VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF ENVIRONMENTAL ENGINEERING
DEPARTMENT OF ENVIRONMENTAL PROTECTION AND WATER ENGINEERING

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ACOUSTIC AND THERMAL PROPERTIES EVALUATION AND ANALYSIS OF RECYCLED TYRE TEXTILE FIBRE WASTE

NAUDOTŲ PADANGŲ TEKSTILĖS PLUOŠTO ATLIEKŲ AKUSTINIŲ IR ŠILUMINIŲ SAVYBIŲ TYRIMAS IR VERTINIMAS

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Title **Acoustic and Thermal Properties Evaluation and Analysis of Recycled Tyre Textile Fibre Waste**

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Academic supervisor **Raimondas Grubliauskas**

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Annotation

In the Master thesis recycled tyres textile fibre waste application possibility was analysed for acoustical and thermal insulation. Aim of the thesis is to evaluate and analyse recycled tyre textile fibre waste performance in acoustical and thermal insulation, as an application of Circular Economy Principles.

In the first chapter of the thesis literature review analysis was conducted on solutions for buildings acoustics, materials sound absorption and thermal insulation properties, their classification, noise and tyres waste impact on environment, and tyres waste recycling technology. In the second chapter the methods, used equipment, materials were described. In the third chapter the results of the experimental research were presented and analysed. In the fourth chapter the modelling results were presented and compared to experimental research. In the end conclusions, references and authors publications were presented.

Thesis consists of 10 main parts: introduction, literature review, methodological part, analysis of the results, analysis of the modelling results, conclusions, recommendations, references, list of author’s publications, and list of author’s presentations.

Thesis volume: 88 pages without appendices, 56 figures, 16 tables, 100 references.

Keywords: Materials sound absorption coefficient; materials thermal conductivity; recycled tyres textile fibre waste; reverberation time reduction.

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Antrosios pakopos studijų **Aplinkos apsaugos technologijų ir vadybos** programos magistro baigiamasis darbas

Pavadinimas **Naudotų padangų tekstilės pluošto atliekų akustinių ir šiluminių savybių tyrimas ir vertinimas**

Autorius **Robert Ružickij**
Vadovas **Raimondas Grubliauskas**

Kalba: anglų

Anotacija

Baigiamajame magistro darbe buvo išanalizuotos padangų tekstilės pluošto atliekų panaudojimo galimybės akustinėje ir šiluminėje izoliacijoje. Darbo tikslas – įvertinti ir išanalizuoti perdirbtų padangų tekstilės pluošto atliekų savybes akustinėje ir šiluminėje izoliacijoje, taikant žiedinės ekonomikos principus.

Pirmajame darbo skyriuje buvo atlikta pastatų akustikos, medžiagų garso sugerties ir šilumos izoliacijos savybių, jų klasifikavimo, triukšmo ir padangų atliekų poveikio aplinkai bei padangų perdirbimo technologijų analizė. Antrajame skyriuje aprašyta taikyti metodai, naudojama įranga bei medžiagos. Trečiajame skyriuje buvo pristatyti ir išanalizuoti eksperimentinio tyrimo rezultatai. Ketvirtajame skyriuje buvo pristatyti modeliavimo rezultatai ir palyginti su eksperimentinių tyrimų rezultatais. Pabaigoje buvo pateiktos išvados, rekomendacijos, literatūros sąrašas ir autoriaus publikacijos bei pristatymai.

Baigiamasis darbas sudarytas iš 10 pagrindinių dalių: įvado, literatūros apžvalgos, metodologijos, tyrimų rezultatų analizės, modeliavimo rezultatų analizės, išvadų, rekomendacijų, literatūros sąrašo, autoriaus publikacijų ir autoriaus pristatymų.

Darbą sudaro: 88 puslapiai be priedų, 56 paveikslai, 16 lentelių, 100 literatūros šaltinių.

Prasminiai žodžiai: Medžiagos garso absorbcijos koeficientas; medžiagos šiluminis laidumas; perdirbtų padangų tekstilės pluošto atliekos; reverberacijos laiko mažinimas.

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ABBREVIATIONS

B – billion
DALY's – disability-adjusted life-years
EU – European Union
GW – glass wool
K – thousand
M – million
RT – reverberation time
RTTF – recycled tyre textile fibre
RW – rock wool
SPL – sound pressure level
WHO – World Health Organization

INTRODUCTION

Problem. Modern world is exposed to the various environmental, human safety problems. Due to high automotisation level in the last century, inhabitants became vulnerable to the ambient air, surface, and underground water, and especially to the noise pollution. In 2011, the World Health Organization published a report entitled 'Burden of disease from environmental noise'. In the study environmental noise from aeroplanes, trains and vehicles, also other city sources, were analysed. The link between the environmental noise and health conditions were estimated that excessive noise causes hearing problems, health issues, sleeping disorders, cardiovascular issues, etc. The WHO team has calculated according to the data – DALYs – disability-adjusted life-years, lost, due to unwanted human-induced dissonance. It has been found that 1 M healthy years of life are lost every year in Europe alone due to noise pollution.

The challenge of today, is that people are becoming more exposed to the noise pollution in their living environment. Due to the willingness of builders to save money on using less qualitative and cheaper materials, new residents suffer from insufficient noise insulation. Concerning this reason many residents complain on the noise coming from adjoining apartments, audible conversations, and other unwanted sounds.

Noise is not the only concern in buildings, since older buildings have low thermal insulation which leads to high energy consumption which is directly related to air pollution in living environment. Nowadays materials are made from raw, non-renewable sources. Although, Europe is moving towards sustainability, this is not enough, and citizens suffer from high costs for heating, mold, high humidity in their apartments.

Each year, only in Europe, about 2.6 M tonnes of tyres are disposed, out of which about 320 K tonnes of recycled tyres textile fibre waste is generated. Many researches were done in order to find the most appropriate solution, however not all were successful. As Europe is moving towards sustainability, the use of tyres textile fiber waste could be promising.

Although, to reduce noise levels and improve thermal insulation at the living environment is complicated, solutions were applied. In this Master Thesis, the main focus will be on the acoustical and thermal insulation properties of material. Acoustical materials are produced for buildings in order to reduce noise transmission through the walls, windows, doors, ceilings, and floors. While thermal insulation materials are designed to detain heat flow across a medium, and in the same time to insulate from noise. Both areas includes many of the new and traditional insulation concepts.

Long and excessive sound level at the living environment causes health deterioration, which can lead to the fatal consequences. Continuous excessive noise sets off the body's acute stress response, which raises blood pressure and heart rate, potentially mobilizing a state of hyperarousal. The response to that can lead to cardiovascular disease and other health issues: annoyance, tinnitus or even hearing impairment and hearing loss. Meanwhile, bad thermal insulation increases heating costs, the resulting mold causes allergies, lung diseases, bronchitis, asthma, headaches, etc., high humidity – a feeling of coldness, home decoration damage.

Actuality of the research. According to the Minister of Environment of the Republic of Lithuania, order No. 387, 17th of July, 2003 *The Approval of the Building Technical Regulation STR 2.01.07:2003 'Protection of the Internal and External Environment of Buildings from Noise'* and order No. D1-754, 11th of November, 2016 *The approval of Building Technical Regulation STR 2.01.02:2016 'Design and Certification of Energy Performance of Buildings'*, there are set minimal requirements for buildings acoustical and energetic classes. By implementing Circular Economy Principles, using recycled materials, acoustical and thermal insulation material will be evaluated and analysed, in order to find out, whether substitute to traditional materials can be developed, to reduce raw materials usage in modern world, moving towards sustainable and healthy population development and at the same time making residents living quality better.

For that reason, solutions should be implemented to reduce noise levels and increase microclimate conditions at living environment, in order to prevent health issues due to excessive noise level and insufficient thermal insulation of building.

Aim of the research. Master Thesis goal is to evaluate and analyse recycled tyre textile fibre waste performance in acoustical and thermal insulation, as an application of Circular Economy Principles.

Tasks of the research. The main tasks of the Thesis are:

1. Evaluate RTTF and conventional materials influence on sound absorption and reverberation time reduction;
2. To determine RTTF thermal conductivity coefficient;
3. To perform materials sound absorption modelling;

Object. The object of the Master Thesis is – recycled tyre textile fibre waste – a potential alternative to traditional conventional materials.

Novelty of the Thesis. Master Thesis novelty is that for acoustical and thermal insulation new option – recycled tyre textile fibre – will be evaluated and analysed, as an alternative to raw, non-renewable, non-recyclable materials, as well as seeking to reduce environmental pollution, and reduction of harmful factors in residents living environment.

Practical value. Noise as being the second most abundant pollution type, and thermal insulation insufficiency in inhabitants living environment becomes, in some cases, threat to population. As modern world moves forward, more people become more conscious about use of natural resources. To prevent raw material use, the reuse of waste opens to the world. Alone in Europe 320 K tonnes of recycled tyres textile fibre waste can be extracted and used as acoustical and thermal insulators. The research of this material will be compared to the traditional one, and the most effective could be obtained. After the research, further knowledge could be used for the future researches and developments.

Hypothesis. It is supposed that the recycled tyre textile fibre waste will have good acoustical and thermal insulation properties, since it has similarities to traditional widely used materials, and it could be used as the substitute to rock and glass wool.

1. LITERATURE REVIEW

In modern world people are becoming more exposed to the different pollution types. Noise as being second the most dangerous type of pollution becomes threat to inhabitants. This problem becomes relevant issue. The noise itself negatively affects society and environment, affects human psyche, can cause tension, this is why it is important to look for a solution, how to curb acoustical noise problem in residents living environment.

1.1. Sound characteristics

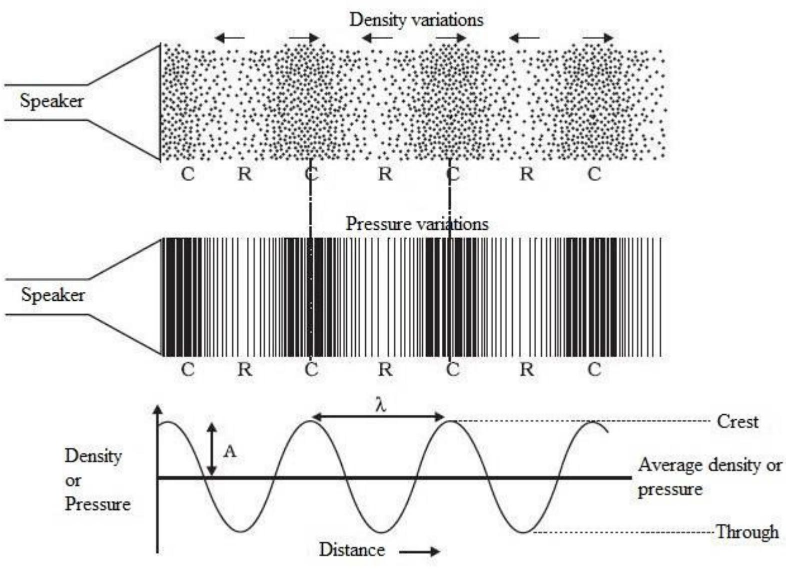
Sound itself, is a physical phenomenon, which occurs when air particles compress and expand towards all directions from vibrations source. Those oscillating waves are simply tiny pressure (from 20 μPa pressure) changes in atmosphere pressure. The frequency in which sound propagates, determines the sound tone: high sound tone (e. g. 5000 Hz) is squeaky; while low sound tone (e. g. 250 Hz) is muffled sound (Passchier-Vermeer and Passchier, 2000).

Passchier-Vermeer and Passchier (2000) have discussed about the noise. They state that environmental noise frequency range is broad. Sound itself varies in atmospheric pressure from 20 μPa to 200 Pa. However, the form of expression in Pascals is not convenient, the logarithmic measurement unit is introduced – decibel (dB).

However, human hearing organ – ear – understands sounds not equally, at different frequencies it understands in differently (Passchier-Vermeer and Passchier, 2000). Human hears sounds, which frequencies varies from 16 to 20 000 Hz. Less than 16 Hz vibrations are called infrasound, more than 20 000 Hz is called ultrasound (Baltrėnas *et al.*, 2010). However, not all sounds are equal, for that reason A-weighting (expressed in dBA) spectra correction (A-weighted SPL) is introduced, which is closely related to which frequencies human hearing organ understands.

Sound as mechanical waves can be described by physical characteristics: sound pressure (p), amplitude (A), sound wave speed (c), frequency (f), wavelength (λ), sound intensity (I), sound wave period (T), etc. Physical characteristics are presented in Figure 1.1a.

a



b

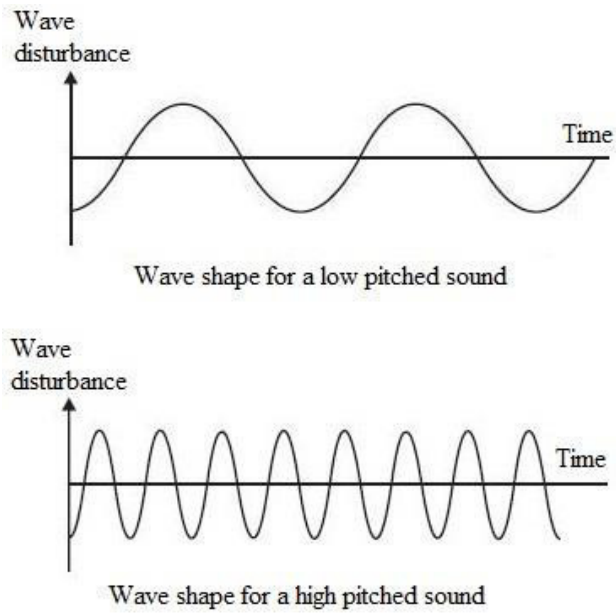


Fig. 1.1 Sound wave physical characteristics and frequency distribution: a – physical characteristics of the sound wave; b – sound wave frequency dependence on environment, speed and wavelength (ekShishka, 2019)

Sound speed mostly depends only from the environment, which can be described as a material and it is not dependable on frequency, wavelength and amplitude (Hamernik and Hsueh, 2005). In Figure 1.1b is presented sound frequency, which depends on propagation environment, wave speed and wavelength. When sounds passes different environments, its' wave speed and wavelength changes. Parameters as wavelength, frequency, period, and wave speed in air can be expressed as dependence (Gao *et al.*, 2016):

$$\lambda = \frac{c}{f} = c \cdot T, T = \frac{1}{f} \tag{1.1}$$

where
λ – wavelength, m;
c – wave speed, m/s;
f – frequency, Hz;
T – period, 1/s.

Sound pressure level are the oscillations in the pressure from the normal atmospheric pressure, induced by a sound wave. Sound pressure is many times lower than atmospheric one. The threshold of hearing is 20 μPa, the highest level, so-called upper threshold of pain is 200 Pa difference from atmospheric pressure. The difference between those thresholds is 1 M times (Parmanen, 2007).

Sound power level is the rate of emitted, reflected and received sound energy, per unit time per area and is measured W/m^2. The hearing threshold is 10-12 W/m^2, while upper pain threshold is 102 W/m^2, i. e. the ratio is 10-14 times (Cremer, Heckl and Petersson, 2005).

Although these parameters – sound pressure level and sound power level – are not convenient, there is used non-systematic unit – decibel (dB). It is accepted that hearing threshold is 0 dB, while upper threshold of pain is ≈120 dB. The sound level can be expressed by the Formula 1.2 (Parmanen, 2007).

$$L = 20 \cdot \lg\left(\frac{p}{p_0}\right) = 10 \cdot lg\left(\frac{I}{I_0}\right) \tag{1.2}$$

where

L – sound level, dB;

p – measured sound pressure level, Pa;

p_0 – threshold of hearing, Pa (which is 20 μPa);

I – measured sound power level, W/m^2;

I_0 – threshold of hearing, W/m^2 (which is 10-12 W/m^2).

Noise usually is described as loud sounds, which can damage human hearing. For instance, loud music at the gig is not considered as the noise, although at the very calm and silent room even the noise from working computer or whispering can be considered as the noise and can irritate human. Different noise sources noise level and its' understanding is presented in Figure 1.2.

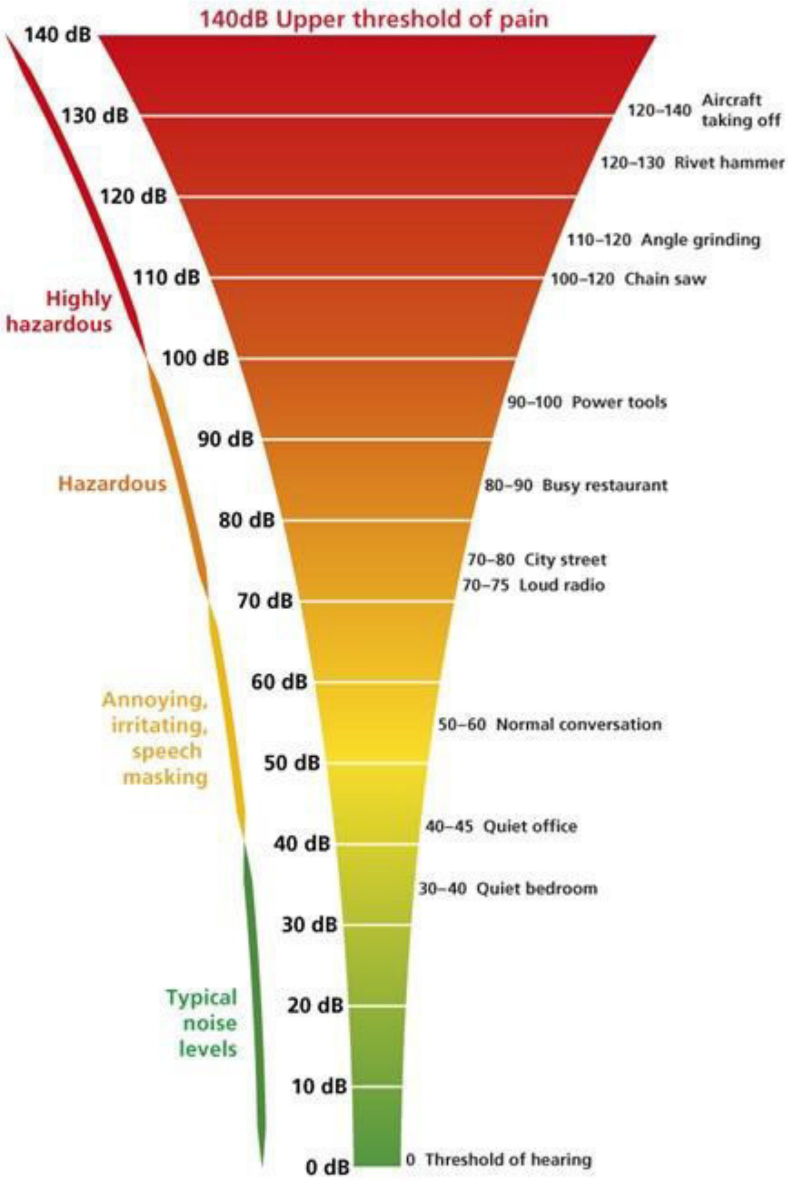


Fig. 1.2 Emitted sound level from different noise sources (IOSH 2019)

The human ear understands not all sounds evenly. At some points, when sound frequency is low, the human ear poorly understands sound, at an average frequency or high frequency level of understanding increases. At the range of 500 till 5000 Hz, human hearing is at the best point. Table 1.1 represent information on how human ear sensitivity responds to increased or decreased sound levels (Saeki *et al.*, 2004).

Table 1.1 The changes of feeling, when sound level differs (Saeki et al., 2004)

Changes in sound level, dB	Changes of feeling
± 1	Do not feel anything
± 3	Slight change
± 5	Change is feelable
± 10	Ear understands double change
± 15	Great change
± 20	Huge change felt as four times

Residents in the buildings are affected by different noise transmitted sources, which can be divided into:

- Airborne noise – is a propagation of noise which is transmitted through the air, caused by music, or other any sound emitting equipment, speech of people. This noise causes air particles to move (vibrate) and they indirectly induce such components as walls, floor, or ceiling, which can be heard through them in adjoining rooms;
- Impact noise – is a special form of structure-borne noise, which is generated by walking, moving, or dropping objects directly into the ceiling (floor). Secondary noise radiates into adjoining rooms;
- Structure-borne noise – if vibrations are generated in the building structure itself – for instance, sewer or water pipes in walls or on the ceiling, repair work induced noise by hammers or drills – all this is assigned to structure-borne noise;
- Sound transmission through flanking elements – this such a noise, which is induced by flanking components, e. g. doors, ventilation, and lift shafts. Those components are possible path for sound propagation through the building. The perceptible amount of noise depends on the presence of all transmission paths (Getzner, 2018).

As it was mentioned, sound can be transmitted through into other rooms in a few ways:

- Directly, by rooms separating wall;
- Indirectly, by other paths, for instance shafts, pipes, ventilation systems, etc., and
- Side constructions, which is one of the indirect sound propagation ways that can be transmitted by walls, overlay, façade, which additionally connects to the direct sound that penetrated the room (Elliott and Nelson, 1993).

1.2. Solutions for buildings acoustics

In order to improve residents living quality, solutions were applied for walls, façades, floors, and ceilings. Materials for noise insulation are grouped into – conventional and unconventional noise insulation materials (Fig. 1.3).

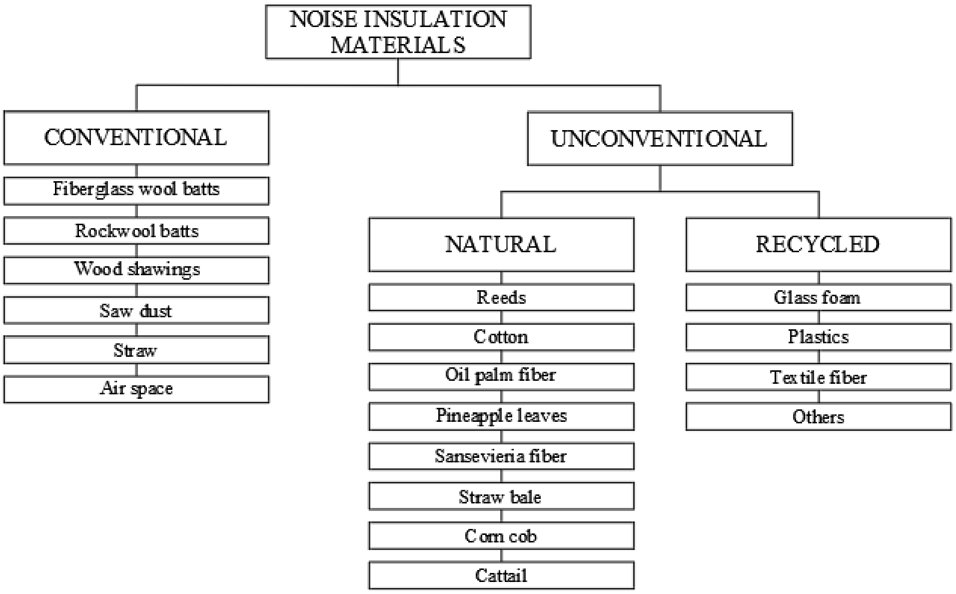


Fig. 1.3 Noise insulation materials classification (Created by the author, 2019; Asdrubali, D'Alessandro and Schiavoni, 2015)

The group of conventional consist of traditional insulation materials that are widely spread in the world and are made from virgin raw materials. Unconventional are mostly secondary use materials and are divided into natural and recycled, which makes the way of sustainable use.

There is a priority in European Union to reduce use of natural resources and move towards secondary use of recycled materials, although mineral wools, such as rock and glass wool, are still the most used acoustical and thermal insulation materials, due to its' reliability. The European Union insulation materials' market value is approximately 3.3 B Euros, and it was estimated:

- 40% – foam plastics;
- 30% – mineral rock wool;
- 27% – mineral fibre glass wool, and
- 3% – other materials

are used in today's buildings constructions (Asdrubali, 2006).

The acoustic properties of traditional materials are presented in Figure 1.4.

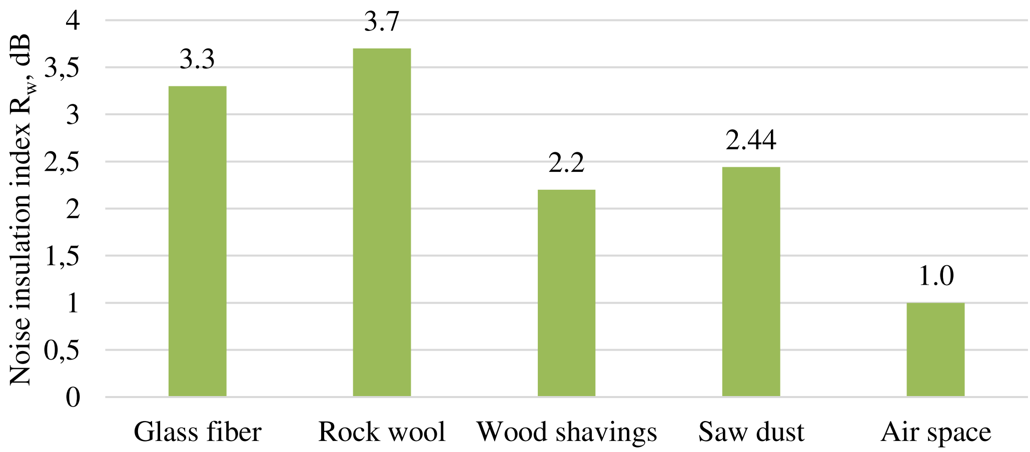


Fig. 1.4 Acoustical properties of materials at thickness of 2,54 cm (Asdrubali, D'Alessandro and Schiavoni, 2015)

According to the table, the best result for air borne noise insulation, rock wool at thickness of 2.54 cm (1 in) shows result of noise insulation of 3.7 dB, while second one is glass fibre with the result of 3.3 dB. The worst result is the gap between walls – air space – which noise insulation in this case is 1.0 dB. Looking from an economic aspect, rock wool price per square meter is approximately 6 Euros, fibre glass – 12 Euros, while air space is 0 Euros. When we look from reduction useful living area, air space is the most non-profitable option, while rock wool stays at good position.

1. Natural materials

Sound absorption. Buildings from noise can be insulated by many natural materials. However, it depends whether it is good noise absorbing material or not. As an example of natural materials can be bamboo fibres, sheep and cotton wool, cork material. Although, natural materials has good properties, but unconventional materials are better starting from 500 Hz frequency. One of the natural sound absorbing materials is claimed to be expanded clay. The performance of the material in a range of 500 to 5000 Hz is > 0,80. (Asdrubali and Horoshenkov, 2002; Koizumi, Tsujiuchi and Adachi, 2002; Teixeira *et al.*, 2003).

Airborne sound insulation. Coconut fibres, sheep and cotton wool are among the most common materials used for acoustic wall insulation – these are widely available on the market. Although, the materials are of natural origin, they are not inferior to artificial materials. Researches were done and it was found out that, for instance, double layer wall filled in with insulators of natural origin (e. g. cotton wool, latex-coco), has the same or advantage in performance comparing to mineral wools. (Desarnaulds *et al.*, 2005; Asdrubali, D'Alessandro and Schiavoni, 2015).

Impact sound insulation. The use of natural materials for impact sound absorption is widely accepted. The most common are cork, coconut fibres, wood wool, etc. To improve sound insulation effect of floor, natural materials may be used for resilient layers production. The performance of those kind of structures do not inferior to the most of conventional materials, if they carefully built and assembled (Asdrubali, 2006).

2. Recycled materials

Since Europe is moving towards sustainable development, the opportunity for recycled materials opens its' way. For instance, nowadays alternatives for buildings acoustics are tyre rubber wastes, plastic, textile wastes. The mix can be created of different materials in order to receive desired effect of the structure.

Sound absorption. Recycled material as natural ones can be used for acoustical comfort in buildings. As an alternative, cellulose derived from old newspapers and other waste-paper, with addition of some chemical elements for resistance. Afterwards, wet cellulose is sprayed onto the walls or ceilings and after hardening it becomes a sound absorber. Comparing to the conventional one rock wool, it has even better sound absorption coefficient (Asdrubali, 2006).

Airborne sound insulation. Many fibres are used nowadays as a filling in spaces between walls or roofs, for acoustical and thermal insulation in buildings. For instance, cellulose fibres, which are made from recycled newspapers, it was found out that for acoustical properties, the performance is good as conventional materials (Desarnaulds *et al.*, 2005).

Impact sound insulation. Currently, tyres are gaining popularity as recyclable material. It became an alternative to traditional materials since they were banned from landfills. Regarding its' large abundance, applications for them was found and the possibility is to use as impact sound absorbing material. The use of tyre rubber waste is very promising and many products are already available on the market, and the performance of the products is very similar to conventional ones (Asdrubali, D'Alessandro and Schiavoni, 2015).

1.3. Materials' properties impact on sound absorption

Sound absorption is a process during which energy of sound is reduced, when the sound wave passes through a medium and loses energy there (Fig. 1.5). The main characteristics of sound absorption is – sound absorption coefficient – which defined as ratio of absorbed energy in absorbent and incident energy (Bai, Lo and Chen, 2015).

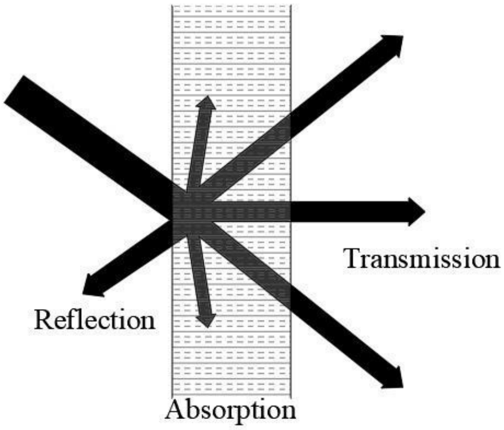


Fig. 1.5 Schematic view of sound absorption in porous materials (Bujoreanu et al., 2017)

Important to note that the higher percentage of energy is absorbed into the material, the better absorption is, and less energy emitted back to the environment. The principle of finding of materials' α absorption coefficient is calculated:

$$\alpha = \frac{E_A}{E_I} \tag{1.3}$$

$$\alpha = 1 - \frac{E_R}{E_I} \tag{1.4}$$

$$\alpha = 1 - |r|^2 \tag{1.5}$$

$$\alpha = \frac{I_{Abs.}}{I_{Inc.}} \tag{1.6}$$

where
α – sound absorption coefficient;
E_I – incident energy;
E_R – reflection energy;
E_A – absorbed energy;
r – incident reflection factor;
$I_{Abs.}$ – sound intensity absorbed;
$I_{Inc.}$ – incident sound intensity (Amares *et al.*, 2017).

Different sound absorbing materials are classified by its' abilities to absorb sound wave. Material considered as a good sound absorbing material which absorbs and transmits more sound wave energy rather than reflects them. The main parameters that affect absorption in materials are:

- Thickness of the material;
- Density of the material, and
- Porosity of the material (Alessandro and Pispola, 2005).

Materials thickness. The thickness of the absorbing material has an influence in sound absorption, although it is only significant at low frequencies, which ranges from 50 to 2000 Hz, and mostly has no significant impact on high frequency > 2000 Hz. This is happens due to that low frequency sound waves has higher wavelength (Azkorra *et al.*, 2015). The result of thicker absorbing material is better sound absorption in low frequencies. Crucial point is the materials thickness has to be at least 1/4 of the wavelength to provide in order to be able to absorb lower frequencies sound waves (Amares *et al.*, 2017).

Materials density. Sound absorption is influenced by the density of the material. By the acoustic impedance determined that reflection of the material depends on the density, since denser it is, the surface becomes more rigid. Widely it is considered that as higher density is, the higher sound absorption, however the phenomenon occurs due to mass increase (Wertel, 2000). However, at higher frequencies materials ability to absorb sound decreased due to thickness, which is dominant factor (Amares *et al.*, 2017). The critical frequencies of 1000 to 4000 Hz strictly limits absorption of the sound, the phenomenon is called the coincidence dip phenomenon (Abdalla, 2010). The coincidence dip phenomenon can be explained as unison of the frequency at which material vibrates and the frequency of incident sound wave.

Material which has high density, has a larger surface per volume unit and fibres content (Lee and Joo, 2004). As the fibres content increases, surface of the absorbent material is exposed to more energy loss due to friction, and sound waves are converted to heat energy (Seddeq, 2009). It was noted by the authors Amares *et al.* (2017) that with decreased size of fibres, airflow increases in-between and friction increases too. The statement is that finer particles are better on sound absorption, rather than coarser.

Materials porosity. Porosity is the factor, which is simply called volume of the pores in the whole volume of material. The role of pores is important, whereas acts crucial part of dispersion of medium sound waves. The principle of behaviour of sound wave reaching a pore is that when it comes into contact with the pore it meets air molecules, which starts to vibrate. The wave loses its' energy due to interaction to air molecules in the pores and the mechanical energy is transformed to heat due to thermal and viscous losses inside the pores' channels (Soltani and Zerrebini, 2012).

The parameter of pore, which makes absorption even better is that pores containing continuous channels are tend to better sound absorbing due to multiple interaction with the wall of the pore (Amares *et al.*, 2017). The other parameter of the pore – diameter – the smaller it is, the better absorption, due to at high frequencies of sound wave large gaps has no profound effect on absorption (Sikora and Turkiewicz, 2010).

1.4. Properties of thermal insulators and their classification

Nowadays buildings energy efficiency is highly prioritised since the world seeks of less impact on environment. Poorly isolated buildings use huge amount of energy (watts per square meter) to maintain set temperature. The high amount of energy requires large amounts of fuel to be burned – which is simply high air pollution in our living environment. To prevent energy losses thermal insulators are applied onto/into buildings.

Thermal insulators are described by seven different important properties. Those properties do influence on the performance of the insulating materials. In order to obtain the best insulator, it is important to understand their impact (GreenSpec, 2020).

Thermal conductivity. Thermal conductivity (λ) described as a potential of the material to transfer heat by process – conduction. The main idea of conduction is that warmer molecules are vibrating faster, rather than the cold one. Warmer molecules moving faster, and excessive energy is transmitted to colder molecule (Burger *et al.*, 2016). Thermal conductivity is calculated by Formula 1.**7**:

$$\lambda = \frac{P}{(A \cdot \Delta T/t)} = \frac{P \cdot t}{(A \cdot \Delta T)}, W/K \cdot m \tag{1.7}$$

where

P – power, W;

A – area of the surface, m^2;

t – thickness of the sample, m, and

ΔT – temperature difference, K (Medina *et al.*, 2017; Zendehboudi, Hosseini and Ahmadi, 2019).

The lower Thermal conductivity value λ is, the better performance of the material.

Thermal resistance. Thermal resistance (R) is described as the ability of the material to resist of heat transfer. Thermal resistance is closely related to the thickness, since greater it is, the lower heat flow, as well as lower heat losses are through the material. A good insulation material determined with high Thermal resistance, while which has low Thermal resistance is considered to be bad insulation material. An insulator which does not have a high Thermal resistant has a risk of burning or melting (Mishra, Militky and Venkataraman, 2019)**.**

The resistance is expressed by the ratio of materials thickness and its' thermal conductivity in Formula 1.8;

$$R = \frac{\delta}{\lambda}, m^2 \cdot K/W \tag{1.8}$$

where

δ – thickness of the material, m;

λ – thermal conductivity coefficient, W/m*K.

Specific heat capacity. It is a term to describe the amount of heat which is required to increase or decrease the temperature of the body by the 1 degree, whether it is ℃ or K. Insulator with high Specific heat capacity is better, due to it takes more time to absorb the higher amount of heat before its' temperature increases (decreases) in order to transfer heat (cold) through its' thickness (Feidt, 2017). The Specific heat capacity is expressed by the Formula 1.9:

$$C = \frac{dQ}{dT}, J/K \tag{1.9}$$

where

dQ - the elemental amount of heat supplied to the system, J;

dT - thermodynamic temperature change, K.

Thermal diffusivity. Thermal diffusivity is a materials' property can be described as ability of temperatures' spread through a material, its' response to the change in temperature. The heat is transferred from warmer to the colder side of the body (Speight, 2019).

Thermal diffusivity can be expressed by the Formula 1.10:

$$a = \frac{\lambda}{\rho \cdot C}, m^2/s \tag{1.10}$$

where

λ – thermal conductivity of the material, W/m*K;

ρ – density of the material, kg/m^3;

C – specific heat capacity, J/K.

For instance, coppers' Thermal diffusivity is 98.8 mm^2/s, while wood is way slower and transmission through the body speed is 0.082 mm^2/s (GreenSpec, 2020).

Density. Density itself very common physical unit. However, in thermal conductivity, density plays an important role. In Figure 1.6 we can see that as density of the material increases, the Thermal conductivity increases as well. This happens regarding to closer bonds of the molecules, since at higher density molecules are more compacted together (Bozsaky, 2012).

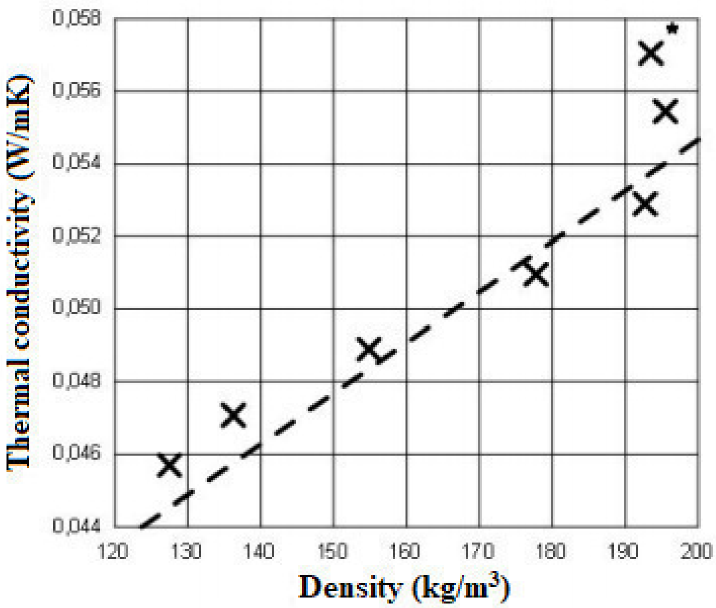


Fig. 1.6 Correlation of density and thermal conductivity (Bozsaky, 2012)

Vapour permeability. Vapour permeability is materials property which describes ability of the material to transmit water vapour through the material. Materials are classified into Vapour Permeable – referred to 'Breathing construction' and Non-vapour Permeable. Ability of water vapour transmission through the material depends on hygroscopic properties of fibres and environmental conditions (Boguslawska-Baczek and Hes, 2014). The vapour permeability can be expressed by the Formula 1.11:

$$\delta_p = W_p \cdot L = \frac{M_w}{R \cdot T} \cdot \delta_v, m^2/s \qquad (1.11)$$

where

M_w – molecular weight of water vapour, kg/mol;

R – universal gas constant, J/mol*K;

T – absolute temperature, K;

δ_v – vapour permeability with regard to humidity by volume, m^2/s (Valovirta and Vinha, 2004).

Air permeability. It is a materials' property which allows air passage through its' interstices or pores. As air permeability increases, thermal conductivity decreases, due to lower contact in between cells. Air permeability of the material can be affected by many factors:

- porosity;
- number, tortuosity, pores size;
- thickness of the material;
- linear density;
- fibres twist;
- fibres crimp
- construction of the material;

- layering (Stevens and Fuller, 2015).

There are various of insulating materials used across the world. By the origin they are classified into organic, inorganic, combined and new materials. Organic and inorganic are divided into foamy and fibrous insulating materials. In Figure 1.7 represented most widely used insulators in Europe (Papadopoulos, 2005). According to the Papadopoulos (2005), around 60% of all used insulators are accounted to inorganic fibrous materials group, from which are widely used rock and glass wools, while 27% of materials are from organic foamy materials group, which are extruded and expanded polystyrene. Last 13% of insulator materials are assigned to the rest – combined and new materials (Papadopoulos, 2005).

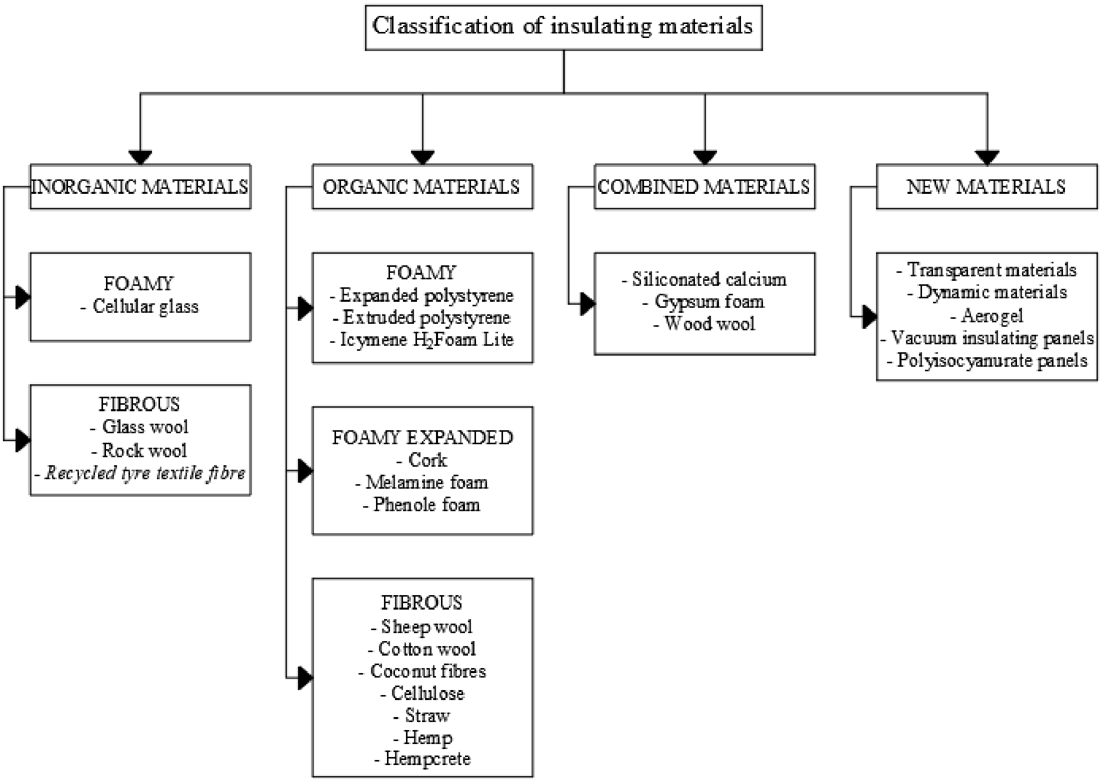


Fig. 1.7 Classification of insulating materials (Papadopoulos, 2005; Created by the author, 2020)

Although, conventional (inorganic fibrous materials) are popular nowadays and still take a large part of the market, new materials are more promising, since their thermal properties are better in many times. For instance, vacuum insulating panel (VIP) thermal conductivity coefficient is 0.007 W/m*K, while rock wool thermal conductivity on average is 0.043 W/m*K. The VIP 6 times is more efficient than rock wool. This is makes new materials to be more efficient and better insulators.

1.5. Excessive noise impact on human health

As it was discussed previously, noise is the second pollution by abundance in modern society and its' impact is obvious. In 2011 World Health Organization Regional Office for Europe has released a report, in which there are serious statements about current impact of excessive noise to the human health. The exposure assessment was implemented by this data:

- Towns with > 50 000 inhabitants were estimated;
- Measured by long term measurements or calculated/predicted exposure by modelling, and

- Distribution of public response to noise.

In this case, the calculation was based on the noise mapping based on EU's Environmental Noise Directive, using the annual average metrics of L_{DEN} and L_{night} proposed in the Directive. The calculation of L_{DEN} is presented in Formula 1.12.

$$L_{DEN} = 10 \cdot lg\frac{1}{24} \cdot \left(12 \cdot 10^{\frac{L_{day}}{10}} + 3 \cdot 10^{\frac{L_{evening}+5}{10}} + 9 \cdot 10^{\frac{L_{night}+10}{10}}\right) \tag{1.12}$$

where

L_{DEN} – average 24 hours day noise exposure, dB;

L_{day} – at daytime (12 hours) noise level, dB;

$L_{evening}$ – at evening time (3 hours) noise level, dB;

L_{night} – at nighttime (9 hours) noise level, dB.

The method of environmental burden of disease assessment was expressed in DALY's in the general population through the Formula 1.13:

$$DALY = YLL + YLD \tag{1.13}$$

where

DALY – disability adjusted life years, years;

YLL – years of life lost, years;

YLD – years lived with disability, years.

$$YLL = \sum_i \left(N_i^m \cdot L_i^m + N_i^f \cdot L_i^f\right) \tag{1.14}$$

where

N_i^m (N_i^f) – the number of deaths of males (females) in age group multiplied by the standard life expectancy L_i^m (L_i^f) of males (females) at the age at which death occurs.

$$YLD = I \cdot DW \cdot D \tag{1.15}$$

where

I – the number of incident cases;

DW – disability weight;

D – average duration of disability, years.

According to these calculation conclusions were made, which provides a great evidence of noise pollution harmfulness to the human health. It was estimated that DALYs lost from noise in the Western European countries are:

- 61 000 years for ischemic heart diseases;
- 45 000 years for children learning disorder;
- 903 000 years for sleep disturbance;
- 22 000 years for tinnitus, and
- 654 000 years for annoyance (WHO, 2011).

If we will sum-up all DALYs, the result will be stunning and at the same time worrying, which shows that in total it will be 1-1.6 M years. Shortly it means that every single year, 1 M of healthy years are lost from the overwhelming exposure of environmental noise. Due to lack of information from Southern and Eastern European countries it was not possible to estimate the years lost in these regions, to provide full view of WHO European Region (WHO, 2011).

Noise is extremely annoying phenomenon, which pollutes living environment and being more than 65 dB(A) becomes threat to human beings (Ising and Kruppa, 2003).

Due to excessive noise inhabitant are exposed to noise-induced hearing impairment, psychosocial effects, noise-induced stress-related health effects (such as cardiovascular diseases, effects on unborn child), also sleep disturbance, tinnitus, effects on performance, noise-induced hearing impairment, annoyance and stress-related disorders and sleep disturbance etc. (Babisch *et al.*, 2001). Figure 1.8 presents model of the sound effect on health quality of resident life.

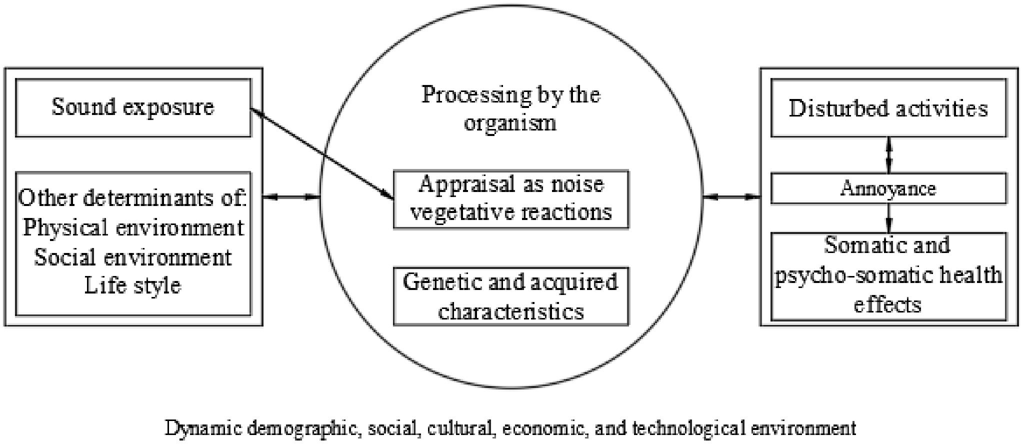


Fig. 1.8 Conceptual model of the interaction of sound with organisms and effects on life health quality (Passchier-Vermeer and Passchier, 2000)

Hearing loss in induced by the increased sound levels, the consequence of that is a human has difficulties to understand normal speech at low background noise. However, hearing loss is closely connected to the person age, since being older the ears sensitivity decreases. The mechanical damage of the ear (inner and outer) occurs due to abrupt noise level increase. At more than 120 dB the hearing can be lost forever (Passchier-Vermeer, 1991).

The exposure to high noise levels can result tinnitus – feeling when it is ringing in the ears. This effect is being observed in teenagers, people who are used for using headphones, due to listening to music loudly. Tinnitus itself can be temporary or permanent. Temporary can last up to 24 hours, permanent depends on duration to noise exposure (Axelsson and Prasher, 1999).

Human reacts to stress in different ways: psychological (fear, depression), behavioural (prone to use spirits, narcotics; social distancing) and somatic (heart diseases, internal organs diseases). Those reactions occurs due to prolonged noise (Miedema and Vos, 1998).

Acoustic trauma occurs when a short-high noise level occurs (more than 130 dB), for example this can be close to the ear shot, explosion, super-jet noise. At this point sound pressure level is extremely high that the ear drum flaws and sound energy inside the ear causes rough mechanical damages, as blood in the inner ear spill and irreversible damage to the auditory nerve receptors (Mačiūnas, 1999).

Cardiovascular diseases due to excessive noise levels are also are dangerous, when noise levels exceeds 70 dB(A), the risk of hypertension increases about 30%, comparing to those who live in the environment with lower than 55 dB(A) (Ising and Ising, 2002)

The scientists Saeki *et al.* (2004) were estimating what are the connections between the noise exposure and the psychological condition of the person. The study was focused on annoyance, performance and fatigue of participants while doing simple mental tasks, for instance simple mathematical operations and listening to the conversations. In this research noise was only meaningless noise at different sound pressure levels, which had no connection to the performing tasks and the tasks itself had different presentations: aural (L=55 dBA) and visual (Fujii, Saeki and Yamaguchi, 2011). The results of the experiment seems to be interesting, as the noise showed it real harmfulness.

Annoyance. Figure 1.9 presents relation between sound level and annoyance. It was ascertain that the psychological experiences of irritation as an ordinary scale could be viewed as an internal scale of equivalent distance (Furihata and Yanagisawa, 1989). As we can see from the figure, by the increase of the noise, annoyance increases as well.

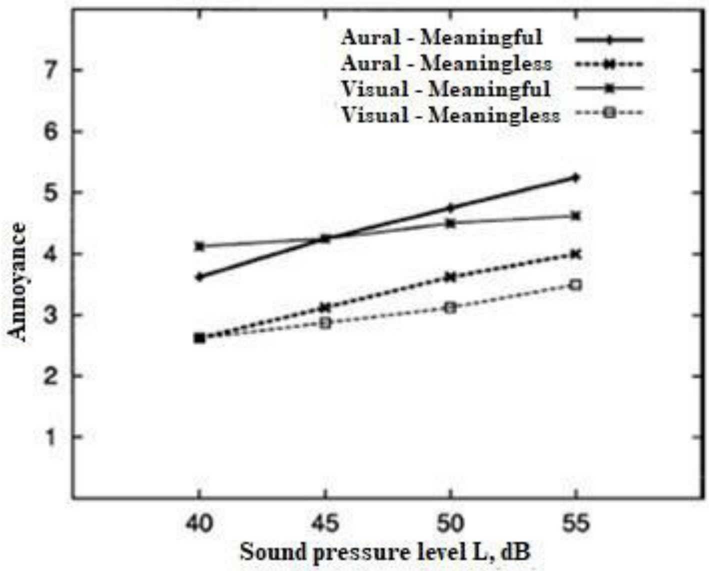


Fig. 1.9 Relationship between noise level and annoyance (Saeki et al., 2004)

Each presentation condition shows that meaningful noise (when the person speaks) tend to be more annoying than meaningless (steady spectrum (e. g. White noise) electronical noise). On the other hand, the response to the aural presentation was stronger than to the visual one (Saeki *et al.*, 2004).

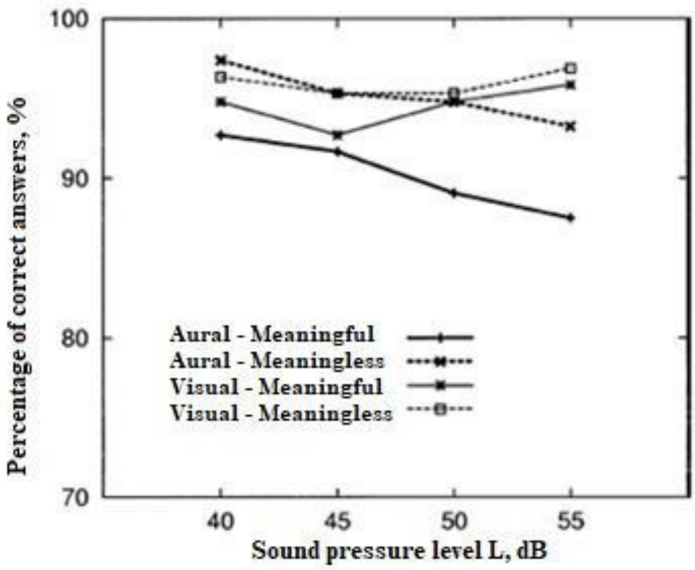


Fig. 1.10 Relationship between noise level and performance (Saeki et al., 2004)

Performance. Figure 1.10 represents relationship between noise level and correct answers number. When aural presentation took place, with increasing sound pressure level, the correct answer number decreased. The other side shows of the noise shows that when meaningful noise interrupts aural presentation it confuses and the correct number to the questions decreases. During visual presentation no difference was seen (Saeki *et al.*, 2004).

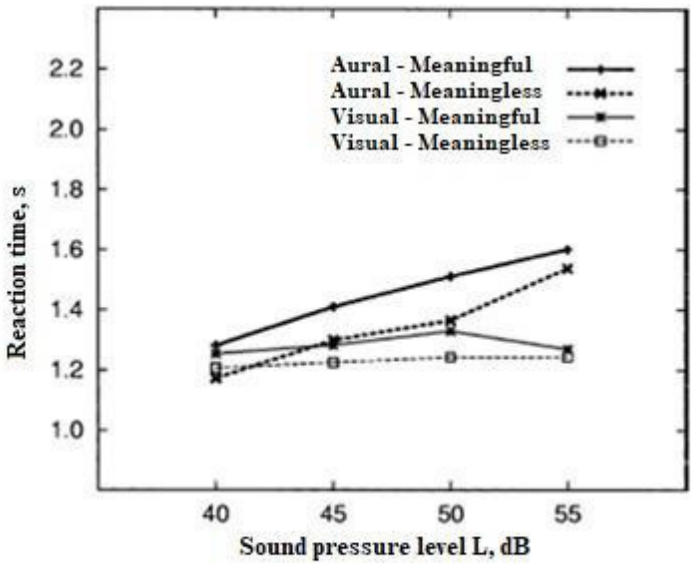


Fig. 1.11 Relationship between noise level and reaction time (Saeki et al., 2004)

Reaction time. Figure 1.11 represents data from experiments reaction time, expressed as from the time hearing or seeing the questions till pushing the button. It was estimated that as the noise level increased, the correct number of answers decreased, the reaction time increased. The correlation coefficient between correct answers and the reaction time was -0.848 seconds (Saeki *et al.*, 2004).

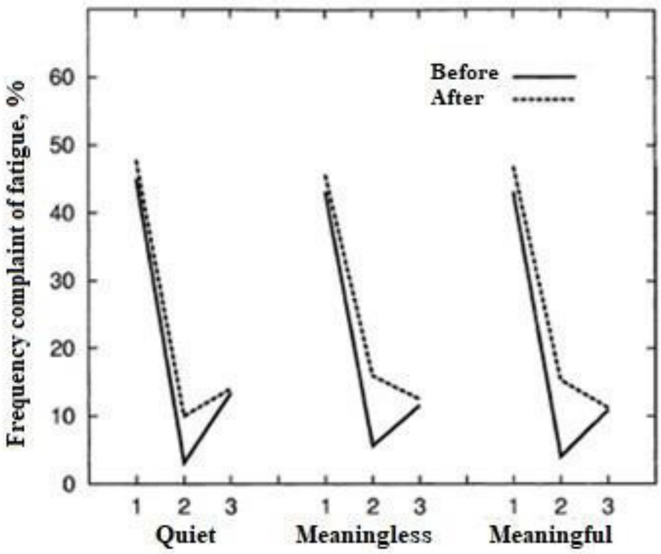


Fig. 1.12 Subjective feelings of fatigue (Saeki et al., 2004)

Fatigue. Figure 1.12 presents fatigue before and after the experiment. Saeki *et al.* (2004) has compared all three conditions of different fatigue groups. The main type of fatigue – drowsiness and dullness – was the most abundant and is accepted as general fatigue. The second fatigue type – difficultness of concentration was the second by abundance after the test. The results showed that keeping concentration and productivity in the presence of noise becomes difficult (Yoshitake 1978).

1.6. Tyres textile fibre waste impact on environment and human

End-of-life Tyres are one of the main sources of waste in End-of-life Vehicles. Alone in Europe, each year about 2.6 M tonnes are disposed, from which about 10% of total weight amount comprises recycled tyre textile fibre, which is about 320 K tonnes (Ecopneus, 2013).

According to the Environmental Protection Agency and Department of Statistics of Republic of Lithuania each year supplied amount of tyres to the local market makes up to 25 K tonnes a year. Figure 1.13 presents historical statistical information of tyres and tyres textile fibres amount in Lithuania.

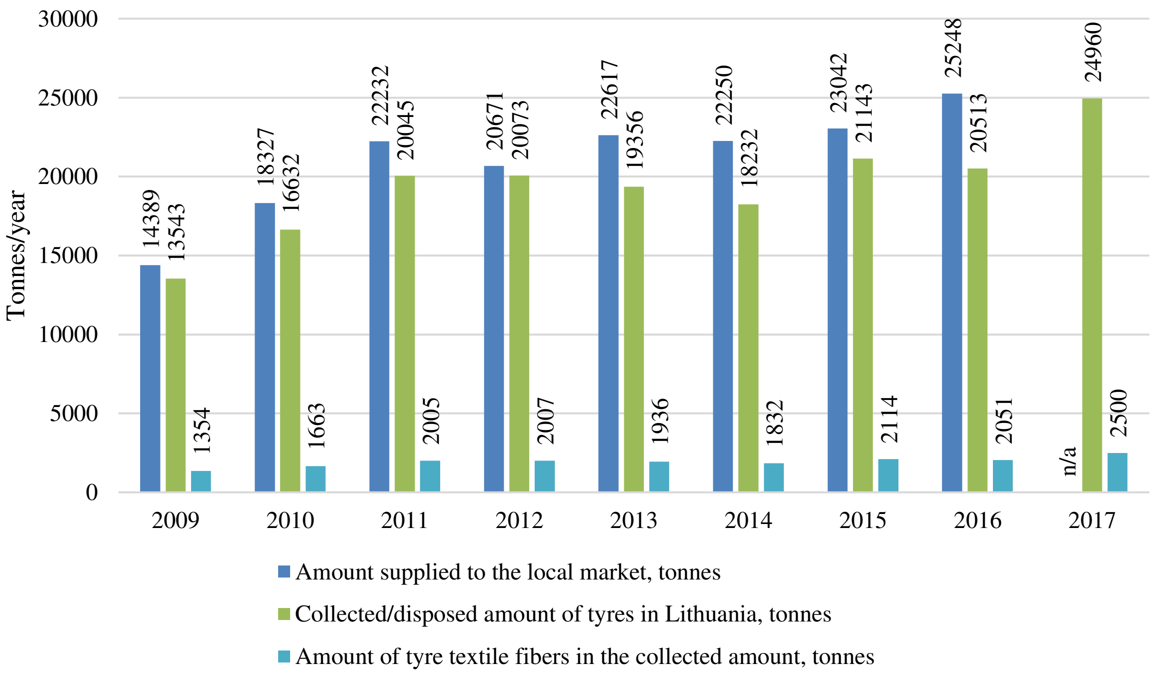


Fig. 1.13 Tyres supply and collection in Lithuanian market through 2009-2017 (Aplinkos apsaugos agentūra, 2017; Lietuvos Respublikos Statistikos departamentas, 2017)

As we can see, according to the figure, each year supplied amount and collected amount of tyres was growing evenly since 2009 till 2016. Unfortunately, there is no data on supplied amount in 2017, but it is predictable that it was growing. Hypothetically possible to say that the amount of tyres supplied and waste generated will grow.

Unfortunately, about data quality cannot be said something good, probably it is tried to make sure that almost same amounts which was released to the market, came back, however the amount can be higher.

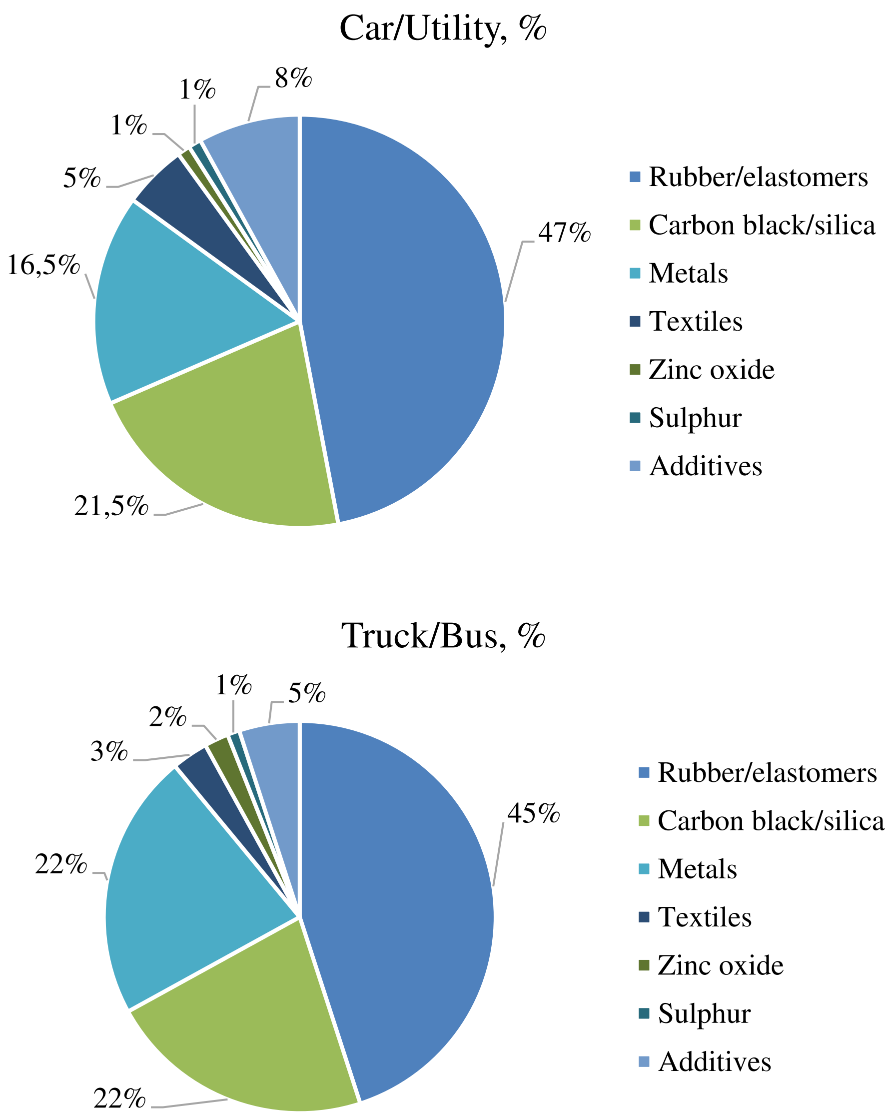


Fig. 1.14 Composition by Mass of EU Car and Truck Tyres (Landi, Vitali and Germani, 2016) (Note: the amount of textile fibre in Cars varies from 5-10% (mostly accepted as 10%), in Trucks 3-5%)

To move forward it is important to understand the composition of the End-of-life Tyre. Landi, Vitali and Germani (2016) and Shulman (2011) in their researches present the composition and amount of material of total tyre weight. Figure 1.14 presents the composition and materials part of total amount of tyre.

According to the Figure 1.14 detailed composition by mass of car and lorry tyres in the EU Market. The data reflects the generic formula for tyres produced for European Market. Material composition varies by category, and nominally in which continent it is produced, although ratio of materials stays relatively very similar (Shulman, 2011).

In Figure 1.15 by Pezer *et al.* (2016) are presented the main parts of radial tyre.

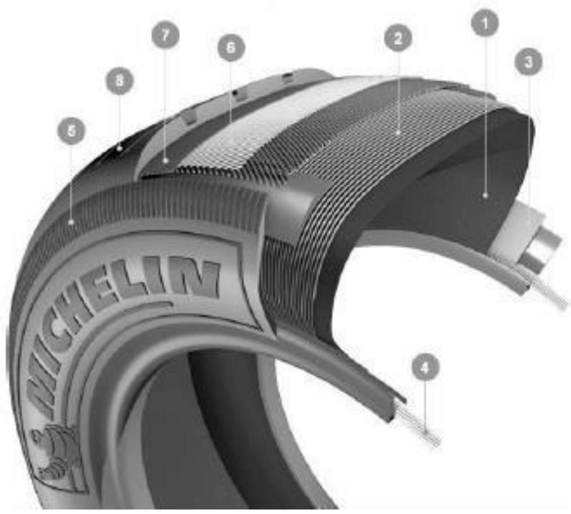


Fig. 1.15 Main parts of the radial tyre. 1 – inner line – an airtight layer of rubber; 2 – carcass ply – the layer consisting of thin textile fibre cords (or cables) integrated into the rubber; 3 – lower bead are – this is where the rubber tyre grips the metal rim; 4 – beads – ensure an airtight fit and keep the tyre properly seated on the rim; 5 – sidewall – protects the side of the tyre from impact; 6 – crown plies – is made up of very fine, resistant steel cords bonded into the rubber; 7 – cap ply – reinforced nylon based cords embedded in a layer with rubber; 8 – tread – provides traction and turning grip for the tyre and is designed to resist wear, abrasion and heat (Pezer et al., 2016)

In the final thesis, the greatest attention will be paid to nylon fibres, which are depicted in Figure 1.15 – tyres parts: 2 and 7. Nylon is a synthetic man-made fibre polymer, based on aliphatic or semi-aromatic polyamides (Fig. 1.16). In European Waste Catalogue (code 19.12.08) tyres textile waste is described as special waste. Nylon fibre from tyres are dirty fibrous material, which must be treated and disposed carefully. Due to this material's condition, it leads to negative impact on environment, economic losses and public costs (Landi, Vitali and Germani, 2016).

a

b

c

Fig. 1.16 Recycled tyre textile fibre (RTTF): a – RTTF pile in the recycling factory; b – RTTF which contains large amount of coarse and fine rubber particles; c – RTTF which contains approximately 10% of fine rubber particles (Pezer *et al.*, 2016)

The nylon one of the XX centuries inventions. The thermoplastic is highly demandable due to its' good physical properties – it is stiff, hard (resistant to rupture, fatigue, and abrasion) and resistant to high temperatures. Its' durability success is in the aliphatic polymers. The nylon consists of methylene units and amide, creating polyamides. Nylon-n or nylon-mn, accordingly PA-n or PA-mn, are defined by the number of carbon groups, i. e. nylon-6 or nylon-6,6 (Dasgupta, Hammond and Goddard, 1996).

Tyres waste impact is significant, whereas due to inhabitants and company's indifference, frequently it occurs in forests, meadows, roadside, near waste collection containers. This kind of waste poses high risk to the environment and human health and is often the source of the forest fires. In the nature, over the time, tyres become highly toxic to wild animals and birds. In the course of biochemical degradation of the polymer and other materials, they spread by soil, mechanically, dispersed and diffused, and become food for various natural populations, resulting in the entry and accumulation of these microparticles in the breathing system, digestive tract, causing diseases and death (Ramarad *et al.*, 2015).

Henry, Laitala and Klepp (2019) have noted that plastics these days are extremely huge problem, but especially – microplastics pollution. Pollution by the microplastics rapid growth sends alerts that solutions must be acted now. Geyer, Jambeck and Law (2017) in their research have announced that plastics accumulation in the environment is extremely high. Taylor *et al.* (2016) in their research presented information that in the world ocean, in the depths of more than 2000 meters, the microplastics were found. The wildlife of the oceans are ingesting thermoplastics, viscose and other kinds of plastics (Taylor *et al.*, 2016)

First idea of creation of polyamides and polymers was as 'biodegradable' synthetic fibres, however, it was found out that they are not completely biodegradable. Of course, the organic part – starch, is degradative, but the polymer fibres are not. Those extremely small particles covers a large part of surface area. Therefore, particles are greatly dangerous to the environment, since their prevalence in the environment grows rapidly and the overall situation becomes uncontrolled (Slater, 2008).

The increase of the microfibres in the environment, it was noticed that the ingestion, the residence time of the particles increased, while the reserves of the energy has been reduced (Wright *et al.*, 2013). The organisms, depending on the size of the particles can be ingested or egested. Large plastic particles can be without big effort egested back to the environment, however small particles, so-called, nanoplastics are absorbed into the organism and are accumulated in the tissues or organs of the creatures. With ingested particles, the animals become highly vulnerable, because organs of any living being are vital (Mattsson *et al.*, 2017). Central nervous system, behavioural changes, reduced population size of living creatures because of impaired reproduction system are the effects of the nano- or micro- fibres on organism (Waring, Harris and Mitchell, 2018).

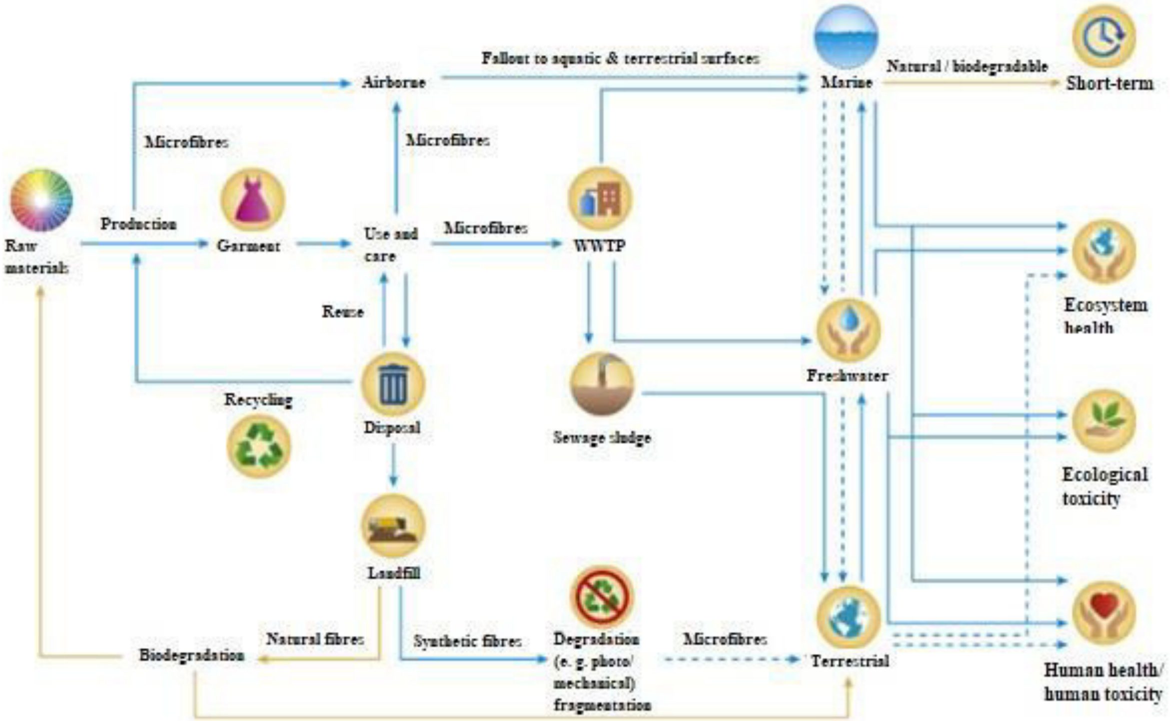


Fig. 1.17 The route of microplastics to the recipient (Henry, Laitala and Klepp, 2019)

Microplastics is the new sphere of the researches, however, the exposure to human has not been assessed yet. Humans, as the wildlife, are prone to accumulate the micro- and nano- particles in their body (Fig. 1.17). Micro- and nano- particles are already found in human daily life. It is not a secret that in the region of Asia it is popular to add plastic particles to the rice, to lower real food amount with substitution of plastics. As well, as the aquatic animals ingest microfibres, it is found in the seafood. Sugar and salt as well are not the exception. This means that we are surrounded by the plastic particles in our life (Rochman *et al.*, 2015; Dris *et al.*, 2017; Mason, Welch and Neratko, 2018).

Waring, Harris and Mitchell (2018) in their research presented that the food contaminated by the microfibres will not cause serious consequences at the current rates. The authors have noted that, although the ingestion of particles can cause leaky gut syndrome, thrombus, etc., the deeper researches must be conducted in order to find real consequences of nanoparticles. The long-term exposure to the microfibres causes the bioaccumulation in human tissues (Revel, Châtel and Mouneyrac, 2017).

Short summary of the impact on human of microfibres – since micro- and nano-plastics is a new field of researches, the real consequences and evidences are lacking to identify impact on human. However, it is undeniable that microparticles accumulate in the human body and cause its changes.

1.7. Tyres recycling and textile fibre extraction technologies

Tyres are one of the products, which has a complicated structure. Its' compounds are bonded together to create persistent product, which can hold high loads. To separate tyres composing materials, there are used different technologies to extract them, which are divided from the simplest one to the most sophisticated:

- Mechanical cutting;
- Complex multiphase chemical processes;
- Mechano-chemical processes;
- Thermal processes (Shulman, 2011).

The tyre recycling process consist of 4 main stages (Fig. 1.18):

1. Destruction of the structure of the tyre;
2. Release and separation of the components of the tyre;
3. Multi-treatment technologies, and
4. Material upgrading (Rodgers, 2015)

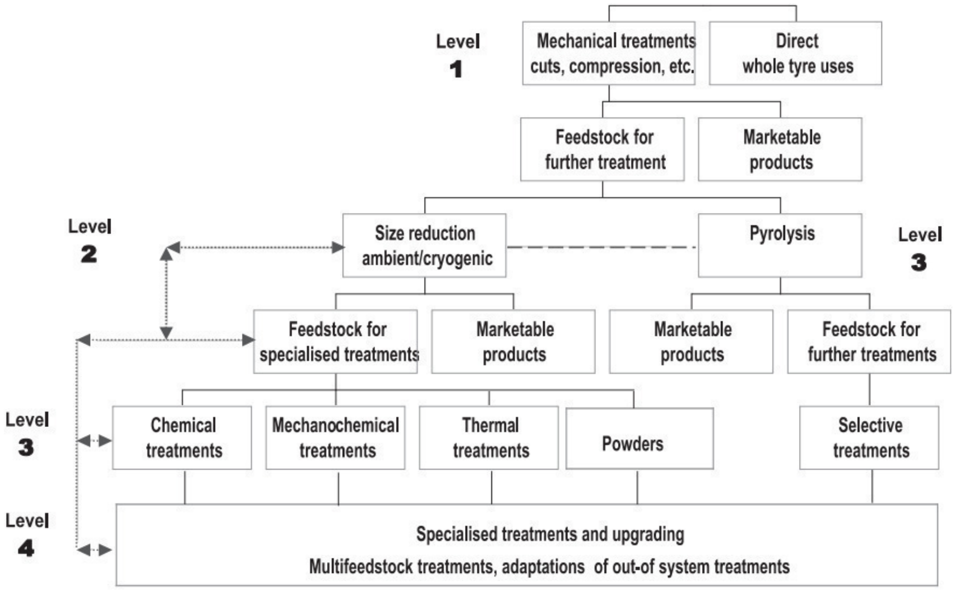


Fig. 1.18 The principal scheme of tyre recycling (Shulman, 2011)

Stage 1. Destruction of the tyre structure. At this stage, the simplest mechanical processing takes place, when physical attributes are destroyed – weight, shape change, rigidity, etc. The most common methods are the removal of bead, sidewall or tread, compression, baling and cutting (Shulman, 2011).

The bead is removed by mechanical process when rubber-coated steel coil wires is removed by cutting or tearing. Rubber coat can be reused directly without any special treatment. Sidewall is removed by cutting when strips of tread are released from the carcass. The removal of sidewall is a pretreatment process. During the balling process the structure of tyres are destroyed mechanically, when a specific number of tyres are placed in the shape under high pressure (approx. 65 tonnes), to deform and pre-shape into cube or rectangular form (Shulman, 2011; Rodgers, 2015).

Stage 2. Release and separation of the components of the tyre. At this stage, tyre treatment from rubber, metals and textiles takes place. The separation taking place by the ambient or cryogenic size reduction – the most common technologies, and more advanced and newer present as well, such as microbes, water jetting, etc. The destructed tyre is moving towards shredding and chipping into irregularly shaped or equidimensional 2.5–5.0 cm piece size, using set of knives (Shulman, 2011).

Ambient grinding uses whole or already pretreated tyres in form of irregularly or equidimensional shaped shred, chips, sidewalls, or treads. This a multistep process when different technologies are used. Processing happening at normal room temperature or a bit above. The shredded fraction of tyres are moving through magnetic, mechanical and pneumatic separators that metals and textile would be removed out of rubber fraction (Rodgers, 2015). After the process, material passes through screens, to ensure, whether any impurities are removed and ensure the consistency of size (Shulman, 2011).

At cryogenic process, the fraction of rubber are processed further. The method uses a very low temperature, which is obtained by using liquid nitrogen or industrial freezers. This is a 4-step system which includes:

1. Size reduction;
2. Cooling;
3. Separation, and
4. Milling (Shulman, 2011).

Frozen material is cooled down and can be milled into much smaller pieces by hammer mill. By this method, usually fraction size of 425-2000 μm is obtained. The fraction again passes through series of magnets to remove the last impurities. Both processes can be repeated as many times, as required to produce finer particles (Rodgers, 2015).

Stage 3. Multi-treatment technologies. The purpose of this treatment stage is to modify one or more characteristics by means of mechanical, thermal, chemical, mechano-chemical, or multi-treatment processes. The material outputs from Stage 1 and Stage 2 are used for modification. Examples of treatments in this stage, for instance, are reclaim, pyrolysis, surface modification and devulcanisation. The outputs are moving directly to Stage 4 (Shulman, 2011).

Reclaim is a process which is consisting of two-phases, when material thermally is broken down. 1st part relies on clean, ambiently produces fraction. 2nd part using plasticising, when fraction is mixed with oils and chemical substances (agents), exposed to heat, mixed mechanically, extruded and cut into the blocks. The purpose of reclaim is that the material can be modified and during process can be customised for specific use. The largest part of recycled material is being returned for production of new tyres (Shulman, 2011; Rodgers, 2015).

Pyrolysis is a two-phase thermal decomposition of rubber in oxygen-free medium, to break the material into carbon, petroleum, steel, etc. The stages of pyrolysis: primary cracking and post-cracking. Primary cracking or depolymerisation, the process when materials are heated progressively, relatively at low temperatures to produce materials, and at high temperatures, to produce aromatic components. During pyrolysis minimum three products – steel, oil and carbon – are produced (Shulman, 2011).

For surface modification peels are used. They are taken from restoration or reduced in size fraction from lorries tyres. This is a 3-stages process. At 1st stage the feedstock is milled to a very fine powder, sized of > 0.04 mm, from which all metals and textiles are totally eliminated. 2nd stage powder is being activated. And at 3rd stage, which occurs during vulcanisation proves on a press that compresses material at high force, after which curing process takes place and bonds are formed between polymer chains of the coating and the polymer, to which powder is added (Rodgers, 2015).

The process, which going on by different measures – microwaves, ultrasound, biologics, chemicals is called – devulcanisation. Main purpose of the process is to reserve the sulphur-carbon crosslinks that were formed during vulcanisation that it could be repeated in new production stage. Each devulcanisation stage begins with cryogenic or ambient size reduction (Rodgers, 2015).

Stage 4. Material upgrading. During the Stage 4 the materials properties are modified, in order to obtain what is aimed from the material (Shulman, 2011).

After the pyrolysis process the leftover carbonised rubber is treated – additionally crushed and purified from impurities. During the stage, new material is obtained. The material has similarities with carbon black, which is broadly used is production (Rodgers, 2015).

For the production of thermoplastic elastomers, the tyres are recycled into grain and powder fractions. The production takes 2 different processes – reactivation and mixing. During the process, the materials are combined together, the leftover production and the current materials. The combination of both materials is done under the pressure. The new compound created when rubber particles are combined into the thermoplastics (Shulman, 2011; Rodgers, 2015).

1.8. The use of tyres textile fibre

Tyres textile fibre was researched in many fields. Researches were done in areas of concrete production with Tyres Textile Fibre, the waste found it place in geotechnical engineering for soil reinforcement, in road engineering for asphalt production, and use for reinforcement of PP (polypropylene) plastic.

Concrete production. The use of textile fibre waste in concrete production was analysed by authors Malaiškienė, Nagrockienė and Skripkiūnas, (2015). In their experimental part the main raw materials were used, i. e. Portland cement, additives-free (CEM I) and with limestone (CEM II). Another standard component used – gravel, which fraction is 4-16 mm, out of which weak rock – limestone, sandstone, etc. – content does not exceed 2% of total weight.

As an additive to concrete tyres textile fibre waste were used, which main characteristics are presented in Table 1.2.

Table 1.2 Properties of tyre textile fibre waste (Malaiškienė, Nagrockienė and Skripkiūnas, 2015)

Characteristics of tyres textile fibre waste	Results
Density, kg/m^3	600
Average length of fibre, mm	7.8
Average width of fibre, mm	0.011

To comply a class of concrete the water and cement (W/C) ratio should be kept constant, however it was changed in order to maintain the consistence class and what amount of water must be added, when tyre textile fibre waste is introduced into the concrete mixture preparation. It was found out that with adding waste material, the demand of waster increased by approximately 100%, when only 10% of textile fibre waste used (substitute to fine part – sand). Cubes with different proportions of waste in concrete were produced. The prepared cubes, sized 100x100x100 mm, were kept for 27 days at 20 °C (Malaiškienė, Nagrockienė and Skripkiūnas, 2015).

The experiment results were presented, which shows the use of tyre textile fibre in concrete production, reduced density of mixture by 18% in CEM I type, and by 16% in CEM II type. Also, interesting note that textile fibre waste increased the amount of fine closed pores, which improve freeze-thaw characteristics, which means it has better resistance in temperature change, although it has negative effect on binding of fibre particles with cement paste, which has significant effect on compressive strength (4% of added waste caused drop by 40% in CEM I and 80% in CEM II), also reduced thermal conductivity of concrete by 35% on adding 10% of tyre textile waste. Another observation that fibres distributes in the mixture unevenly (Malaiškienė, Nagrockienė and Skripkiūnas, 2015; Baričević *et al.*, 2018).

Soil reinforcement. Series of experiments were performed in order to find out, whether the RTTF is good agent in soil bonding. The aim of the experiment was to stabilise soil which is affected to seasonal freeze-thaw conditions (Sellaf *et al.*, 2014).

In the research of Abbaspour, Aflaki and Moghadas Nejad (2019) was found out that by adding RTTF to the soil for its' reinforcement, the Maximum Dry Density decreased and Optimum Moisture Content (OMC) increased. Changes were captured while comparing sand and clay that in clay OMC level was higher rather than in sand. According to the authors, this difference probably was caused due to amount of water which presence in boundaries between RTTF and clay particles (Abbaspour, Aflaki and Moghadas Nejad, 2019).

Interesting results were recorded when performing shear test, with addition of RTTF up to 2% any effect was not recorded, although while adding 3% and 4% of textile fibre waste, the cohesion of particles increased, and the soil was more stable. Assessment on sand did not showed any positive change, since under low stress stiffness was increasing, but when moved to normal, RTTF made negative effect on parameter (Lin, Cao and Wang, 2013).

Performing Unconfined Compressive Strength test, showed that RTTF has no significant impact strength of soil, or has more negative side, due to it layered all mixture. This effect resulting that there is fading film of water between the fibre and clay particles which reduces bonding of these two materials. In total the use of RTTF in soil reinforcement will not give any positive effect, only it will pollute the environment (Abbaspour, Aflaki and Moghadas Nejad, 2019).

Asphalt production. The scenario of reuse of RTTF as reinforcing material for bituminous conglomerates. An average use of bitumen in Europe reaches amounts of about 325 M tonnes. RTTF could be a great substitute to expensive bonding materials, for instance, cellulose fibre, which will help to reduce of raw materials and at the same time implement Circular Economy Principles in European Union. This use method will close lifecycle loop, which is European main framework strategy (Landi *et al.*, 2018).

Before proceeding the fibre, it must be separated from residuals of rubber impurities. The mechanical and chemical properties of the fibre already have been studied, and the scenario of this kind of reuse is possible. The results showed that RTTF mostly consists of Polyamide 6,6 (nylon made of two monomers each containing 6 carbon atoms). For its' reuse the melting temperature should be kept lower than 259 °C, for this reason lubricants waxes added (Landi *et al.*, 2018).

Table 1.3 Properties of asphalt before and after adding RTTF (Landi et al., 2018)

	Asphalt without fibres	Asphalt with fibres
Bitumen, %	5.4	5.4
Filler, %	6.0	8.0
Indirect tensile module, MPa	4882	5212
Indirect tensile strength, MPa	1.37	1.38

The result of reuse of RTTF showed notable growth of the tensile modulus and fatigue strength. The result was 6-7 times higher comparing to standard bitumen (Table 1.3).

Polypropylene reinforcement. As an alternative use of RTTF is the production of polypropylene. The ability of use of RTTF for production of PP is because both materials has closely related mechanical performance. By using RTTF, the raw material for production of polypropylene can be reduced and saved. The use of RTTF in PP production is an possibility of implementation of Circular Economy, since raw material will be saved, and recycled used (Marconi *et al.*, 2018).

As in a previous method, the use of RTTF, for production of reinforced PP, fibre must be purified. After this process, check should be carried out for the reuse scenario possibility:

- to check the extrudability of the clean fibre, and
- check that fibre is injectable with non-virgin PP compound (Marconi *et al.*, 2018).

Table 1.4 Testing between reinforced and non-reinforced PP product (Marconi et al., 2018)

Fibre quantity, %	Max Stress, MPa	Deformation % to max stress	Max deformation, %	Young module, MPa
0	28.72	9.2	712	1465
50	23.92	7.96	12.22	1305

After the merging both materials into one, results have been conducted and presented in Table 1.4. Fibre content of 50% increases PP durability, its' resistance to the stress test.

1.9. Digital modelling programs

Nowadays during the projection of buildings, computer models are used as the basis for prediction. Digital modelling programs are used to predicts theoretical calculations of sound level or any other parameters. Different modelling programs are used to evaluate the desired parameter, e. g. absorption, reflection, sound transmission through structure, insertion loss, etc. This is relatively cheaper option, than constructing model to and perform measurements.

ODEON. The software for simulating and measuring the interior acoustics of buildings. The program allows to predict, illustrate and listen to (ODEON, 2019). This modelling software uses hybrid method, which firstly calculates the early sound wave reflection using a combination of the image source method and ray tracing, while the late reflections are calculated by a special ray tracing process generating diffuse secondary sources (Passero and Zannin, 2010).

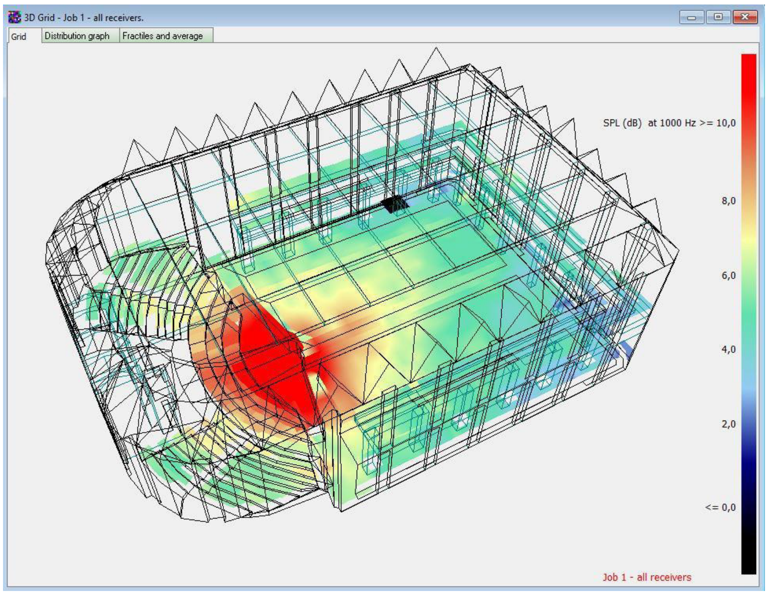


Fig. 1.19 ODEON results of SPL results (screenshot from software) (ODEON, 2019)

ODEON modelling software allows to import rooms, with different objects in it (for instance tables, chairs). The program accepts products from other programs, as CAD files from AutoCAD, also from programs, such as 3DS MAX, Rhinoceros, etc. Geometry simplification algorithms can reduce size of the object up to 10 times, which results clean models, fast calculation, without damaging the accuracy (Fig. 1.19) (ODEON, 2017).

The software is especially advanced in sound absorption materials database, which is one of the largest in prediction software's. Due to easy use and control this program is user friendly and easily adaptable (Christensen, 2013)

ZORBA. Zorba software is created by the Marshall Day Acoustics. This is the tool for predicting absorption performance in porous materials, such as rock wool, glass fibre, mineral wool, polyester, and others (Fig. 1.20). Software is suitable for designing specific acoustical environments, for instance concert halls, record studios, classrooms, etc. The software calculates statistical absorption coefficients in 1/3 octaves frequency bands (Vitkauskaite and Grubliauskas, 2018).

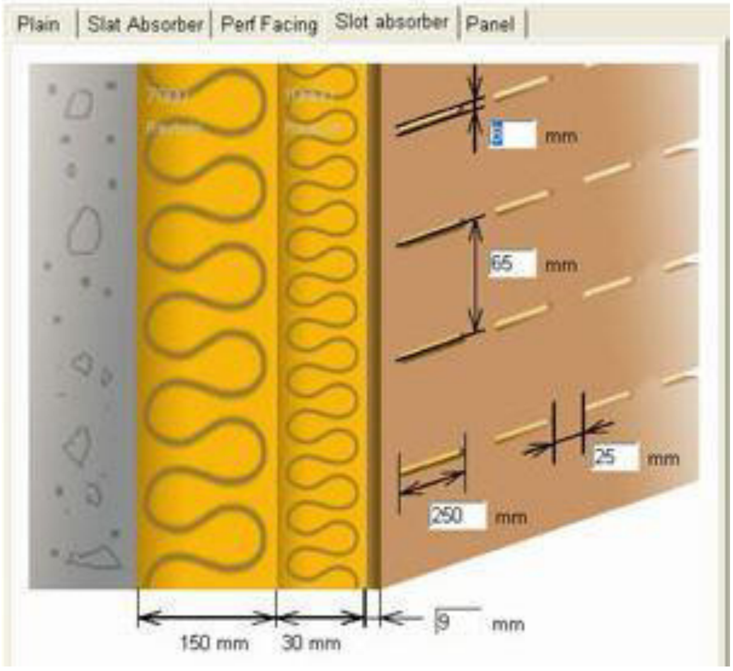


Fig. 1.20 Input data which can be inserted for calculations (screenshot from software) (Zorba, 2019b)

The calculation of absorption coefficient is done in 3 steps:

- The specific impedance and propagation coefficient of porous materials is determined;
- Calculation performed of specific impedance of the system;
- The specific impedance is being converted into the absorption coefficient, to perform calculations of normal and random incidence, transmission loss (Zorba, 2019a).

Using Zorba, it is possible to choose 9 different models of sound absorption prediction (impedance and reflection coefficient). Program calculates the impedance of the system by adding the impact of different elements, for instance, starting from infinite real impedance of the rigid wall (Zorba, 2019a).

The performance of the design and absorption can be compared by the Zorba, as well as, there is a possibility to import additional reference data and display it in the graph (Zorba, 2019b).

Program offers convenient ways of exporting results of the calculations. User friendly program lets to generate PDF file with all summary of calculations, as well software lets to copy the results and letting to transfer them to other software, such as Microsoft Office package (Zorba, 2019b)

All results are presented in 1/3 octave band, and access to them lets to be displayed in graphical form, the change of absorption curve with varying frequency band, the view of complex plane of specific impedance of the system, or table data representation can be provided, with values of absorption, specific impedance, propagation coefficient and transmission loss of the first layer of porous material (Zorba, 2019a, 2019b).

AMFG SoundFlow. The software is used for computational simulation of acoustical parameters: sound absorption and reflection coefficient, the transmission of sound wave energy through the multilayer structure. The calculation of acoustical parameters is implemented by the data stored in the system, which allows to use any kind of material with full data set, in order to implement modelling (Fig. 1.21) (Kosała, 2019).

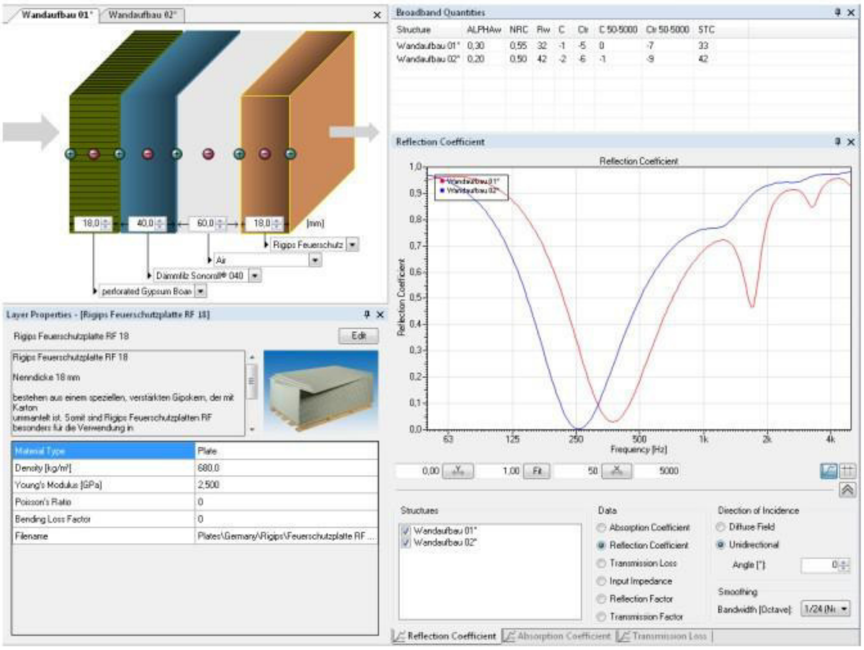


Fig. 1.21 AFMG SoundFlow software main window (screenshot from software) (AFMG SoundFlow, 2019)

Parts comprising the house – walls, floor (ceilings) – with different comprising layers can be modelled. Mechel and Bies theory is the base of the modelling program. The program is an exact copy of their theory (AFMG SoundFlow, 2019).

The parameters determined by the program are all reflected in the 1/3 octave band (provides deeper look of the noise impact). The software allows to investigate the reflector partitions, for instance, acoustical parameters (Kosała, 2019).

INSUL. The program purpose is to simulate and predict insulation of walls, floors, roofs, ceilings, and windows, as well, impact sound and rain noise of floors and roof (Fig. 1.22). The program in 1/3 octave band estimates good results of impact sound (L_n) and sound reduction index (R_w). This prediction software can be used for quick evaluation of brand-new materials and systems or check the changes of existing designs. Database of program is rich and any materials can be estimated (INSUL Features, 2019).

Fig. 1.22 INSUL software main window (screenshot from software) (INSUL Features, 2019)

The overall program is not a substitute to real measurements, although comparing with measurements data, INSUL predicts values within 3 dB error for most of constructions. Program is able to calculate single – up to 6 layers), double and triple structures, however it does not include intersections between structures, ventilation holes, doors, and windows into calculations of sound reduction index. The results are presented in tables, the modelling construction presented in 2D or 3D views (INSUL, 2019).

The first chapter conclusions

1. Sound can be described as the physical phenomenon when compression or expansion of air propagates in all directions. Sound as mechanical waves can be described by these physical characteristics: sound pressure (p), amplitude (A), sound wave speed (c), frequency (ν), wavelength (λ), sound intensity (I), sound wave period (T). Sound can divided into low, medium, and high frequency. To describe sound level, the terms sound pressure level and sound power level are not convenient, for this reason there is used non-systemic logarithmic measurement unit decibel (dB). It is accepted that sound threshold is 0 dB, and upper pain threshold is about 120 dB. Sound can be transmitted in the building in three ways: directly, indirectly and by side constructions.
2. To improve residents living conditions solutions for noise insulation have been applied for walls, façades, floors, and ceilings. The broad range of materials has been used, starting from the most usual rock wool, fibre glass wool, clayite and to new and non-traditional – reeds, cotton, oil palm fibres to recycled materials such as tyres textile fibre, plastics, etc.
3. Sound absorption is a phenomenon, when sound wave enters porous medium and loses its' energy and giving away heat. The materials ability to absorb sound is called sound absorption coefficient, which varies from $0 > \alpha < 1$, and defined as a ratio of absorbed and incident energy. The main parameters of the material is materials thickness, density, and porosity. As thicker material, the longer waves can be absorbed. Due to high density of material the absorption increases, due to mass. Material's property – porosity – acts crucial part of sound behaviour, due to pores containing continuous channels, the sound wave interacting with the pore and afterwards loses the energy.
4. Good thermal insulator is described by seven different properties: thermal conductivity, thermal resistance, specific heat capacity, thermal diffusivity, density, vapour permeability and air permeability. A good insulator should contain those properties, since they are crucial on their performance. Insulating materials are classified into four groups: inorganic, organic, combined, and new materials, those groups contain foamy or fibrous insulating materials. Most known are rock and glass wools, from natural – sheep and cotton wool, coconut fibre and from new materials – vacuum insulating panels, aerogel, etc. Regarding insulators properties they have different thermal conductivity.
5. It was estimated that concerning to excessive noise level each year alone in Europe about 1–1.6 M of healthy years are being lost, due to unwanted sound. Excessive noise causes hearing impairment, psychosocial effects, stress-related health issues, sleep disturbance, tinnitus, etc. Acoustic trauma occurs at level of more than 130 dB, when ear drum damages membrane. By the research it was estimated during study time noise causes annoyance, lowers performance results on mental tasks, decreases reaction time, and causes fatigue.
6. Each year in Europe about 320 000 tonnes of tyre textile fibre are extracted, while in Lithuania about 2 500 tonnes. The percentage of total composition, textile makes up to 10%. The main ingredient for textile is Polyamide 6,6, or simply called Nylon. In European Waste Catalogue tyres textile (19.12.08) is described as a special waste that cannot be landfilled, although due to strong bonds it does not absorb any dangerous chemical substances. The impact from nylon to environment and human is significant. Due to its' presence in environment animals and humans are already ingesting it as a microplastic and it is accumulates in tissues.

7. The tyres recycling process is complicated and takes many steps. It is divided into 4 stages – destruction of the structure of the tyre, liberation and separation of the elements off the tyre, multi-treatment technologies, and material upgrading. During the 2nd Stage metals, textiles and rubber are separated. By the pneumatic device, textile are blown away.
8. Tyres textile fibre usage in other fields was estimated. The main areas of use that have been investigated – concrete production, soil reinforcement, asphalt production and polypropylene production. It was noted that for production of concrete textile worsens results, regarding compressive strengths, when 4% of fine fraction was substituted by textile, the results dropped up to 80% in different cements types. The other failure was in soil reinforcement. By adding up to 4% of tyre textile waste in clay, the cohesion increased insignificantly, while in sand the results were negative. The reinforcement by textile fibres – thermoplastics – will create secondary pollution on soil, which is negative aspect of using it in this field. The positive results were obtained in asphalt production, whereas textile fibres are good substitute to bituminous conglomerates. By adding 8% of fibre, the fatigue strength increases by approximately 6–7 times, comparing to standard bitumen. The use of polyamides in polypropylene production showed positive results. The first advantage that will be saved virgin polypropylene compound, and the second increases resistance to deformation and increases durability of the product.
9. The reviewed digital modeling programs ODEON, ZORBA, AMFG SoundFlow and INSUL can be used to calculate noise or impact insulation index, as well as absorption coefficient.

2. METHODOLOGY OF THE RESEARCH

In this chapter the methodology of the research will be presented, as well as the object of the research. Measurements of Reverberation time are estimated according to the ISO 3382-2 standard, Sound Absorption measurements held according to the ISO 10534 standard. Measurement of thermal conductivity held at the laboratory by using λ-meter. The results of the experiments were compared in between to estimate the most appropriate choice.

2.1. Reverberation chamber and used equipment for the experiment

Reverberation Chamber is located at Vilnius Gediminas Technical University, created by the Department of Environmental Protection and Water Engineering. This chambers' purpose is to estimate different materials absorption, reflection, and sound isolation determination.

Chamber consists of two rooms, which are separated by the brick wall, additionally isolated by tyres rubber coating. The size of each room is 2.0 m x 2.5 m (height 2.5 m), in total 10 m^2. The nearby facilities are designated for measurement equipment. The photos are shown in Figure 2.1.

Fig. 2.1 Reverberation chamber view (Created by the author, 2019)

The part of the room where noise source is located, the room is covered with reflective material – laminated HDF panel (saw dust panel), and the receiver part is covered by absorbing material – acoustical foam. In the both chambers' rooms separating wall where is installed 1.0 m^2 size opening, where the sample or reflective window is tightly is being installed.

The noise Reverberation time held by precise sound level meter ‘Bruel & Kjaer 2270’ (Fig. 2.2). The sound level meter made by Danish company is one of the most modern, 1st class sound level meters and sound analysers. The instrument is being calibrated before and after the experiment.

Fig. 2.2 Sound level meter ‘Bruel & Kjaer 2270’ (Bruel & Kjaer, 2019)

During experiment used devices are presented in the Table 2.1. All devices comply the newest sound level meters standard IEC 61672, as well as the older IEC standard 60651 and IEC 60804 and the newest ANSI standards. White noise is a random signal that has equal intensity at different frequencies, always giving constant power spectral density.

Table 2.1 Equipment used in experimental part (Created by the author, 2019)

No.	Equipment	Model
1.	Sound level meter ‘Bruel & Kjaer’	2270
2.	Microphone	4190
3.	Microphones calibrator	4294
4.	Sound source with stand ‘Bruel & Kjaer Omnipower’	4292L
5.	Power Amplifier (500 W)	2734
6.	Environmental condition measuring device ‘Rotronic’	HP32

All measured data was analysed by ‘Bruel & Kjaer’ software Qualifier Type 7830. This program generates reports of the measurements that can be analysed further. The abilities of the software is to provide real time 1/1 or 1/3 octave range analysis, information about Reverberation time, the results portrayal as the graphs.

2.2. Description of analysed materials

In the experiment, three different materials were analysed in order to identify the best noise isolating material. The chosen materials were divided into two group: conventional and unconventional. Conventional group represents two commonly used materials – rock and glass wools, while as an unconventional – recycled tyre textile fibre – the object of the research. However, RTTF was mechanically treated and in total 3 different samples were obtained: shredded, purified, and raw which makes in total 5 samples to be investigated (incl. conventional materials).

Tables 2.2 – 2.4 presents the materials which were used in the experimental part of the thesis.

Table 2.2 Rock wool parameters (Paroc, 2019)

Material	Rock wool
Thickness, cm	5 / 10 / 15
Density, kg/m3	38.0 – 120.0
Mass, kg/m^2	11.0 – 25.0

Table 2.3 Glass wool parameters (Isover Saint-Gobain, 2019)

Material	Glass wool
Thickness, cm	5 / 10 / 15
Density, kg/m3	16.0 – 64.0
Mass, kg/m^2	0.8 – 3.6

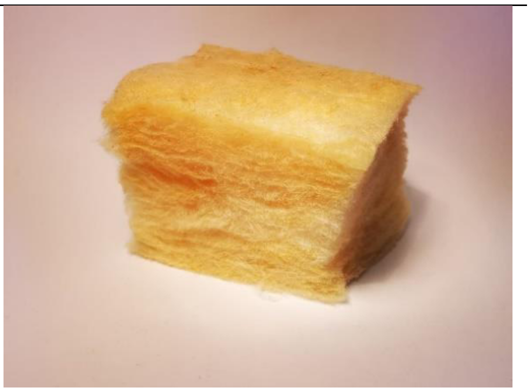


Table 2.4 Recycled tyre textile fibre (Created by the author, 2019)

Material	Recycled tyres textile fibre
Thickness, cm	5 / 10 / 15
Density, kg/m3	96.0 – 171.0
Mass, kg/m^2	8.5 – 10.3

The materials chosen for experiment will be tested at different standard thicknesses and densities, to evaluate the most effective combination to estimate the best noise insulation result. Depending on the measurement, materials will be prepared in different sizes.

Conventional materials are already pre-shaped, however for the recycled tyre textile fibre there will be held in the shape needed for the experiments.

2.3. Measurements of reverberation time

Reverberation time reduction (R_{T60}). The Reverberation time (RT) measurement procedures are described in ISO 3382-2 standard. The method used for the measurement of RT – the interrupted noise method. The measurement frequency range from 100 Hz to 5000 Hz is used for the engineering and precision methods in 1/3 octave band (Fig. 2.3).

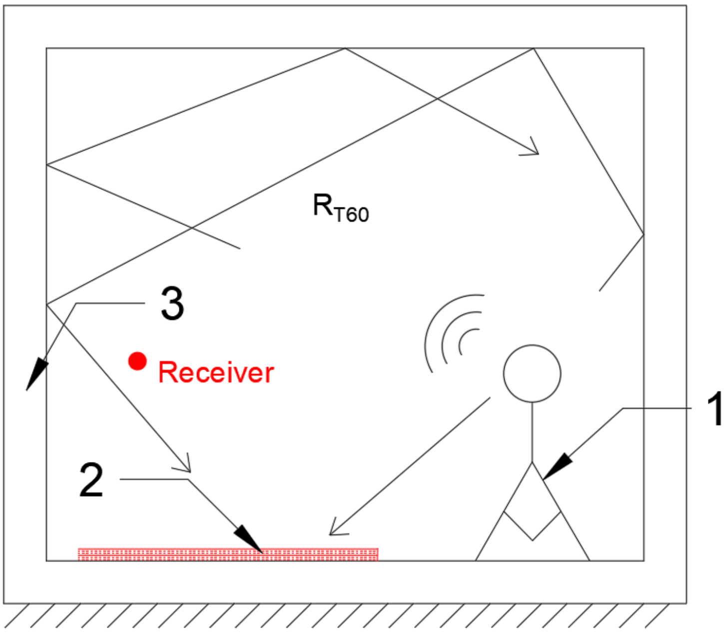


Fig. 2.3 Principle scheme of reverberation time measurements: 1 – airborne noise source; 2 – sound absorbing sample; 3 – reverberation room, R_{T60} – reverberation time, s
(Created by the author, 2019)

Method description. Loudspeaker source should be used as a broadband random noise source. The source must be able to produce a sound pressure level sufficient to ensure a decay curve starting at least 35 dB above the background noise in the corresponding frequency band. If method of measurement of T_{30} is selected, the level created should be at least of 45 dB higher than the background level (ISO, 2008).

For measurements in 1/3 octave bands, the bandwidth of the signal has to be greater or equal to 1/3 octave. The spectrum must be reasonably flat within the actual octave band to be measured. The minimum number of measurement positions to achieve an appropriate coverage in a room are presented in Table 2.5 (ISO, 2008)

Table 2.5 The number of positions and measurements (ISO, 2008)

	Engineering
Source-microphone combinations	6
Source positions	≥ 2
Microphone positions	≥ 2
Number of decays in each position (interrupted noise method)	2

For the interrupted noise method, the total number of decays is normally obtained by a number of repeated decays in each position. For each decay, its' allowed to take a new position (ISO, 2008).

Source positions were chosen as the normal position according to the use of the room. In small rooms, as small rooms, one source position should be in a corner of the room.

Microphone should be set at least 2 meters from the source, i. e. half of a wavelength of soundwave. The distance from any nearest reflecting surface, incl. floor, should be 1/4 of wavelength, or normally around 1 m. The minimum distance of microphone position to source is calculated according to the Formula 2.1 (ISO, 2008):

$$d_{min} = 2 \cdot \sqrt{\frac{V}{c \cdot \hat{T}}}, m \tag{2.1}$$

where
V – volume of the room, m^3;
c – sound wave speed, m/s, and
T – an estimate of the expected reverberation time, s (ISO, 2008).

While sound speed c, at temperatures from 15.0 °C to 30.0 °C is calculated by Formula 2.2:

$$c = 331 + 0.6 \cdot t, m/s \tag{2.2}$$

where
t – air temperature in the reverberation chamber, °C.

Material for this experiment should be dense to absorb sound energy and reduce Reverberation time. The RTTF in this case should bonded that it does not loose properties needed for noise absorption.

2.4. Measurements of sound absorption coefficient

In order to determine sound absorption coefficient α equipment called – impedance tube, is used. Impedance tube (Fig. 2.4) – a special equipment used for investigation of sound absorption and reflection of material, when the sound wave moves towards the sample. Impedance tube made of the thick shell, sound source, microphones, and the space for sample. Using impedance tube, non-acoustic parameters of the material can be determined by indirect methods – porosity, tortuosity and airflow resistivity (Doutres *et al.*, 2010).

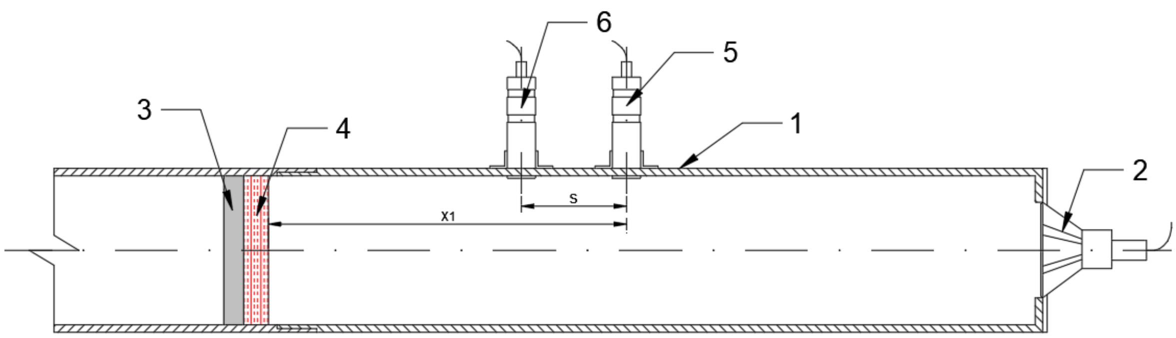


Fig. 2.4 Impedance tube principle scheme: 1 – impedance tube shell (acrylic glass), 2 – sound speaker, 3 – rigid backing, 4 – sound absorption sample, 5 – microphone No. 1, 6 –microphone No. 2 (Created by the author, 2020)

Impedance tubes differ in their parameters depending on the properties to be investigated. The main parameter – diameter. Regarding the diameter, the frequency range in which sound absorption coefficient can be measured, determined (Umnova *et al.*, 2005).

Method description. According to the standard ISO 10534-1:

1. Ambient air temperature in impedance tube measured and the sound wave speed is determined (Formula 2.2). The variation of the temperature in

impedance tube cannot differ by more than 1.0 Kelvin, otherwise if a drastic change is found, the results are considered unrepresentative and the experiment must be repeated (ISO, 1998);

2. The sample is tightly installed before the rigid backing and all connecting parts are sealed with lithium grease, to prevent sound leaking;
3. Using sound speaker in impedance tube, pink sound pressure level is released. The sound level in impedance tube must be 10 dB higher than the background noise, during the experiment;
4. The released sound from the sound source is recorded by the microphones (maximum and minimum sound pressure levels);
5. Sound absorption and reflection coefficients are calculated using software and mathematical physical formulas;
6. All measurements are repeated 3 times in order to calculate standard deviation and have representative data (ISO, 1996).

After the measurements, the pressure is determined at each frequency by transfer function method (ISO 10534-2 standard):

$$H_{12} = \frac{p_{2(f)}}{p_1(f)} \tag{2.3}$$

where
H_{12} – transfer function between microphones No. 1 and No. 2;
p_2 – pressure recorded by the second microphone, Pa;
p_1 – pressure recorded by the first microphone, Pa;
f – frequency, Hz (ISO, 1998).

$$k_0 = \frac{2\pi f}{c_0} \tag{2.4}$$

where
k_0 – wave number in the air;
f – frequency, Hz;
c_0 – sound wave speed in the air, m/s (ISO, 1998).

$$H_I = e^{-jk_0 s} \tag{2.5}$$

where
H_I – incident wave transfer function;
s – distance between microphones, m (ISO, 1998).

$$H_R = e^{jk_0 s} \tag{2.6}$$

where
H_R – reflected wave transfer function;
s – distance between microphones, m (ISO, 1998).
Sound wave reflection is calculated by the Formula 2.7:

$$R = \frac{H_{12}-H_I}{H_R-H_{12}} e^{2jk_0 x_1} \tag{2.7}$$

where
R – sound reflection coefficient;
H_I – incident wave transfer function;
H_R – reflected wave transfer function;
k – wave number;
x_1 – distance between microphone No. 1 and the sample (x_1 = 190 mm) (ISO, 1998).

Sound absorption ability is inverse value of sound reflection coefficient of the materials. Sound absorption for the flat waves is calculated by the Formula 2.8:

$$\alpha = 1 - |r|^2 \tag{2.8}$$

where

α – materials sound absorption coefficient (ISO, 1998).

2.5. Measurements of thermal conductivity coefficient

For the measurements of thermal conductivity coefficient, it was taken 3 different samples – raw material, shredded material, purified material. For the measurement of the coefficient, it was prepared 2 kg of samples of each type, data presented in Table 2.6.

Table 2.6 Sample preparation data (Created by the author, 2020)

Sample No. & type	Size of the shape	Mass of the shape	Mass of the sample	Control thickness of the sample (start position)
Sample No. 1 Shredded RTTF	259 x 262 mm	Total = 99.64 g Frame = 35.18 g	606.81 g	90 mm
Sample No. 2 Raw RTTF	263 x 258 mm	Total = 139.55 g Frame = 45.76 g	696.41 g	
Sample No. 3 Purified RTTF	246 x 251 mm	Total = 162.88 g Frame = 93.9 g	534.31 g	

Sample No. 1	Sample No. 2	Sample No. 3
		

Thermal conductivity of the sample is determined in the heat flow meter equipment. Thermal conductivity is determined by the measuring of the heat flux, sample thickness, and temperature difference through the sample. Thermal conductivity measured by the heat flux transducers, which are placed on heating or cooling plates. The thickness measurement precision is 0.002 cm, and temperature 0.01 °C. Principle scheme of the measurement presented in Fig. 2.6.

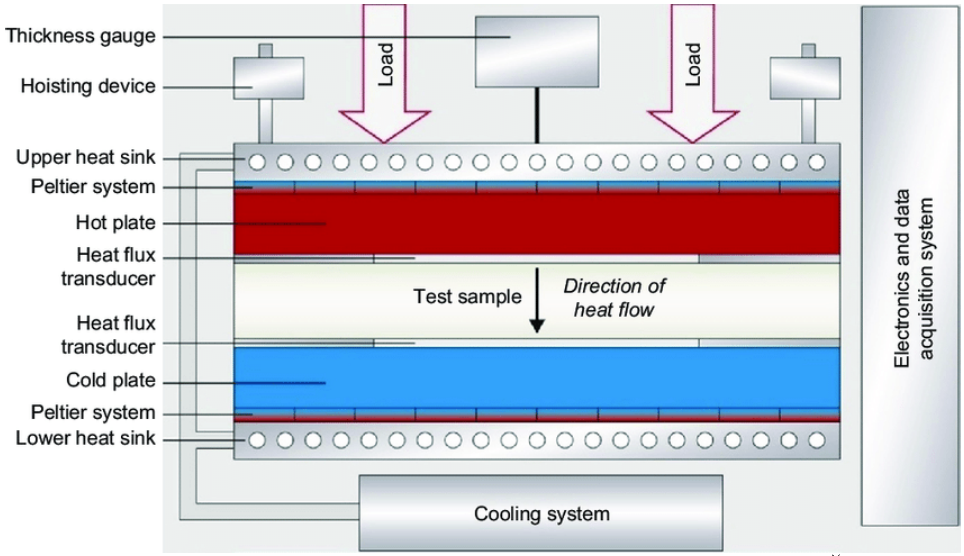


Fig. 2.5 Thermal conductivity meter principle scheme (Ugovšek and Šubic, 2017)

The principle of the measurement is to prepare the sample in the shape (Fig. 2.7). For each measurement, the inner measurements are considered.

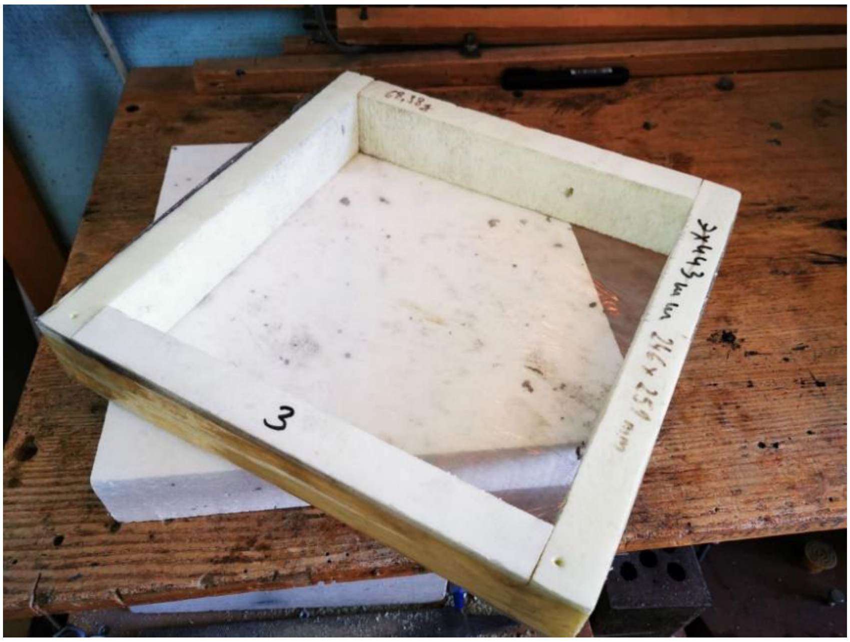


Fig. 2.6 Shape of the sample (Created by the author, 2020)

The shape is filled in with the sample till top of the shape and 50 mm on top (Fig. 2.8). This made because, the sample in the measurement machine will be compressed in order to obtain the best result. The measurement will start at 90 mm of thickness, which will be changed during the measurement. There are thicknesses set: 90, 80, 70 and 60 mm. According to this the density will vary, as more it compressed, the bigger density it is.

Fig. 2.7 Shape filled with the sample (Created by the author, 2020)

The measurement is performed by LaserComp FOX 314 Heat flow meter instrument (Fig. 2.9). Prepared sample is placed into the machine, into computer programme data is entered – sample size (shape inner size), thickness, mass of the sample, and the name of the measurement. The temperatures are selected: cooling plate – 0.0 ℃, heating plate – 20.0 ℃ (±0.01 ℃). The doors of the machine are closed, and measurement starts. The whole measurement of one sample takes approximately 4-5 hours.

Fig. 2.8 LaserComp Heat flow meter instrument (Created by the author, 2020)

The results are presented by measuring 3 times at the same point, and after average result is being calculated. The absolute error of the measurement is 1%. The measurement performed many times, after the results are presented as the curve, where the best thermal conductivity coefficient can be determined. The best result estimated as the lowest value.

The second chapter conclusions

1. For the experimental part, three different materials were used, conventional – rock wool, glass wool and unconventional – recycled tyre textile fibre. Previous two are the most commonly used in building sector and are good examples to be compared to RTTF.
2. Reverberation time reduction measurements were done in Reverberation Chamber, which is located at VGTU. Department of Environmental Protection and Water Engineering. It is small scale chamber with total dimensions are 10 m^2. The used measurement equipment is the 1^{st} class, the most modern sound level meters and sound analysers Bruel&Kjaer 2270. As well as additional, high class equipment is been used. To analyse data Bruel & Kjaer software has been used. Experiment of reverberation time reduction measurements were done at three standard thicknesses (5, 10, 15 cm) in order to estimate the best result.
3. Sound absorption coefficient measurements were done using impedance tube. Impedance tube – a special equipment used for investigation of sound absorption and reflection of material. The sample was tightly installed before the rigid backing and all system sealed to prevent sound leaking. Pink sound was released from sound speaker and using microphones sound pressure levels were recorded. After experiment was done, using software materials sound absorption coefficient was calculated.
4. For thermal conductivity measurements three different samples of RTTF were taken: raw, shredded, purified (to determine if rubber particles influence on thermal conductivity). All they were inserted into the shape, specially prepared for the measurements for heat flow meter. The samples were at the reference thickness of 90 mm, and during each step, thickness was lowering and increasing the density. Measurements for one sample took approximately 4-5 hours.

3. RESULTS

In the Results chapter, all results of the measurements are represented – Reverberation time reduction, materials sound absorption and thermal conductivity measurements. Measurements are done in accordance to the methodology which is presented and described in Chapter 2.

3.1. Reverberation time measurements results

For Reverberation Time (RT) measurements 3 different materials were selected. As it was previously mentioned in Chapter 2, two conventional material – rock wool (RW) and glass wool (GW), and one unconventional researchable material – raw recycled tyre textile fibre (RTTF) were analysed in laboratory experiment.

First of all, the reference measurements were performed in order to obtain RT in empty room that we would be able to obtain difference of materials, their thicknesses, on RT reduction in the room.

It was noticed after processing the results that at low frequency from 50 to 200 Hz it is meaningless to analyse due to standing wave occurs. Standing wave is such phenomenon when two waves are moving in opposite direction and each of them having the same amplitude and frequency (Encyclopaedia Britannica, 2020). This is happens due to insufficient area of the room, the wavelength in this case varies from 6.88 m (@ 50 Hz) to 1.72 m (@ 200 Hz). Therefore, those frequencies will not be evaluated.

Fig. 3.1 presents measurements data of rock wool, at different sample thicknesses. The thicknesses which were estimated are 5, 10 and 15 cm height. The figure shows comparison between 3 different thicknesses to reference measurement of empty room.

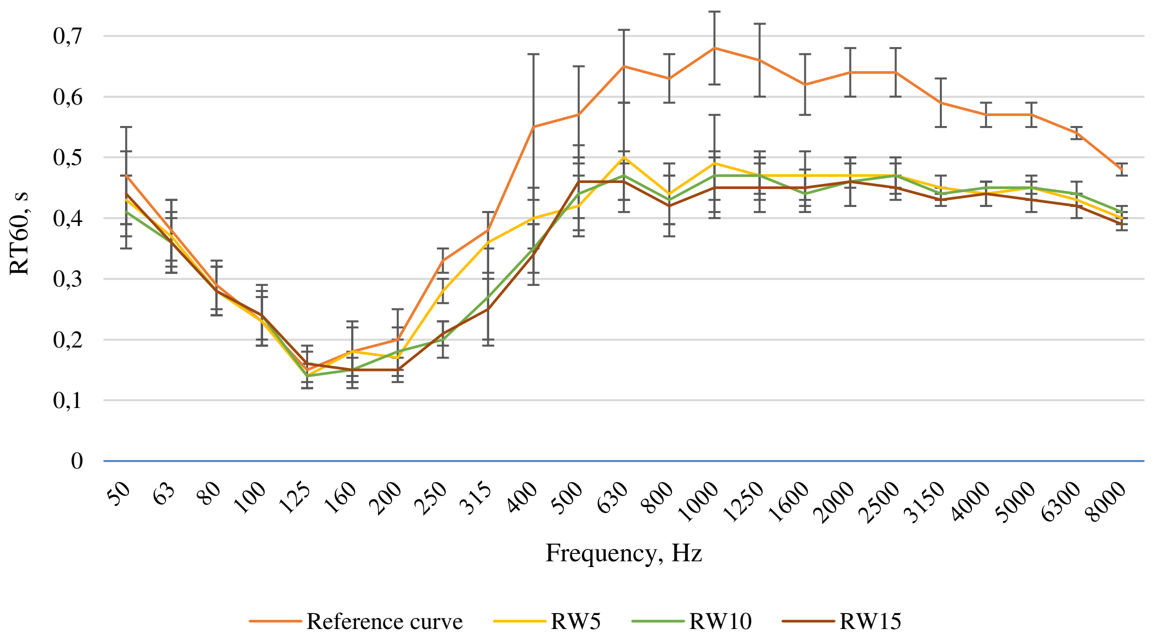


Fig. 3.1 Reverberation time difference on RW thickness (Created by the author, 2020)

The measurements results shows that the low frequency range from 200 to 500 Hz better performance is visible at samples RW10 and RW15 at an average reduction of 0.15 seconds of Reverberation time (comparing to the reference curve). RW15 at 400 Hz frequency shows 0.21 seconds of RT reduction. In the medium frequency range from 500 to 1000 Hz, better performance visible RW15 sample, average Reverberation time reduction is 0.15 seconds. At frequency of 800 Hz RT reduction obtained is 0.21 seconds comparing to reference curve. Although, RW15 shows better performance. RW5 and RW10 has very similar characteristics. At high frequency range from 1000 till 8000 Hz. RW15 sample in average has 0.015 seconds better performance comparing to RW5 and RW10. Highest RT reduction was obtained at 1000 Hz frequency of RW15 sample – 0.23 seconds. In conclusion. we definitely see that thicker sample has advantage in RT reduction. though. this difference is not particularly observable.

Fig. 3.2 presents measurements data of glass wool, at different sample thicknesses. The thicknesses which were estimated are 5, 10 and 15 cm height. The figure shows comparison between 3 different thicknesses to reference measurement of empty room.

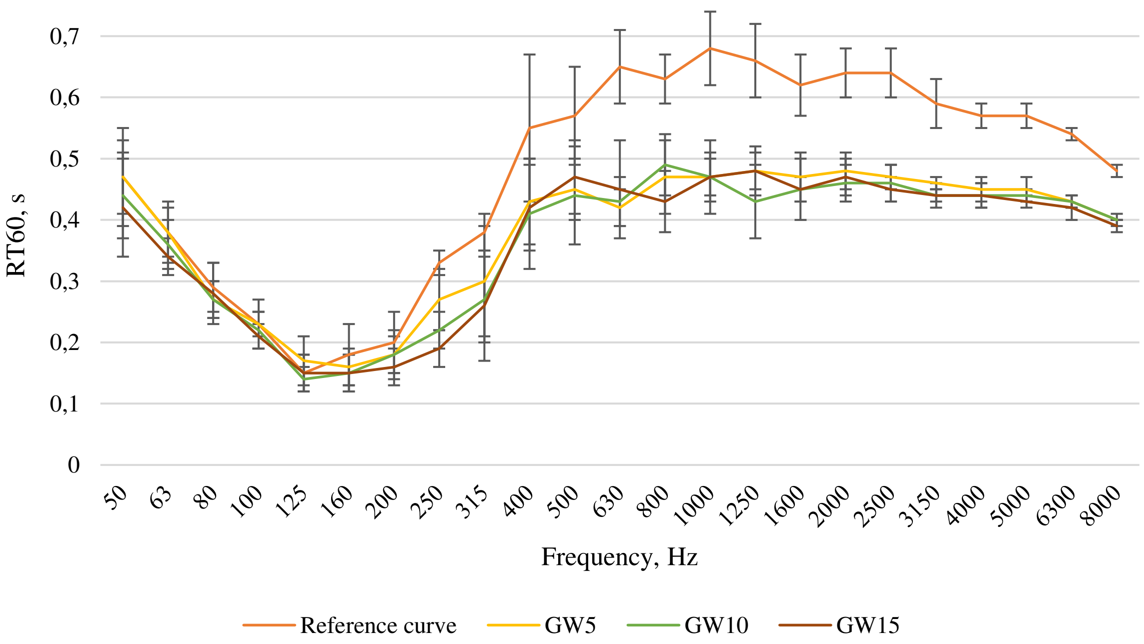


Fig. 3.2 Reverberation time difference on GW thickness (Created by the author, 2020)

The measurement results shows that the low frequency range from 200 to 500 Hz better performance is visible at sample GW15 at mean reduction of 0.13 seconds of Reverberation time (comparing to the reference curve). However, the highest RT reduction was obtained GW10 sample at 400 Hz frequency. In the medium frequency range from 500 to 1000 Hz, it is not possible to identify which sample has a better performance, whereas at different frequencies samples behave in different ways. Only noticeable, at 630 Hz frequency GW5 has 0.23 seconds RT reduction. At high frequency range from 1000 till 8000 Hz, all samples has almost identical behaviour on Reverberation time reduction. On average, Reverberation time is reduced by 0.15 seconds. The best performance was obtained of GW10 sample at 1250 Hz frequency, with the RT reduction of 0.23 seconds. Although, we can identify thicker sample, according to the Figure 3.2, as being more efficient in RT reduction, but as it was mentioned, difference is not particularly observable.

Fig. 3.3 presents measurements data of RTTF, at different sample thicknesses. The thicknesses which were estimated are 5, 10 and 15 cm height. The figure shows comparison between 3 different thicknesses to reference measurement of empty room.

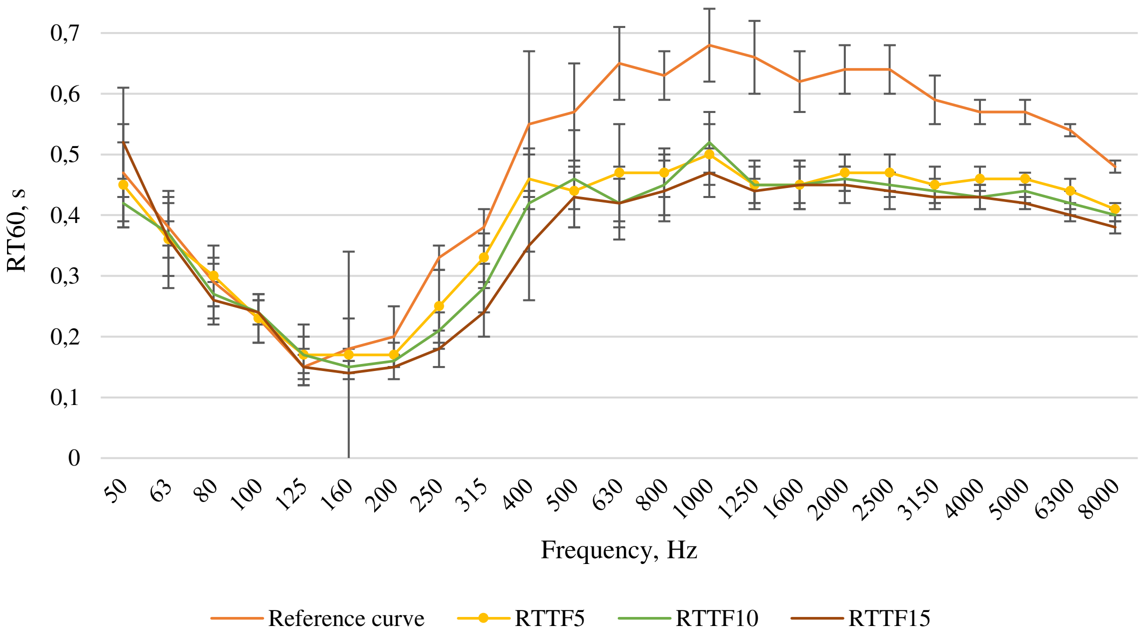


Fig. 3.3 Reverberation time difference on RTTF thickness (Created by the author, 2020)

The measurements results shows that the low frequency range from 200 to 500 Hz better performance is visible at sample RTTF15 at an average reduction of Reverberation time comparing to the reference curve of 0.16 seconds. At frequency of 400 Hz RTTF15 shows 0.19 seconds of RT reduction comparing to reference curve. In the medium frequency range from 500 to 1000 Hz. from the Figure 3.3 we can definitely see that RTTF15 has better performance in RT reduction with an average reduction of 0.19 seconds. At 630 Hz both RTTF10 and RTTF15 shows 0.23 seconds of RT reduction. At high frequency range from 1000 till 8000 Hz. RTTF15 has an average of 0.17 seconds of RT reduction. The best result is obtained at 1000 Hz frequency of RTTF15 sample of 0.21 seconds of RT reduction. In conclusion, we can see that RTTF15 has the best performance out of other samples.

After we have compared the RT reduction dependency on the same material but variable thickness, we can move forward to compare the same thickness, but different materials and obtain which of those has a better performance. Figure 3.4 shows comparison of 3 different materials at same 5 cm thickness.

The results shows that the low frequency range from 200 to 500 Hz better performance on RT reduction is visible at sample GW5 with an average reduction of 0.09 seconds. However, GW5 shows better performance in this range, at constant frequency of 400 Hz, RW5 result is 0.15 seconds. In the medium frequency range from 500 to 1000 Hz, the performance of single material cannot be identified, all behave similarly and reduction ranges from 0.16 to 0.17 seconds. However, the best result, was obtained at single frequency of 630 Hz of GW5 to be 0.23 seconds. At high frequency range from 1000 till 8000 Hz, the same situation is observed that there is no distinct feature to obtain the most efficient on RT reduction material. In the range of high frequency, reduction time is in average of 0.14 seconds. To conclude, at thickness of 5 cm sample, we cannot distinct a particular material, all they behave similarly.

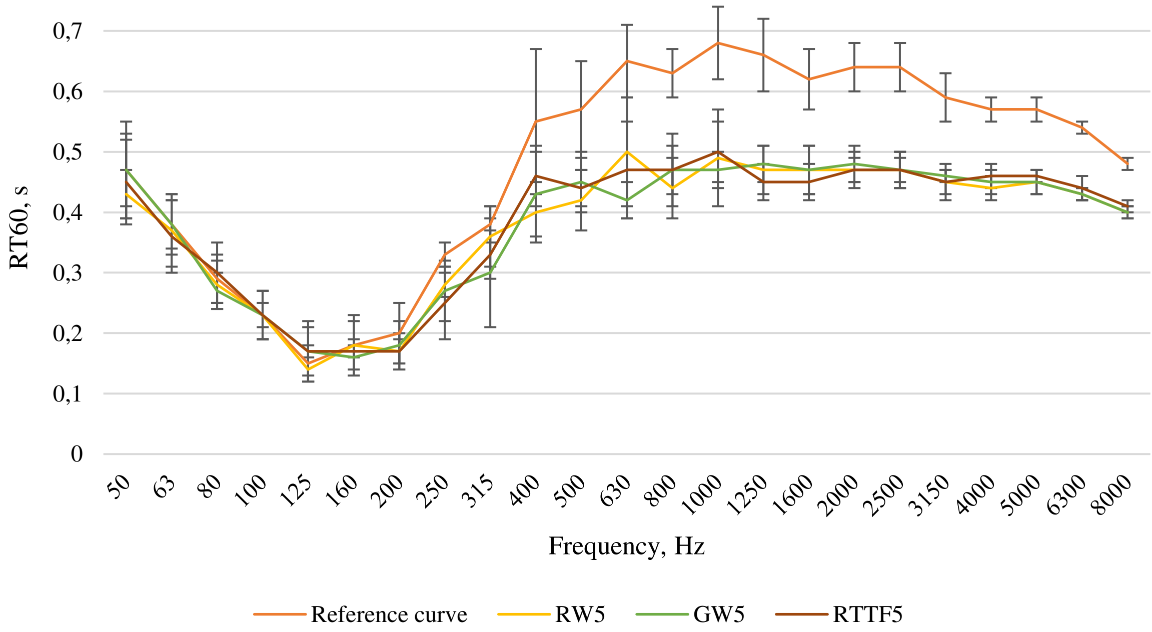


Fig. 3.4 Reverberation time reduction of 5 cm thickness by different materials
(Created by the author, 2020)

Figure 3.5 presents RT reduction comparing to reference curve. By calculating difference between reference curve and each measurement, in the Figure 3.5 we can see that materials behave similarly on RT reduction, which was discussed previously. According to the figures' trendlines we can definitely see that materials are similar and can be used as a substitution to conventional materials at particular thickness.

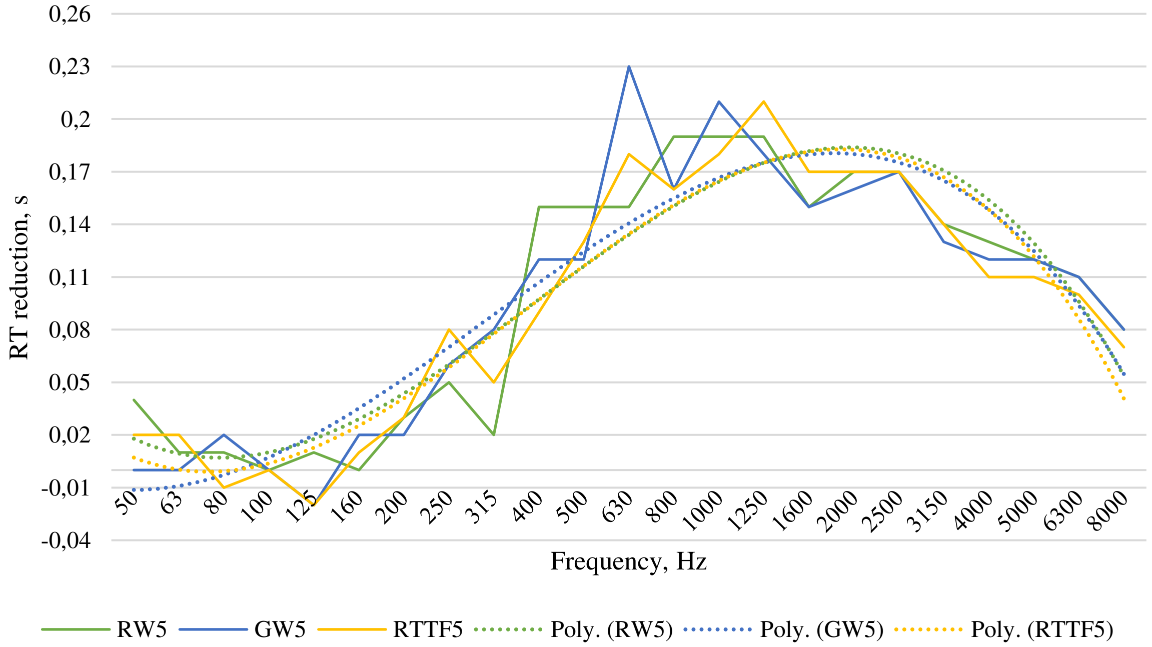


Fig. 3.5 Reverberation time reduction regarding materials 5 cm thickness
(Created by the author, 2020)

Figure 3.6 results shows that the low frequency range from 200 to 500 Hz better performance on RT reduction is visible at sample RW10 with an average reduction of 0.15 seconds. At constant frequency of 400 Hz, RW10 result is 0.20 seconds. In the medium frequency range from 500 to 1000 Hz. the performance of single material cannot be identified, all behave similarly and reduction ranges from 0.16 to 0.17 seconds. However, the best result, was obtained at single frequency of 630 Hz of RTTF10 to be 0.23 seconds. At high frequency range from 1000 till 8000 Hz, the same situation is observed that there is no distinct feature to obtain the most efficient on RT reduction material. In the range of high frequency, reduction time is in average of 0.15 seconds. To conclude, at thickness of 10 cm sample, we cannot distinct a particular material, all they behave similarly.

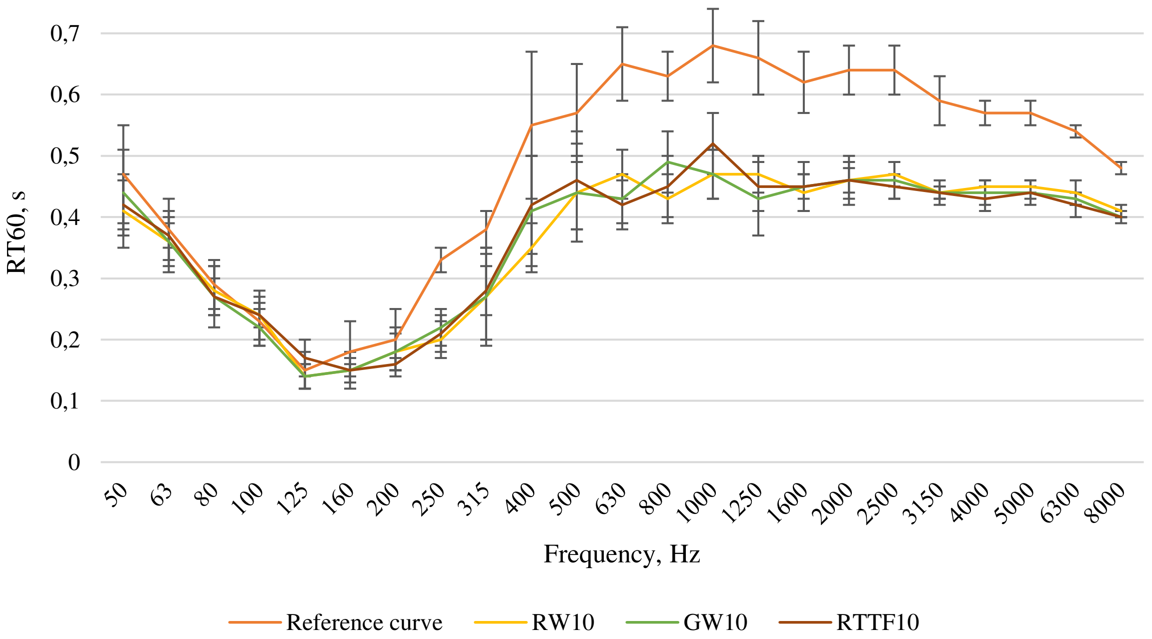


Fig. 3.6 Reverberation time reduction of 10 cm thickness by different materials
(Created by the author, 2020)

By calculating difference between reference curve and each measurement, in the Figure 3.7 we can see that materials behave similarly on RT reduction, which was mentioned previously. According to the figures' trendlines we can definitely see that materials are similar and can be used as a substitution to conventional materials at particular thickness.

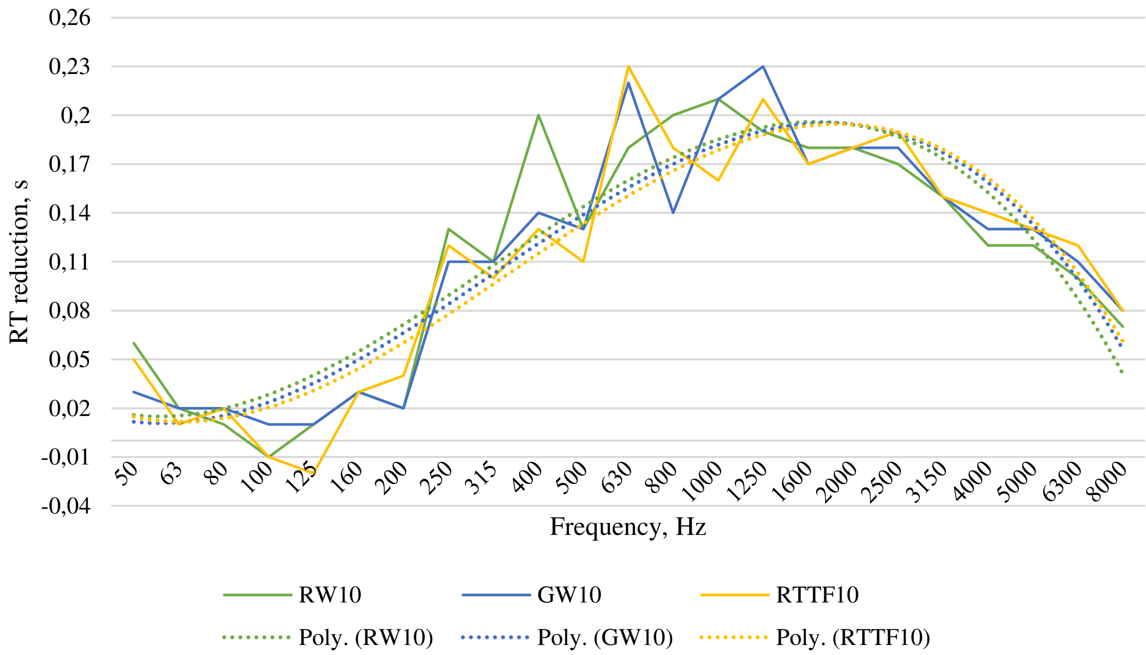


Fig. 3.7 Reverberation time reduction regarding materials 10 cm thickness
(Created by the author, 2020)

The results shows that the low frequency range from 200 to 500 Hz better performance on RT reduction is visible at sample RTTF15 with an average reduction of 0.16 seconds (Fig. 3.8).

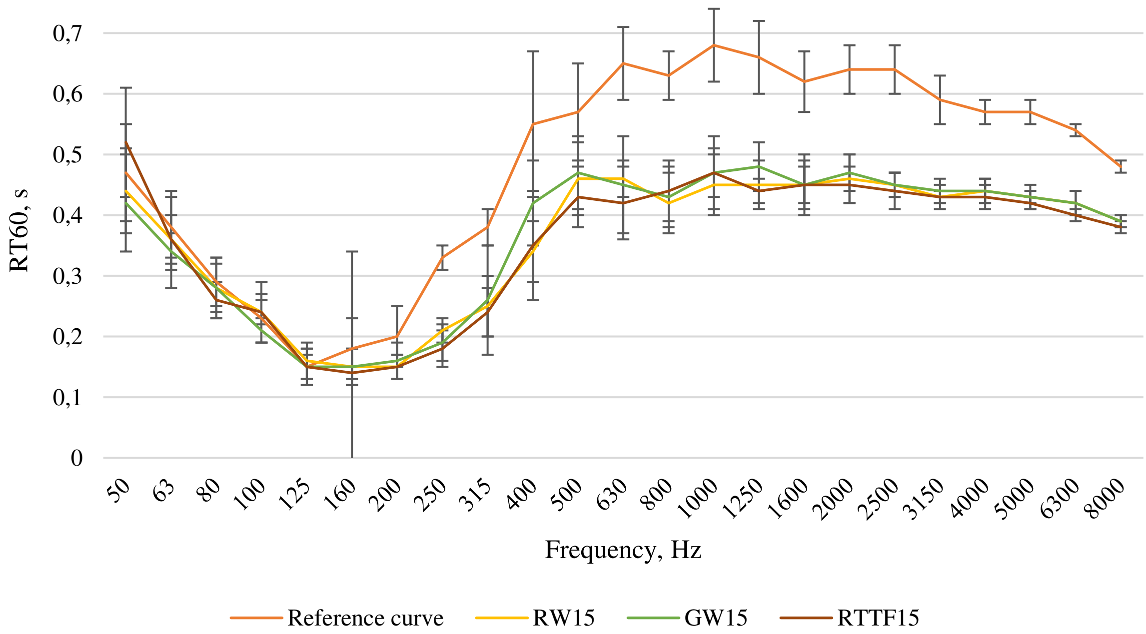


Fig. 3.8 Reverberation time reduction of 15 cm thickness by different materials
(Created by the author, 2020)

At constant frequency of 400 Hz, RW15 result is 0.20 seconds. In the medium frequency range from 500 to 1000 Hz, we can as well determine that RTTF15 efficiency on RT reduction is visible, in average RTTF15 reduces reverberation 0.19 seconds. At constant frequency of 630 Hz RTTF15 reduction of RT is 0.23 seconds. At high frequency range from 1000 till 8000 Hz, the same situation is observed that RTTF15 shows better performance on RT reduction, with an average reduction of 0.17 seconds, while RW15 and GW15 reduces RT in average 0.15 seconds. In conclusion, at thickness of 15 cm sample, we see that RTTF can reduce RT no worse than other materials.

By calculating difference between reference curve and each measurement, in the Figure 3.9 we can see that RTTF15 has a potential in reduction of RT. In this case it was exceptional and showed greater performance than conventional materials. According to the figures' trendlines we can definitely see that RTTF15 has greater potentiality at this thickness.

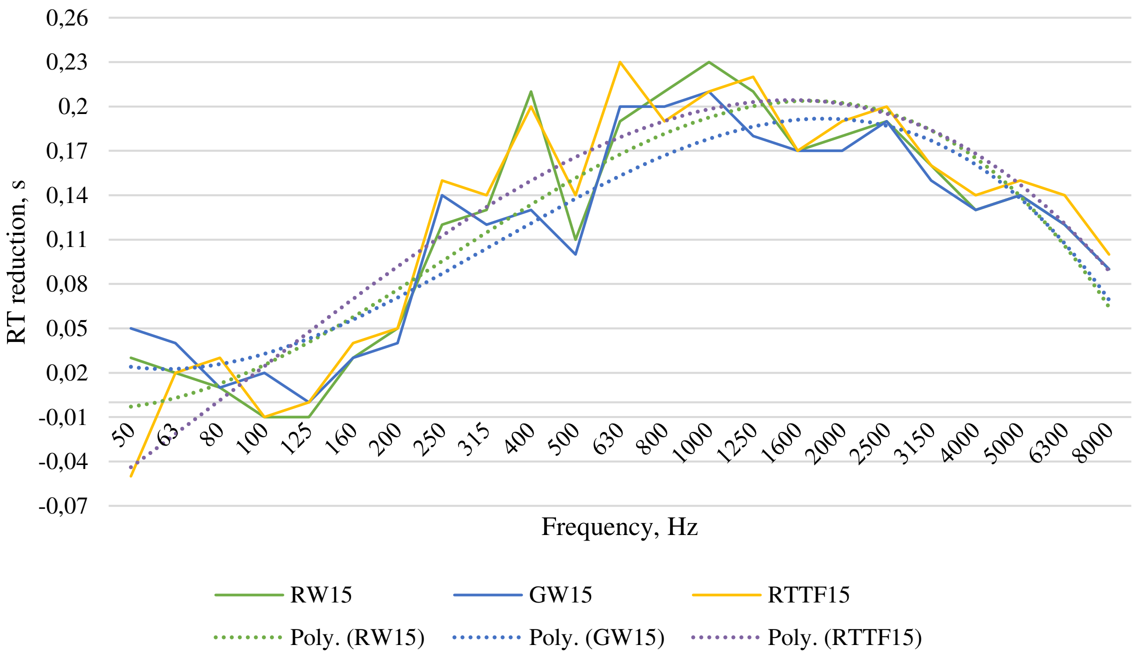


Fig. 3.9 Reverberation time reduction regarding materials 15 cm thickness
(Created by the author, 2020)

To conclude the whole RT experiment, we can see that RTTF has great potentiality to be used in Reverberation time reduction. It has very similar or even, in some cases, better performance than conventional materials. This is confirms hypothesis that RTTF has good Reverberation time reduction properties and could be used as the substitute to conventional RT reduction materials.

3.2. Materials sound absorption measurements results

For sound absorption measurements 3 different materials were taken. In Chapter 2 materials were named: two conventional materials – rock wool and glass wool, however one unconventional – recycled tyre textile fibre was subdivided into three mechanically treated samples: shredded, raw, and purified RTTF.

All samples were measured individually. Results of materials sound absorption, measured by impedance tube, are presented below.

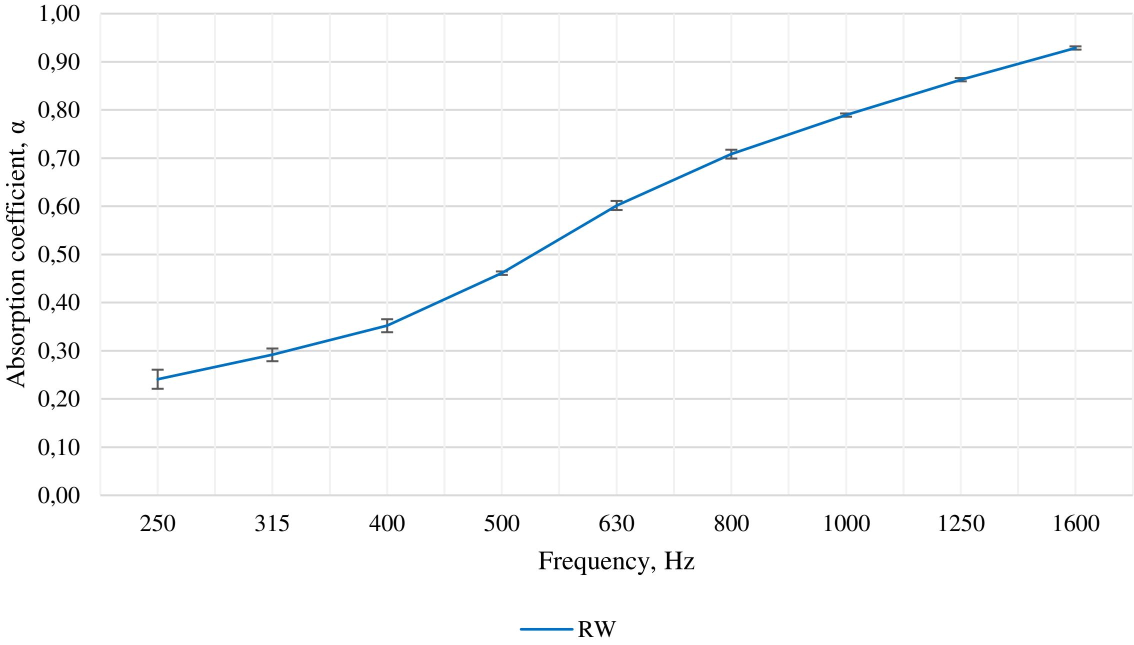


Fig. 3.10 RW sound absorption results (Created by the author, 2020)

We see the tendency, that at lower frequencies sound absorption is very low, since the fact, materials ability to absorb sound wave depends on the frequency and sound absorbing materials thickness. At very low frequency, in our case 250 Hz, the sound wavelength is 1.38 meters, and comparing to 1600 Hz, where sound wavelength is 0.22 meters, this means that to obtain ideal situation, of an absorption coefficient being, for instance, $\alpha = 1.0$ at the 250 Hz frequency, materials thickness should be at least 0.17 meters thick. As the sound absorption law says, sound absorbing material is effective, when materials thickness is 1/4 of wavelength at the selected frequency.

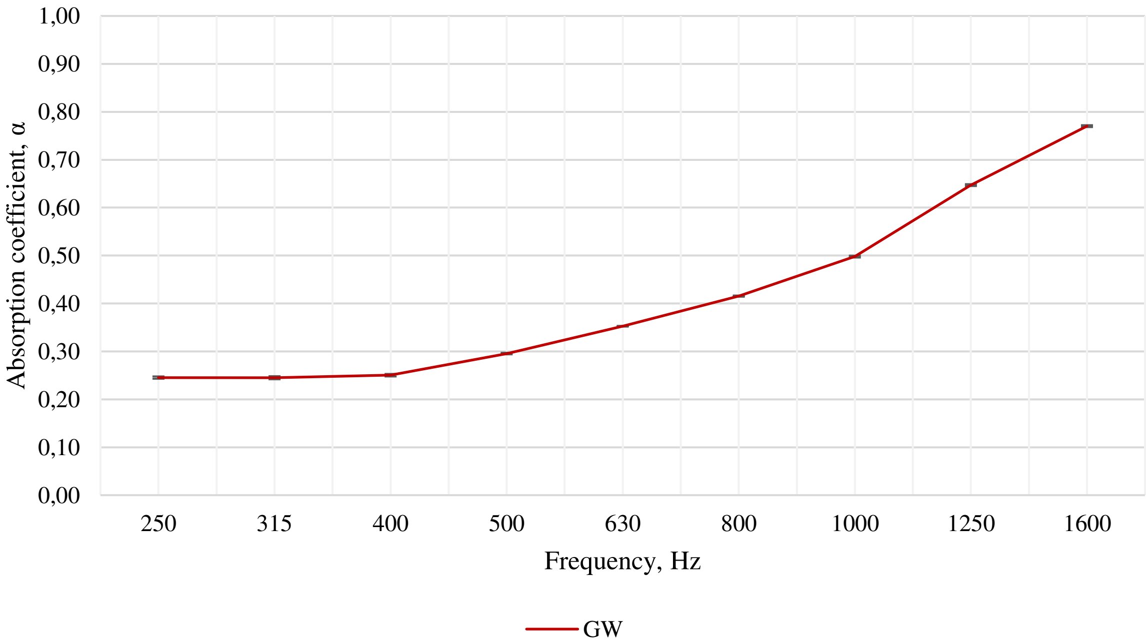


Fig. 3.11 GW sound absorption results (Created by the author, 2020)

Figure 3.11 represents results of glass wool sound absorption measurements. From the figure we can see that lowest result was obtained at low frequency of 250 Hz and sound absorption is 0.25. The same tendency can be seen till 400 Hz frequency. The best sound absorption result was obtained at 1600 Hz, i. e. sound absorption coefficient is 0.77.

Assessing Lithuanian legislation. sound absorption coefficient of 0.30 @ 500 Hz. and 0.50 @ 1000 Hz. The probability of reduction of propagation of sound at buildings, using glass wool may not be sufficient, due to low sound absorption coefficient.

Overall, the performance in sound absorption of glass wool is relatively low. Since, absorption coefficient at the highest peak of 0.77. Such phenomenon occurs due to absorption law, which depends on materials thickness, density, and porosity. In this case, density plays an important role, since glass wool density is very low, comparing to, for instance, rock wool. Average density of glass wool varies from 16.0 to 64.0 kg/m^3. For absorption density is extremely important, as higher the density is, the higher sound absorption. Mass increase of the material makes it harder for the sound wave to set in motion particles and convert mechanical wave into heat energy, due to friction between the particles.

Figure 3.12 represents comparison between two conventional sound absorbing materials. From the figure we can see a contrast difference between rock wool and glass wool. At the 250 Hz, low frequency band, sound absorption is quite similar, by only difference of 0.02. While as the frequency of the sound wave increases, the difference between two materials becomes clearly visible. The difference becomes visible from 315 Hz, and the biggest difference is observed at 800 Hz frequency, where rock wool absorption coefficient is 0.71 and rock wool's absorption coefficient is 0.42 which makes difference of 0.29, as well as at 1000 Hz frequency.

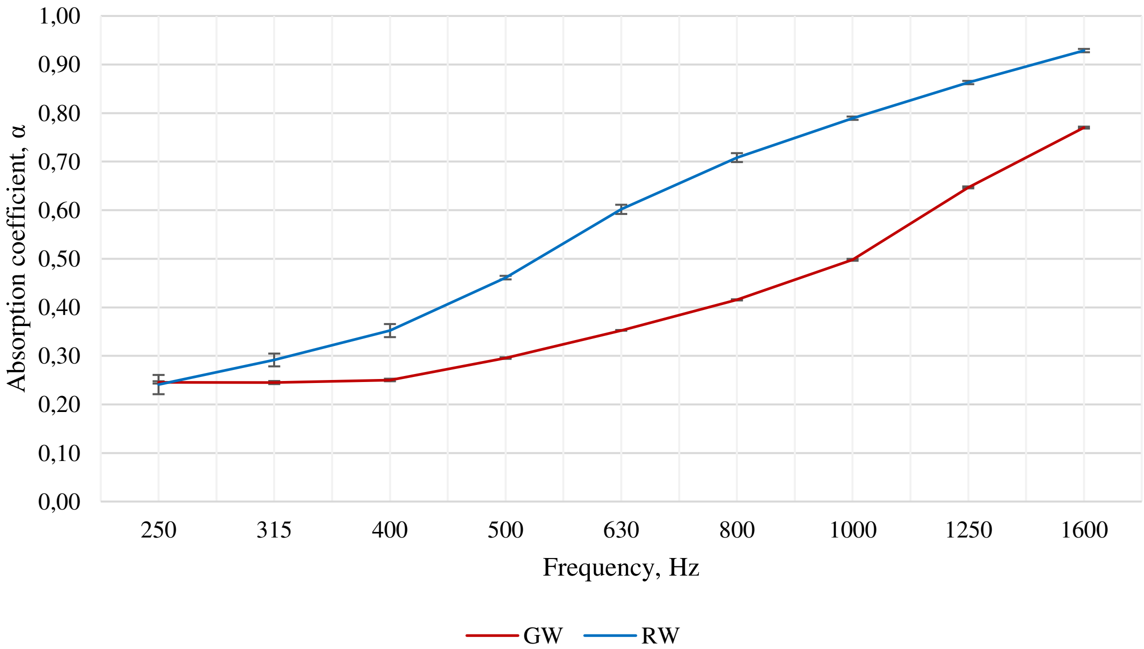


Fig. 3.12 Comparison of two conventional materials: rock wool vs. glass wool
(Created by the author, 2020)

Overall, the result we see can be explained by only phenomenon – density, which was mentioned in description of glass wool. On average, rock wool density is from 38.0 to 120.0 kg/m^3, and average density of glass wool is 16.0 to 84.0 kg/m^3, which makes quite big difference in between them. Porosity can be considered as well, since glass wool seems to be very loose, cannot hold its' shape steadily, while rock wool performs perfectly in holding its' shape. Stiff material may have a better porosity, comparing to loose one.

Figure 3.13 represents sound absorption ability of shredded recycled tyre textile fibre waste. According to the figure, the lowest result is obtained at 250 Hz frequency, with sound absorption coefficient of 0.28. Comparing to rock and glass wools, we can see steep raise of the sound absorption curve. At 500 Hz the sound absorption is 0.57, while at higher frequency of 1600 Hz 0.95 sound absorption coefficient is observed. As wavelength decreases (frequency increases), the sound absorption coefficient increases.

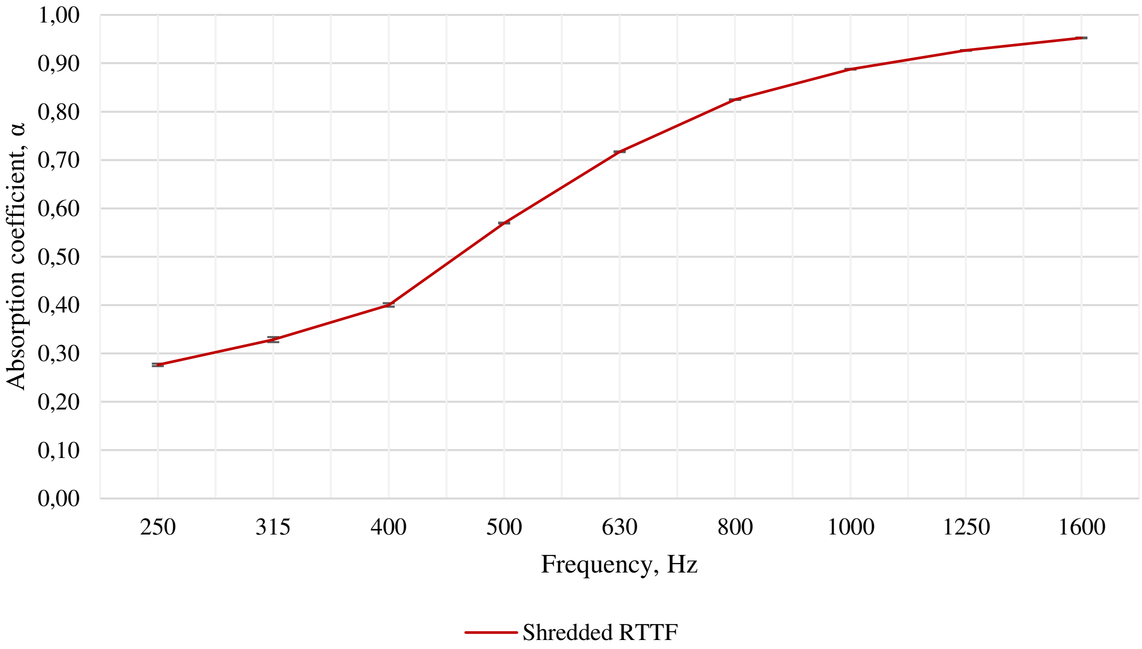


Fig. 3.13 Shredded recycled tyre textile fibre sound absorption results
(Created by the author, 2020)

Since the investigated material is dense, porous material, the results quite promising. Regarding to the Lithuanian legislation for buildings acoustics, sound absorption coefficient at 500 Hz is 0.57 and at 1000 Hz is 0.89. The result seems to be good enough for absorption of noise in the buildings and may be used for acoustics purposes.

For this measurement was taken shredded raw material (not purified from rubber particles remains), one of the three samples that were used for Thermal conductivity experiment. Rubber remains make up to 10% of total amount of the Tyre textile fibre waste.

Figure 3.14 represents sound absorption results of raw recycled tyre textile fibre waste (the primary material received from recycling factory).

As we can see from the figure, lowest sound absorption result was gained at 250 Hz, with α coefficient of 0.28. We can the same tendency as in shredded RTTF sound absorption measurements that the sound absorption coefficients raise quite steep. At 500 Hz sound absorption coefficient is 0.62, which a bit better than in shredded sample. The highest result was gained at 1600 Hz frequency with the result of sound absorption of 0.92.

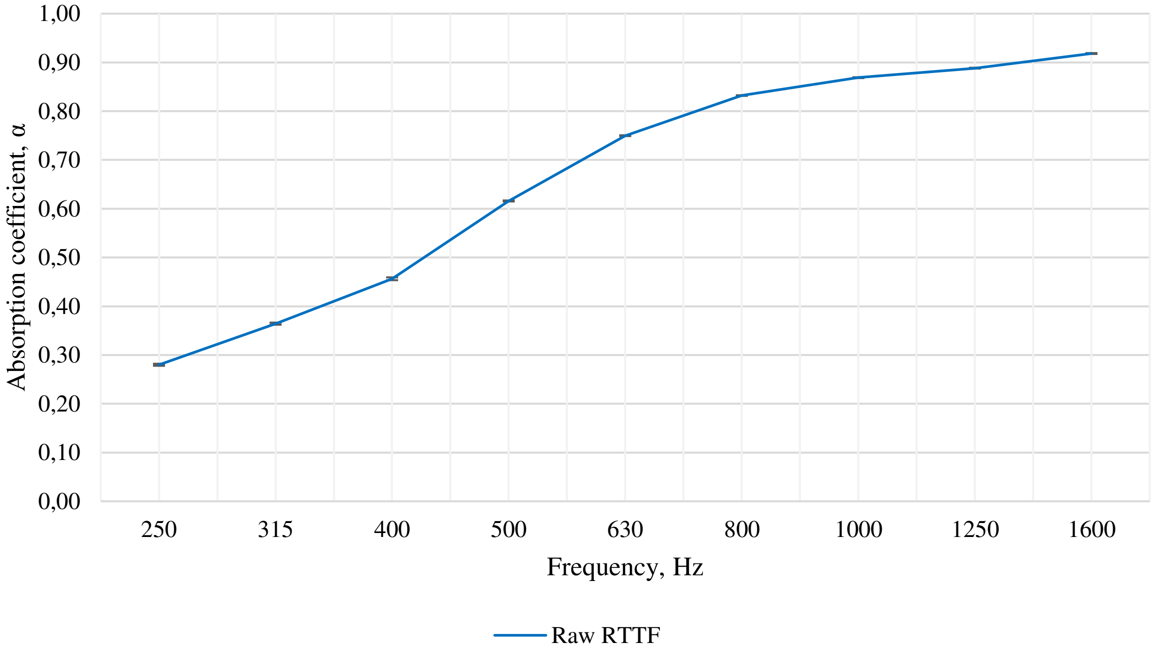


Fig. 3.14 Raw recycled tyre textile fibre sound absorption results (Created by the author, 2020)

Considered Lithuanian legislation, our sphere of interest are 500 Hz and 1000 Hz frequency bands. At 500 Hz, as it was mentioned, sound absorption coefficient is 0.62, while at 1000 Hz result is 0.87. Comparing to the previous sample, shredded RTTF, we can notice not a big difference between them.

The question arises if there is any sense to process RTTF in any other forms, by means of shredding into smaller particles or to keep the RTTF in its' primary condition. Regarding those two measurements we see similarities, Table 3.1 presents comparison of two closely similar samples.

Table 3.1 Comparison of shredded RTTF and raw RTTF (Created by the author, 2020)

	Frequency, Hz								
α coefficient	250	315	400	500	630	800	1000	1250	1600
Shredded RTTF	0.28	0.33	0.40	0.57	0.72	0.82	0.89	0.93	0.95
Raw RTTF	0.28	0.36	0.46	0.62	0.75	0.83	0.87	0.89	0.92
Difference between two samples	0.0	0.03	0.06	0.05	0.03	0.01	0.02	0.04	0.03

As we can see from the table maximum difference in sound absorption is visible at 400 Hz frequency band, although as sound wave frequency increases the difference decreases. Although, there is a difference between two options, but they will not drastically influence on sound insulation.

Figure 3.15 represents results of sound absorption measurements of purified recycled tyre textile fibre waste. Purified sample is described as the sample, which was separated from rubber particles remain. Tyre textile fibre waste purified and particles were removed. As we can see from the figure, purified RTTF as well as, shredded and raw RTTF at low frequency band performs the same way, at 250 Hz sound absorption coefficient is 0.28. The raise of sound absorption is not steep and rotated S-like increase shape. However, sound absorption at high frequency, i. e. at 1600 Hz, sound absorption coefficient is 0.97, very close to the ideal 1.0.

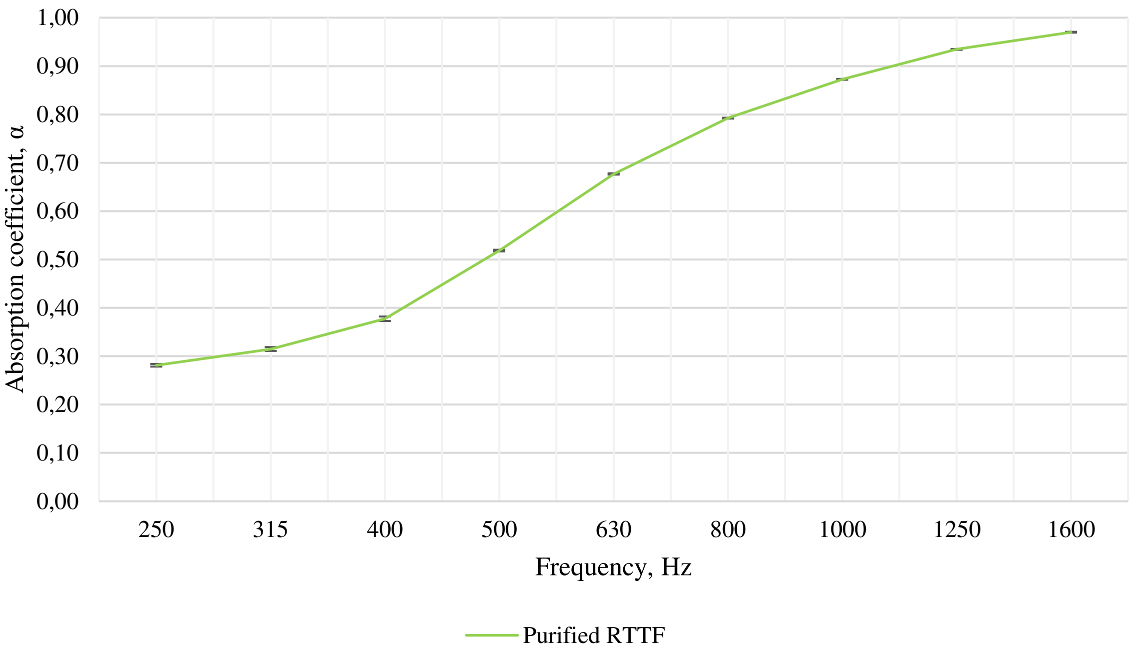


Fig. 3.15 Purified recycled tyre textile fibre sound absorption results
(Created by the author, 2020)

Regarding the Lithuanian legislation on buildings acoustics, at regulated frequency of 500 Hz, sound absorption is 0.52, while at 1000 Hz the absorption is 0.87. At 500 Hz absorption is quite low, however at 1000 Hz it is the same as at the raw RTTF sample.

Figure 3.16 represents comparison of all three, different recycled tyre textile fibre waste samples. According to the graph, we can see that at low frequency range of 250 Hz all samples behave the same way and sound absorption coefficient is equal to 0.28. By increase of frequency band, raw recycled tyre textile fibre performance on sound absorption is better, comparing to shredded and purified RTTF. At higher frequency range of 1000 Hz purified RTTF moves forward and its absorption comparing to shredded and raw RTTF is leading.

Previously, shredded, and raw RTTF were compared, and low difference in sound absorption was identified. Now by comparing all three samples, we can see that from 250 Hz to approximately 1000 Hz, raw recycled tyre textile fibre waste has better absorption properties. Better performance can be explained by that the raw RTTF was more packed and compressed, which made it denser and more porous. While preparing other samples, they were shredded, purified – mechanically treated. It means material became more separated into small ‘cotton balls’, while raw RTTF stayed in big chunks.

If we will look at frequency bands from approximately 1000 Hz till 1600 Hz, better performance identified in purified sample of RTTF, however in overall at this frequency range all samples perform very similarly.

As the conclusion, we can see that there is no big difference, whether the samples is somehow treated or left in its’ primary way. By implementation of Circular Economy Principles, in order to save energy, raw RTTF can be used, which does not requires any additional energy for treatment.

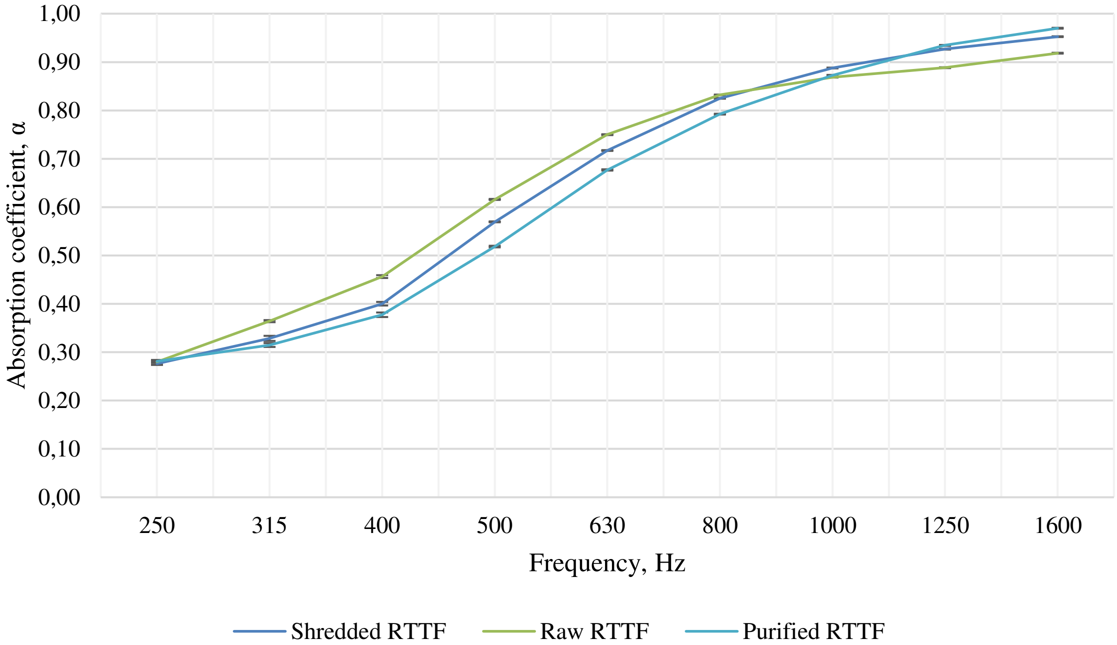


Fig. 3.16 Comparison of non-conventional materials options: shredded RTTF vs. raw RTTF vs. purified RTTF (Created by the author, 2020)

Lastly, Figure 3.17 represents comparison of all measured samples. According to the figure most efficient performance of all samples can be identified. As we can see, conventional material – rock wool and glass wool – performance on sound absorption is lower than recycled tyre textile fibre waste.

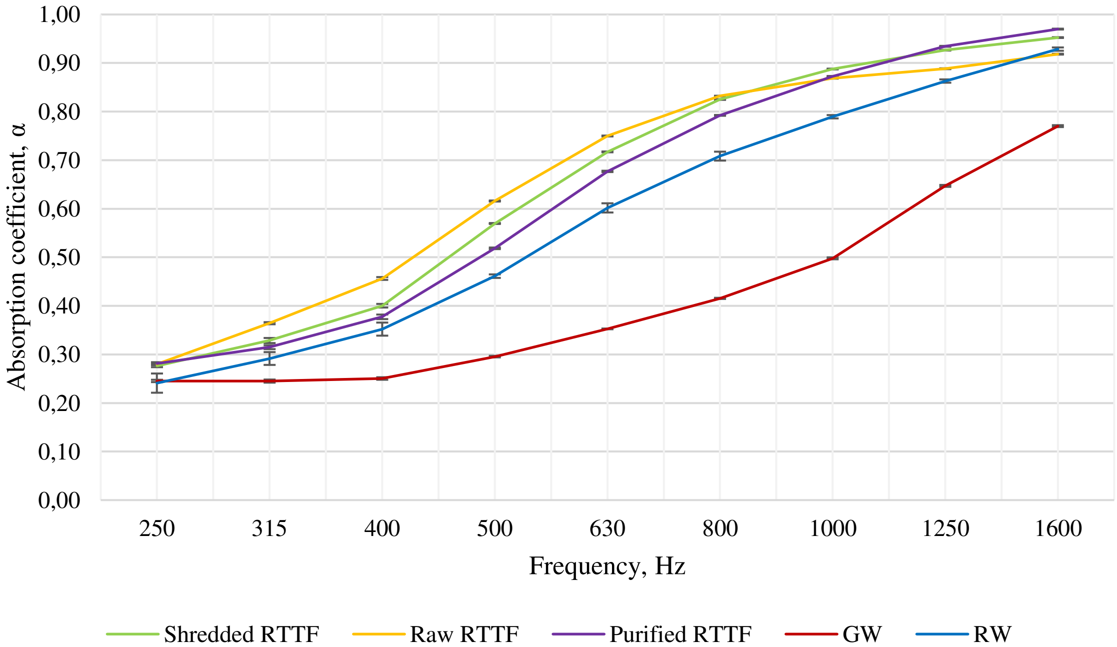


Fig. 3.17 Comparison of all measured samples (Created by the author, 2020)

If we would compare any of RTTF options to GW, we will see that alternative materials performance is better. For instance, comparing results by Lithuanian legislation, at 500 Hz frequency band GW absorption coefficient is 0.30, while raw RTTF sound absorption at this frequency is 0.62, which is twice better performance on sound absorption. Comparing 1000 Hz results: GW performance on sound absorption is 0.50 and raw RTTF is 0.87. Previously it was mentioned on what depends the performance, and this is can applied to this situation. Glass wool as a material is very light, not extremely dense, while RTTF has weight and its' fibres are interlaced, this is makes performance of RTTF better.

To conclude sound absorption measurements by impedance tube results, we can see, that non-conventional material RTTF has an advantage in sound insulation comparing to rock and glass wools. At low, initial frequency of 250 Hz, all of the sample's performance is low, however by increasing frequency of the sound wave, sound absorption increases, and some have bigger advantage. Overall, recycled tyre textile fibre waste can be considered as a possible alternative to be used in buildings acoustics for sound insulation.

3.3. Thermal conductivity measurements results

All samples were measured individually, and results are presented below. First sample which was estimated is shredded RTTF, results are presented in Table 3.2 and Fig. 3.18.

Table 3.2 Shredded RTTF thermal conductivity measurements results
(Created by the author, 2020)

Material type	Thickness of measurement, mm	Density of the sample, kg/m^3	Thermal conductivity coefficient λ, W/m*K
Shredded RTTF	90	99.4	0.04545
	80	111.8	0.04440
	70	127.8	0.04394
	60	149.0	0.04440

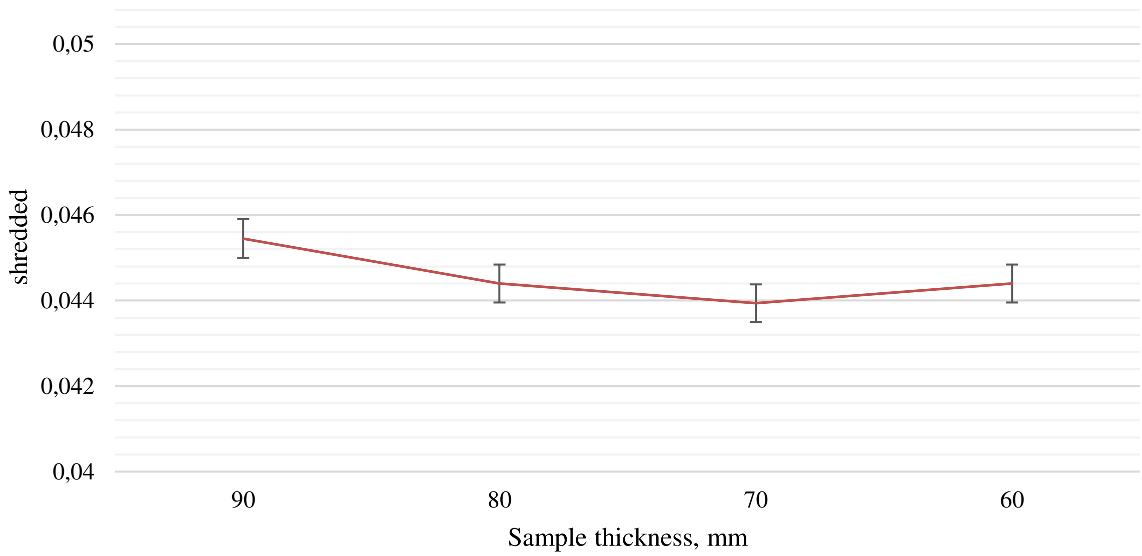


Fig. 3.18 Thermal conductivity change on the compression ratio of shredded RTTF
(Created by the author, 2020)

After measuring thermal conductivity at different thicknesses, the λ thermal conductivity coefficient was estimated. It was found out that as lowering the thickness of the sample, the thermal conductivity coefficient is increasing. At this experiment, of measurement of shredded RTTF (the rubber particles were not removed), at thickness of

70 mm. the best result was obtained of 0.04394 W/m*K (density 127.8 kg/m^3) (Fig. 3.18). Results at 60 mm thickness were lower than at 70 mm, due to phenomenon described in Chapter 1, that by increasing density, particles become more compact and heat can be conducted through the media and had low air permeability.

The second sample was estimated, Raw RTTF thermal conductivity coefficient was measured, and results are presented in Table 3.3 and Fig. 3.19.

Table 3.3 Raw RTTF thermal conductivity measurements results (Created by the author, 2020)

Material type	Thickness of measurement, mm	Density of the sample, kg/m^3	Thermal conductivity coefficient λ, W/m*K
Raw RTTF	90	114.0	0.04855
	80	128.3	0.04747
	70	146.6	0.04667
	60	171.1	0.04950

Thermal conductivity of the second sample at different thicknesses was estimated. Measuring the second sample the best result was estimated at thickness of 70 mm, which is 0.04667 W/m*K (density 146.6 kg/m^3) (Fig. 3.19). For this measurement thermal conductivity of raw material (primary material received from the recycling factory) was estimated. As well, as with the first sample, we see that at thickness of 60 mm result is dropping. The same phenomenon occurs as in the shredded RTTF measurements: due to increased density and low air permeability.

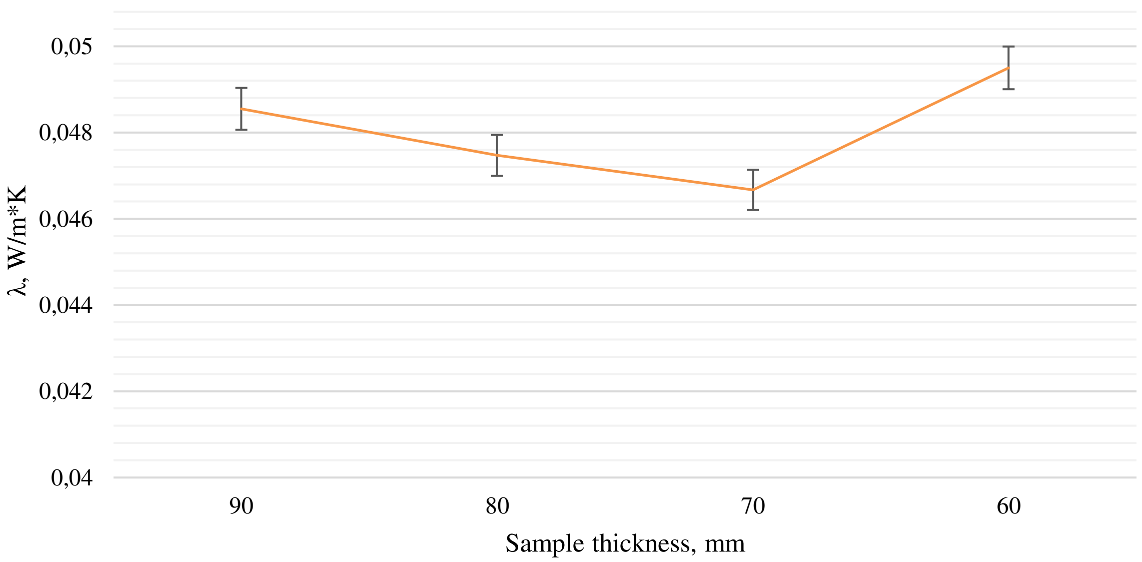


Fig. 3.19 Thermal conductivity change on the compression ratio of raw RTTF (Created by the author, 2020)

The third and the last sample was estimated. Purified RTTF thermal conductivity coefficient was measured, and results are presented in Table 3.4 and Fig. 3.20.

Table 3.4 Purified RTTF thermal conductivity measurements results (Created by the author, 2020)

Material type	Thickness of measurement, mm	Density of the sample, kg/m^3	Thermal conductivity coefficient λ, W/m*K
	90	96.1	0.04338

Material type	Thickness of measurement, mm	Density of the sample, kg/m^3	Thermal conductivity coefficient λ, W/m*K
Purified RTTF	80	108.2	0.04429
	70	123.6	0.04699
	60	144.2	0.04505

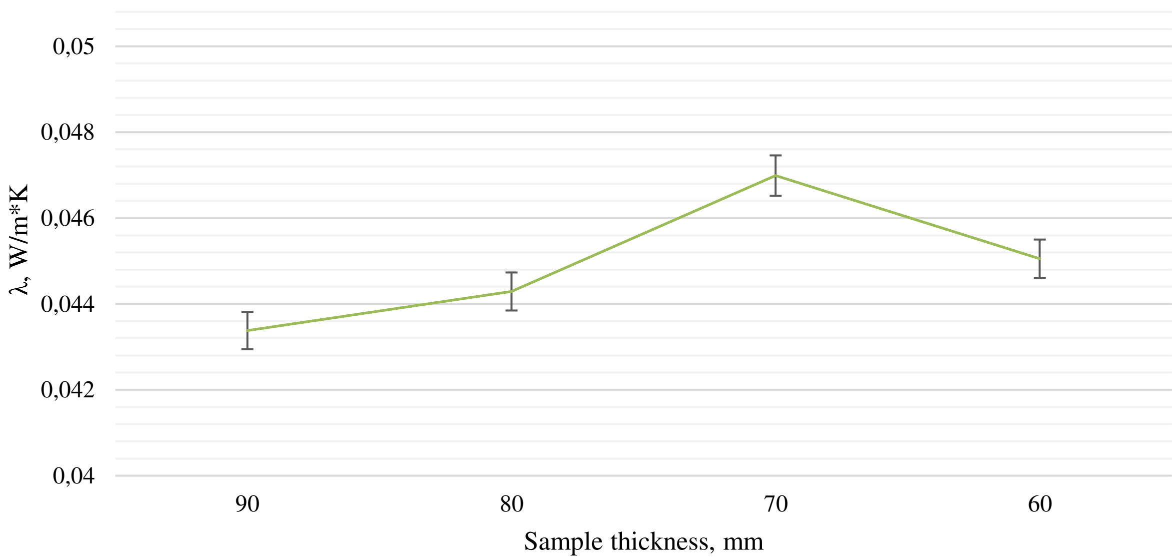


Fig. 3.20 Thermal conductivity change on the compression ratio of purified RTTF (Created by the author, 2020)

Thermal conductivity of the third type of RTTF was estimated by the measurements. As we can see, the third sample – purified RTTF – shows us a different behavior of thermal conductivity. While in previous samples, by lowering the thickness of the sample, the thermal conductivity coefficient λ was increasing, in this case not. The best result was obtained at the thickness of 90 mm, which is 0.04338 W/m*K (density 96.1 kg/m^3) (Fig. 3.20).

The RTTF used for this measurement were separated from rubber particles. The reason of such low results may be that when sample has been prepared (separation from rubber particles remain) single ‘RTTF cotton balls’ were compacted and density was high and air permeability low and while pressing the sample down during the measurements those parameters became even worse.

By comparing all RTTF forms, we can see that the best performance of the RTTF was determined in form of – shredded type (Fig. 3.21; Table 3.5).

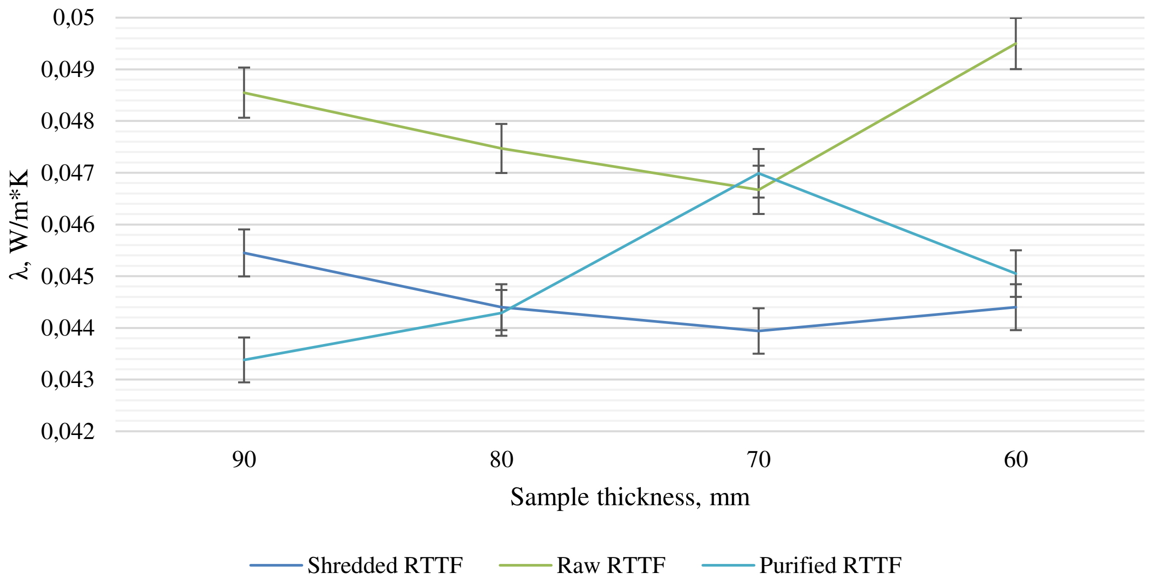


Fig. 3.21 Thermal conductivity comparison of different RTTF forms (Created by the author, 2020)

Although, comparing different thicknesses performance, we can definitely see that at 90 mm thickness the best result obtained of purified RTTF, the result was 0.04338 W/m*K. At 80 mm thickness, the result was similar at 2 different samples – shredded and purified one. The results were 0.04440 W/m*K and 0.04429 W/m*K, respectively. At thickness of 70 mm, the thermal conductivity coefficient result was 0.04394 W/m*K in shredded RTTF form. And lastly, at 60 mm thickness, the best result was obtained in shredded material – 0.04440 W/m*K.

The overall conclusion would be that shredded RTTF showed best performance in thermal conductivity, whereas we see from the figure that the curve points in most measurement cases were lower or close to the others.

Table 3.5 Comparison of thicknesses dependency on thermal conductivity coefficient (Created by the author, 2020)

	Thickness, mm			
	90	80	70	60
Sample form	λ thermal conductivity coefficient, W/m*K			
Shredded RTTF	0.04545	0.04440	0.04394	0.04440
Raw RTTF	0.04855	0.04747	0.04667	0.04950
Purified RTTF	0.04338	0.04429	0.04699	0.04505

We have compared in previous figure thermal conductivity of different forms of RTTF. In this figure, the conventional materials, such as rock and glass wools, will be compared to the RTTF (Fig. 3.22).

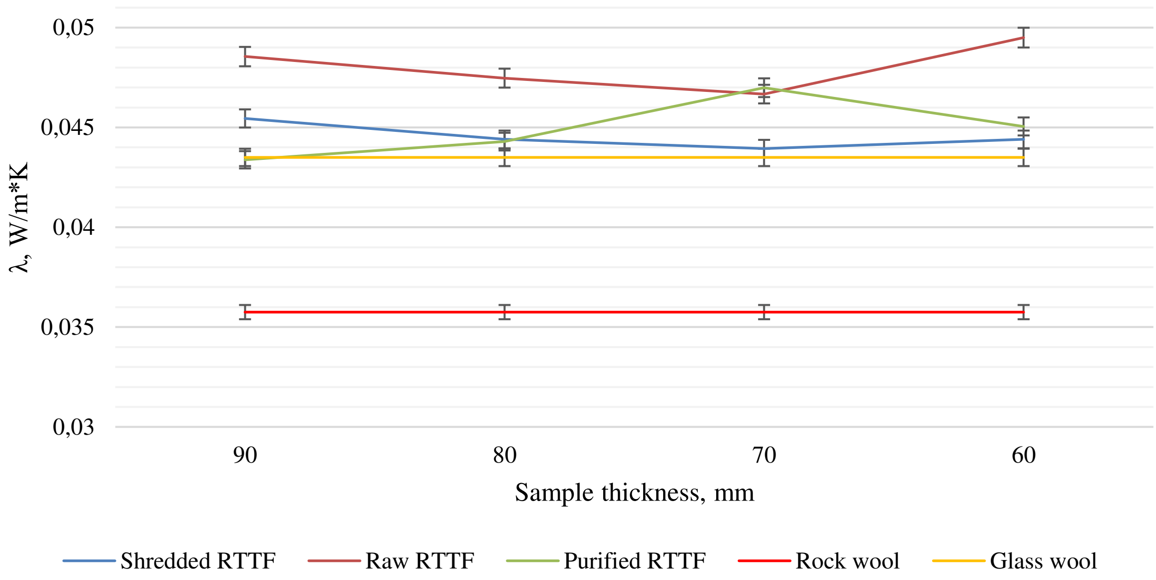


Fig. 3.22 Thermal conductivity comparison to conventional materials
(Created by the author, 2020)

As we can see, rock wool (red line) has much better performance in thermal conductivity, which coefficient in average is 0.03575 W/m*K or less. This result has bigger advantage comparing to RTTF, but meanwhile, comparing glass wool, thermal conductivity coefficient is 0.04350 W/m*K in average. The glass wool thermal conductivity coefficient is relatively close to the shredded RTTF form. The conclusion is that RTTF can be a substitute, as a cheaper form with promising performance material, in Thermal conductivity.

The third chapter conclusions

1. Reverberation time measurements were done using three materials: RW, GW and RTTF. For each materials' type there were three different thicknesses of the material used – 5, 10 and 15 cm. The reference measurement was done in order to be able compare reduction of RT. At measurements of RW, it was obtained that no particular difference on RT, regarding materials thickness. On average RT was reduced 0.20 seconds. During GW Reverberation time measurements, as in previous sample, no particular difference was obtained, however thicker sample is more efficient. Lastly RTTF was measured, and on average reduction of RT was 0.21 seconds. The best performance was obtained at sample RTTF15. Same thickness, but different samples were compared in between. Starting from 5 cm thickness it was obtained that or it is RW5, or GW5, or even RTTF5 they behave very similar and an average reduction of RT was 0.14 seconds. Comparing 10 cm, average reduction of samples was 0.15 seconds, but materials behave very similar, as in 5 cm measurements. Lastly, 15 cm samples were measured, and it was estimated that RTTF15 sample had 0.17 seconds of reduction of RT, while RW15 and GW15 on average reduced RT about 0.15 seconds. Concluding, materials reduction of RT is very similar, however thicker sample is superior.
2. Sound absorption was measured for two conventional materials – RW and GW, and one unconventional which had three options – shredded, raw, and purified RTTF. It was estimated that RW sound absorption at 250 Hz is 0.24, while at 1600 Hz is 0.93. Secondly, GW sound absorption coefficient at 250 Hz was 0.25, and at 1600 Hz was only 0.77. By comparing those two, we see that RW performance on sound absorption is better than GW. The reason of that is insufficient density of the GW. Sound absorption was measured for shredded RTTF, the results were that minimum sound absorption gained at low frequency of 250 Hz, and coefficient is 0.28, while at 1600 Hz the absorption was 0.95. Raw RTTF was examined, at 250 Hz sound absorption was 0.28 and at 1600 Hz was 0.92. Lastly, purified RTTF was measured. At 250 Hz frequency 0.28 sound absorption coefficient was gained and at 1600 Hz the results was 0.92. By comparing unconventional material options, we can see that they perform very similarly, since they are dense and porous samples. The question is, is it necessary to put more investment into purification of RTTF? The answer is – probably not since they do behave on similar way. All measured samples were compared, in order to find out which one is the most efficient in sound absorption. Since, GW showed the worst results, we can say that this is not the most suitable choice, while RW had an intermediate result. RTTF in sound absorption measurements case showed quite satisfying results and may be considered as the best and possible alternative option for sound absorption in buildings acoustics.
3. Thermal conductivity measurements were done for recycled tyre textile fibre. Three mechanically treated options – shredded, raw, and purified RTTF, were examined. It was found out that at 70 mm (optimum thickness) shredded RTTF has the best thermal conductivity result – 0.04394 W/m*K. Second sample examined was raw RTTF and it was found out that, as well, at 70 mm, optimum thickness, the best results of thermal conductivity was obtained, with a result of 0.04667 W/m*K. In both cases, worst result was at 90 mm thickness. Lastly, the third sample was examined – purified RTTF. In this case, the opposite, 90 mm thickness showed the best result 0.04338 W/m*K, while 70 mm thickness was the worst. Since, thermal insulation depends on many factors, in this measurements case, density and air permeability played an important role. Overly dense material becomes very good thermal conductor and transfer heat faster, while air permeability is decreased due to increased density. Out of all three samples, it was

estimated that at 90 mm thickness better performance of the thermal conductivity is at purified RTTF, but if considering space saving, 70 mm shredded RTTF showed better performance. By comparing to conventional material, RTTF had similarities to glass wool thermal conductivity.

4. MODELLING

Materials flow resistivity is the parameter which is used for the determination of materials sound absorption coefficient. By knowing materials air flow resistivity, it is possible to determine by theoretical calculation air flow resistance and sound absorption coefficient. For the measurements of flow resistivity, test stand was designed and checked (Fig. 4.1). The test stand consist of the tube, through which air flows close the laminar one and the air compressor with rotameter.

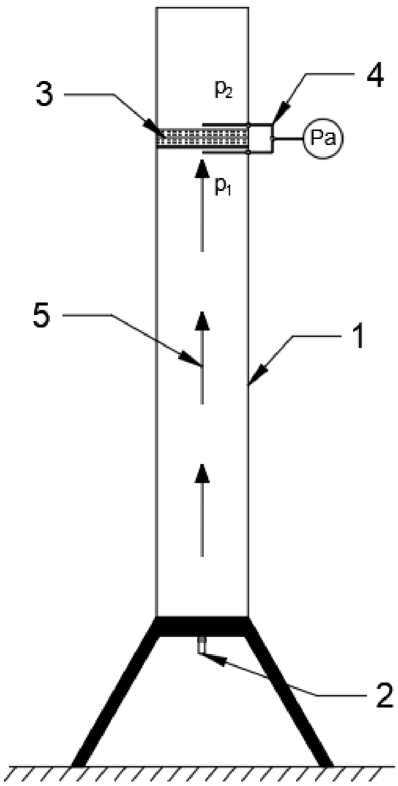


Fig. 4.1 Test stand for air flow resistivity principle scheme: 1 – air flow resistivity tube shell, 2 – inlet for air compressor, 3 – sample in the sample holder, 4 – differential pressure gauge, 5 – air flow movement direction (Created by the author, 2020)

To determine air flow resistivity, the direct method is used. This method is based on the difference in air pressure created by directional air movement between two exposed surfaces of a material. The length of the tube must be long enough to ensure a directional air flow close to laminar, approximately from 160–200 Re. The sample holder consists of 50% cross-sectional area of evenly spaced open holes with a diameter of 10 mm. An air compressor is used to generate the pressure, and a differential pressure gauge Retrotec DM32 (accuracy of 0.1 Pa). The air flow-rate is measured with an air flow meter Testo 452. The method is based on the ISO 9053 standard.

In order to determine flow resistivity, firstly, air pressure difference ΔP and air flow velocity v are determined:

$$\Delta p = p_1 - p_2 \tag{4.1}$$

where

p_1 – pressure before the sample, Pa;

p_2 – pressure after the sample, Pa (ISO, 2018).

After, air flow resistance R is calculated:

$$R = \frac{\Delta p}{q \cdot v} \tag{4.2}$$

where

q – the air flow rate through the sample, m^3/s (ISO, 2018).

Specific air flow resistance R_s is determined, which describes the air flow resistivity through the samples area:

$$R_s = R \cdot A \tag{4.3}$$

where

A – samples cross-section area, m^2 (ISO, 2018).

Finally, static air flow resistance σ of the material is calculated:

$$\sigma = \frac{R_S}{d} \tag{4.4}$$

where

d – thickness of the sample, m (ISO, 2018).

Delany-Bazley model is based on the knowing the static air resistance of the material, there is a possibility to determine acoustic resistance and sound absorption coefficient:

$$Z_2 = \mathrm{c}\rho\left[1 + 9.08\left(10^3\frac{f}{\sigma}\right)^{-0.75} - j11.9\left(10^3\frac{f}{\sigma}\right)^{-0.73}\right] \tag{4.5}$$

where

Z_2 – characteristic acoustical resistance of porous material, Pa/m^3;

ρ – air density, kg/m^3;

c – sound velocity in air, m/s;

j – complex numbers operator;

f – frequency of the sound wave, Hz;

σ – static air resistance of the material, Pa/m^2 (Delany and Bazley, 1970).

$$k = \frac{\omega}{c_0}\left[1 + 10.8\left(10^3\frac{f}{\sigma}\right)^{-0.70} - j10.3\left(10^3\frac{f}{\sigma}\right)^{-0.59}\right] \tag{4.6}$$

where

k – complex number of the wave;

ω – angular frequency, rad/s.

According to the Champoux-Allard model. the effective density is calculated by the formula:

$$\rho_e = k_s\rho_0\left[1 + \frac{\sigma\varepsilon}{j\omega k_s\rho_0}\sqrt{1 + \frac{4kk_s^2\eta\rho_0\omega}{\sigma^2\Lambda^2\varepsilon^2}}\right] \tag{4.7}$$

where

ρ_e – effective density, kg/m^3;

k_s – tortuosity;

η – viscosity;

Λ – characteristic particle length (Panneton and Olny, 2006).

The dynamic modulus of air elasticity is calculated by the same model:

$$K_e = \frac{\gamma P_0}{\gamma-(\gamma-1)/\left(1+\frac{8\eta}{j\Lambda^2 N_p \omega\rho}\sqrt{1+\frac{j\rho\omega N_p \Lambda^2}{16\eta}}\right)} \tag{4.8}$$

where

γ – the ratio of specific heat capacities;

P_0 – atmospheric pressure, Pa;

N_P – correction factor (0.77) (Panneton and Olny, 2006).

A simplified expression of the characteristic acoustic resistance of a material can be derived from these two models (Panneton and Olny, 2006):

$$Z_c = \sqrt{K_e \rho_e} \tag{4.9}$$

The relationship between the reflection coefficient and the acoustic resistance of the material is used to calculate the absorption coefficient of the material:

$$R = \frac{\frac{z_3}{\rho_0 c_0}\cos(f)-1}{\frac{z_3}{\rho_0 c_0}\cos(f)+1} \tag{4.10}$$

where

R – sound reflection coefficient (Doutres *et al.*, 2010).

The theoretical sound absorption coefficient is calculated according to the formula:

$$\alpha = 1 - |R|^2 \tag{4.11}$$

where

α – sound absorption coefficient (Panneton, 2017).

4.1. Sound absorption coefficient modelling results

The modelling of sound absorption is conducted using MATLAB software and special script written for the model. The initial data, which is used to calculate static air resistance, is presented in Table 4.1.

Table 4.1 Initial data for modelling (Created by the author, 2020)

Parameters	Raw RTTF	Shredded RTTF	Purified RTTF
ΔP, Pa	15.5	13.3	10.3
d, m		0.4	
v, m/s		0.01	
Static air resistance σ, $N.s.m^{-4}$	34292	25833	29351

For the modelling were chosen three mechanically treated RTTF samples – raw, shredded and purified, in order to check whether the theoretical research corresponds to the practical research, which can be used for the future research of unknown materials. Static air resistance was calculated in Excel using Formulas 4.1 to 4.4. For raw RTTF static air resistance is 34292 $N.s.m^{-4}$, for shredded RTTF is 25833 $N.s.m^{-4}$ and for purified RTTF is 29351 $N.s.m^{-4}$.

The Figure 4.2 presents the comparison of the measurements of materials sound absorption coefficient by impedance tube and the Delany-Bazley theoretical model of raw RTTF. The results of modelling shows that the difference of the real-time experiment and the theoretical model differs in the first sample approximately on 4.20%. As we can see from the figure, we obtained better results of sound absorption in real-time experiments up to 1000 Hz, however theoretical model shows that from 1000 Hz in theory it is better.

At 250 Hz, the sound absorption of real time was 0.28, while the theoretical sound absorption was 0.26. The maximum sound absorption obtained at 1600 Hz, in the real-time measurements was 0.92, and the theoretical model result was 0.93.

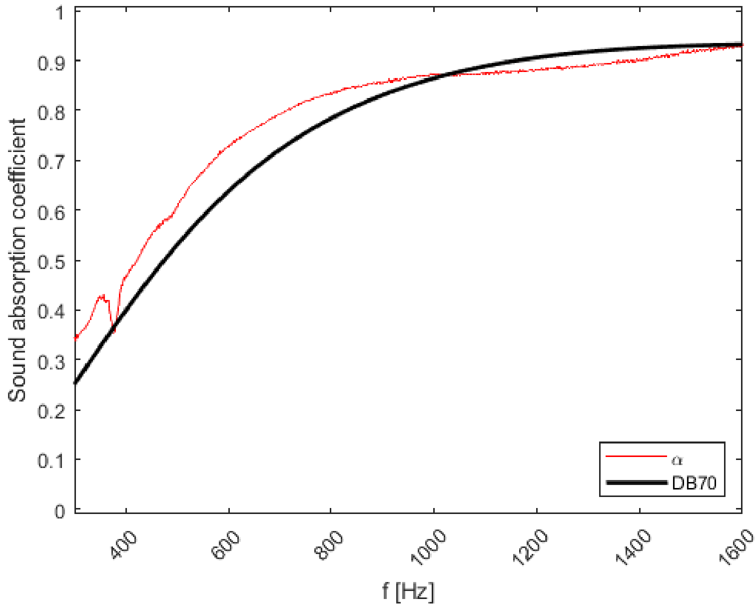


Fig. 4.2 Results of modelling of raw RTTF (Created by the author, 2020)

The Figure 4.3 presents the comparison of the measurements of materials sound absorption coefficient by impedance tube and the Delany-Bazley theoretical model of purified RTTF. The results of modelling shows that the difference of the real-time experiment and the theoretical model differs in the second sample approximately on 2.90%. According to the figure, the real-time and the theoretical model almost corresponds each other, which that the real-time experiment results are correct.

At 250 Hz, the sound absorption of real time was 0.28, while the theoretical sound absorption was 0.22. The maximum sound absorption obtained by the real-time measurements was 0.97, and the theoretical model result was 0.97 (at 1600 Hz frequency).

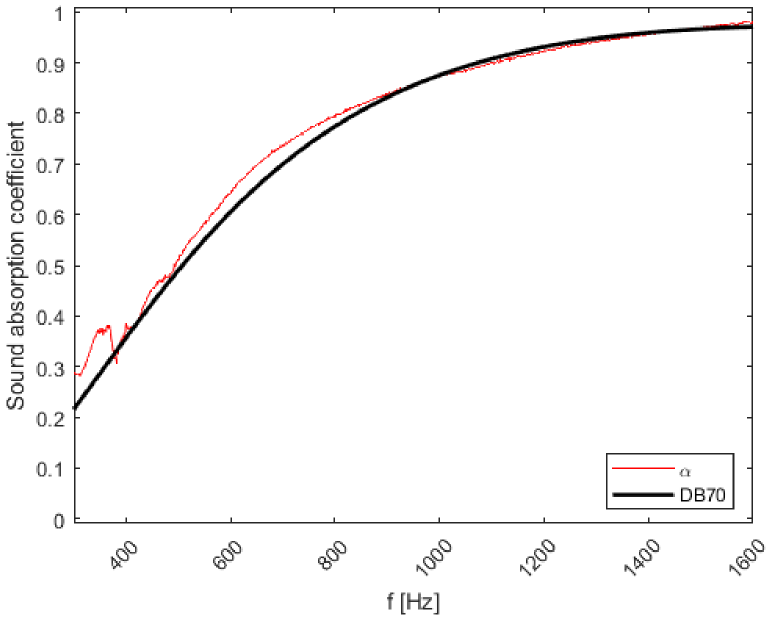


Fig. 4.3 Results of modelling of purified RTFF (Created by the author, 2020)

The Figure 4.4 presents the comparison of the measurements of materials sound absorption coefficient by impedance tube and the Delany-Bazley theoretical model of shredded RTTF. The results of modelling shows that the difference of the real-time experiment and the theoretical model differs in the first sample approximately on 4.20%. As we can see from the figure, we obtained better results of sound absorption in real-time experiments up to 1100 Hz, however from approximately from 1100 Hz real-time experiment and theoretical researches corresponds each other.

At 250 Hz, the sound absorption of real time was 0.28, while the theoretical sound absorption was 0.23. The maximum sound absorption obtained at 1600 Hz – the real-time measurements was 0.95, and the theoretical model result was 0.95.

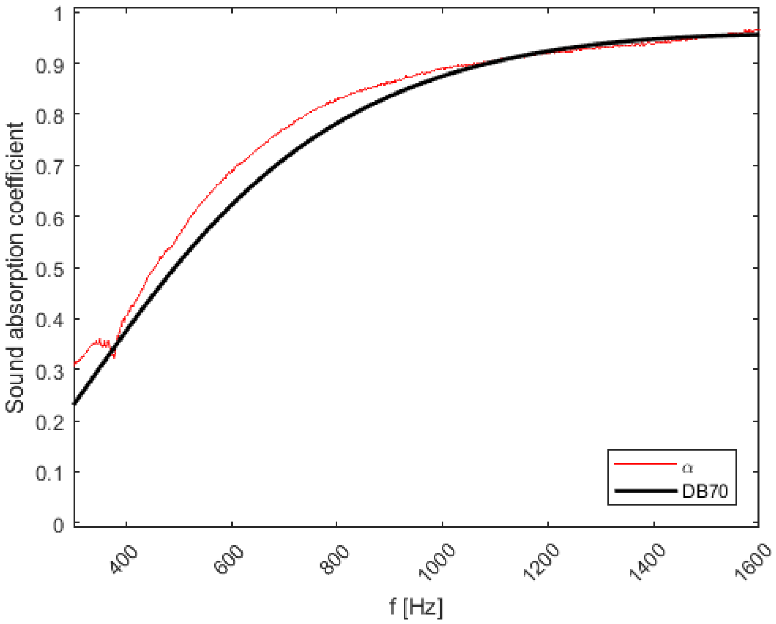


Fig. 4.4 Results of modelling of shredded RTTF (Created by the author, 2020)

To conclude, we can see that the real-time and theoretical experiments are correct, having small difference. The Delany-Bazley model is correct and it can be used for the future researches of sound absorption of the materials.

The fourth chapter conclusions

1. The modelling of sound absorption can be conducted using Delany-Bazley theoretical model. The sound absorption depends on the static air flow resistance, which can be found out by knowing the pressure difference, sample thickness, and the velocity of air in the test stand. Using designated formulas, static air resistance is calculated, and the data is inserted into MATLAB script, where all calculations are done, and graphical data is presented.
2. The results of the modelling showed that the theoretical model corresponds the real-time experimental measurements of the materials sound absorption coefficient. It was found out that deviations between theoretical and experimental model – raw RTTF it is 4.20%, for purified RTTF it is 2.90%, and for shredded RTTF it is 4.20%. Raw RTTF minimum results was obtained at 250 Hz, in real-time experiment 0.28, while in the theoretical model it was 0.26. The maximum values where 0.92 and 0.93, respectively. The purified RTTF results are – real-time measurements, minimum result is 0.28, theoretical is 0.22. Maximum, obtained at 1600 Hz, was 0.97 and 0.97, respectively. Lastly, the shredded RTTF was checked. It was found out that minimum sound absorption coefficient at 250 Hz was 0.28 in real-time experiment, while in the theoretical model it was 0.23. The maximum values were obtained at 1600 Hz, and they were 0.95 and 0.95, respectively.

CONCLUSIONS

1. 320 K tonnes of RTTF are generated each year by the discarded end-of-life tyres. The recycled tyre textile fibre waste can be used as a substitute for sound absorbing materials which is defined to be thick, dense, and porous. Since, most of the sound absorbing materials are used as thermal insulators (or vice versa), materials could be used for both purposes – reduction of sound mitigation and thermal insulation in buildings. An alternative use of RTTF was investigated by other authors, e. g. in production of polypropylene, asphalt, concrete and, the use for soil reinforcement, however not all applications were successful.
2. Reverberation time measurements results are compared for 5 cm thickness of different materials. It was noticed, that or RW5, or GW5, or even RTTF5 do behave similarly in Reverberation time reduction, on average RT was reduced by 0.14 seconds. Comparing 10 cm samples, on average reverberation time was reduced by 0.15 seconds, however distinct material was not obtained, the performance is quite similar. 15 cm samples were compared, in this case RTTF15 performance was better, and an average reduction of RT time was 0.17 seconds.
3. RW sound absorption at 250 Hz is 0,24, while at 1600 Hz is 0,93. GW sound absorption coefficient at 250 Hz was 0,25, and at 1600 Hz was 0,77. By comparing those two, we can see, that RW performance on sound absorption is greater than GW. Sound absorption was measured for RTTF, all samples had the same minimum results at 250 Hz frequency – 0.28. While at maximum available frequency of 1600 Hz, the results were – raw RTTF 0.92, shredded RTTF 0.95 and purified RTTF 0.97.
4. 70 mm shredded RTTF had the best thermal conductivity result – 0.04394 W/m*K. Raw RTTF, at 70 mm, the best results of thermal conductivity was obtained, with a result of 0.04667 W/m*K. Purified RTTF (90 mm thickness) showed the best result 0.04338 W/m*K. By comparing to conventional materials, it was noticed, that shredded RTTF has similar thermal conductivity as a glass wool.
5. The modelling results were obtained by modelling theoretical sound absorption coefficient. It was found out that the theoretical model deviation from real-time measurements has a low difference which confirms that model is correct. Raw RTTF deviation from real-time measurements was 4.2%, purified RTTF deviation was 2.9%, and lastly, shredded RTTF deviation – 4.2%.

RECOMMENDATIONS

1. According to the materials sound absorption coefficient measurements it was investigated that the recycled tyre textile fibre waste has a great opportunity to be used for sound absorption in buildings. Traditional materials as rock and glass wools can be definitely be substituted by the RTTF since the material showed promising results on the sound absorption.
2. According to the conducted thermal conductivity measurements it was estimated that RTTF has a closely related coefficient to the glass wool. RTTF can be used as a substitute for thermal insulation in buildings, instead of conventional materials. It is recommended to use 70 mm thickness of RTTF for thermal insulation.

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Ružickij R., Astrauskas T., Valtere S., Grubliauskas R. (2020) 'Sound absorption properties evaluation and analysis of recycled tyre textile fibre waste', *Journal of Environmental and Climate Technologies*. (In review)

LIST OF AUTHOR'S PRESENTATIONS

Poster presentation on 'Sound absorption properties evaluation and analysis of recycled tyre textile fibre waste' in the International Scientific Conference of Environmental and Climate Technologies CONECT 2020, 13–15 May 2020.

APPENDICES