Figure 1**(**c**) and **1**(**d**)). The panel shown in **Figure 1**(**c**) is made from thermally fixed hemp and kenaf fibers (ISOLKENAF30, ISOLKENAF80). This production process ensures long-lasting thermal and acoustic performance while also making the panels resistant to moisture. These panels can be used for external or internal insulation, as well as in dry construction systems. Installation typically involves the use of mechanical dowels or lime-based adhesives on brick surfaces. Additionally, this material is fully recyclable at the end of its life cycle. The panel shown in **Figure 1**(**d**) (ISOLMIX40) is made from a mixture of fibers recycled from various yarns of different types and colors. These fibers are thermally bonded through a process that does not require the addition of chemical components. This method ensures the material remains stable over time and highly resistant to moisture and infiltration. The material is easy to handle and is suitable for thermal and acoustic insulation in walls, floors, and roofs. Like the previous panel, it is fully recyclable at the time of dismantling.

Table 2 – Thermal conductivity test performed on ISOLMIX40, ISOLKENAF30 and ISOLKENAF80 panels. For each panel three different subsequent thermal conductivity tests were performed.

Test specimen	**ρ (kg/m^3)**	**λ (W/(m K))**
ISOLMIX40	31.3	0.043 – 0.045 – 0.045
ISOLKENAF30	33.7	0.048 – 0.049 – 0.049
ISOLKENAF80	64.9	0.035 – 0.035 – 0.035

Table 2 presents the results of the thermal tests performed. As shown, three different tests were conducted for each type of panel, following a conditioning process to remove residual moisture from the panels until the weight change over 24 hours was less than 1%. This procedure resulted in a high level of test repeatability, particularly for the higher-density panel. It was also found that the declared density differed from the actual measured density. Specifically, for ISOLMIX, the declared density was 40 kg/m^3, while the measured value was 31.3 kg/m^3. For ISOLKENAF30, the declared density was 30 kg/m^3, but the measured density was 33.7 kg/m^3. Finally, for ISOLKENAF80, the declared density was 80 kg/m^3, whereas the measured value was 64.9 kg/m^3. Despite these differences, the thermal conductivity values obtained are suitable for use in building

insulation, particularly for the higher-density panel (ISOLKENAF80). As observed, there is a trend of decreasing thermal conductivity as the panel density increases.

The results of the thermal analysis, along with the fire resistance tests for some of the samples, have been published in an article in an international journal [**4**]. Currently, thermal conductivity measurements are also being conducted on different types of fabrics, and the complete results will be reported later, as they are still preliminary and not included in this report.

3. Acoustic tests

Table 3 – Sample identification and density.

Test specimen	Declared ρ (kg/m^3)	Measured ρ (kg/m^3)	Identification code
ISOLKENAF30	30	38	K30
ISOLKENAF30	30	31	K30
ISOLKENAF80	80	71	K70
ISOLKENAF80	80	68	K70
ISOLKENAF480	480	340	K340
ISOLMIX40	40	45	M45
ISOLMIX40	40	36	M35

Acoustic conductivity measurements have been performed on panels made of natural fibers (ISOLKENAF) and those made of recycled textile materials (ISOLMIX), which were previously analyzed for thermal conductivity. The characteristics of the tested panels are shown in **Table 3**. As observed, the declared density differs from the one measured in the laboratory. **Figure 4** presents the images of the tested panels, where their thickness is particularly noteworthy, as it plays a significant role in evaluating and comparing acoustic performance, along with density. The sound absorption coefficient (α) and Transmission Loss (TL) are the key parameters used to acoustically characterize the panels. The absorption coefficient α measures the amount of sound power reflected by a sample back to the sound source. It ranges from zero to one, with one indicating that no sound energy is reflected, meaning the sound is either absorbed or transmitted through the material. Transmission Loss (TL) quantifies the amount of sound energy that is prevented from passing through the material from the source room to the receiving room. A higher TL value indicates less sound power is transmitted to the receiving room. An impedance tube with a diameter of 45 mm (Kundt Tube, as shown in **Figure 5**) is used to measure these parameters. The measurements are carried out in the frequency range of 50–4000 Hz. The measurement setup for α evaluation is shown in **Figure 6**, and the measurements were conducted in accordance with ISO 10534-2 [**6**]. The TL is measured using the two-load method, as depicted in **Figure 7**. In this method, the termination of the tube is changed to vary the impedance at the end. In this case, the two loads are represented by an open end and a closed end.


(a)


(b)


(c)


(d)


(e)

Figure 4 – Test specimen for acoustic characterization: **(a)**, **(b)** and **(c)** refers to hemp and kenaf panels (ISOLKENAF), while **(d)** and **(e)** refers to textile and polyester panels (ISOLMIX).

Figure 5 – Kundt tubes for (a) sound absorption coefficient and (b) transmission loss measurements.

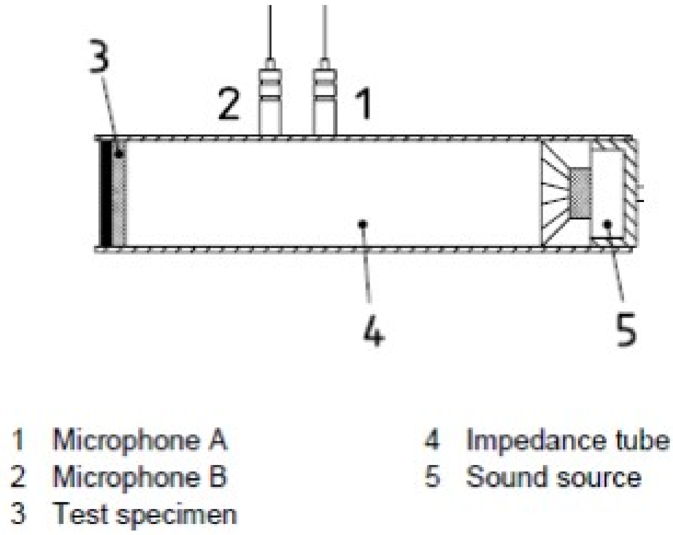


Figure 6 – Measurement set-up for absorption coefficient.

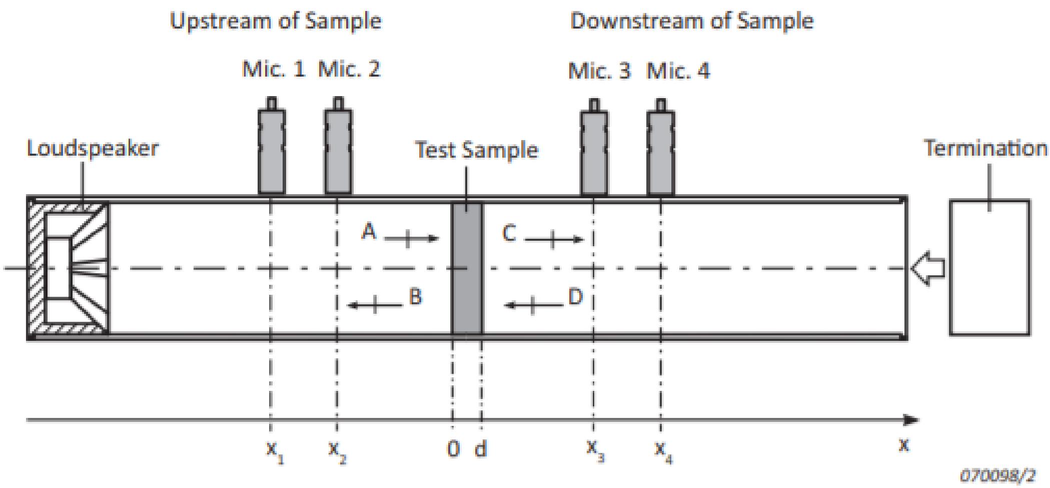


Figure 7 – Measurement set-up for transmission loss with the two loads technique.

Figures 8 and **9** report α and TL curves of the ISOLKENAF panels with different density. Samples of same panels typology evaluate the reproducibility of the measurements, thus highlighting a homogeneous composition of the panels. Samples K30 and K70 have the same thickness and K70 curves are shifted to lower frequency providing higher values of α. Such behavior is in line with the effect of the higher density of samples K70 in respect to K30 ones. Specimens K340 show the lowest α values, but it is less thick than the other samples (1 mm vs 4 mm) and more rigid. For what concern the TL, the samples show a behavior in line with their density and surface rigidity: higher is the density and higher is the TL.

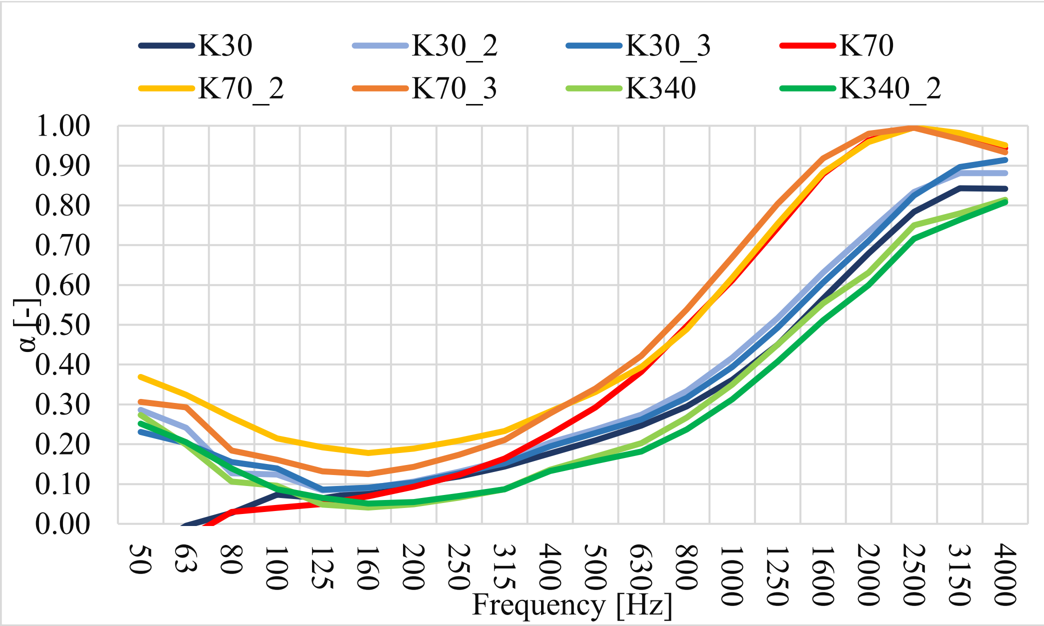


Figure 8 – Sound absorption coefficient of Isolkenaf samples.

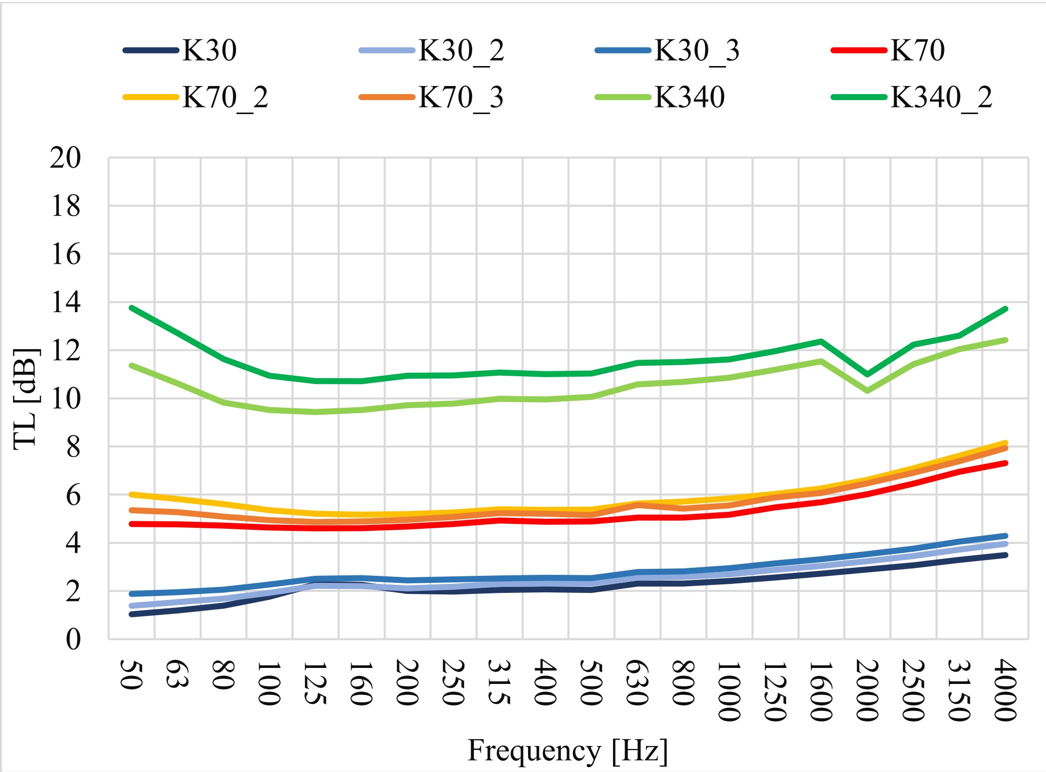


Figure 9 – Transmission loss of Isolkenaf samples.

Figure 10 and **Figure 11** report α and TL curves of the Isolmix panels with different measured density. In this case measurements show a higher variability, probably due to the inhomogeneity of samples. Such consideration is derived also by the thermal analysis and confirmed by the producer, as the panels are produced with different type of recycled textile fiber. M35 and M45 samples have the same thickness (5 mm), but different density. As previously seen, samples with higher density show higher α and TL values.

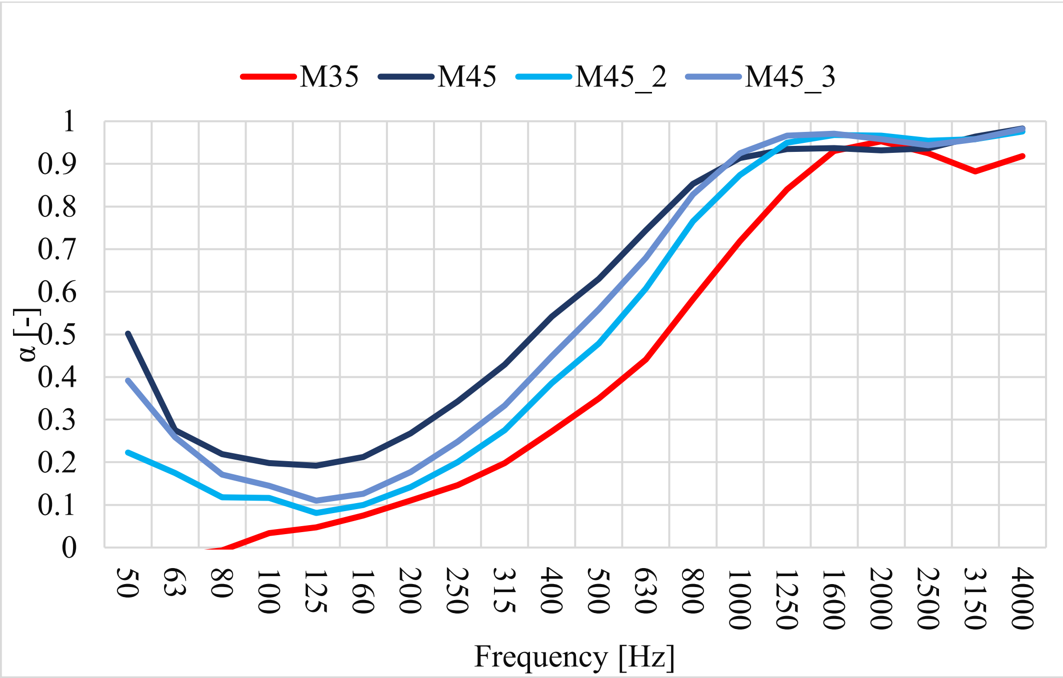


Figure 10 – Sound absorption coefficient of Isolmix samples.

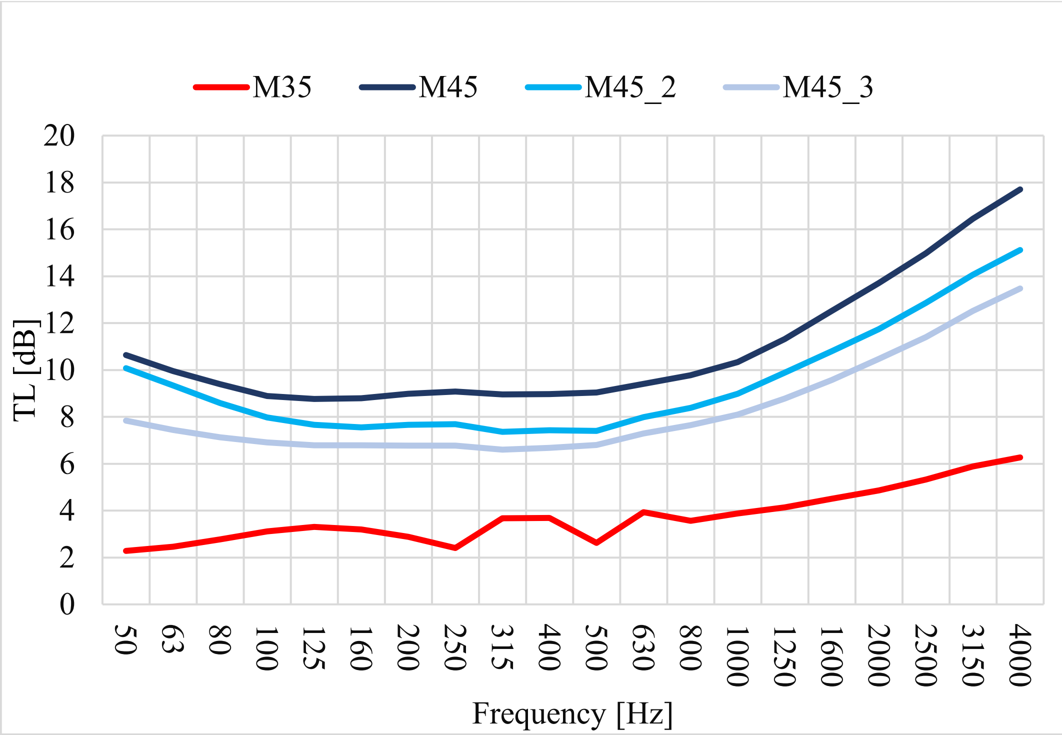


Figure 11 – Transmission Loss coefficient of Isolmix samples.

4. Fire resistance tests

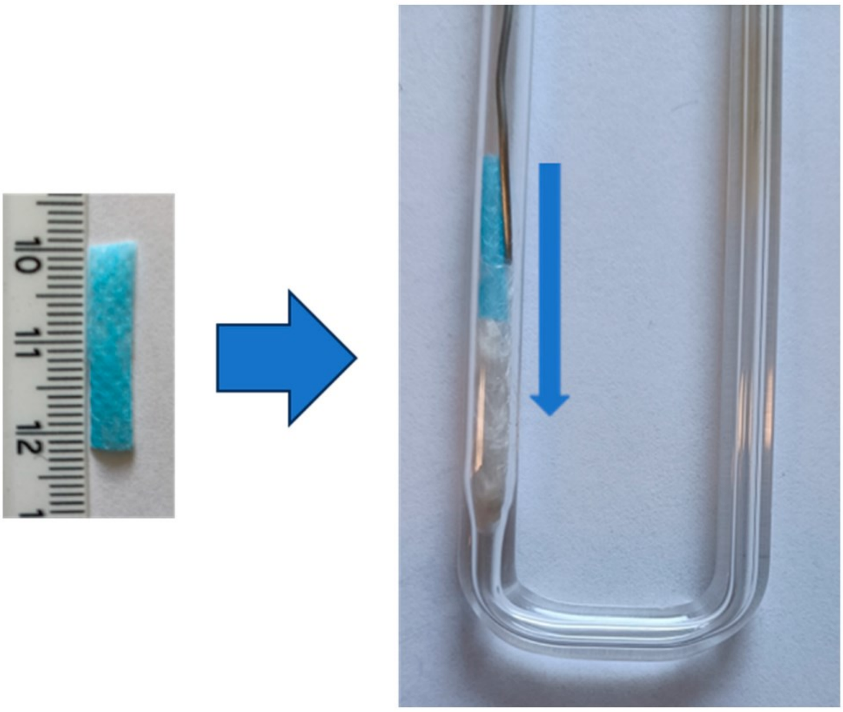
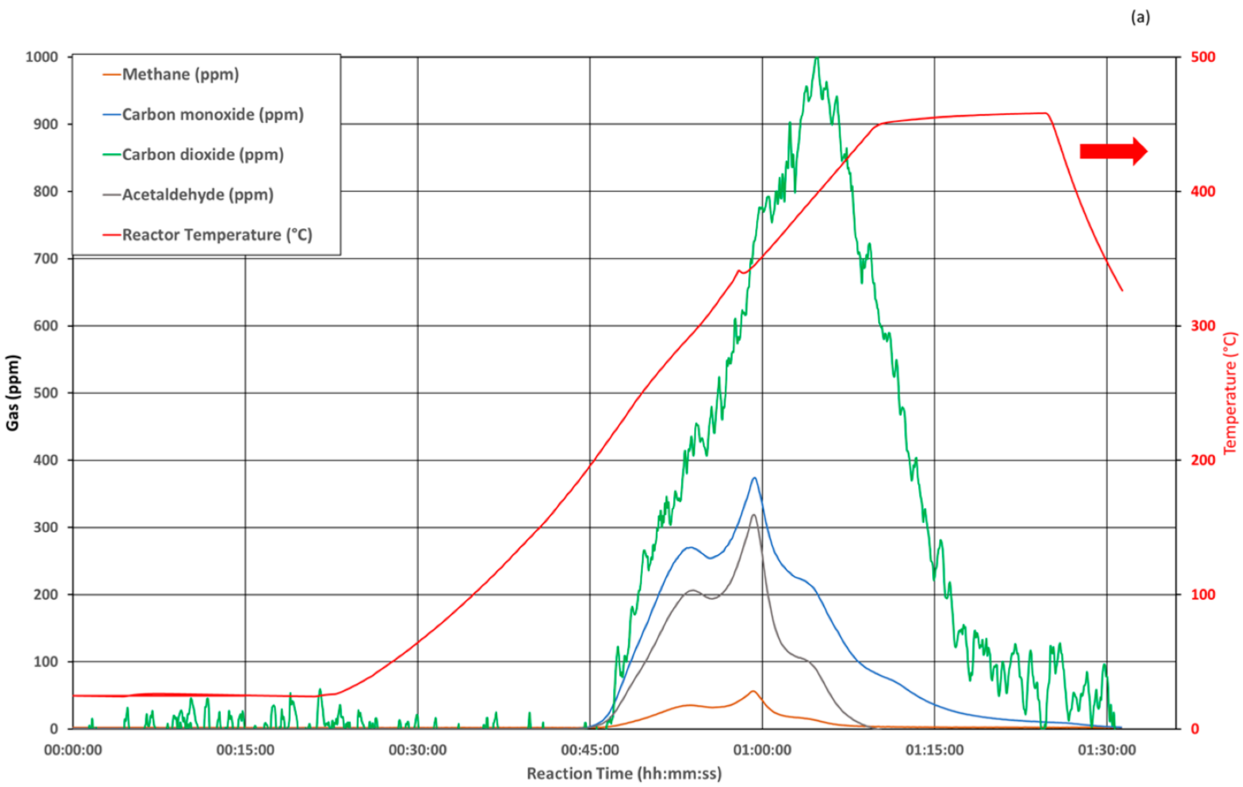


Figure 12 – Test specimen made for the fire resistance analysis (SFM sample) and the flow microreactor loaded with the SFM (right arrow): The vertical arrow indicates the direction of the airflow. A K-thermocouple was vertically inserted into the SFM layer to continuously monitor the temperature. The SFM was held in place using glass wool. [**4**]

Fire resistance tests have been carried out so far on surgical face masks (SFMs). The fire resistance of both untreated and fire retardant-treated SFMs was evaluated using the Temperature Programmed Oxidation (TPO) technique [**6**]. In this method, a sample of the SFM was heated in a flow reactor at a constant rate of 10 °C/min, starting from room temperature up to 500 °C, with an airflow of 200 mL/min. This approach allowed us to determine the auto-ignition temperature, or the temperature at which the material spontaneously ignites. A rectangular piece of approximately 10–15 × 2–3 mm in size (weighing 7–15 mg) was cut from the center of the SFM, placed in a U-shaped flow microreactor (**Figure 12**), and subjected to the aforementioned thermal treatment. The outflow from the reactor was continuously monitored using a Multigas 2030 FTIR analyzer by MKS Instrument Inc., Andover (MA), USA.

As shown in **Figure 13**, the fire resistance characteristics were similar for both untreated and fire retardant-treated samples, with ignition occurring at around 200 °C. However, there was a noticeable difference in the combustion pattern, specifically in the $CO2$ evolution. In untreated SFMs, a broad peak with a maximum at around 400 °C was observed, whereas in fire retardant-treated SFMs, this peak split into two overlapping peaks at 295 °C and 415 °C. The molar composition of the emitted gases remained largely consistent between the two samples: 65% $CO2$, 20–24% CO, 3% $CH4$, and 12–13% acetaldehyde for both untreated and treated SFMs. However, the total amount of gases evolved from the fire retardant-treated SFM decreased by 20% compared to the untreated sample. Additionally, a small amount of solid residue was found at the outlet of the TPO reactor, indicating partial decomposition of the material in the treated sample.



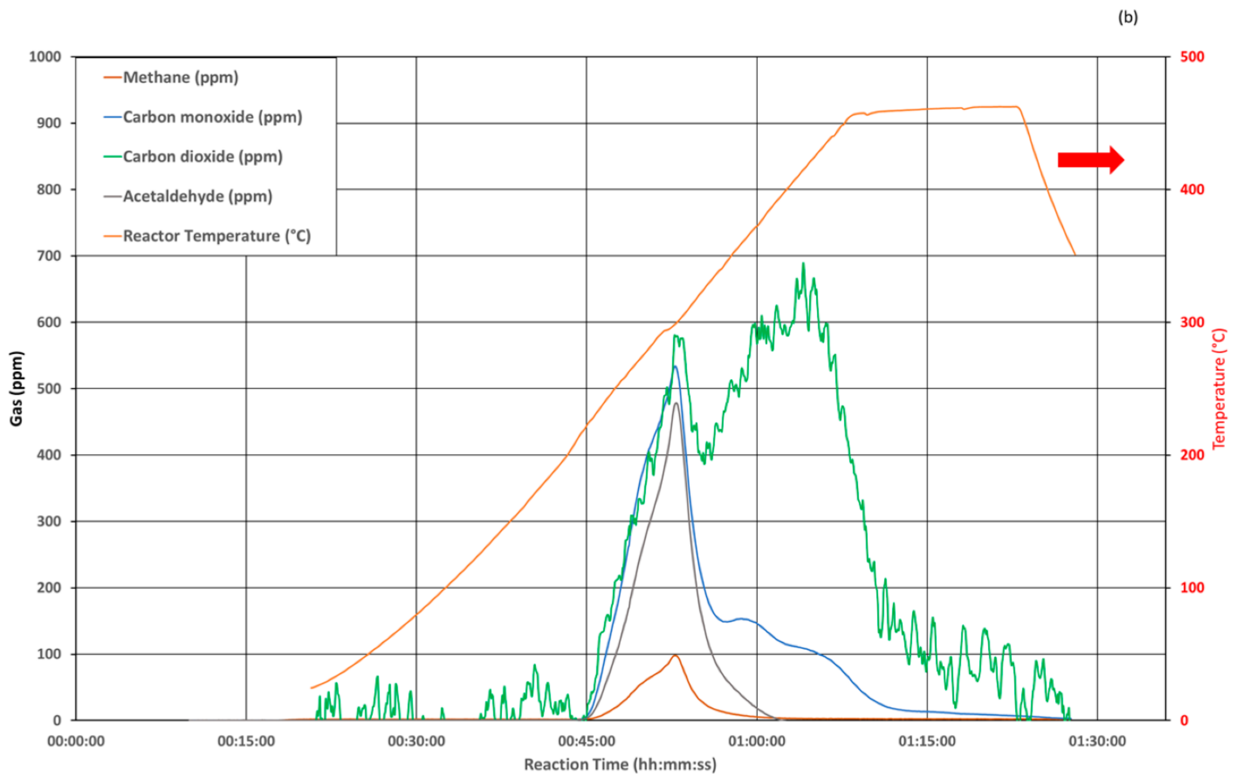


Figure 13 – Examples of Temperature Programmed Oxidation profiles obtained on (a) untreated and (b) fire retardant-treated SFMs. Gas concentration (ppm) and temperature profile (°C) are reported as a function of time (hh:mm:ss). [**4**]

References

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[2]: CEN, European Committee for Standardization., 1999., Thermal performance of building products and components — Specific criteria for the assessment of laboratories measuring heat transfer properties — Part 2: Measurements by the guarded hot plate method (Standard. No. 1946-2).

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