Experimental characterization of recycled surgical face masks used directly as acoustic treatments

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Abstract

Nowadays, sound absorbing treatments made from recycled materials are increasingly common. This paper focuses on the sound absorption properties of surgical face masks and discusses their possible use. Several ways of assembling entire raw masks as self-sufficient thick sound absorbing material are tested as well as the influence of density. The performance of the different surgical face mask test samples is assessed using impedance tube measurements. The behaviour of the mask test samples is similar to that of porous materials classically used for building insulation. Results show sound absorption coefficients close to those of traditional commercial materials and even better on the 100 – 700 Hz frequency band. Surgical face masks may have the potential to be used as an alternative low-cost, environmentally friendly and easily manufactured sound absorbing material.

1 Introduction

With the expansion of cities and the development of industrial and technological fields, noise pollution reduction is growing in importance in our society [1]. Porous materials such as mineral wools, synthetic fibers and polymeric foams are traditionally used for sound insulation purposes. As noise reduction requirements in transport, building and industry are becoming more and more stringent to protect population's health, the development of more efficient sound absorbing materials is needed. At the same time, the increase of environmental effects such as waste pollution and global warming encourages researchers and industries to create new sound absorption materials not derived from petroleum-based resources. Acknowledging both ecological and economic concerns, studies have been conducted in the last two decades on low-cost environmentally-friendly sound absorbing materials.

A first way of addressing this topic is to use natural fibers. Sound absorption characteristics of various vegetable (tea leaf [2], cotton, luffa, bamboo, wood) or animal (feathers [3], wool, coat) fibers have been assessed [4, 5, 6]. These fibers can be used as raw, assembly or composite material. It has been shown that many natural fibers have comparable sound absorption performances and that their properties (diameter, length, etc.) play an important role in sound absorption. Kapok, pineapple-leaf and hemp fibers for instance appear to be good alternatives to mineral fibers. These materials present moreover the advantage of being biodegradable.

Another way of developing ecological sound absorbing materials is to use waste material present in the environment. Different studies have shown that there is the potential to recycle rubber tire crumbs [7], cigarette butts [8], textile and paper fibers as sound absorbing materials [6, 9, 10]. Acoustic performances of these kinds of raw or composite materials are highly dependent on their structural properties (density, porosity, etc.). Some of them seem to be feasible alternatives to chemical building materials for sustainable building insulation.

Recently, the COVID-19 pandemic has led World Health Organisation to offer sanitary advice to limit the spread of the virus and protect the population [11]: physical distancing, wearing a mask, keeping rooms well ventilated, cleaning hands, etc. This has driven the use of a huge amount of single-use plastic objects such as gloves, bottles, packages, masks, test kits, leading to an unprecedented increase of medical and domestic waste [12]. Among the waste generated, masks are a serious threat to the environment and biodiversity. Indeed, many countries have greatly increased their production of such devices. Globally, in 2020, 3.4 billion single-use face masks or face shields were discarded per day as a direct result of the COVID-19 pandemic [13]. The most widely used masks for the public are single-use surgical face masks made from non-woven fabric of polypropylene fibers. In 2022, they remain part of the daily life of a significant part of the population.

As the presence of plastic in these masks makes them difficult to recycle [14], an idea is to take advantage of the plentiful supply of waste generated from the COVID-19 pandemic by developing cheap sound absorbing material. The non-woven fabric is favourable for sound absorption, and non-woven textiles and fibers are commonly used as acoustic treatments [2, 3, 15]. The capacity of these masks to absorb sound has been recently addressed in the case of samples made of fibers coming from masks without nose clip and elastic strap [16]. The present study proposes to assess the sound absorption potential of material samples made from entire raw masks using impedance tube measurements. Their sound absorption coefficient and impedance are measured. The interest of using these materials compared to traditional chemical building ones is also discussed.

2 Methodology

2.1 Test samples

All samples used in this study are made of porous materials allowing the dissipation of the incoming acoustic energy. By directing the air particles through the porosities of the material, viscous friction of the particles between each other and on the inner surface of the material produces heat. The amount of energy dissipated is directly related to the sound characteristics of the porous material. Typical porous materials retain a constant or slightly increasing sound absorption ability for all high frequencies, which makes them suitable for a number of applications in the building, automotive, industrial fields and suchlike requiring efficient noise control [3, 15, 16].

Commercial materials commonly used for building and industrial sound insulation were used for comparison purposes. Two different chemical building materials were selected: a rock wool (Alpharock from ROCKWOOL) and a polyurethane composite (Simfofit® from RECTICEL). Corresponding samples are named RW and PC respectively. As PC is partly made from fabric and cloth, it will be particularly interesting to compare its acoustic characteristics to those of mask samples.

A variety of samples were prepared by hand from entire raw masks (including nose clip and elastic strap). Every mask is a single-use polypropylene type that was previously used and collected by the authors. Three layers compose these masks: a non-woven repelling water layer, a middle melt-blown filter layer and an inner soft non-woven layer to absorb moisture. Three new sample materials were fabricated from these masks. Different factors (thickness, density, pore size...) have an influence over a porous material's sound absorption coefficient [7, 17]. No variation of thickness was studied, as increasing a sample's thickness usually has a predictive behaviour on the sound absorption coefficient: it decreases the frequency at which sound begins being absorbed efficiently. Each sample, whether commercial or hand-made, has a thickness of 40 mm but several densities and assembly techniques were investigated.

Table 1: Porous material samples used in the experiment.

Sample	Material or Kind	Bulk density ($g\cdot cm^{-3}$)
RW	Rock wool	0.070
PC	Polyurethane composite	0.080
C1	Mask crumples	0.120 ± 0.005
C2		0.180 ± 0.010
S1	Mask shreds	0.120 ± 0.008

An overview of samples used in this work is presented in Table 1. The first kind of mask samples, named crumples (C-samples), is simply made by manually folding 1 entire mask (C1) and 1.5 masks (C2). The second kind, named shreds (S-sample), is made by cutting pieces of 1 mask with scissors (S1). Shreds of about 0.5 cm^2 in size with random dimensions within the range [0.3 : 0.8] cm are obtained. Both kinds of mask samples are illustrated in Figure 1. Each mask sample is composed of two identically made specimens to assess the hand-made manufacturing reproducibility. Additionally, two different sample diameters are considered, 29

Figure 1: Photograph of crumple and shred specimens (from left to right), each made from one mask.

and 100 mm for high and low frequency measurements respectively. Low frequency measurements were only performed when possible (C1). The bulk density of the mask samples is deduced from their volume and mass. Samples C1 and S1 have the same density, while sample C2 is denser. It can be noticed that mask sample density is slightly higher than commercial samples density.

2.2 Experimental setup

Determining the sound characteristics of a porous material in a given range of frequencies is by far the most widespread measurement in the literature concerning acoustics. This is commonly performed in an impedance tube; a Bruel & Kjaer type 4206 (Figure 2) is used in the present study. This impedance tube is linked to an OROS OR35 integrated multi-analyzer data acquisition system by means of a Bruel & Kjaer 2706 Power Amplifier (10 Hz - 20 kHz & 75 VA) and two Bruel & Kjaer type 4187 1/4" microphones in order to ensure sound generation and recording. To take into account atmospheric conditions, microphones are calibrated before measurements by using a GRAS type 42AG sound calibrator.

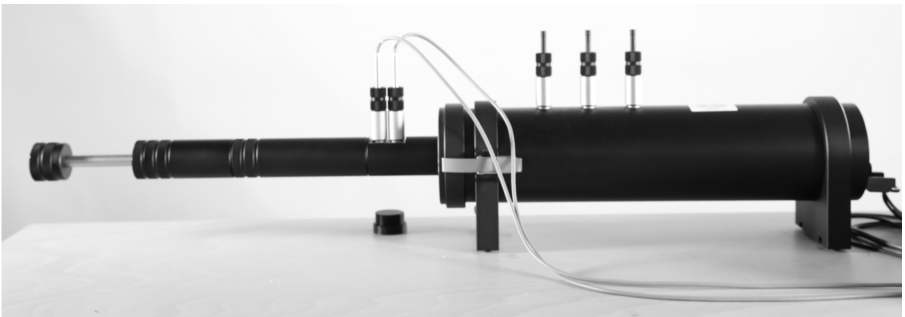

Figure 2: Impedance tube used for the experiments.

The acoustic characterization of test samples can be carried out within the range of frequencies 50 to 6400 Hz by using two different setups: a tube of 100 mm diameter for the frequency range 50 to 1600 Hz and a tube of 29 mm diameter for the frequency range 500 to 6400 Hz. The frequency is limited upward because of a threshold at which non-plane wave modes appear [18]. This threshold is dependent upon the inner diameter of the tube d according to equation (1). The frequency is also limited downward by the accuracy of the signal processing equipment, as shown in equation (2), where s is the distance between the two microphones [19], f is the frequency and c_0 the speed of sound in air.

$$f \cdot d < 0.58 c_0 \tag{1}$$

$$f \cdot s > 0.01 c_0 \tag{2}$$

Measurements are performed at a sampling frequency of 25600 Hz and fast Fourier transforms (FFT) are computed to obtain narrow band spectra with a frequency resolution of 1.5625 Hz.

2.3 Measurement method

The two-microphone transfer function measurement method is detailed fully in the standard ISO 10534-2:1998 [18]. The sound reflection coefficient r can be determined from the measured transfer function H_{12} between the two microphones in response to a random white noise generated by the speaker. A diagram of the setup is displayed in Figure 3.

Equations (3) to (4) show the process to determine r, based on the following parameters:

1. The distances from the sample to the farthest and closest microphones, x_1 and x_2 respectively.
2. The distance between the two microphones: $s = x_1 - x_2$.
3. The wave number: $k_0 = \frac{2\pi f}{c_0}$.
4. The complex sound pressures at the two microphone positions, p_1 and p_2 respectively.

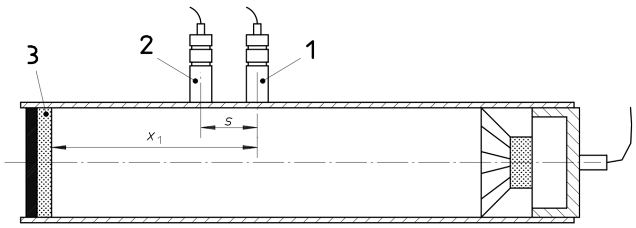

Figure 3: Simplified diagram of an impedance tube. From right to left: speaker, microphones (1 & 2), test sample (3). Image retrieved from [18].

H_I and H_R represent the transfer functions between the two microphones respectively for the incident wave alone, and the reflected wave alone.

$$H_{12} = \frac{p_2}{p_1} = \frac{e^{jk_0x_2} + re^{-jk_0x_2}}{e^{jk_0x_1} + re^{-jk_0x_1}} \tag{3}$$

$$\begin{cases} H_I = e^{-jk_0s} \\ H_R = e^{jk_0s} \end{cases} \Rightarrow r = \frac{H_{12} - H_I}{H_R - H_{12}} e^{2jk_0x_1} \tag{4}$$

The imposed frequency range, along with adequate distances x_1 and s, ensure that the sound is reflected at normal incidence and that no non-plane wave modes appear. In these conditions, the sound absorption coefficient, which can be defined as the ratio of absorbed energy to incident energy and encompasses most of the acoustic characteristics of a material, can be determined from equation (5).

$$\alpha = 1 - |r|^2 \tag{5}$$

The specific normal sound impedance Z_s can also be deduced from the sound reflection coefficient (eq. (6)). This value is linked to the characteristic impedance of the medium ρc_0, where ρ is the air density. The impedance is real for a progressive plane wave. In the case of impedance tube propagation, the specific normal sound impedance is complex, its real part corresponding to the sound resistance R and its imaginary part corresponds to the sound reactance X.

$$Z_s = R + jX = \frac{1+r}{1-r} \times \rho c_0 \tag{6}$$

The reproducibility of the positioning and the sample's hand made manufacturing reproducibility were also evaluated by performing a measurement three times after repositioning of the same specimen, and with another specimen with the same characteristics. Six different measurements per sample presented in Table 1 were thus performed. Furthermore, each individual measurement was performed twice in a row in order to assess its repeatability.

3 Results & discussion

3.1 Measurements fidelity

The repeatability of the measurement procedure was verified by successive measurements of the same specimen without changing its position. The maximum local deviation observed after repeated measurements is 1.5% of the value of the sound absorption coefficient. This result ensures good confidence in the experimental setup and measurement procedure.

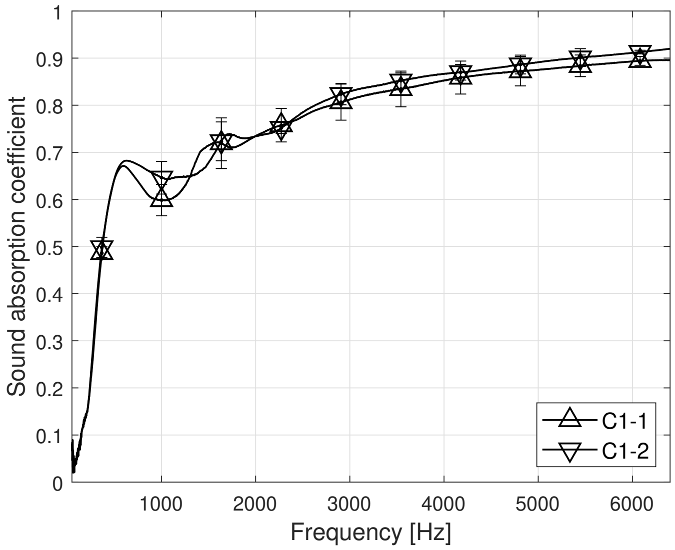

Figure 4: Sound absorption coefficient of crumples: sample C1.

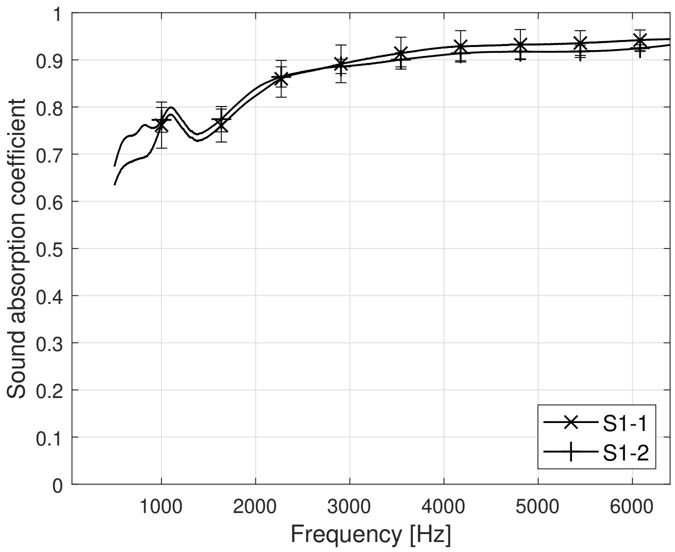

Figure 5: Sound absorption coefficient of shreds: sample S1.

The reproducibility of sample positioning and hand made manufacturing reproducibility were also assessed for each kind of sample presented in Table 1. Averages and standard deviations obtained by measuring after repositioning three times each of the two specimens C1-1 and C1-2 constituting the crumple sample C1 are presented Figure 4. Each individual curve represents the mean value and standard deviation of the sound absorption coefficient of one specimen, for three different positionings in the tube. It appears that every measurement on sample C1 presents very similar trends. The same conclusion can be drawn for the shred sample S1 Figure 5: absorption curves after repositioning or changing specimen present the same general characteristics. Small differences occur between each measurement because mask samples used in this experiment are not perfectly homogeneous. In particular, the orientation and size of each fold (for C-samples) or each piece of mask (for S-samples) affect the local porous absorption characteristic: mask samples are not isotropic at a small scale.

For the same sample, the error bars on both Figures 4 & 5 show that the sound absorption coefficient varies both depending on the positioning of the specimen in the tube and the specimen used. In other words, comparing a specimen to its counterpart from the same sample is equivalent to comparing it to itself after repositioning. This feature was expected, it ensures that mask sample kind and density are the only two parameters affecting the results and their influence is thus discussed in the following sections.

3.2 Shred and crumple sample performances

The comparison of average sound absorption coefficients obtained for all mask samples is presented Figure 6: here, each curve represents the mean value and standard deviation of the sound absorption coefficient for the six measurements performed on each sample. Samples C2 and S1 were not tested with the larger tube corresponding to low frequency measurements because of difficulties to fit them or to ensure the stability of small mask pieces in the large sample holder. The general behaviour of lower density samples is comparable for crumples and shreds, but S-samples perform slightly better than C-samples. From 500 to approximately 2000 Hz, small sound absorption peaks are observed for measurements C1 and S1. In particular, a characteristic absorption peak is present at 1300 Hz for sample S1 and two smaller peaks at 600 Hz and around 1500 Hz for sample C1. The same type of low frequency behaviour was observed by Maderuelo-Sanz et al. [16]. Above 3000 Hz, the sound absorption coefficient increases slightly towards a constant value, around 0.9 for sample C1 and around 0.95 for sample S1.

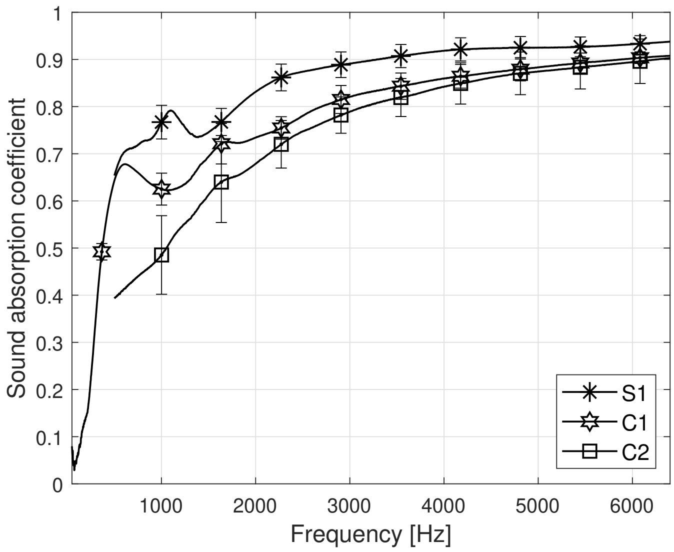

Figure 6: Sound absorption coefficient of shreds and crumples.

Overall, both C and S-samples behave like traditional porous materials, having a high sound absorption coefficient for a very broad band of frequencies with better performances at high frequencies, as shorter sound waves interact more with the small porosities of the material. The higher sound absorption coefficient of S-samples could be explained by their better homogeneity and intricate structure. Friction may occur between the individual pieces of mask forming the sample, dissipating additional energy. It can be inferred that a better absorption can be reached overall by shredding a mask into tiny pieces rather than other processes. However, the folding process is simpler to execute than the shredding process, which could be a huge benefit for low-cost applications. Additionally, folded masks may retain a more rigid structure when used in large quantities, for example inside a wall, while shredded masks may form a denser material at the bottom than at the top, due to weight. As discussed afterwards, a high density can have detrimental effects on sound absorption performance.

3.3 Effect of density

Figure 6 also allows an assessment of the influence of mask samples density on sound absorption by comparing the performance of both C-samples. Sample C2 does not have a consistent behaviour from 500 to 2000 Hz, with disparate values of sound absorption coefficient depending on the specimen and position used, as shown by the large error bars. As a result, the peaks observed for samples of lower density tend to be flattened or absent on the C2 curve. However, it also acts as a typical porous material, with its sound absorption coefficient increasing with the frequency up to a constant value.

As a general trend, sample C2 has a lower sound absorption coefficient than other mask samples. As previously observed for mask samples of similar bulk density [16], a higher density is correlated to a slightly lower absorption. Indeed, absorption may drop when flow resistance becomes too high, preventing a fraction of the incoming energy from being transmitted through the material. In that case a significant portion of the energy of the incoming sound wave is reflected and does not interact at all with the material inside the sample, leading to the lower dissipation observed.

As noted in Table 1, S-samples were only manufactured in the less dense version because of difficulties to ensure the stability of a large number of mask pieces in the sample holder. The effect of density has thus not been studied for this sample kind, but it can be assumed that the influence of this parameter would be similar to that observed for C-samples.

3.4 Comparison with commercial samples

In Figure 7 the performance of mask and commercial samples is compared. A logarithmic scale is used to have a better resolution in the low frequency range. At low frequencies up to 700 Hz, lower density masks samples present sound absorption coefficients higher than commercial ones, which can be advantageous for industrial or building insulation where low frequencies are sometimes difficult to reduce. From 1000 to 3000 Hz, both commercial samples show a peak of absorption and perform significantly better, whereas the sound absorption coefficient increases gradually for mask samples. At higher frequencies, the absorption coefficient of commercial samples is close to 1, slightly higher than that of mask samples. Between 3000 and 6400 Hz, the average absorption coefficients of RW, PC, S1, C1 and C2 samples are 0.97, 0.96, 0.92, 0.87 and 0.86, respectively.

The real and imaginary part of the specific normal impedance of mask and commercial samples are also compared Figure 8 and Figure 9. The resistance, which is associated with energy losses, and the reactance, which is associated with phase changes related to the reflection capacity of the material, are quite similar for all samples. Mask samples present a slightly higher resistance than commercial ones between 700 and 2000 Hz, which could explain the lower absorption coefficient in this frequency range. Between 500 and 2000 Hz, the high reactance of sample C2 is correlated to its high reflection coefficient discussed subsection 3.3.

A quantitative global comparison with commercial samples is also provided in Table 2. Two key criteria are given for two sets of frequencies following the standard ASTM C423-17 [20]. The noise reduction coefficient (NRC) is defined as the average of the sound absorption coefficients on the 250, 500, 1000, 2000 Hz octave bands and rounded off to the nearest multiple of 0.05. This set is widely used and representative of speech noise [3, 9, 10, 16]. The second set is chosen to highlight low frequency performance of mask samples: the sound absorption average (SAA) is defined here as the average of the sound absorption coefficients on the one-third octave bands 63 to 800 Hz and rounded off to the nearest multiple of 0.01. This choice also complies with the frequency range of the test setup. It can be noticed that sample C1 has a NRC slightly lower than RW and PC. These results are similar to previous ones for samples of comparable thickness and made of recycled material (feather [3], kenaf [4], mask [16]). However, at constant thickness, sample C1 performs better than commercial samples in the 63 - 800 Hz range where the absorption capability of classical porous material is limited.

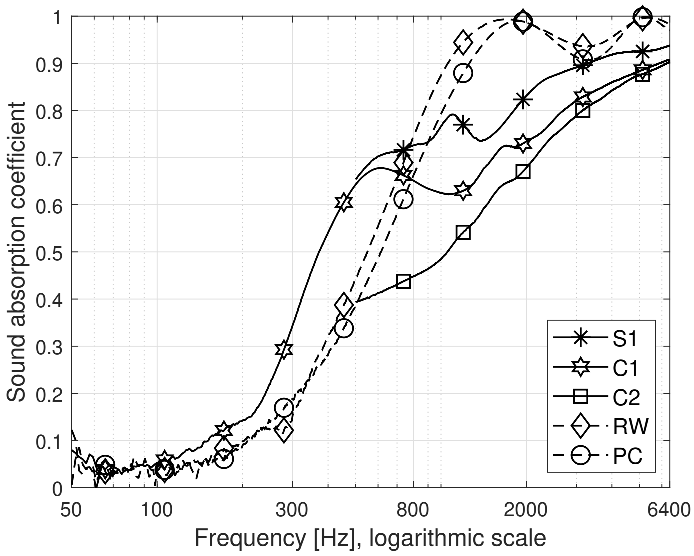

Figure 7: Sound absorption coefficient of all mask and commercial samples.

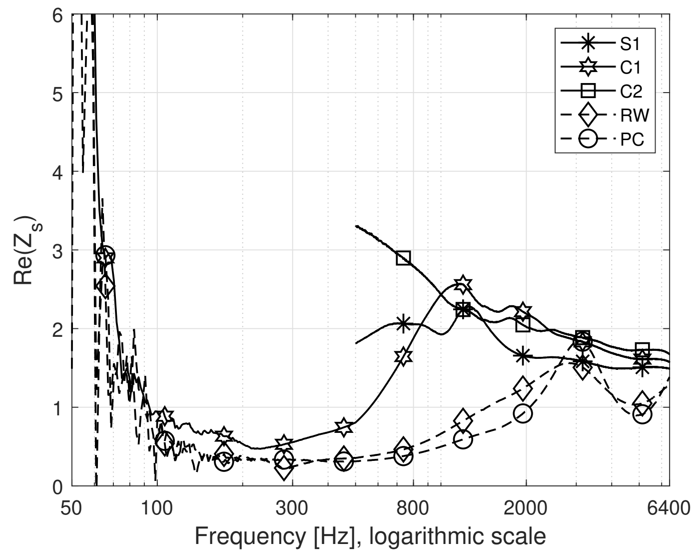

Figure 8: Sound resistance: real part of the specific normal impedance for all mask and commercial samples.

4 Conclusion

This work presents an assessment of the sound absorption performance of material samples made from entire raw surgical face masks. The sound characteristics of two different kinds, shreds (S) and crumples (C), of homemade test samples has been determined using impedance tube measurements. The repeatability and the reproducibility of the measurement as well as the hand-made manufacturing reproducibility is first addressed, showing that repositioning a specimen or changing it for another one with the same characteristics is equivalent. It appears that surgical face masks have an absorbing behaviour typical of porous materials, with additional small sound absorption peaks on the frequency range 500 – 2000 Hz. S-samples perform slightly better than C-samples with an average sound absorption coefficient of 0.92 between 3000 and 6400 Hz. The influence of the test sample density was also investigated, showing that an increase of density leads to a lower sound absorption coefficient at frequencies above 500 Hz associated to a higher reactance.

Compared to common commercial porous materials (rock wool and polyurethane composite), mask samples of appropriate density show a slightly lower global performance, but still demonstrate very high sound absorption coefficient at high frequencies and even a higher sound absorption coefficient on the frequency

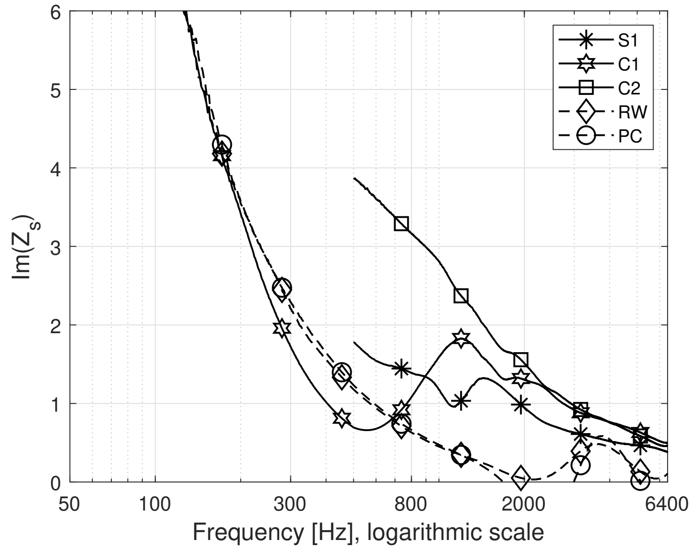

Figure 9: Sound reactance: imaginary part of the specific normal impedance for all mask and commercial samples.

Table 2: Noise reduction coefficient and sound absorption average of several samples

Sample	NRC (250 - 2000 Hz)	SAA (63 - 800 Hz)
RW	0.60	0.23
PC	0.60	0.21
C1	0.55	0.30

range 100 – 700 Hz, which can be useful for applications for which low frequency noise is a concern, such as sound-proofing of urban environments, industrial machinery, or air-conditioning units. A new criteria is also proposed to assess with a single number the sound absorption capabilities of the samples, highlighting the low frequency sound absorption capability of mask samples in a frequency range where classical porous materials present lower performances.

Finally, it can be concluded that using surgical masks for sound absorption is promising. Although more in-depth studies are necessary to complete their characterization and optimize their manufacturing parameters for specific applications, the fact that easily-made samples display such performance is encouraging. Additionally, creating the material from smaller pieces may be a viable solution to increase sound absorption even more and decrease non-homogeneity. An advantage of the samples proposed here is that they are economically and environmentally efficient as little or no change is involved from the waste product (mask) to the final material (sound absorber). Moreover, no recycling sub-product is generated as the entire mask is used.

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References

[1] C. Marquis-Favre, E. Premat, and D. Aubrée, "Noise and its effects - a review on qualitative aspects of sound. part ii: Noise and annoyance," *Acta Acustica united with Acustica*, vol. 91, pp. 626–642(17), July 2005.

[2] S. Ersoy and H. Küçük, "Investigation of industrial tea-leaf-fibre waste material for its sound absorption properties," *Applied Acoustics*, vol. 70, pp. 215–220, Jan. 2009.

[3] E. Dieckmann, S. Dance, L. Sheldrick, and C. Cheeseman, "Novel sound absorption materials produced from air laid non-woven feather fibres," *Heliyon*, vol. 4, p. e00818, Sept. 2018.

[4] E. M. Samsudin, L. H. Ismail, and A. A. Kadir, "A review on physical factors influencing absorption performance of fibrous sound absorption material from natural fibers," *ARPN Journal of Engineering and Applied Sciences*, vol. 11, pp. 3703–11, Mar. 2016.

[5] T. Yang, L. Hu, X. Xiong, M. Petrů, M. T. Noman, R. Mishra, and J. Militký, "Sound absorption properties of natural fibers: A review," *Sustainability*, vol. 12, p. 8477, Oct. 2020.

[6] N. H. Bhingare, S. Prakash, and V. S. Jatti, "A review on natural and waste material composite as acoustic material," *Polymer Testing*, vol. 80, p. 106142, Dec. 2019.

[7] F. Asdrubali, F. D'Alessandro, and S. Schiavoni, "Sound absorbing properties of materials made of rubber crumbs," *The Journal of the Acoustical Society of America*, vol. 123, pp. 3037–3037, May 2008.

[8] R. Maderuelo-Sanz, V. Gómez Escobar, and J. M. Meneses-Rodríguez, "Potential use of cigarette filters as sound porous absorber," *Applied Acoustics*, vol. 129, pp. 86–91, Jan. 2018.

[9] A. Balan and N. Shivasankaran, "Noise control using waste materials reinforced composites," *London Journal of Research in Science*, vol. 19, pp. 47–52, Apr. 2019.

[10] J. P. Arenas and F. Asdrubali, "Eco-materials with noise reduction properties," *Handbook of Ecomaterials*, pp. 3031–3056., Nov. 2018.

[11] WHO, "Advice on the use of masks in the context of covid-19: interim guidance," *World Health Organization*, June 2020.

[12] A. L. Patrício Silva, J. C. Prata, T. R. Walker, D. Campos, A. C. Duarte, A. M. Soares, D. Barcelò, and T. Rocha-Santos, "Rethinking and optimising plastic waste management under COVID-19 pandemic: Policy solutions based on redesign and reduction of single-use plastics and personal protective equipment," *Science of The Total Environment*, vol. 742, p. 140565, Nov. 2020.

[13] N. U. Benson, D. E. Bassey, and T. Palanisami, "COVID pollution: impact of COVID-19 pandemic on global plastic waste footprint," *Heliyon*, vol. 7, p. e06343, Feb. 2021.

[14] B. Joseph, J. James, N. Kalarikkal, and S. Thomas, "Recycling of medical plastics," *Advanced Industrial and Engineering Polymer Research*, vol. 4, pp. 199–208, July 2021.

[15] X.-L. Gai, Z.-N. Cai, T. Xing, F. Wang, X.-H. Li, B. Zhang, and X.-W. Guan, "Experimental study on sound absorbing property of spatial absorber of non-woven fabric with micro-perforated plate-like structure," *Applied Acoustics*, vol. 160, p. 107156, Mar. 2020.

[16] R. Maderuelo-Sanz, P. Acedo-Fuentes, F. J. García-Cobos, F. J. Sánchez-Delgado, M. I. Mota-López, and J. M. Meneses-Rodríguez, "The recycling of surgical face masks as sound porous absorbers: Preliminary evaluation," *Science of The Total Environment*, vol. 786, p. 147461, Sept. 2021.

[17] F. Han, G. Seiffert, Y. Zhao, and B. Gibbs, "Acoustic absorption behaviour of an open-celled aluminium foam," *J. Phys. D: Appl. Phys.*, vol. 36, pp. 294–302, Feb. 2003.

[18] ISO Standard 10534-2:1998, "Acoustics - Determination of sound absorption coefficient," tech. rep., International Organization for Standardization, Geneva, Nov. 1998.

[19] ASTM Standard E2611-19, "Acoustics - Standard Test Method for Normal Incidence Determination of Porous Material Acoustical Properties Based on the Transfer Matrix Method," tech. rep., ASTM International, West Conshohocken, 2019.

[20] ASTM C423-17, "Acoustics -Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room," tech. rep., ASTM International, West Conshohocken, 2017.