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PREDICTION OF SOUND ABSORPTION OF WASTE TYRE TEXTILE FIBRE COMPOSITE MATERIAL

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Abstract. Waste Tyre Textile Fibres (WTTF) are one of the main components of end-of-life tyres. During the recycling process, it is been separated from the rubber and the metal parts. According to the EU Directive on Landfills 1999/31/EC end-of-life tyres may not be accepted by the facility, and it is encouraged to recycle them. Rubber has been successfully recycled and reused for asphalt and playground surfaces production, while metals could be remelted and used again. However, there is a lack of knowledge how to use WTTF. In this research we are proposing WTTF composite material for sound absorption applications. To bind the fibres, polyurethane resin was used. Different percentage by weight of binder was used to determine its' effect on sound absorption coefficient. The sound absorption coefficient determination method is based on the experimental data based on the ISO 10534-2 standard, and Delany-Bazley-Miki (DBM) acoustic prediction model of fibrous materials, using non-acoustic parameters of the material. The results showed that DBM model accuracy rate varied from 4.9 to 12.7%. Such result indicated that DBM acoustic model has errors in prediction. The aim of this study is to predict the sound absorption coefficient using Delany-Bazley-Miki acoustic model and compare to the experimental study using impedance tube.

Keywords: composite material, Delany-Bazley-Miki acoustic model, reuse, sound absorption coefficient, Waste Tyre Textile Fibres.

Introduction

An increasing demand in goods is raising as an increasing population in the world. Such demand requires more and more means of transport to carry food, household items, etc. An increased demand in transportation leads to more road transport, as a result tyre wear inevitable. Such problem results that around 324 million were sold in year 2020 in Europe alone (Valentini & Pegoretti, 2022), meaning that the same number of worn tyres would be disposed or potentially recycled. Demand shows that end-of-life tyres causes environmental problems, potential fire hazards in storage areas, loss of valuable resources (Archibong et al., 2021; Muttil et al., 2022; Sharma et al., 2022). End-of-life tyres should not end up in storage areas and should be recycled as much as possible in order to reduce environmental pollution (Council of the European Union, 1999).

It is well-known that tyres recycling is complex process which requires good equipment to separate all parts of the tyre. Tyre is mainly consisting of rubber, metal and textile cords. Rubber found its way in reuse in new asphalt products, children playground surfaces, anti-vibrating mats, etc. (Aljarmouzi et al., 2022; Armada et al., 2022). Knowing that metals could be remelted unlimited number of times without losing its quality, it is also found its niche in metals processing factories. However, Waste Tyre Textile Fibre (WTTF) is quite a problem. Although, some studies were conducted on the use of WTTF in construction field, geotechnics area, etc. (Jelcic Rukavina et al., 2021; Narani et al., 2020). However, such material has potential in use for sound absorption applications, yet few studies were conducted on such applications. Since that material is fibrous it can be great alternative to conventional materials used for sound absorption applications in room acoustics (Rubino et al., 2019).

To make WTTF in such shape as conventional sound absorbing materials (mineral wools, sound absorbing panels) binder should be used. The most commonly used binders in the studies were polyvinyl acetate (PVA), polyurethane and epoxy resins, polylactic acid, etc. (Bhingare & Prakash, 2020; Chin Vui Sheng et al., 2020; Prabhu et al., 2020). Although, use of binders is needed, the optimum amount of it should be found to obtain the highest sound absorption coefficient as possible (Bhingare &

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Prakash, 2020). Produced composite material should be not too robust, neither too loose. For that reason, different amount should be used to find out the best variant.

To obtain theoretical sound absorption coefficient through modelling, the main non-acoustic parameter of fibrous materials is airflow resistivity. The parameter itself represents the ability of the porous material to resist to the air flow through the material. It is known that as higher airflow resistivity of the material, the higher sound absorption coefficient can be obtained (Liu et al., 2021). Mainly, fibrous sound absorbing materials are influenced by the density, porosity, and fibre size and its amount in the sample. Such phenomenon explains that whether having same density, in the sample could be found more or less fibres which influence airflow resistivity (Rusli et al., 2019). By having one parameter – airflow resistivity, well-known acoustic model – Delany-Bazley-Miki (DBM) – could be applied to predict sound absorption coefficient of the composite material. Although, DBM acoustic model predicts quite precisely, though, in the lower frequency errors occur (do not predict low frequencies precisely) (Abawi et al., 2021). Such errors occur due to the fact that model is based only on one parameter. Therefore, the model has errors, though it can be used to predict sound absorption coefficient.

As previously was mentioned, such fibrous material was little studied experimentally in impedance tube and using predicting models. There is little knowledge on WTTF composite material and its application for sound absorption. Such studies type is lacking of information what is the best proportion of WTTF and binder to obtain high sound absorption coefficient. The study will contribute to the reduction of tyre recycling generated waste amounts and new sound absorbing material would be created. It is believed that Delany-Bazley-Miki acoustic model would be suitable option for prediction of sound absorption coefficient which will provide more information on its accuracy. Such development of composite material will contribute to the new knowledge and experience in creation of new sound absorbing composite materials.

The considered composite material was made of WTTF and polyurethane binder. Total eighteen composite materials were tested for sound absorption and predicted by the Delany-Bazley-Miki acoustic model.

The aim of this study is to predict the sound absorption coefficient using Delany-Bazley-Miki acoustic model and compare to the experimental study using impedance tube

The article is organised as follows: in Section 1 the methods and the materials used in the study were presented, in Section 2 main results and discussion are presented, and in Section Conclusions, conclusions of the study were presented.

1. Methods and materials

In this section, method of composite samples preparation based on WTTF and polyurethane resin will be described, as well as determination method of acoustic parameters, and Delany-Bazley-Miki acoustic model.

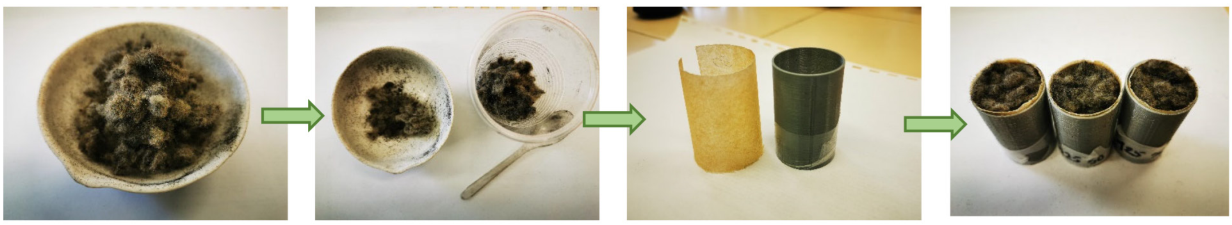
1.1. Method of samples preparation

Waste Tyre Textile Fibre (Figure 1) used in this study was obtained from the tyre recycling company in Lithuania. During recycling process of the tyre, rubber, metals and textile fibre are separated.

Figure 1. Waste Tyre Textile Fibre used as raw material in the study

Received WTTF in the first step of the sample preparation, was dried in a dryer at 60 °C temperature for 3 days. The drying process ensured that all moisture in the material was eliminated. The bulk density of the WTTF was 40.1±2.3 kg/m^3, and the fibre diameter ranged from 20 to 30 μm (Maderuelo-Sanz et al., 2012). WTTF is not perfectly pure, since it has up to 10% of rubber remains in it, and dominant rubber particles size was 0.1–0.2 mm.

After the drying process was finished, composite samples were prepared. The composite samples preparation was based on the mix of WTTF and the binder.



(a) (b) (c) (d)

Figure 2. Sequence of composite sample preparation: (a) loose fibre, (b) fibre is mixed with binder, (c) mould with parchment lining, (d) prepared composite sample

Polyurethane resin is known for its good binding properties and excellent elasticity (Cong et al., 2019).

The required amount of WTTF was placed into the mixing container and polyurethane resin was added (Figure 2). The mixing of the components was carried out mechanically, using mixing tools. The mixing time was 2 minutes, that period of time ensured that binder was incorporated into the WTTF. After incorporation of both materials was complete, the mixture was place into the mould (inner diameter – 29.9 mm), which was lined with parchment paper, the purpose of which was to prevent the sample from sticking to the mould. Sample was left to dry for 24 h at the room temperature. After 24 h sample was taken from the mould and was prepared for the acoustic parameters' determination. The samples details are presented in the Table 1.

Table 1. Mix proportions and non-acoustic parameters of samples used in the study

Sample Code	Density, kg/m^3	Thickness, mm	Binder, wt%	WTTF, wt%	Airflow resistivity, kPa·s/m^2
S100_0	100	50	0	100	42.0
S100_10			10	90	37.4
S100_20			20	80	30.5
S100_30			30	70	17.9
S100_40			40	60	13.5
S100_50			50	50	5.4

For each sample type, 3 specimens were prepared. Total eighteen measurements were done. Such number of samples was prepared in order to be able to evaluate measurements uncertainty. In the table of samples characteristics, airflow resistivity was determined and presented. Such data is required for Delany-Bazley-Miki acoustic model.

1.2. Determination method of sound absorption coefficient in impedance tube

The method of determination of sound absorption coefficient is based on the ISO 10534-2 standard, transfer function method, two microphones technique (Figure 3) (International Organization for Standartization [ISO], 1998). Inner diameter of the tube used in the study was 30 mm, samples were rigidly backed. The measurement range of the impedance tube was 160 to 5000 Hz, results were presented in 1/3 octave band. Using microphones No. 1 and No. 2 low frequency (160–1000 Hz) sound absorption coefficient was determined, and using microphones No. 2 and No. 3 high frequency (1000–5000 Hz) sound absorption coefficient was determined. The distance x_{12} between microphones was 100 mm, while distance for high frequency x_{23} was 20 mm. Distance from microphone No. 3 and the sample was 60 mm. Total number of averages per sample was 50.

According to the method, in the first step transfer function is determined. The transfer function H_{12} and H_{23} is obtained as the ratio of pressures recorded by the microphones No. 1 and No. 2, and microphones No. 2 and No. 3 at whole frequency range (Eq. (1) (ISO, 1998):

$$H_{12}=\frac{p_{2(f)}}{p_1(f)},\ H_{23}=\frac{p_{3(f)}}{p_2(f)}; \tag{1}$$

$$H_{I(160-1000\,Hz)}=\frac{p_{2I}}{p_{1I}}=e^{-jk_0(x_{12}+x_{23})},$$
$$H_{I(1000-5000\,Hz)}=\frac{p_{3I}}{p_{2I}}=e^{-jk_0(x_{23})}; \tag{2}$$

$$H_{R(160-1000\,Hz)}=\frac{p_{2R}}{p_{1R}}=e^{-jk_0(x_{12}+x_{23})},$$
$$H_{R(1000-5000\,Hz)}=\frac{p_{3R}}{p_{2R}}=e^{-jk_0(x_{23})}. \tag{3}$$

Afterwards, sound reflection coefficient is determined from Eq. (2) and Eq. (3) (ISO, 1998):

$$R_{(160-1000\ Hz)}=\frac{H_{12}-H_{I(160-1000\ Hz)}}{H_{R(160-1000\ Hz)}-H_{12}}e^{2jk_0(X_{12}+X_{23}+X_{3s})},$$

$$R_{(1000-5000\ Hz)}=\frac{H_{23}-H_{I(1-5\ kHz)}}{H_{R(1-5\ kHz)}-H_{13}}e^{2jk_0(X_{23}+X_{3s})}, \tag{4}$$

where: p_1, p_2, p_3 – pressure recorded by the microphones, Pa; H_I – incident wave transfer function; H_R – reflected wave transfer function; x_{12} – distance between microphone No. 1 and No. 2, mm; x_{23} – distance between

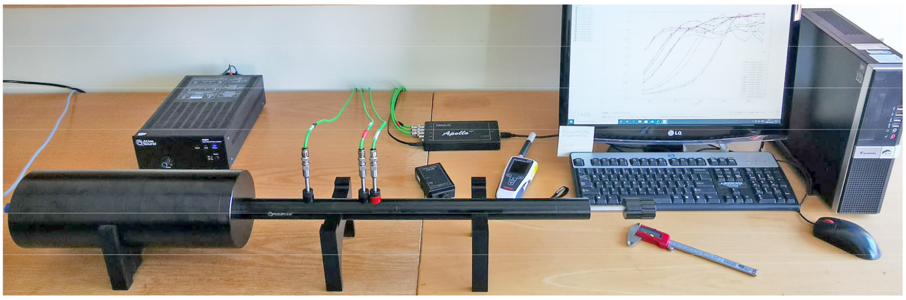


Figure 3. Sound absorption coefficient measurement setup

microphone No. 2 and No. 3, mm; x_{3S} – distance between microphone No. 3 and the sample, mm; R – sound reflection coefficient; j – complex number; k_0 – wave number.

In the last step, sound absorption coefficient is determined (Eq. (5) (ISO, 1998):

$$\alpha = 1 - |R|^2, \quad (5)$$

where R – sound reflection coefficient.

The sound absorption coefficient range is from 0 to 1, without dimensions.

1.3. Delany-Bazley-Miki acoustic model

Delany-Bazley-Miki model is based on the knowing the static air flow resistivity of the material (results or airflow resistivity presented in Table 1) (ISO, 2018), acoustic impedance and sound absorption coefficient can be estimated (Miki, 1990):

$$Z_c = \rho_0 c_0 \left[1 + 5.50 \left(10^3 \frac{f}{\sigma} \right)^{-0.632} - j8.43 \left(10^3 \frac{f}{\sigma} \right)^{-0.632} \right]; \quad (6)$$

$$k = \frac{\omega}{c_0} \left[1 + 7.81 \left(10^3 \frac{f}{\sigma} \right)^{-0.618} - j11.41 \left(10^3 \frac{f}{\sigma} \right)^{-0.618} \right], \quad (7)$$

where: Z_c – characteristic acoustical impedance of porous material, Pa/m^3; ρ_0 – air density, kg/m^3; c_0 – sound velocity in air, m/s; j – complex numbers operator; f – frequency of the sound wave, Hz; σ – static air flow resistivity of the material, Pa/m^2; k – complex number of the wave; ω – angular frequency, rad/s.

A simplified expression of the surface impedance of a material can be derived from the Eq. (6) and (7) (Miki, 1990):

$$Z_c = jZ_c \cot(k_c d). \quad (8)$$

The theoretical sound absorption coefficient is calculated according to the formula (Miki, 1990):

$$\alpha = 1 - \left| \frac{Z_s - \rho_0 c_0}{Z_s + \rho_0 c_0} \right|^2, \quad (9)$$

where α – sound absorption coefficient.

To identify accuracy rate of the prediction model, it should be compared to the measurements done with the impedance tube. The accuracy can be calculated according to the Eq. (10).

$$\upsilon = \frac{\sum_{n=1}^{n} \left(\frac{\left| experimental_f - predicted_f \right|}{experimental_f} \times 100 \right)}{n}, \quad (10)$$

where: $experimental_f$ – sound absorption coefficient obtained by the measurements in impedance tube, in 1/3 octave band frequency; $predicted_f$ – sound absorption coefficient obtained by the prediction model, in 1/3 octave band frequency; n – number of sound absorption results in measured spectrum.

The Eq. (10) presents the accuracy of the prediction model and gives user knowledge whether model is working properly or not.

2. Results and discussion

In this section, the results of sound absorption coefficient using two methods presented – experimental impedance tube measurements and Delany-Bazley-Miki acoustic prediction model results. The controlled parameter in this study was fibre and binder content in the composite material. Depending on the content of the binder, airflow resistivity varied respectively. An increasing airflow resistivity indicated that samples had higher resistance to the passing air, which results lower porosity and lower sound absorption coefficient (Jafari et al., 2018).

In Figure 4 sound absorption results are presented. The graphs present experimental (solid line) and predicted (dashed line) sound absorption results of the composite material with different amount of binder. It was noticed that an increasing binder amount in the composite material decreased airflow resistivity, which lead to lower sound absorption in whole frequency range, comparing to the sample with 0% of binder.

In Figure 4a are presented results of the sample, where no binder was used. Experimental sound absorption results varied in whole spectrum varied between 0.18 to 0.96, while Delany-Bazley-Miki acoustic prediction model results showed in range between 0.21 to 0.95. Such results show that acoustic prediction model predicts in accuracy rate of 4.9%, which means that model works properly. However, if looking deeper into the model, taking low frequency range results (160–500 Hz), the accuracy rate dropped to 9.2%. Such phenomenon can be explained as that Delany-Bazley-Miki acoustic model based on airflow resistivity only, and material is influenced by other parameters too, such as tortuosity, which is important for sound absorption in low frequencies (Asadi et al., 2015). Comparing accuracy results in mid- and high-frequency range, rate varied between 0.5 and 3.5%.

In Figure 4b–4f are shown results of the samples with 10–50% by weight of binder. The experimental sound absorption coefficient results in whole spectrum varied between 0.10 to 0.99, while Delany-Bazley-Miki acoustic prediction model results varied in the range of 0.09 to 0.99. The overall model accuracy of all samples varied between 5.2 to 12.7%. However, after breaking down the results in smaller pieces, model lapses were noted. In low frequency range were noted large exceptions in models presented in Figures 4c and 4d. There was observed

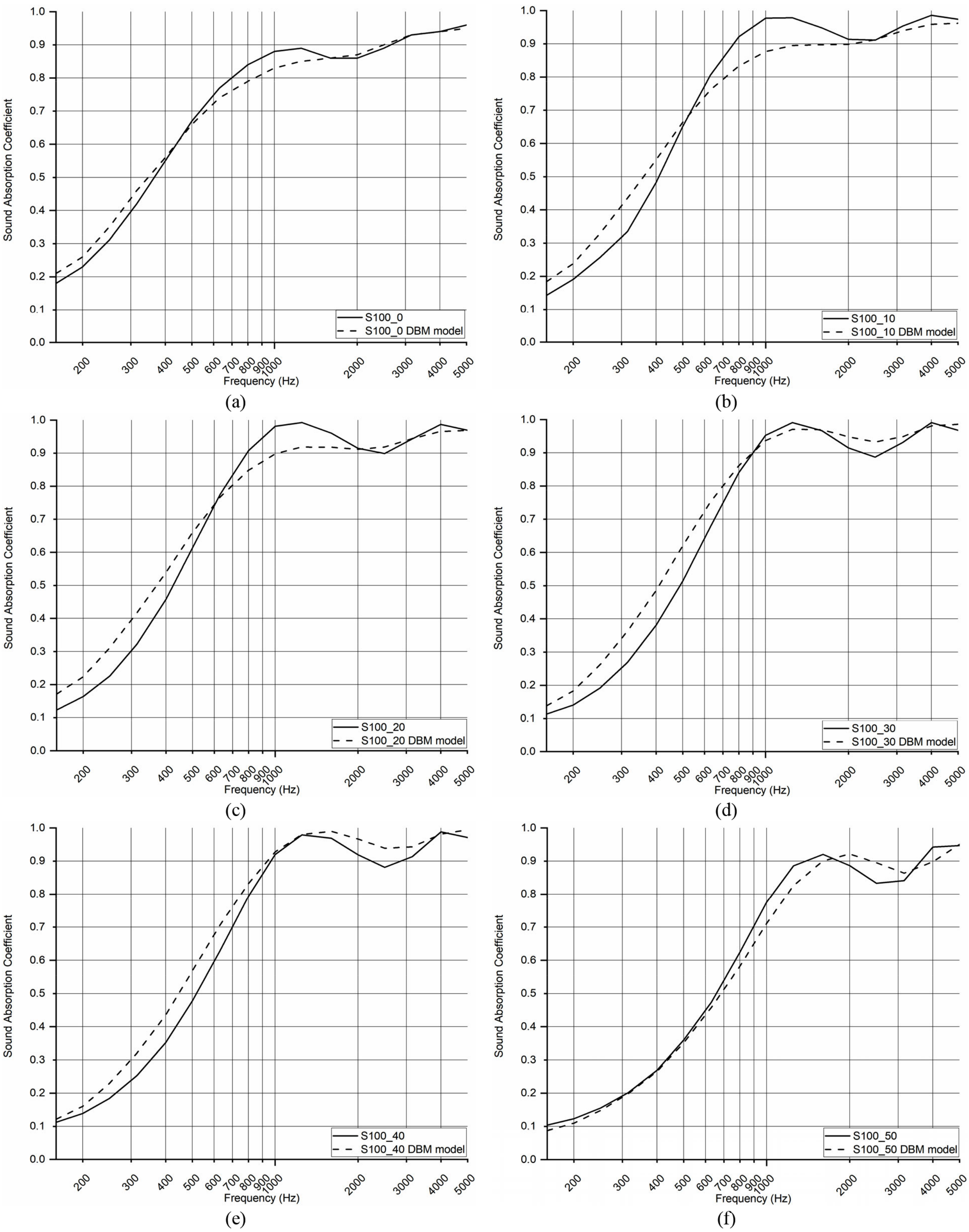


Figure 4. Results of experimental impedance tube measurements and Delany-Bazley-Miki acoustic prediction model of WTTF and polyurethane resin composite material: (a) samples without binder; (b) samples with 10% of binder; (c) samples with 20% of binder; (d) samples with 30% of binder; (e) samples with 40% of binder; (f) samples with 50% of binder

accuracy rate drop between 28.1 and 28.7%. Such large differences were observed due to the fact of unsustainable increase of airflow resistivity (17.9 → 30.5 kPa·s/m^2). As well noting that model has minor discrepancies in low frequency range. In mid-frequency range the accuracy rate increased and varied between 3.5 to 6.8%, while in high frequencies, model was quite accurate, and accuracy rate varied between 1.1 to 3.8%.

Fibrous materials have been studied by other authors. Such interest in the fibrous materials and their composites shows interest in the topic. The authors Lee et al. (2012) performed sound absorption measurements of nano-silica and polyurethane foam and found that at density of 100 kg/m^3 results was 0.65 (at 1000 Hz). Such results indicate that WTTF and polyurethane resin composite material has a great potential, since its results varied from 0.78 to 0.98.

The authors Yang et al. (2022) in other study with fibrous materials used nonwoven polyester fibre for sound absorption applications. It was found out that almost double lower thickness (27.48±0.19 mm) their peak sound absorption was 0.70 (at approx. 4000 Hz), while in our case at such frequency was 0.94 to 0.99. It is well-known that sound absorption peak increases with increased thickness. Such results indicate that composite material produced from WTTF and polyurethane resin could be good for use in sound absorption applications.

Conclusions

In this study, composite material made of WTTF and polyurethane resin was presented. The results of such composite material show good results in sound absorption applications. It was identified that use of binder in composite material lowers sound absorption in low frequency range. The highest results experimentally determined sound absorption coefficient using binder was found in sample S100_10, and results varied in low frequency range from 0.14 to 0.65, in mid- and high-frequency range 0.81 to 0.99.

The Delany-Bazley-Miki acoustic prediction model used in the study was compared to the experimental data, expressing as accuracy rate. The prediction model showed the highest accuracy rate of 4.9% of the sample S100_0. The lowest accuracy was obtained by the sample S100_30, with the result of 12.7%. Although, accuracy rate was lower, however model predicts results quite precisely, within error limits.

The results obtained in the study evaluated only macro-parameters of the composite material (airflow resistivity and sound absorption coefficient). However, to deepen the knowledge about the composite material, we need to estimate micro-parameters of the material (porosity, tortuosity). As well as, expand the study into different densities to identify difference between samples.

Regardless the limitations, the use of WTTF and polyurethane resin composite material has a great potential in use for sound-absorbing structures for improvement of Speech Transmission Index in the rooms. Future work will focus on use of different, environmentally friendly binders, which may show higher results in sound absorption. In the future, authors looking forward to perform Life Cycle Assessment (LCA) to enhance knowledge on the materials influence on environment.

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Contribution

The authors contributed equally.

Disclosure statement

Not applicable.

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