A PILOT STUDY ON THE DEVELOPMENT OF AN ECOLOGICAL, UNPERFORATED SOUND ABSORPTIVE MATERIAL

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ABSTRACT

A PILOT STUDY ON THE DEVELOPMENT OF A NEW SUSTAINABLE SOUND ABSORBING MATERIAL

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Awareness of the nature has a limited capacity and the consideration that the future generations are in danger due to the rapid waste with the development of technology in the last century, is leading to sustainability and green building design concept. The hazardous effects of the industrial materials are coming out, thus, healthier, natural materials and production methods are being discovered to design healthier interior environments.

Architectural acoustics requirements are one of the vital topics to provide healthy and comfortable environments. The materials that are consumed in Turkey to provide acoustical comfort requirements in terms of room and building acoustics are commonly synthetic fibers, such as glass wool and rock wool or perforated materials consisting of those fibers. The preference by architects is mostly smooth, unperforated and plain sound absorbers because of aesthetical reasons. This kind of materials frequently imported from other countries with high costs and yet, that are supported with synthetic fibers. Rock wool and glass wool are hazardous for respiration; furthermore physical touch may induce itching. Moreover, synthetic fibers, such as glass wool and rock wool are produced with high energy demands in addition to transportation costs which result in high carbon footprints. The investigation of ecological and natural materials is indispensable to provide acoustical requirements considering the health and energy efficiency.

This study is focused on the development of a sound absorptive material having smooth surface and ecological features. The material is made of pumice which has large reserves in Turkey and reed, which grows in wet areas such as rivers and lakes. The binding agent for the pumice is lime, which is a more ecological binder compared with cement and gypsum products in terms of energy efficiency and acoustical performance. The selected materials are found to have great potential for improved acoustical performances in addition to being economic and ecological. The measurements of the composite acoustical performance are realized with Impedance Tube.

Key words: Natural Sound Absorber, Pumice, Reed, Lime, Sound Absorption Coefficient, Acoustical Material.

ÖZ

EKOLOJİK VE SES YUTUCU BİR MALZEME GELİŞTİRİLMESİ ÜZERİNE ÖNCÜ BİR ÇALIŞMA

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Doğanın rezervlerinin sınırlı olduğu ve son yüzyılda teknolojinin gelişmesiyle birlikte kaynakların hızla tüketilmesinin insanlığın geleceği için tehlike oluşturduğu bilinci sürdürülebilirlik ve yeşil bina kavramını ortaya çıkarmıştır. Endüstriyel yapı malzemelerinin sağlığa zararları ortaya çıkmakta ve daha sağlıklı, doğal malzemeler keşfedilerek ve daha sağlıklı üretim teknikleri geliştirilerek iç hava kalitesinin daha iyi olduğu mekânlar tasarlanması amaçlanmaktadır.

Mimari akustik gereklilikler de sağlıklı ve konforlu yaşam şartlarının sağlanması için ön plana çıkan konulardan biridir. Hacim akustiği ve yapı akustiği konfor şartlarını sağlamak amacıyla ülkemizde yaygın olarak kullanılan malzemeler taş yünü ve cam yünü gibi sentetik lifler veya bu tür malzemelerle desteklenen delikli ürünlerden oluşmaktadır. Mimarların genel olarak tercih ettiği düz yüzeyli ses yutucu malzemeler ise daha çok yurt dışından ithal edilen yüksek maliyetli ve yine sentetik lifli malzemeler ile desteklenen ürünlerdir. Cam ve taş yünü gibi malzemeler tozuma sebebiyle solunum yollarında rahatsızlıklara sebep olabilirken fiziksel olarak temas edildiğinde cilt problemlerine de yol açabilmektedirler. Diğer yandan bu tür malzemeler, üretiminde kullanılan yüksek miktardaki enerji ve taşıma maliyeti sebebiyle karbon ayak izi de yüksek olan ürünlerdir. Sağlıklı yaşam koşulları ve enerji

tasarrufunun ön plana alınarak daha ekolojik ve doğal ürünlerin araştırılması ve geliştirilmesi kaçınılmazdır.

Bu tez çalışmasında geliştirilen doğal ve yerel ürünlerle ekolojik, düz yüzeyli ve deliksiz ses yutucu malzeme, ülkemizde bol miktarda rezervi bulunan pomza taşı ve ülkemizde su kenarlarında oldukça fazla üretilen ve büyük miktarı ABD'ye ihraç edilen saz bitkisinden oluşmaktadır. Pomza taşının bağlayıcısı kireç ise yüksek miktarda enerji kullanılarak üretilen ve yaygın olarak kullanılan çimentoya alternatif olarak seçilmiştir. Seçilen malzemeler sektörde yaygın olarak kullanılan malzemelere göre daha ekonomik ve ekolojik olmakla birlikte akustik performansları da oldukça yüksek olan malzemelerdir. Seçilen malzemelerle oluşturulan ürünün akustik performansı Kundt Tüplerinde ölçülerek kompozit malzemenin ses yutuculuk özellikleri ve yapısı araştırılmıştır.

Anahtar kelimeler: Doğal Ses Yutucu Malzeme, Ekolojik Yapı Malzemesi, Pomza, Saz Bitkisi, Kireç, Kundt Tüpü

to peace and justice…

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ABBREVIATIONS

λ Wavelength (m)

f Frequency (Hz)

Hz Hertz

c Speed of wave propagation (m /s)

dB Decibel

α Sound absorption coefficient

α_s The individual sound absorption coefficients in 1/3 octave bands, measured in accordance with BS EN ISO 354 in reverberation room

α_w A weighted sound absorption coefficient

NRC Noise Reduction Coefficient

RT Reverberation Time

CHAPTER 1

INTRODUCTION

The increase of population and technological development has induced various implications in the 20th century. There are many challenges that were elusive one century before. One of the critical challenges is noise pollution. In history, the population in cities was less, the natural environment had not been disturbed and technological devices weren’t widespread as today. The most significant spaces to be acoustically controlled were religious buildings and theatres. However, reverberation and noise evokes as a critical concern in today’s life standards. The increase of technology has provided significant machine and traffic noise mainly in crowded cities. Thus, acoustics and noise control is a very important issue from houses to office spaces, shopping malls to metro stations as well as acoustically sensitive spaces such as religious buildings, concert houses, opera houses, conference halls and theatres at the present time.

Acoustical control issues were being handled with asbestos-based materials which are hazardous for human health 40-50 years before now. The health foundations directed sector to mineral wool based fibers like rock wool and glass wool since then (Arenas & Crocker, 2010). Although these materials are less harmful for human health, synthetic chemicals used in production of these materials are hazardous that their fibers may cause skin and eye irritation in short term period, have lung cancer risk in long term period (Unionsafe, 2002) and their carbon footprint caution is quite significant (Arenas & Crocker, 2010). Nevertheless, most of the sound absorptive materials in construction industry are synthetic fibers or supported with synthetic fibers such as perforated wood and gypsum panel products. Some precautions are being handled to avoid wool dusts with fiberglass nets on the products, but at least, they cannot be considered as healthy, ecologic and economic solutions for acoustical issues.

Ecological and healthy material solutions are being developed and natural raw materials are being discovered for sound absorption and isolation, recently. Hemp, jute, straw and coconut fibers are some examples to natural fibers. Most of them have very significant sound absorption and insulation performances compared to rock wool and glass wool (Gle *et al.* 2011), (Oldham *et al.*,2011), (Saadatnia *et al.*, 2008), (Mohd *et al.*, 2004). They all are environmental friendly, healthier and produced with renewable energy. If harvesting is done carefully, emulating the balance of the nature and environmental issues, their production and aggregation is beneficial for natural environment. Besides, low energy building materials are being selected to give less harm to the environment. For example, fiber reinforced concretes such as hemp concrete (Gle *et al.* 2011) are being worked on to develop materials more ecological, durable and have high isolation characteristics.

The most effective factor that directs the construction industry to ecological materials is undoubtedly, sustainable design certification systems which obtain to increase the prestige of the buildings and conversant as well as energy efficient, ecological and sustainable. Green building design procedures such as LEED and BREEAM which control the design, construction and utilization phases of buildings completely, also encourage natural and healthy construction materials. Especially for indoor air quality and energy efficiency; healthy and natural materials are in advance. Acoustical comfort is one of the essential issues for indoor air quality. Since these certification systems are quiet new as revealed in 1990s, the construction industry recently captivates the details. Natural lightening, natural ventilation and sustainability gain prominence in design periods. These issues necessitate large glass surfaces for lightening, air flow between volumes, outdoor and durable flat surfaces for sustainability. All of these issues, if applied regardless of acoustical issues, cause sound isolation and reverberation problems. For instance, natural ventilation issues, if not handled carefully, cause environmental noise to get into working spaces. Especially in office buildings, it causes lack of speech privacy and noise at working spaces. Furthermore, large glass surfaces, solid walls and ceiling surfaces cause high reverberation times which disturb the working people and lead health problems. Thus, most of the recent constructed sustainable and energy certificated buildings have worse acoustical performances than traditional buildings (Muehleisen, 2010).

Acoustical issues and sustainable design requirements should be handled simultaneously. Adverse to common sound absorbers as glass and rock wool based materials, relevant sound absorptive materials that do not decrease the indoor air quality should be discovered. The healthiest and most energy efficient alternative sound absorptive materials are natural organic and inorganic materials. Accordingly, the purpose of this thesis is to develop an alternative ecologic sound absorptive material that is based on appropriate, local, natural, organic and inorganic materials in Turkey.

1.1 MOTIVATION

Modern architectural spaces interior finishing materials are flat rough surfaces in public buildings which reflect the sound and cause high reverberation times in those spaces. High reverberation time may cause health problems among people. Acoustical precautions should be handled to provide acoustical comfort requirements in, especially, large public spaces.

Sound absorptive materials, used for acoustical requirements are mostly perforated panels with mineral wool based backing fibers which are not preferred by most of the architects since they affect the architectural view significantly due to the perforation. The ceiling surfaces like rock wool suspended ceilings and painted mineral wool panels pose suture in application. Most of the indoor surface materials are fine finishing simple flat white surfaces especially on ceiling surfaces, for all that, the most effective and simple acoustic precautions can be taken on ceiling surfaces as they are most confident surfaces for common areas. Therefore, some of the material manufacturers have produced sound absorptive plasters with mineral wool backing. Yet, most of these materials are imported from other countries and very high in price or native ones are of poor quality. Furthermore, they contain mineral wool. Mineral wool is a synthetic fiber which can be produced as glass wool and rock wool. Both of the fibers are produced with high energy intake and they cause allergenic problems because of the dust. Subsequently, they are not recommended materials for design of energy efficient and green buildings.

Natural materials are produced by renewable energy and they do not cause health problems in contrast to synthetic fibers. They do not contain toxic gases, they are not hazardous for environment and they are recyclable. Natural fibers can be used as sound absorptive materials in construction industry. There are many researches about natural materials to be used as an alternative to mineral wools for sound absorption as described in the following chapters of this thesis. Most of these materials have good absorption properties at high frequencies nevertheless; medium and low frequencies are more essential as human ear is sensitive at medium frequencies for speech. In addition, most of these materials are measured for sound absorption but there exist little research on how they can be integrated to construction materials and produced as sound absorptive materials for use in buildings.

1.2 AIM AND OBJECTIVES

The aim of this thesis is to develop an ecological smooth, sound absorptive material made of natural and local materials which are energy efficient, healthy and aesthetically preferred.

The objectives of the thesis are to construct a material configuration made of reed and pumice stone which are natural and appropriate for Turkey, to make investigations on various experimental samples according to acoustical parameters that are effective on sound absorption and discover the variables that are effective to improve the sound absorptive properties of the configuration. The constructability of the composition, chemical properties of the plaster, fire resistivity and durability issues are out of the scope of this thesis work.

1.3 PROCEDURE

The study primarily covers a general literature survey on green building design and ecologic materials, architectural acoustics and integration between green building design criteria and acoustical requirements. Subsequently, the investigations on ecologic building materials sound absorption properties are given. Next, literature information about the materials that are used in this study is described. Thereafter, a general discussion about the literature survey and the details about the inspiration of the study are given.

The stages of the experimental study are given in material and methodology. This stage of the thesis study is based on an experimental analysis series constructed according the previous experiment results. There are four basic experiments that cover the related experiments with same material contents. There is a main hypothesis covering the aim of the thesis research and 9 sub- hypotheses that are investigated on the ideas of parameters to increase the sound absorption performance according to acoustical parameters that are expected to be effective on the sound absorption. The acoustical parameters that are investigated in the experiments are effect of pumice plaster thickness, granule sizes of pumice, percentage of lime content in pumice plaster, time, variations of diameters of reeds and porosity of the pumice plasters.

The results and discussion about on the experiments according to the measurement results to the related hypotheses are given in the fallowing stage. Last, a brief summary of the research and analyses of the effects of the parameters on the sound absorption performance of the configuration are described and the future studies that may be executed to develop the study are discussed.

1.4 DISPOSITION

There are 4 chapters following the introductory chapter. Chapter 2 covers introduction to green building design, introduction to architectural acoustics issues, sound absorption and measurement methods, relation between green building design criteria and acoustics, case studies on ecologic sound absorptive materials made of natural resources and the literature information about the materials that are used in this thesis study. The chapter is concluded with the general discussion about the literature survey and the inspiration of the study with the light of the literature information.

Chapter 3 covers the digest material properties used in the experiments and detailed information about the formation of the configuration. Subsequently, the chapter covers the method of production and application of the materials to the configuration and measurement process to predict sound absorption coefficients of the composite. The main and sub hypotheses for the relating experiments are given in the methodology, as well.

Chapter 4 covers the experimental measurement results and discussion of the results with related hypothesizes. The analyses of the produced experimental samples according to various parameters are assessed.

Chapter 5 covers the concluding remarks of the survey, the effects of the investigated acoustical parameters on the results and the issues for further research.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the topics related to this thesis research, green building design, architectural acoustics and the relationship between the two topics are described. Besides, ecologic sound absorbers in literature are analyzed and the related information materials that are used in this study are disclosed. Last, a brief evaluation of the literature survey is realized.

2.1. INTRODUCTION TO GREEN BUILDING DESIGN

Industrialization caused a vast amount of natural destruction due to unconscious use of sources in the last century. Nations realized that the nature will not be able to handle the demand of people if the energy and source consumption continue in the same intensity. The Nations World Commission on Environment and Development published a report in 1987 which is quoted as:

> "*Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs.*"

Sustainability cannot be defined under a single field. The term covers all levels of human activities from global to regional including behavior of individuals to organizations. The basic concerns of sustainability can be described as environment, social and economics. Social issues cover public health, education, peace, security, social justice, poverty, people relations with nature, occupational and customer safety etc. Environmental issues cover natural source use, energy use, climate change, pollution of land, sea and air, protection of biodiversity, natural habitats etc. Economic issues cover employment, business formation, income, economic opportunity, nature as an economic externality etc. These three concerns have to be considered in all fields that sustainability is subjected. Sustainability in construction industry is also related to social, environmental and economic issues. Desarnaulds *et al.* (2009) describes the sustainable construction as an attempt to harmonize environment, economy and society by providing a healthy built environment based on resource efficient and ecological principles.

Nationalities have developed energy efficiency certification systems to encourage construction industry to design and construct buildings that are healthy, comfortable and have less energy consumption. Acoustical performance criterion is included but not deeply examined in the sustainable design practices (Field, 2008). Whereas, the precautions for green building design considerations if applied without regarding the acoustical requirements cause to design of worse spaces than non-green buildings in terms of acoustical comfort (Field, 2008 and Muehleisen, 2010).

According to Cotana and Goretti (2008), the primary objective of energy efficiency certifications comprises:

I. Reducing dangerous effects of building materials
II. Designing and constructing buildings that are harmonious with natural environment
III. Improving integrity in building industry
IV. Encouraging industry and community sensitivity in ecologic and sustainable materials

Ecological material criteria describe the requirements of a material to be considered as "Green Material". Environmental Assessment and Specifications of Green Building Design (Froeschle, 1999) forms a matrix of environmental material assessment that provides to compare similar products to each other which is given in Table 2.1.

Table 2.1 Environmental material assessment matrix (Froeschle, 1999)

Environmental Criteria
Low Toxicity
Minimal Emissions
Low-VOC Assembly
Recycled Content
Resource Efficient
Recyclable Materials
Reusable Components
Sustainable Sources
Durable Materials
Moisture Resistant
Energy Efficient
Improved IAQ
Water Conserving
Healthful Maintenance
Local Product
Affordable Material
Environmental Score

The table helps to realize what to consider while selecting green building materials. It is not compulsory for material to provide all the recommendations, however; these terms should be taken into account during selection or production period of an ecological material.

2.2. BRIEF INTRODUCTION TO ACOUSTICAL CONCEPTS

Acoustics is defined as a science that deals with the production, control, transmission, reception, and effects of sound. Acoustics is directly related with one of the human sense organ, the ear, and also has physiological and psychological secondary relationships with human perception. Sound is the sensation caused by small pressure perturbations in elastic media.

Sound is a mechanical wave, an oscillation of pressure transmitted through a solid, liquid, or gas, composed of frequencies within the range of hearing. Two principle parameters are to be considered when dealing with acoustical concerns; frequency (f) and wavelength(λ). Frequency is the number of occurrences of a duplication event per unit time. Acousticians discuss sound pressure levels in terms of frequency that is how human ear interpret sound. The unit of frequency is Hertz corresponding to 1 cycle per second and abbreviated as(Hz). The human ear can detect sounds ranged from approximately 20 to 20,000 Hz but most sensitive in frequency range 500 Hz to 8000 Hz. This upper limit tends to decrease with increased age. Wavelength is the distance traveled by a harmonic (sound) wave in one period. Frequency and wavelength obtain to express the nature of pressure variation in a medium that are experienced as sound in the brain. Frequency and wavelength have an inverse relation related to velocity of sound which is defined as direction and time of sound travel to reach listeners. The correlation between wavelength and frequency is given in Equation (2.1). As the frequency increases the wavelength decreases. The general equation of frequency and wavelength is as follows (Long, 2006, p.38):

$$\lambda = {}^{c}/_{f} \tag{2.1}$$

where λ = wavelength (m)

c = velocity of wave propagation (m /s)

f = frequency (Hz)

Noise can be simply defined as undesired sound. Noise can arise from the people speaking in next room, clatter in a shopping mall or traffic on the road. Noise should be avoided to provide acoustically comfortable spaces. Noise can be reduced by engineering methods according to origin of the noise. These are noise control at the source, noise control in the path and noise control at the receiver.

If the noise origin is high reverberation times and echoes in the space, noise absorption is applied with sound absorptive materials. Reverberation is the persistence of sound in a particular space after the original sound is produced. If the Reverberation Time (RT) is longer than needed, it becomes a nuisance. Echo is repetition of the original sound caused by distinct reflections of long delay. Sound absorption treatment is an effective noise control solution for echo and reverberation in spaces, where the intelligibility is important (Long, 2006).

2.2.1. REFLECTION, TRANSMISSION AND ABSORPTION OF SOUND

When the sound wave encounters with the material, the energy incident in the sound wave is reflected, transmitted through the material and absorbed within the material (Long, 2006). Basically, the dynamics of reflection and transmission depend on the boundary conditions and the incidence angle of the incoming acoustic wave.

Sound absorption is energy dissipation at the boundary or within the fluid or conversion of acoustical energy into thermal energy. The absorption in fluids, typically air varies with the temperature, moisture and frequency. For room acoustics, the sound energy is reduced by the interior surfaces as well as during the propagation in the air (Kuttruf, 2000, p.147). The interaction of sound waves with a surface is given in Figure 2.1. The relation between incidents, reflected, absorbed and transmitted sound is given in Equation (2.2)

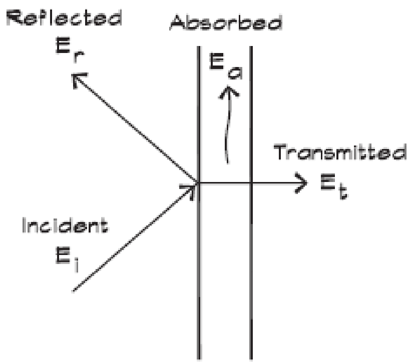


Figure 2.1 Interaction of Sound Waves with a Surface (Long, 2006).

$$E_I = E_a + E_t + E_r \tag{2.2}$$

Sound absorption coefficient (α) is the proportion of intensity/power of the sound wave that is absorbed by the material to intensity/power of the incident sound wave. The equation is given in (2.3).

$$\alpha = E_a \,/\, E_I \tag{2.3}$$

For a two layered section, the system works as shown in Figure 2.2:

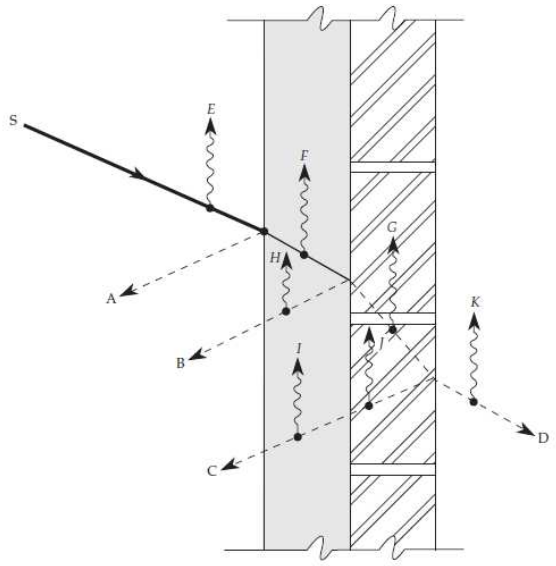


Figure 2.2 Sound absorption of porous material with masonry wall behind (Everest & Pohlmann, 2009, p. 201).

For a two layered system it can be easily seen from the picture that sound wave is imposed by multiple reflections, absorption and transmission. Thus, layered systems have more complex absorption algorithm. In this case, E and K are heat loss in the air, F, I, J and G are heat loss in the materials, D is refraction of the sound and A, B and C are reflection of sound energy to the room media (Everest & Pohlmann, 2009, p. 201).

If a material is placed with an air cavity next to a wall surface, the cavity has a significant effect on the sound absorption properties of the material. The peak frequencies at which the sound absorption takes its maximum value are affected by the depth of the cavity (h) behind the material surface. These peak frequencies can be calculated as (Çalışkan, 2004)

$$f\max = 0.25 * (2n - 1) * c/h \tag{2.4}$$

where n is an integer.

The molecular structure as well as the thickness of the material affects the reflection, absorption and transmission of a sound on the material surface. Commonly, hard surfaces like gypsum, metal and wood are described as reflective surfaces, porous media generally absorb the sound and perforated or thin surfaces transmit the sound to other volumes. Transmission of sound to other volumes is generally undesired for building acoustics. The thickness of the material as well as density of the material is influential on sound absorption and transmission characteristics of the material.

2.2.2. SOUND ABSORPTIVE MATERIALS

Sound absorbers are materials that absorb the sound energy and transform into various types of energy, especially thermal energy. All of the materials have sound absorption characteristics from stone to even human himself. Nevertheless, if the material has low sound absorption coefficients it is named as a reflective material rather than absorptive material. The sound absorption characteristics of materials are classified according to the level of absorption capacity. Sound absorption capacity of materials ranges between 0-1 in frequency base.

Sound absorption class according to BS EN 11654 is given in Figure 2.3. Class A has the best ability to absorb sound, whereas Class E is the lowest. The installation method together with material properties has a great impact on the result.
American Society for Testing Materials (ASTM) has adopted Noise Reduction Coefficient (NRC), for comparing sound absorbers, which is the arithmetic average of sound absorption coefficients in octave bands centered at 250 Hz, 500 Hz, 1000 Hz and 2000 Hz.

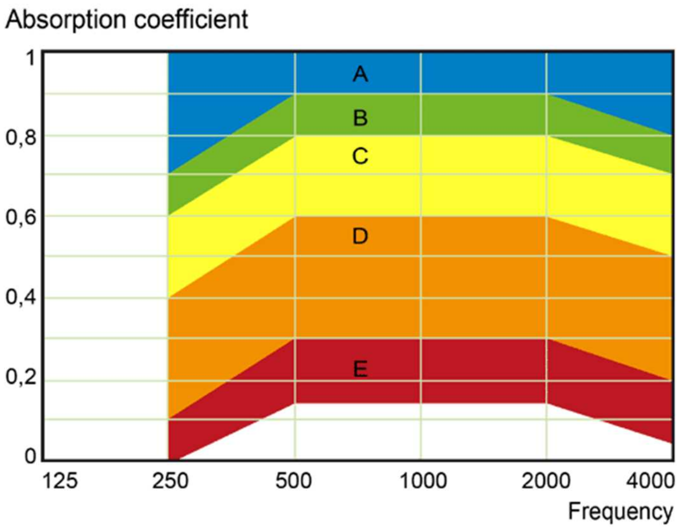


Figure 2.3 Sound Absorption Class according to BS EN ISO 11654 (Paroc, 2013).

Acoustic absorbers are commonly used in room acoustics to control the acoustic comfort requirements according to acoustic criteria. The basic criterion that affects the room acoustics requirements is reverberation time. The RT control provides other acoustical criteria to be controlled easily. For example, STI (Sound Transmission Index) which indicates the intelligibility increases with the decrease of RT. Other criteria such as EDT (Early Decay Time), C (Clarity) and LF (Lateral Fraction) are mostly controlled with changing sound absorption and scattering properties of the materials. Thus, sound absorption properties of the materials that are used in interior surfaces of a volume and their location are the most significant criteria for room acoustics.

Sound absorptive materials can be grouped in four main categories; porous materials, Helmholtz resonators (absorbers), membrane (resonant) absorbers and perforated absorbers.

2.2.2.1. Porous Sound Absorptive Materials

Porous sound absorptive materials are networks of interconnected pores within which viscous losses occur by converting acoustic energy into heat (Kinsler et al., 2000, p.

340). Materials that have high sound absorption coefficients are usually porous. The thickness of the porous material affects the lower frequencies seriously as the thickness is comparable with the wavelength of the sound and wavelength of the low frequencies are extremely long (Everest.& Pohlmann, 2009, p. 201). Porous sound absorptive materials can be classified in three main groups; cellular, granular and fibrous according to their microscopic configurations which are shown in Figure 2.4. (Arenas & Crocker, 2010).

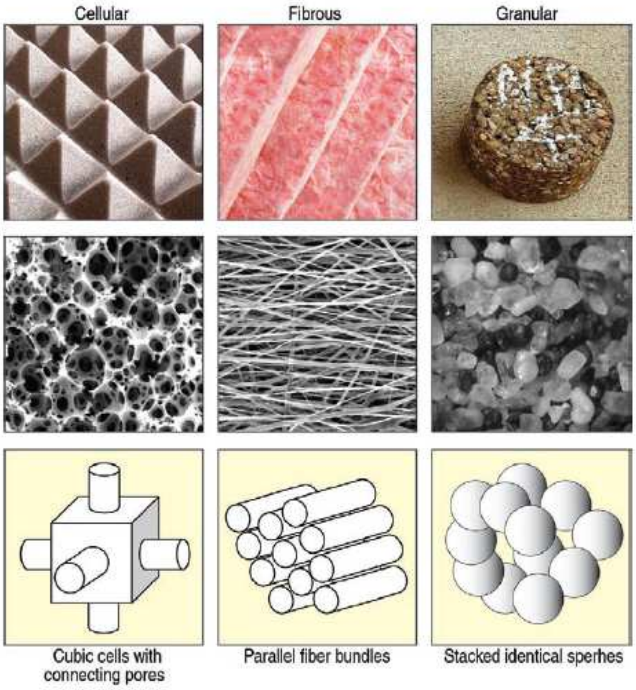


Figure 2.4 Three main types of porous sound absorptive materials (Arenas & Crocker, 2010).

Main illustrations of cellular porous materials are polyurethane and foams. Granular porous materials are porous concrete, sands, gravel and some kinds of asphalt. Fibrous sound absorptive materials are synthetic fibers such as glass wool and rock wool and natural fibers like jute, cotton, kenaf and hemp.

Commonly used fibrous materials are synthetic mineral fibers such as rock wool and glass wool which are given in Figure 2.5. Synthetic fibers are formulated by polymers and minerals and they have significant carbon footprints in addition to high demand of production energy. Glass wool is produced with 1200-1250 ºC heat and rock wool is produced with 1350-1400 ºC. Besides, they contain petrochemicals and synthetics which are hazardous for human health.

Figure 2.5 Mineral wool sound absorbers: 1. Glass wool (left picture)

2. Rock wool (right picture).

Conversely, natural fibers are produced by renewable energy, do not disturb nature, do not contain chemicals and are more economical and healthy for human being. Furthermore natural fibers conduce to CO_2 absorption, have no polluting risks, match health issues for indoor air quality and they are recyclable. On the other hand, their resistivity to fungal attracts, dampness risk and treatments for solving those problems are critical (Desarnaulds, 2005). Examples of natural fibers are given in Figure 2.6.

Figure 2.6 Natural sound absorptive panels: 1. Wood Wool Acoustic Panel (left picture) 2. Jute Fiber Acoustic Panel (right picture).

2.2.2.2. Helmholtz Resonators

Helmholtz resonator is an enclosed volume that has a small neck and opening at one end, which is a special type of air-spring oscillator (Long, 2006, p. 203). Helmholtz resonators are generally effective at a single frequency, particularly at low frequency sound absorption. Typically, blow across a mouth of a bottle resonates at its natural frequency. The air in the cavity of the bottle with the edges of the bottle forms a resonating system (Everest & Pohlmann, 2009, p. 209).

2.2.2.3. Resonant (Membrane) Absorbers

Non-porous thin materials, mounted away from a solid backing, vibrate under the influence of incident sound and dissipative mechanisms of the panel convert some of the incident sound energy to thermal energy (Kinsler et al., 2000, p. 340). The panels mounted away from the wall vibrate in their natural frequency and the sound absorption of the material is highest at the resonant frequency of the material. This kind of materials can be thin panels like gypsum, plywood and sheetrock mounted away from solid wall. Examples of resonant absorbers are given in Figure 2.7. Porous sound absorbers applied in the cavity behind the material increases the low frequency sound absorption (Everest & Pohlmann, 2009, p. 201).

Figure 2.7. Resonant panel absorbers.

2.2.2.4. Perforated Absorbers

Perforated absorbers are generally made of gypsum, wood and metal; each hole on the perforated panel works as a neck of Helmholtz resonator, thus perforated panels can be seen as a host of coupled resonators (Everest & Pohlmann, 2009, p. 212). Examples of various perforated panel illustrations are given in Figure 2.8.

Figure 2.8 Various Perforated panel illustrations.

Generally, as the cavity increases behind the panel the low frequency sound absorption increases, besides, porous and/or non-woven fabric behind the panel increases the mid frequency sound absorption. Commonly used sound absorptive panels in Turkey are perforated panels with mineral wool based backing materials.

Architects mostly do not prefer perforation on interior surfaces because of aesthetical reasons. Furthermore, rock wool or glass wool behind these materials is produced by very high energy demands and their fibers may cause allergenic symptoms and decrease indoor air quality.

2.2.3. FACTORS INFLUENCING SOUND ABSORPTION OF MATERIALS

Sound absorptive materials convert the mechanical motion of the sound wave into heat. The performance of the absorption changes not only with physical and chemical properties of the materials but also with the mounting decisions when applied in volumes. Factors influencing sound absorption are given below:

Fiber Size: Increase in fiber diameter causes in decrease in sound absorption (Koizomi et al. (2002) in Seddeq, 2009). The need of more fine fibers to reach the same volume of material results in more airflow resistive and tortuous media which is more sound absorptive according to Seddeq (2009).

Air Flow Resistance: The friction quantity expressed by resistance of the material to airflow is named as airflow resistance. Flow resistance per unit thickness is inversely proportional to the square of the fiber diameter for a fibrous material with a given porosity (Ingard (1994) in Seddeq, 2009).

According to ASTM D-1564-1971, flow resistance R is determined using Equation (2.5):

$$R = {}^{P}\!/_{v \times l} \tag{2.5}$$

where;

P is measured static pressure differential of both faces of the sample, in dyn/cm^2 $(10^{-1}\ Pa)$ unit.
v is air velocity, in cm/s unit.
l is thickness of sample, in cm unit.

Porosity: The porosity of a porous material is the ratio of the volume of the voids in the material to its total volume (Allard et al. (1989) in Seddeq, 2009) Increase in porosity provides higher sound absorption. Following Equation (2.6) gives the definition for porosity:

$$Porosity(H) = {}^{V_a}/_{V_m} \tag{2.6}$$

where:
V_a is volume of the air in the voids.
V_m is total volume of the sample of the acoustical material being tested.

Tortuosity: Tortuosity is a measure of "non-straightness" of the passage way through the pores. Tortuosity mainly affects the quarter-wavelength of the peaks, whereas porosity and flow resistance affect the height and width of the peaks (Horoshenkov *et al.* (2001) in Seddeq, 2009). Value of the tortuosity also determines the high frequency behavior of the porous material.

Thickness: Thickness influences basically low frequency sound absorption. Experiments show that increase in thickness raises the sound absorption of the material at low frequencies, while thickness has an insignificant effect at high frequencies. (İbrahim *et al.* (1978) in Seddeq, 2009).

Density: Sound absorption of a material increases with higher density at middle and high frequencies, while less dense and more open structure is more absorptive at low frequencies (Koizomi *et al*. (2002) in Seddeq, 2009).

Compression: Compression of fibrous materials decreases the sound absorption of the material. Compression results in increase in tortuosity and airflow resistivity and decrease in porosity and thermal characteristic length i.e., shape factor, but the major reason of decrement in sound absorption with the compression is sample thickness (Castagnede *et al.* (2000) in Seddeq, 2009).

Surface Impedance: Surface impedance increases with higher resistivity which results in more reflection and lower sound absorption (Seddeq, 2009).

Placement and Position of Sound Absorber: Position of sound absorbers affects the sound absorption. Sound absorbers placed near corners and along edges in rectangular rooms are more effective. Furthermore, lower surfaces of high walls in large volumes are more effective for sound absorption (Everest, 2009).

Placement of the sound absorber in the room significantly affects the room's acoustical condition. For instance, sound absorptive materials are placed to the back wall in conference rooms especially to absorb the direct sound coming from the sound source in the stage and avoid the echoes. Placing the same area of sound absorber to another place in the room would not be as efficient as this placement.

Performance of Sound Absorbers: Properties of sound absorptive material have significant effects on sound absorption certainly. The characteristics of absorption coefficient, reflection coefficient, acoustic impedance, propagation constant, normal reduction coefficient and transmission loss of material defines the acoustical performance of the material (Seddeq, 2009). The sustainability of the material's sound absorption performance is also a significant point. Painting the absorptive surfaces for example decreases the performance of the material. Especially fabric covered mineral wool based absorbers' acoustical performances are likely to decrease with time because of the dust and dirt if not cleaned.

2.2.4. MEASUREMENT METHODS FOR SOUND ABSORPTION COEFFICIENT

Standardized measurement methods for absorption coefficients of materials are Reverberation Chamber Method (ISO-354-2003), Impedance Tube Measurement Method Using Standing Wave Ratio (ISO-10534-1:2001) and Impedance Tube Measurement Method Using Transfer Function (ISO-10534-2:2001). Besides, there are unstandardized measurement methods such as scale model measurement (Jaatinen, 2011) and the reflection method using periodic pseudo-random sequences of maximum length in situ (Garai, 1993). In this research standardized methods; reverberant room method and the impedance tube method are expressed and the research measurements are made with Impedance Tube method using transfer function.

2.2.4.1. Reverberation Chamber Method

Reverberation chamber method is a sound absorption coefficient measurement method that provides to measure the acoustic performance of a material sample which has the simulation of the application conditions in reality. The standard ISO 354-2003 specifies the room volume at least 150 m^3 and not greater than 500 m^3. the temperature should be at least 15 ºC and the relative humidity should be in the range of 30% and 90% range according to standard. The area of the material sample should be between 10 m^2 and 12 m^2 and if the room volume is greater than 200 m^3 the area should be determined with the Equation (2.7):

$$A\mathrm{T} = (V/200m^3)^{2/3} \tag{2.7}$$

AT: The area of test specimen

Reverberation room reflectors with microphones and sound source are given in Figure 2.9.

Figure 2.9 Reverberation room reflectors, microphones and sound source (Kırbaş, 2013).

Advantages of this method is its being done in diffuse field, which is more realistic than one dimensional wave in contrast to impedance tube, to get the most accurate results of the materials sound absorption performance and being able to measure almost any type of material in various types of mounting . The disadvantages of this method are edge diffraction of the material which leads inaccurate results and necessitate of large samples to be tested. (Kuttruff, 2009, p. 284-285)

2.2.4.2. Impedance Tube Measurement Methods

Impedance tube method is a sound absorption performance measurement method that is based on a framework that plane waves travelling in rigid tube (Kuttruff, 2009, p.280). The tube has a rigid surrounding in circular or rectangular shape and there is a loudspeaker at the end of the tube acting as a sound source. The signal travels along the tube until it reaches to material sample and there are one or two microphones that receive the sound that is faced with the material. The material sample absorbs more or less the sound, reflects the residual sound energy and the microphones in the tube collect the sound wave’s maximum and minimum sound pressure. The result of the decrease in the sound wave pressure level gives the sound absorption of the material.

For the standing wave ratio measurement method, the sound source produces a standing wave inside the tube and the impedance of the material is defined as the ratio between sound pressure and the particle velocity. Only one frequency sound absorption coefficient is measured in one measurement. The figure of standing wave tube is given in Figure 2.10.

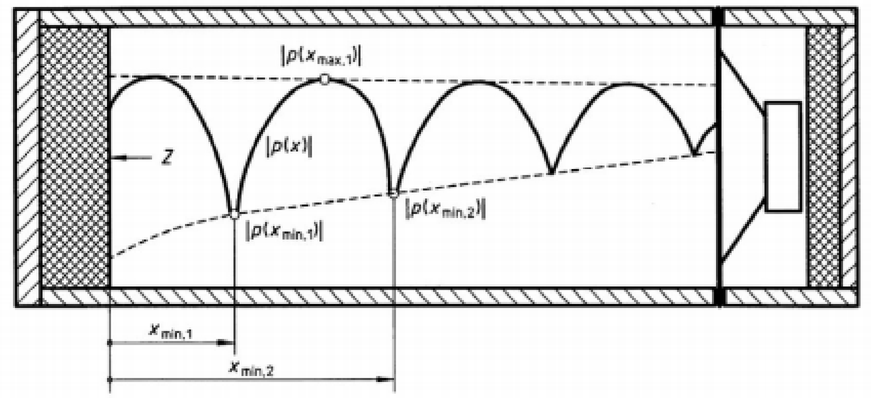


Figure 2.10 Standing wave method (Adopted from ISO 10534-1).

Using the definition of the standing wave ratio (s):

$$s = \frac{|p_{max}|}{|p_{min}|} \quad (2.8)$$

the reflection factor (r) can be easily defined as:

$$|r| = \frac{s-1}{s+1} \quad (2.9)$$

yielding the sound absorption coefficient (α) for plane waves:

$$\alpha = 1 - |r|^2 \quad (2.10)$$

p_{max} and p_{min} : measured maximum and minimum pressure amplitudes, respectively.

(Suhanek *et. al*., 2008)

For the Transfer Function Method, the same prerequisites are used but in this method, more complex transfer functions between two microphones are measured as distinct from previous method. This measurement method provides measuring the sound absorption coefficient of the material in the whole frequency spectrum unlike standing wave measurement method which measures only one octave frequency sound absorption performance of the material. The two microphone transfer function method measures the full frequency band sound absorption with two different dimensions of tubes according to the wavelength of the frequencies.

Dimension of the wider side $< 0.5\ \lambda_{min}$ for rectangular tubes
Diameter $< 0.586\ \lambda_{min}$ for circular tubes

According to the formula, sound absorption coefficients for 50 Hz to 1200 Hz are measured in 100mm diameter for circular impedance tube and for 800 Hz to 6300 Hz in 28mm diameter. The transfer function method using two microphones is given in Figure 2.11.

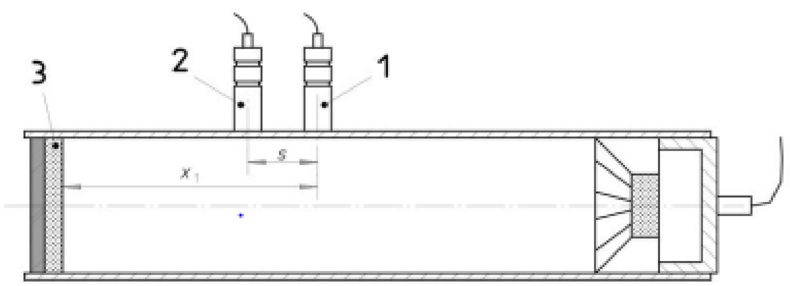


Figure 2.11 The transfer function method using two microphones

(Adopted from ISO 10534-2).

The normal incidence reflection factor (r) can be calculated using the formula:

$$\mathrm{r} = \mathrm{e}^{j\text{Ø}_r} = \frac{H_{12}-H_I}{H_R-H_{12}}\, e^{2jk_0x_1} \tag{2.11}$$

where:

$\boldsymbol{x_1}$ is the distance between the sample and the farther microphone location;
$\text{Ø}_{\boldsymbol{r}}$ is the phase angle of the normal incidence reflection factor;
$\boldsymbol{H_{12}}$ is the transfer function from microphone one to two, defined by the complex ratio $^{p_2}/_{p_1} = {}^{S_{12}}/_{S_{21}}$;
$\boldsymbol{H_R}$ and $\boldsymbol{H_I}$ are the real and imaginary parts of $\boldsymbol{H_{12}}$ respectively;

The sound absorption coefficient (α) can be calculated as:

$$\alpha = 1 - |r|^2 = 1 - r_r^2 - r_i^2 \tag{2.12}$$

(ISO 10534-2)

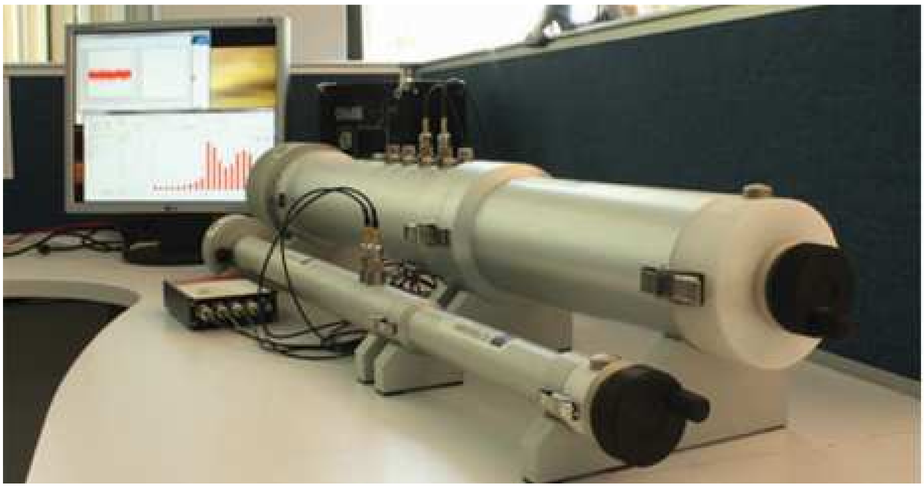


Figure 2.12 Circular Impedance Tube.

The impedance tube, two microphone transfer function method measurement standards are described in ISO 10534-2 and ASTM E1050-98 international standards. There are rectangular and circular types of Impedance Tubes. In this research Circular Impedance Tube is used given in Figure 2.12.

The advantage of the Impedance tube method is that test setup is more practical due to its small dimensions, so that the needed samples to measure. Besides, it measures surface impedance as well as absorption coefficients; nevertheless, the disadvantages are that only sound at normal incidence is measured and there are uncertainties when measuring heterogeneous materials like samples taken from different regions of a large sample (Oldham et al. 2011).

2.3. GREEN BUILDING DESIGN AND ACOUSTICS

Acoustics is one of the significant criteria to design healthy and comfortable living spaces. There are investigations about the content of acoustical criteria in green building design certification systems. Şan *et al.* (2011) explores the acoustical performance criteria in energy efficiency certification systems worldwide such as BREEAM, LEED, CASBEE, GREEN STAR, DGNB and SBTool. Acoustical performance is included under “indoor air quality assessment” part in most of the certification systems. The acoustical criteria range from schools to hospitals, offices to residents, industrial buildings to prisons in terms of purpose of buildings, including existing buildings, new constructions and renovations (Şan et al., 2011). Although acoustical performance is an important issue, it is included only for limited building types in some cases. In certification systems, Muehleisen (2010) points out that acoustical comfort is still poor, even worse in green buildings compared to non-green buildings shown in Figure 2.13, and 2.14.

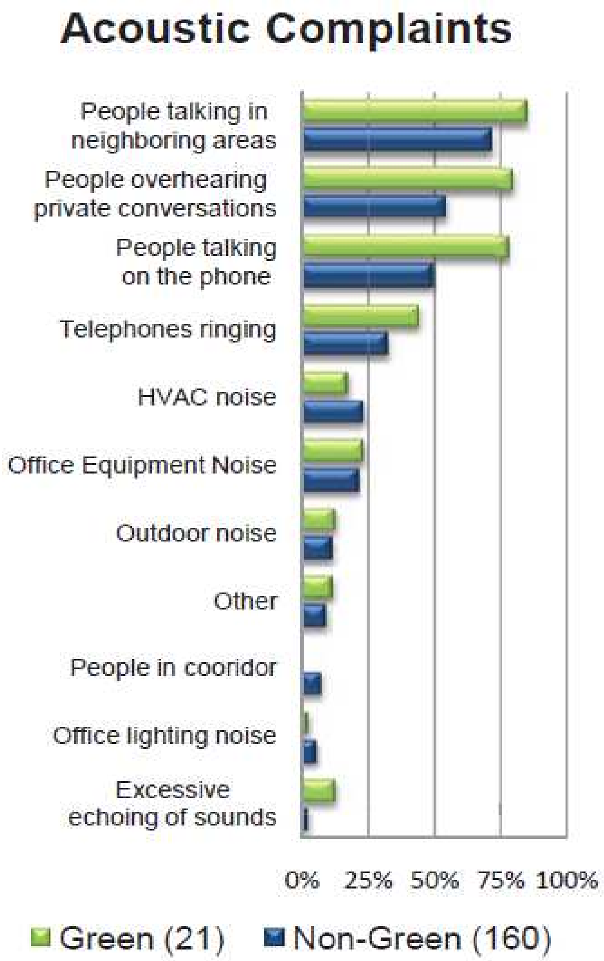


Figure 2.13 Acoustical Complaints, CBE (The Center for the Built Environment)'s POE (Post Occupancy Evolution) (Muehleisen, 2010).

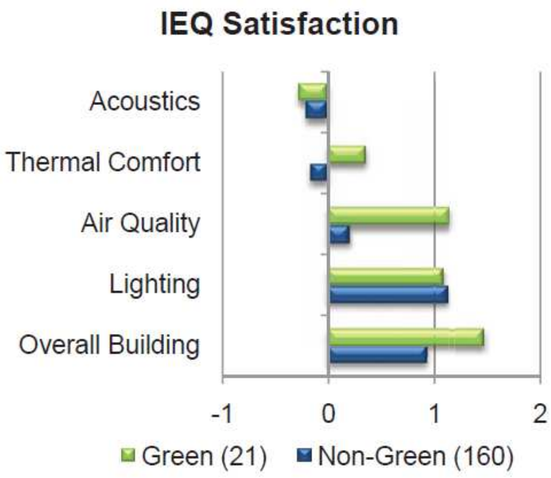


Figure 2.14 Environmental Satisfaction Results from CBE's POE Results (Muehleisen, 2010).

The major acoustical problems in green buildings and reasons are stated as follows (Field, 2008) and (Muehleisen, 2010):

I. Excessive noise (background noise): Amplified use of glass surfaces for natural lightening and natural ventilation gaps cause to reduce sound insulation from outside the building and also, reduce the sound insulation from neighboring rooms if there are interior glass partitions.

II. Lack of speech privacy: The increment of usage of glass and reflecting surfaces leads to high reverberation times and natural ventilation gaps between rooms lead to unintended eavesdropping.

III. Lack of speech clarity: The increment of usage of glass surfaces, reduction of usage of acoustical ceilings due to natural ventilation of fabric surfaces due to air quality and sustainability of surfaces and open plan office configurations for natural ventilation leads to increased reverberation times and poor speech clarity in buildings.

Field (2008) recommends being aware of these challenges exposed by green building design strategies, therefore, practical solutions to control acoustical requirements should be applied to designs. Muehleisen (2010) suggests that these problems caused by green building design decisions should be regarded and optimizations in terms of glass and solid wall surfaces should be developed. Besides, solutions for problems caused by natural ventilation and use of sound absorptive surfaces will provide better green buildings with better acoustical conditions. Madsen (2010) suggest full height wall partitions for natural ventilated office volumes and suggests green, sustainable, acoustically efficient products in addition to these substances. The authors also suggest baffles with acoustic louvers for naturally ventilated offices. Şan *et al.* (2011) claim that the problem should be defined clearly, the most economical and efficient solutions should be discovered and applied according to noise control principles in terms of acoustical criteria.

2.3.1. NATURAL FIBROUS SOUND ABSORBERS

Sound absorbing materials are generally produced from synthetic fibers such as glass wool, rock wool, foam plastics etc. and are widely used in European countries due to their good acoustic performance and low cost (Astrubali, 2006). On the other hand, their fibers may cause skin irritation as well as they affect the lung alveoli. In addition their resistivity to water, oil and chemicals are very weak according to Astrubali (2006). In contrast, the author explains the advantages of natural fibers, providing the thermal and acoustical requirements together, as low toxicity, being healthy, cheaper, lighter, recycled or raw materials that have low impact on environment and using renewable or low energy in production phase. The author mentions that natural fibers are less resistive to fungal attracts and fire compared to mineral wool based products. Energy consumption of some sound absorbing materials can be seen in Figure 2.15.

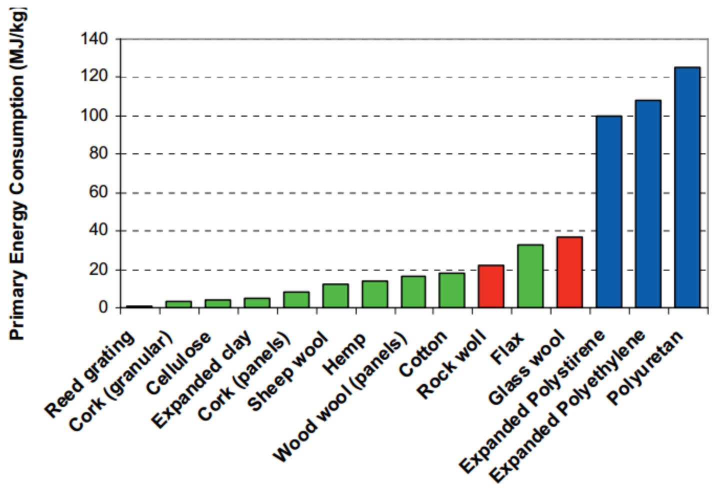


Figure 2.15 Estimation of primary energy consumption of some sound insulating materials' life cycles ((Secchi, 2005) in Astrubali, 2006).

Mineral wool products have low energy impact compared to expanded polystyrene, polyethylene and polyurethane according to Figure 2.18. Conversely, most of natural fibers have half or less energy consumption than mineral wools, besides they are healthy and have low impact to the environment.

Mahzan *et al.* (2009), illustrate natural fibers more advantageous to synthetic fibers in terms of nominal cost, weight and density, specific properties, recyclability and biodegradability.

2.3.2. GREEN SOUND ABSORPTIVE MATERIALS IN LITERATURE

According to Arenas & Crocker (2010), the production of specialized sound absorbing materials has increased rapidly for the last 4-5 decades. They state that asbestos-based materials, commonly used for sound absorption are replaced with synthetic fibers by public health concerns in 1970's. Although these materials are healthier then asbestos-based products; the contribution of greenhouse gas emotions (methane and nitrous oxide) in production and transfer phase of these materials cause high carbon footprints.

In addition, they claim that guidance and awareness of green building materials prompt the consumers to natural, recycled and renewable sound absorptive materials.

Mahzan *et al.* (2009) assesses the acoustic properties of rice-husk reinforced composite using polyurethane as a binder with impedance tube measurement method. They explore α (sound absorption coefficient) value of cleaned and dried rice husk mixed with polyurethane foam in different percentages for samples in 25 mm thicknesses. They prove the α values of rice husk are mostly increased especially in low frequencies and the optimum percentage of husk-rice is 25 % for this composite. The results are given in Figure 2.16.

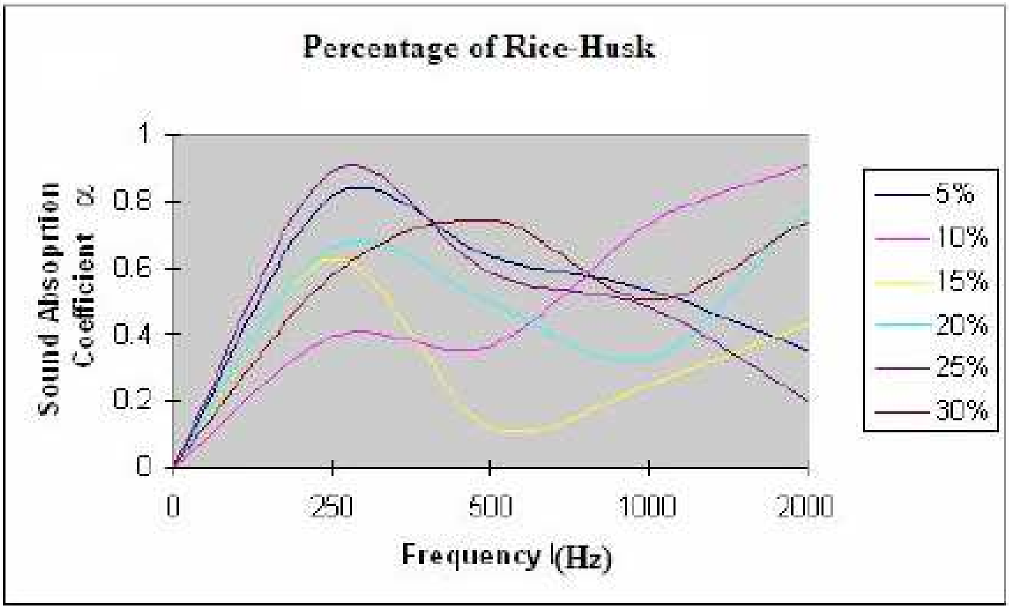


Figure 2.16 Sound absorption coefficient related to percentage ofce-husk (Mahzan et al., 2009)

Saadatnia *et al.* (2008) discusses the sound absorption performances of aspen particles with variable proportions of wheat and barley straw using impedance tube method. They use 1 to 4 cm wheat and barley straw samples in different percentages (0%, 10%, 20%, and 30%), urea-formaldehyde resin as a binder and $25 \times 25 \times 105\ cm$ aspen particles in different densities (0.2 gr/cm^3, 0.4 gr/cm^3, 0.6 gr/cm^3). They suggest that wheat and barley straw have similar effects on α values but negligible and the percentage of the fibers do not make significant changes on sound absorption, on the other hand, the effect of density on α of aspen particles vary according to frequencies and the optimum α values are ensured at density of 0.4 gr/cm^3. The results are given in Figure 2.17 and Figure 2.18.

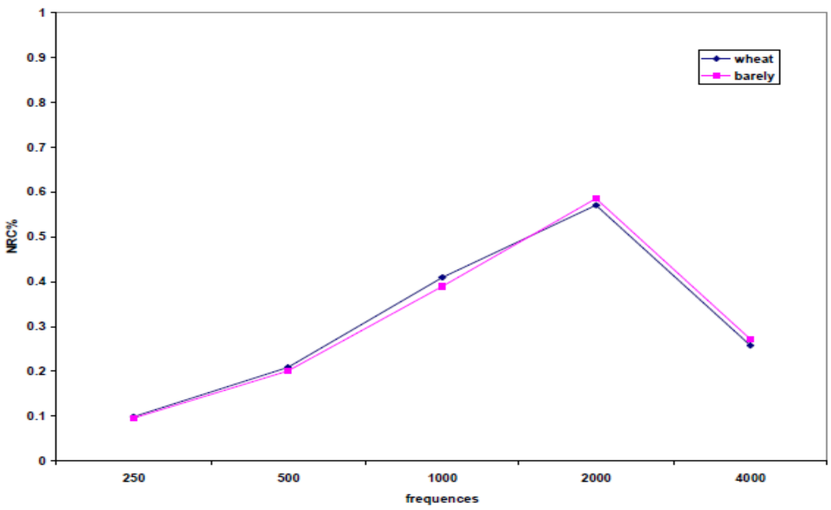


Figure 2.17 Effect of two kinds of straw (Wheat and Barely straws) on NRC %. All points are in the same groups (Saadatnia et al., 2008)

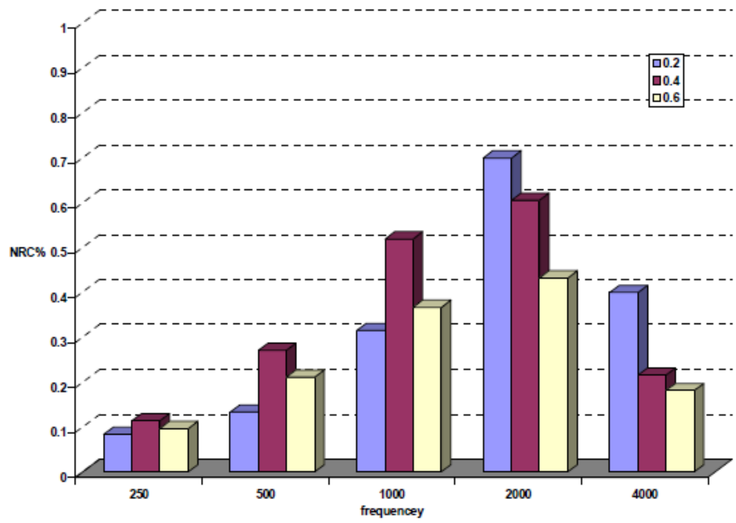


Figure 2.18 At low frequency, density of 0.4 gr/cm^3 was superior but for frequency upper than 1000 Hz, density of 0.2 gr/cm^3 had the highest NRC % (Saadatnia et al., 2008).

D'Alessandro & Pispola (2005) analyze sound absorption performances of sustainable fibrous materials, kenaf and recycled polyester using reverberation chamber method and compare the results with α of glass wool and mineral wool. Results show that sound absorption performances of kenaf fiber and recycled polyester fiber are similar, but polyester fiber is a number of higher in α value and both materials α values are very close to glass and mineral wool α values which makes them alternative sustainable materials to these synthetic fibers. The picture of kenaf and its fibers are given in Figure 2.19. The characteristics of the test samples are given in Table 2.2 and the measurement results are given in Figure 2.20.

Figure 2.19 Kenaf: a) rows; b) bast fibres (left) and core fibres (right) (D'Alessandro & Pispola, 2005).

Table 2.2 Characteristics of the tested samples (D'Alessandro & Pispola, 2005)

Parameter	Unit	Kenaf Layers	Pet Layers
Structure	-	Thermo bonded panels with no added adhesives	Thermo bonded panels with no added adhesives
Raw material	-	Natural hemp fibres, polyester backing fibres	Recycled polyester fibres
Thickness	mm	50	50
Density	Kg/m^3	30	30
Surface Area of the test specimen	m^2	7.56	7.56

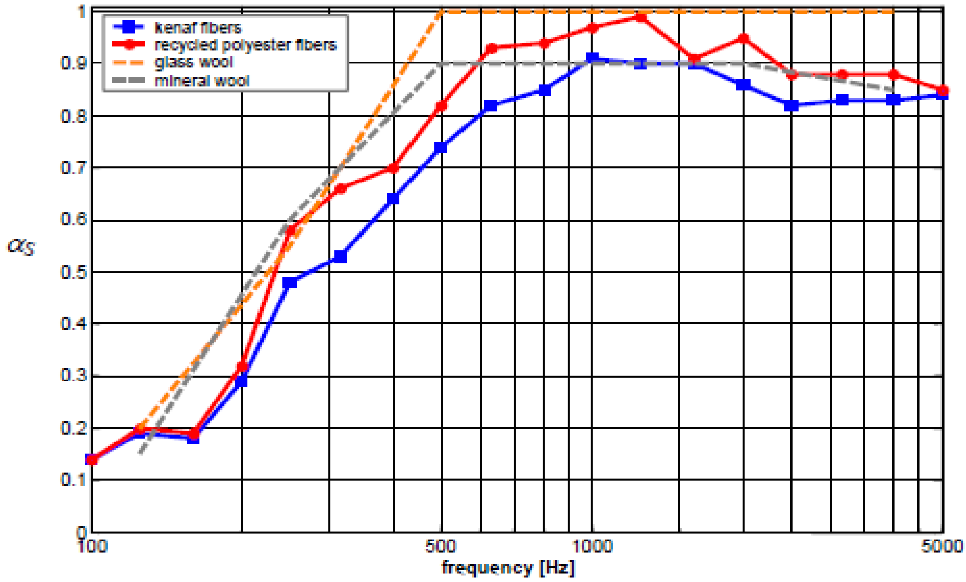


Figure 2.20 Third-octave band sound absorption coefficient α_s of kenaf and recycled polyester fibrous blankets in comparison with traditional fibrous absorbers (D'Alessandro & Pispola, 2005).

Nor *et al.* (2004) probe the sound absorption properties of multilayered coconut coir fibers in different configuration with and without airspace and micro perforated aluminum panels using Win FLAG computer simulation program. The picture of coconut coir fiber is given in Figure 2.21.

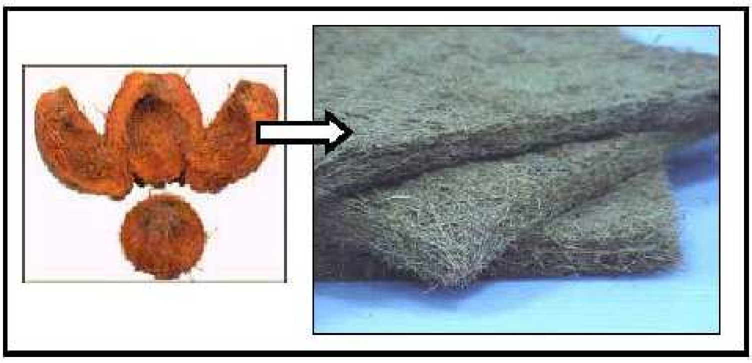


Figure 2.21 Raw coconut coir fiber (Nor et al., 2004).

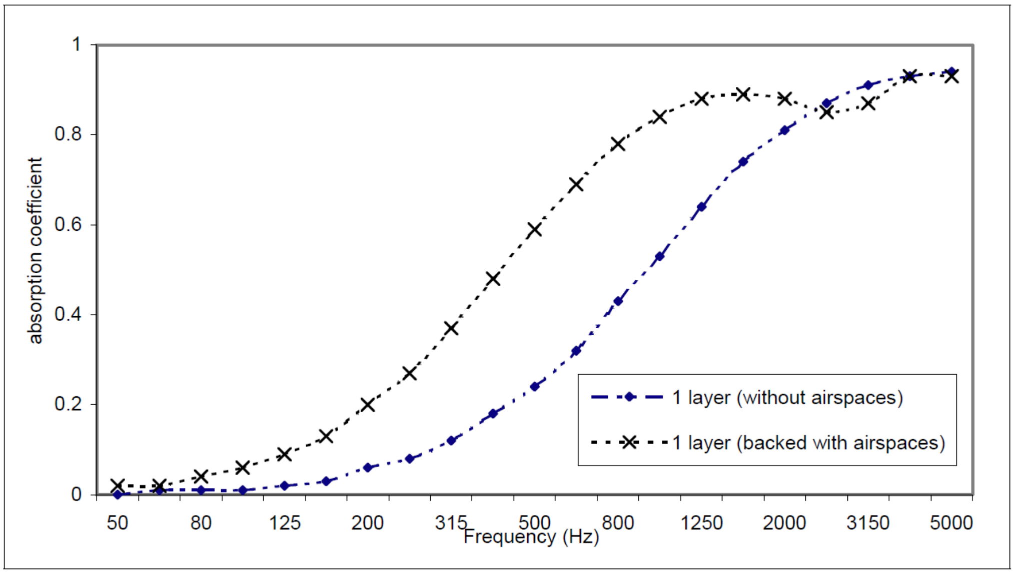


Figure 2.22 Comparison of the diffused incidence sound absorption coefficients of 20 mm thick coconut coir fiber sample of density 74 kg/m^3 without airspace and backed with airspace (Nor et al., 2004).

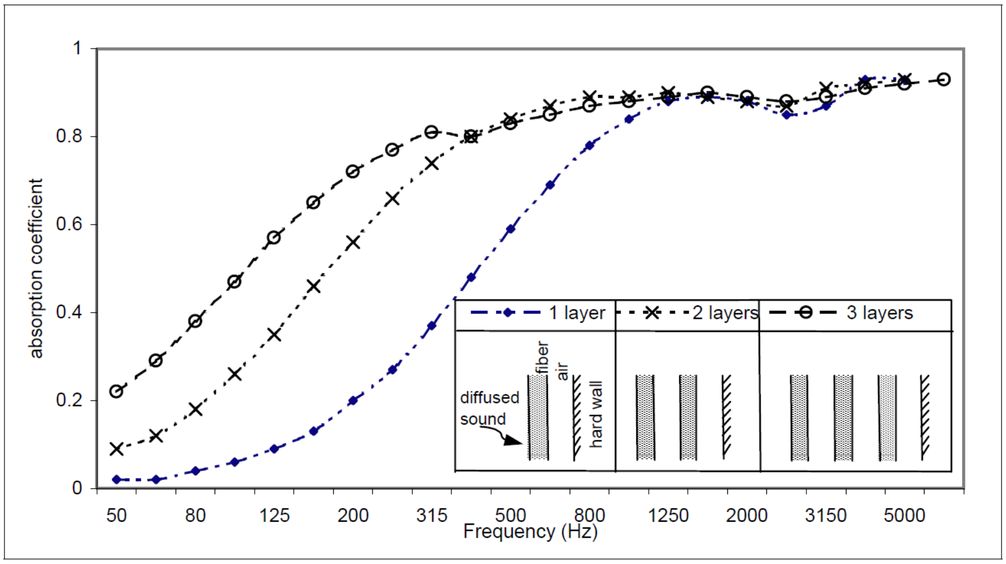


Figure 2.23 Diffused incidence sound absorption coefficients of 20 mm thick coconut coir fiber sample of density 74 kg/m^3 backed with airspaces and without micro perforated aluminum plate facing.

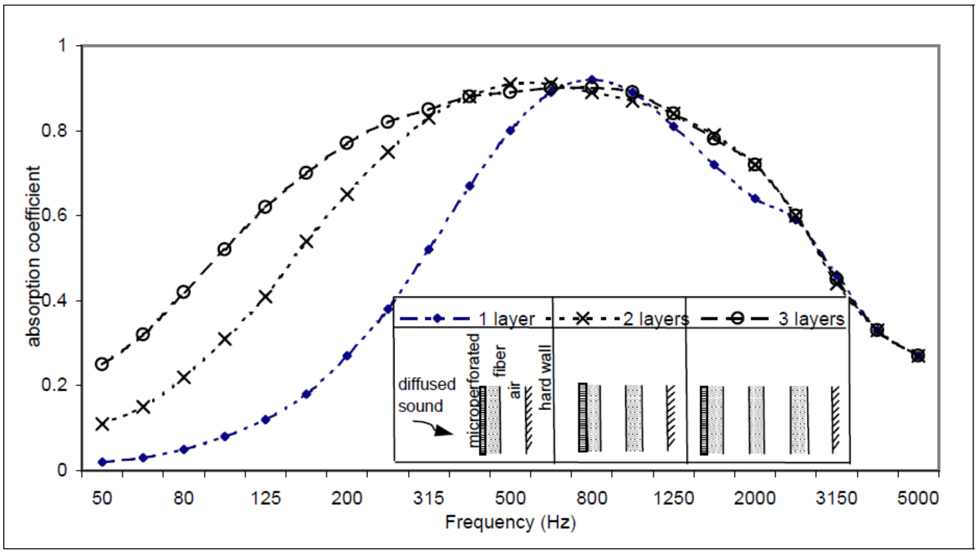


Figure 2.24 Diffused incidence sound absorption coefficients of 20 mm thick coconut coir fiber sample of density 74 kg/m^3 backed with airspaces and with micro perforated aluminum plate facing

The simulations are made regarding 20 mm thick coconut coir fiber with 74 kg/m^3 density. The results are given in Figure 2.22, 2.23 and 2.24.

The results of the study (Nor *et al.*, 2004) show that:

- Airspace behind the material decreases the peak frequency of α,
- Micro perforated panel decreases the α_s values in high frequencies,
- Layered systems with airspaces increases the α_s values at low frequencies
- Micro perforated panel, yet, decreases the α values in previous configuration.

As a progression of Nor *et al.*'s study, Zülfikli *et al.* (2008) measure the material in reverberation chamber and different from simulation results, α_s values decrease both with and without micro perforated panel configurations. The simulation and measurement results which are compatible in low and medium frequencies show that the coconut coir fiber can be an alternative sound absorptive natural material to synthetic based fibers according to authors.

In another study, Zulfikli *et al.* (2009) examine the comparison of α_s values between coir fiber and palm fiber using reverberation room method. They confirm that both materials have good α values and attitude in frequency base from low to high frequencies, yet, coconut coir fiber has a number of high α values compared to oil palm frond fiber. They also clarify that α values depend on thickness, fiber diameter, bulk density and other sound absorption factors and for a future work they would work on standardized thickness and densities.

İsmail *et al.* (2010) discuss the acoustical properties of arenga pinnata natural fiber for different thicknesses (10 mm, 20 mm, 30 mm and 40 mm) using impedance tube measurement method. They demonstrate that α values of arrenga pinnata escalate with the increase of thickness. The results are given in Figure 2.25 and 2.26. The material can be an alternative raw sound absorptive material at high frequencies.

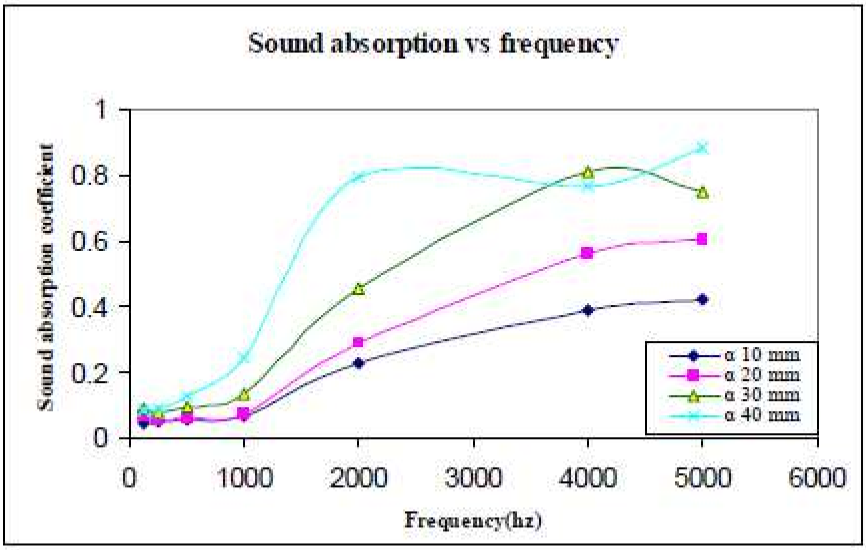


Figure 2.25 Sound absorption of Arenga pinnata fiber (İsmail et al., 2010)

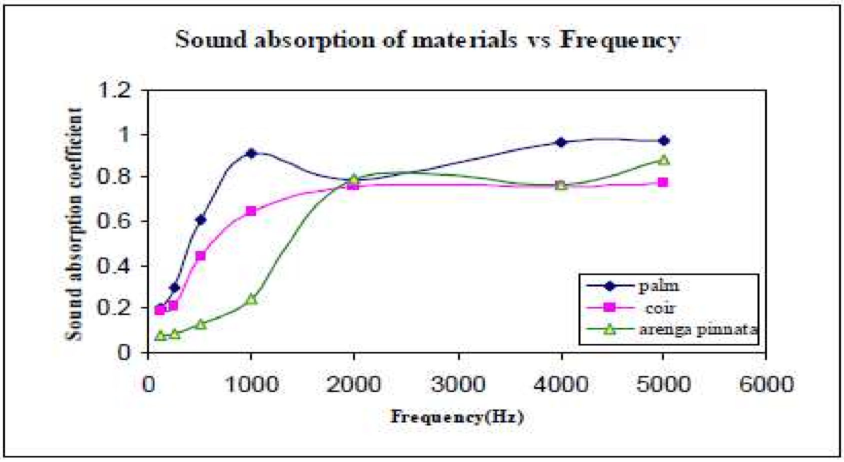


Figure 2.26 Sound absorption coefficient versus frequencies of pal, coir and Arenga pinnata fiber (İsmail et al., 2010).

Sihabut & Laemsak (2012) also investigates the sound absorption properties of oil palm fiberboard using impedance tube method. The picture of material samples are given in Figure 2.27. The material is cut into pieces, dried in sunlight, soaked in water for 24 hours, cooked at 162 $\pm$ ℃ for different durations (16, 19 and 21 minutes), then cut to different thicknesses (0.5, 0.6 and 0.7 mm) and soaked in aluminum sulfate for 30 minutes. Although the measured α results show similar values, the oil palm fiberboard cooked for 21 minutes with 0.5 mm thickness show the optimum α values with NRC 0.43. The results are given in Figure 2.28.

Figure 2.27 A set of specimens with various finishing; rough surface (left), screen surface (middle) and perforated surface (right) (Sihabut & Laemsak, 2012)

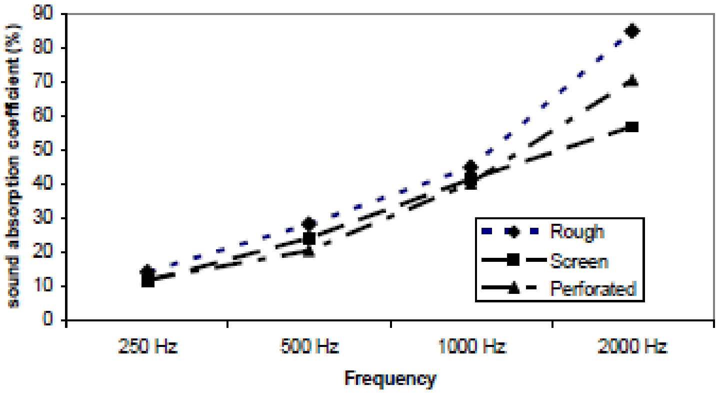


Figure 2.28 Percentage of sound absorption of oil palm frond fiberboard with different finishing (Sihabut & Laemsak, 2012).

Oldham *et al.* (2011) examine the sustainable acoustic absorbers from the biomass. They analyze the α of fibrous materials; raw cotton, flax fiber, ramie, raw wool, jute carded fiber, wool batts, jute raw fiber, hemp batts and sisal fiber using impedance tube method and compare the measurements with prediction results explored by other authors in literature. They expose that cotton fiber, flax fiber and ramie fiber have comparable α values with mineral wool based products, on the other hand, wool fiber, jute (raw and carded) fiber and wool batt and hemp batt medium α values and sisal fibre has low α values. They observe that the experimental results are compatible with prediction results. They secondly measure the non-fibrous unmodified reed and straw using combination of impedance tube and reverberation chamber method. They review that normal incidence α values of end-on and aligned reed and straw are similar. They prove that the peak frequency of the end-on and aligned reed decreases with the thickness increment both impedance tube and reverberation chamber method. Last, they explore composite absorbers made of a layered system of hemp and reed, binding them with mechanical systems, using reverberation room method which demonstrates promising results from low to high frequencies.

Sakamoto *et al.* 2011) explore the sound absorption properties of rice straw, rice husk and buckwheat husk in many configurations. For the first step they discover the relationship between α, length of the rice straw and direction of particles to the sound. They come to realize that, the α of the 100 mm straw, parallel to incident sound does not change with the chopping or cutting unless the total thickness changes. However, the direction of the particles change the α that parallel to incident direction is more absorptive and also peak frequency is decreased. The results are given in Figure 2.29.

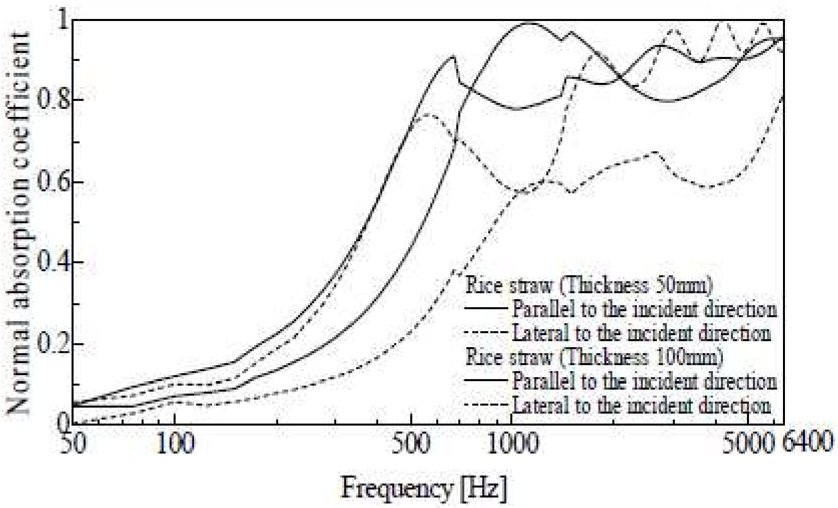


Figure 2.29 Absorption coefficient of rice straw (Comparison between parallel and lateral direction) (Sakamoto et al., 2011).

For a second step they explore the effect of thickness (25 mm to 100 mm) of the rice straw and they realize that as the particle length increases, the peak of α slides to lower frequencies. The comparison results of different thicknesses of rice straw are given in Figure 2.30.

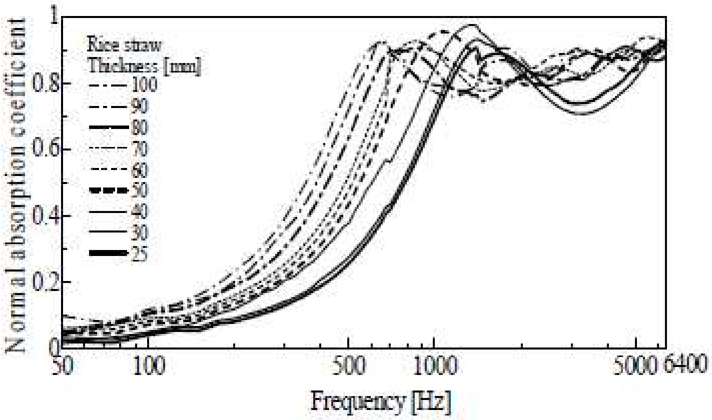


Figure 2.30 Absorption coefficient of rice straw (Comparison between various thicknesses) (Sakamoto et al. 2011).

As a third step Sakamoto *et. al.* (2011) work on the effect of the diameter and length (ϕ2.5 mm to ϕ8.0 mm) of rice straw on α_s with artificial tubes. They realize that α increases with the decrease of diameter and changing the lengths 25 mm to 100 mm affect the number of peak frequencies. The results of absorption coefficients of 50 mmplastic straws and 100 mm straws with various diameters are given in Figure 2.31 and 2.32.

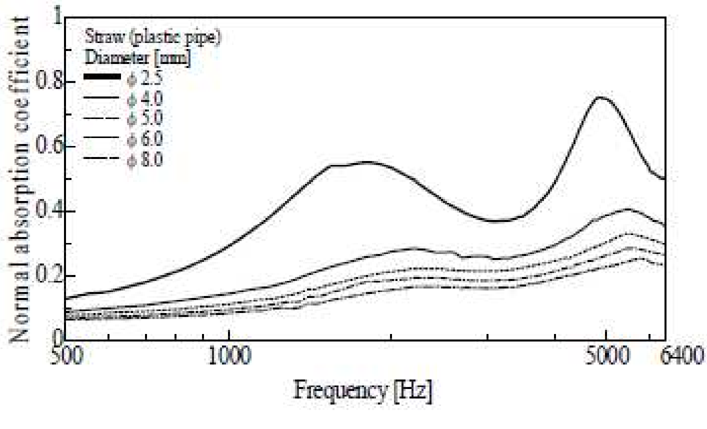


Figure 2.31 Absorption coefficient of plastic straw (Thickness 50 mm) (Sakamoto et al. 2011).

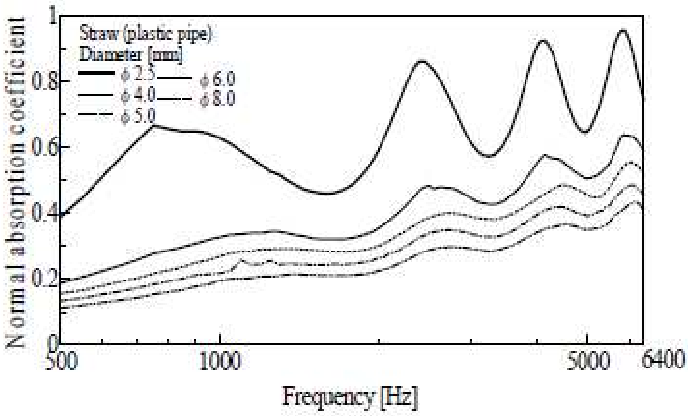


Figure 2.32 Absorption coefficient of plastic straw (Thickness 100 mm)(Sakamoto et al. 2011).

For forth step Sakamoto *et. al.* (2011) use round tubes, honeycomb tubes and concentric tubes to understand the attitude of shape of the tubes. They realize that the airspace between tubes effects the α positively and the concentric tube configuration is more suitable in terms of sound absorption.

In fifth step Sakamoto *et. al.* (2011) measure the absorption coefficients of rice husk and buckwheat husk. Both of the materials expose good acoustic behavior and the peak frequency decreases with the increment of thickness of the materials.

For the last step Sakamoto *et. al.* (2011) explore the effect of airspace behind these materials and they prove that the absorption performances are increase, however; the number of peak frequencies increase because of the airspace behind. They also calculate the sound absorptions of the materials and the experiment and estimations are compatible. The results are given in Figure 2.33.

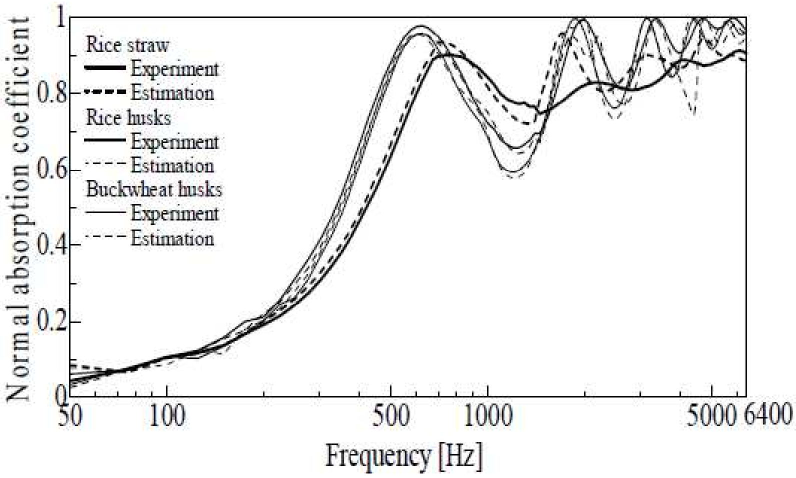


Figure 2.33 Comparison between estimation and experiment (Single layer 80) (Sakamoto et al. 2011).

Ersoy *et al.* aim to develop a reinforced composite material made of recycled materials, multi-axial knitted fabrics, hazelnuts shell and thermoset polyester resin. They work on both hazelnuts broken piece shell and hazelnut powder as ingredients in composites with two layer of fabric and make measurements in kundt tube for low frequencies. The picture of the materials is given in Figure 2.34. The results are given in Figure 2.35. The results show that α is around 0.12 for both composites in low frequencies, in other words, they reflect sound at low frequencies. Also Ersoy and Küçük (2009) try tea leaf fibre (TLF) and poly-propylene based non-woven fibre (PNF) for 10 mm, 20 mm and 30 mm sample thicknesses with and without woven cotton cloth (WCC) in high frequencies. The results reveal that α increases with the thickness and WCC backing increases the values seriously for high frequencies, but the results indicate that the α is around 0.3 for medium frequencies which means the materials are not very sufficient for speech frequencies.

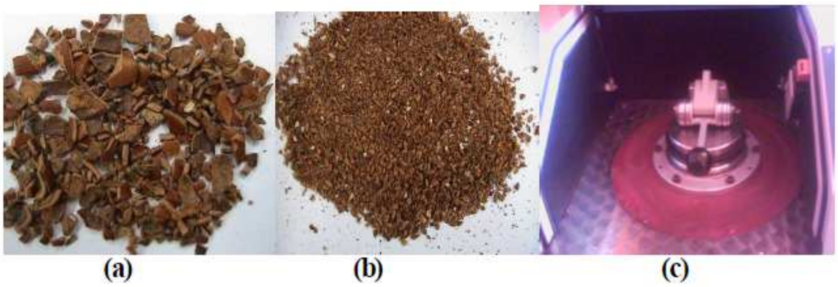


Figure 2.34 (a) Picture of pieced Hazelnut shell; (b) Picture of powered Hazelnut shell; (c) Centrifuge machine (Ersoy et al.)

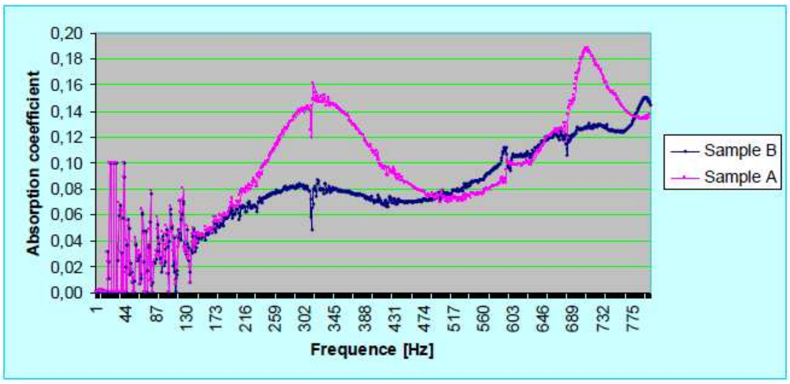


Figure 2.35 Acoustic absorption graphic samples (Ersoy et al.)

Gle *et al.* (2011) introduce hemp concrete made of varying particle characteristics of hemp with different binders. They measure three sizes of hemp with two lime based and one cement based binders. The measurement results are given under Lime heading. The hemp concrete show better absorption performance with lime binders one of which is mixture of hydraulic lime, aerated lime and puzzolanic lime and one of which is just hydraulic lime. The sizes of hemp do not make a serious change for α, but the content ratio of hemp seriously affect the α, such as around 0.3 for 60% hemp and around 0.8 for 91% hemp at medium frequencies. Consequently, lime is a more effective material as a binder compared to cement, even though increase in binder ratio in hemp concrete results in decrease in α. All in all, hemp concrete can be well alternative sound absorptive natural and ecologic material for medium frequencies.

Bastos *et al.* (2012), examine sound absorption properties of non-toxic, renewable, low cost and appropriate natural materials for Brazil; sisal, palm, coconut and acai fiber. The panel respective samples are given in Figure 2.36. The fibers are washed with industrial neutral detergent and dried to avoid fungal growth and then pressed integrated with acrylate and water as a binder and subjected to temperatures 70 ± 2℃ and then 23±2℃. The α results are measured with reverberation chamber method and to compare α measurements of these materials with traditionally used sound absorptive materials (Sonec Roc and Sonec Flexonic). The comparison results are given in Figure 2.37. The results show that fibers as unifibers have low α but multifibers with palm/sisal and acai/coconut have compatible α values and at high frequencies superior values with traditional sound absorptive materials.

Figure 2.36 Panels and their respective samples (Bastos et al., 2012).

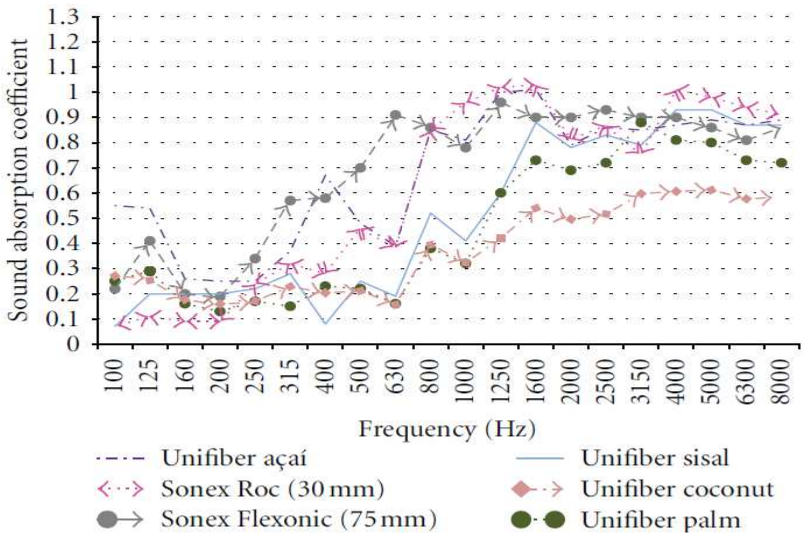


Figure 2.37 Comparison between unifiber panels and conventional acoustic materials sound absorption coefficients (Bastos et al., 2012).

2.4. RESEARCH ON THE MATERIALS USED IN THIS THESIS WORK

2.4.1. PUMICE

Erection of gases in the magma during sudden cooling forms the pumice, which is a volcanic, glassy, porous structure. Pumice contains up to 80% air void, which are parallel cells to each other and sometimes interconnected (İlter, 2010). According to TS 3234 pumice is defined as:

- Volcanic origin natural lightweight aggregate
- Contains up to 80% air voids
- Voids disconnected with each other
- Sponge looking
- Silicate essential
- Unit weight usually less than 1gr/cm^3
- Specific gravity generally more than 2.1gr/cm3
- Mohs hardness scale is around 5.5-6.0

- Glassy texture

(İlter, 2010)

Formation mechanisms of volcanic activity generate two types of pumice, basaltic and acidic pumice which are chemically differing from each other. Both of the pumice structures have very porous media, yet, the acidic magma is lower than basic magma. Density of acidic pumice is 500 – 1000 kg/m^3 and basaltic pumice is 1000 – 2000 kg/m^3, which means acidic pumice have more porous media than basaltic pumice (İlter, 2010). Smaller sizes of pumice means higher density, so, particle sizes should be higher to get a more porous media. The specific gravity of pumice stone is generally more than 2.1 gr/cm^3. The chemical content of acidic and basaltic pumice is given in Table 2.3.

Table 2.3 Chemical content of acidic and basaltic pumice in general (İlter, 2010).

Chemical Composition	**Acidic Pumice**	**Basaltic Pumice**
SiO_2	70%	45%
Al_2O_3	14%	21%
Fe_2O_3	2.50%	7%
CaO	0.90%	11%
MgO	0.60%	7%
$Na_2O + K_2O$	9.00%	8%

SiO_2 provides abrasiveness and Al_2O_3 ensures heat and fire resistivity to pumice. As can be seen from the Table 2.6, SiO_2 has a higher percentage in acidic pumice compared to basic pumice, which makes the acidic pumice have higher puzzolanic reaction, thus, more useful for construction (İlter, 2010).

Another source (Sarıışık & Sarıışık, 2012) gives the chemical and physical properties of acidic pumice in Nevşehir Region in Table 2.4.

Table 2.4 Chemical and physical properties of acidic pumice in Nevşehir Region (Sarıışık & Sarıışık, 2012).

Chemical and Physical Properties of Acidic Pumice	**Unit**	**Values**
SiO_2	%	70.06
Al_2O_3	%	12.74
Fe_2O_3	%	1.30
CaO	%	0.85
MgO	%	0.34
Na_2O	%	3.20
K_2O	%	4.06
Color	-	White
Mohs hardness	-	6
pH	-	5.5-6.0
Specific gravity	kg/m^3	2,260.0
Dry bulk density	kg/m^3	423.0
Water absorption	%	34.0
Compactness ration	%	18.5
Real porosity	%	69.0
Visible porosity	%	81.5
Thermal conductivity	W/mK	0.132
Plaster holding	-	Very good
Specific heat capacity	kcal/kg ºC	0.255
Sound conductivity coefficient	-	0.20

Dry unit weight of pumice with respect to particle size is given in Table 2.5. Percentage of real porosity of pumice with respect to particle sizes is given in Table 2.6.

Table 2.5 Dry Unit Weight of Pumice with respect to Particle Size (İlter, 2010).

Range of Particle Size (mm)	Dry Unit Weight (kg/m^3)
≥32	319±5%
16-32	408±5%
8-16	502±5%
4-8	594±5%
2-4	688±5%
1-2	780±5%
0.5-1	873±5%
0.25-0.5	966±5%

Table 2.6 Percentage of Real Porosity of Pumice with respect to Particle Sizes (İlter, 2010).

Range of Particle Size (mm)	Real Porosity (%)
≥32	86.29±3%
16-32	82.47±3%
8-16	78.43±3%
4-8	74.47±3%
2-4	70.43±3%
1-2	66.48±3%
0.5-1	62.48±3%
0.25-0.5	58.49±3%

The tables indicate that as the range of particle size increases, the dry unit weight increases, conversely, real porosity decreases.

Pumice reduces heat of hydration damage 10-40% during the first 100 hours and helps to a cooler more controlled set. Furthermore, pumice increases the long term compressive strength of lime according to laboratory tests made with 4 pumice-lime aggregate day by day. Besides, pumice does not contain crystalline silica and other harmful materials which make it healthy and safe. Pumice is naturally calcined by nature and has a minimal contribution to the carbon footprint (Thomas, 2012).

Pumice reserves in Turkey are very significant. Turkey has the second largest pumice reserve proportion with 2.8 billion tons of 18.0 billion world reserves after USA (Elmastaş, 2012). In Turkey approximately 50% of the pumice reserves exist in Bitlis-Tatvan and a high percentage (35%) of exist around Kayseri and Nevşehir region. In recent years, Turkey has passed Italia in terms of pumice export and became the leading export country in the world (Elmastaş, 2012). If usage in production with new developments and export of this mine can be improved in Turkey, it can also provide an economic opportunity for Central and Eastern Anatolian Region.

2.4.2. LIME

The binder is a very important ingredient for a sound absorptive material that affects the porosity (Gle *et al.*, 2011). Cotana & Goretti (2008) define the lime to have low energy consumption, optimum biological qualities and availability. They add that water (hydraulic) lime can be used instead of concrete due to obtain greater transpiration, absorption, insulation, thermo-hygrometric regulation properties as a result balanced indoor microclimatic conditions.

In construction industry, commonly used binding agents for acoustic plasters include basically cement. Nevertheless, during production cement demands considerable energy as limestone, sand and other metal ores are heated to 1500 °C with coal to form clinker (Spencer, 2012). The objective is to create an ecological low carbon foot-print material so decreasing the manufacturing energy is vital for low energy consumption. Lime is a more acceptable binder than cement in terms of both energy issues and acoustical properties. Production of lime requires less energy than cement and lime takes back the given CO_2 during its life time in building. Although the carbonation of lime that helps to take the CO_2 back is a positive feature in terms of indoor air quality, as the porosity of the material is being decrease, this may affect the sound absorption capacity negatively.

The work of Gle *et al.* (2011) on hemp concrete, previously mentioned includes measurement and comparison of three types of binders:

A. 75 % aerated lime, 15% hydraulic lime and 10% puzzolanic lime,
B. Hydraulic lime
C. Quick natural cement

The sound absorption coefficient measurement results of hemp concrete according to the binders are given in Figure 2.38. The results show that the composites produced with lime binders have higher sound absorption performances compared to the composite with cement binder.

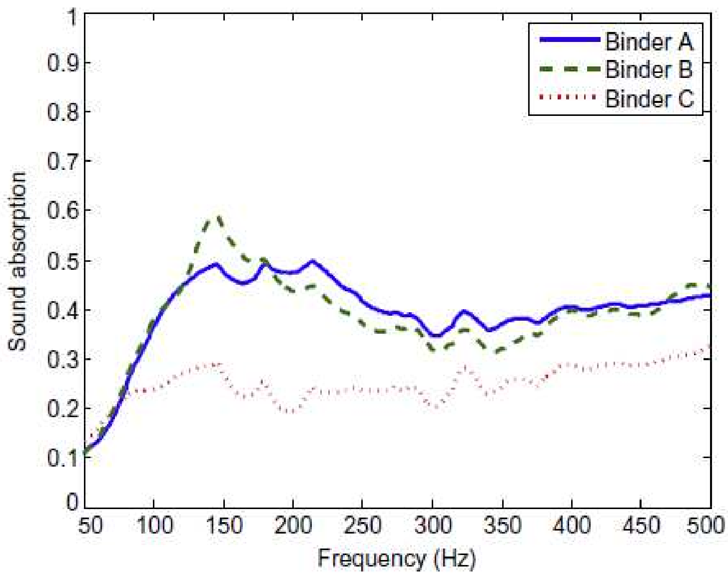


Figure 2.38 Sound absorption of hemp concrete according to the binder. (Gle et. al., 2011).

2.4.3. PUMICE AND LIME AS A PLASTER

Pumice and lime extends to Roman architecture in construction industry as a plaster such as Pantheon and Coliseum still standing today (Thomas, 2012). In ancient Roman, hydrated lime with pumice puzzolan, CSH (Calcium Silicate Hydrate) is produced which is a densified and durable plaster with no additional destructive by product such as CH (Calcium Hidroxide). Grasser & Minke (1990) assume that the first building brick made of pumice and milk of lime as a slow hardening binder dates back to 1845 in Germany.

Grasser & Minke (1990) indicate that panels, plasters or blocks made of pumice should be dried before use. They also indicate that pumice can be mixed with lime instead of cement to make building materials. The authors warn that the characteristic of the lime is significant and hydraulic or better eminently hydraulic lime should be preferred. Besides, lime should contain as little salt as possible particularly in the form of sulfuric acid because of its destructive effect on mechanical strength. The authors recommend;

-250 kg lime with water for 1 m^3 pumice (approximately 250 kg lime/450-500 kg pumice)
-250 kg lime and 150 kg Portland cement with water for 3 m^3 pumice.

Nozahic *et al.* (2012) explore pumice and lime as binder for lime hemp concrete. They work on an ecologic fiber reinforced concrete made of hemp and lime. As the idea is to create an environmentally friendly material, they try to generate an energy efficient composite and use pumice and lime as a binder rather than cement. They assume that pumice and lime mixture with water create a lightweight, smooth and plaster-like binder as Romans had used centuries before. The authors explain that they use a hydrated calcic lime rather than hydraulic lime because of the ability of generating only puzzolanic and carbonation reactions, besides better durability. The chemical properties of the pumice and lime that are used in the research are given in Table 2.7 and pumice sand granulometric curve is given in Figure 2.39.

Table 2.7 Chemical composition and densities of binder raw materials (Nozahic et al., 2012)

	CaO (%)	**SiO_2 (%)**	**Al_2O_3 (%)**	**Na_2O (%)**	**K_2O (%)**	**Fe_2O_3 (%)**	**Bulk density**	**Specific density**	**Saturated solution (pH)**
Pumice sand	1.1	62.2	17.3	5.9	6.3	2.7	1050	2115	7.5
Pumice sand soluble part in hydrofluoric acid	–	52.6	17.5	6	6.3	–	–	–	–
Lime CL90 (EN 459-1)	>94	–	–	–	–	–	450	2525	12.6

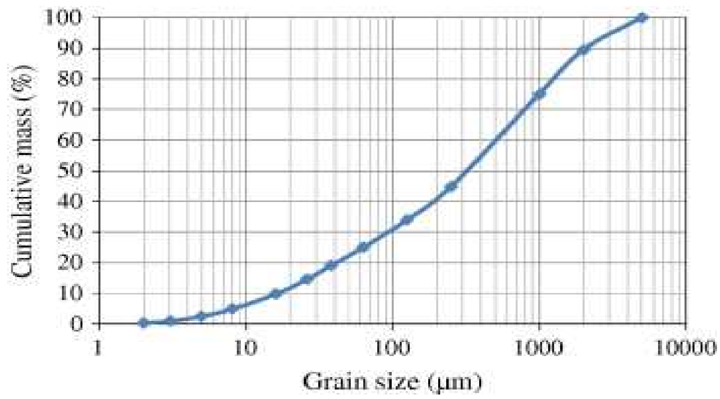


Figure 2.39. Pumice sand granulometric curve (Nozahic et al., 2012).

The binder including pumice and lime are conducted several mechanical tests by Nozahic et al. (2012) shows that the content of lime at 10% and pumice of 90% by weight has the optimum compressive strength. Test result show that pumice lime mixture has 8.3 MPa compressive strength at 28 days for a 5 MPa compaction.

Besides, increasing the lime content from 10% to 20% does not make a significant improvement on compaction. The test results are given in Figure 2.40 and Figure 2.41.

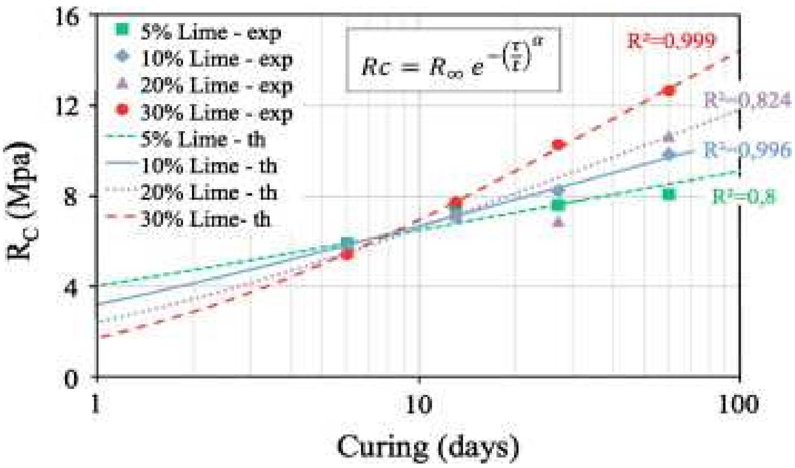


Figure 2.40. Pumice–lime binders compressive strength evolution with lime mass content and time (Nozahic et al., 2012).

Figure 2.41 shows that compression strength of the pumice-lime binder increases with time, and the lime content effects the strength of the plaster positively. Yet, the experimental results show that the compression strength is stabilized after 100 days of curing.

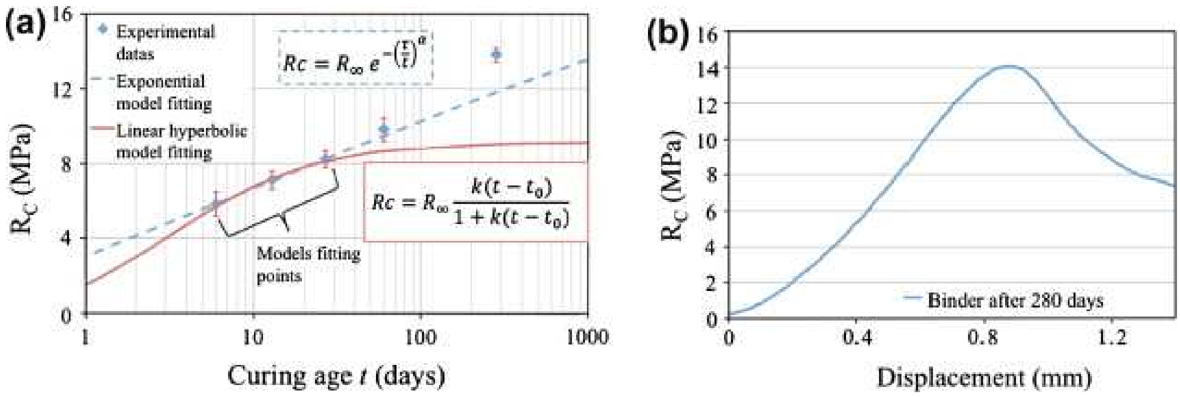


Figure 2.41. Compressive strength evolution during curing and comparison between linear hyperbolic and exponential models (a), mechanical behavior at 280 days compressive test (b) for the pumice–lime binder B-5 MPa (Nozahic et al., 2012).

Nozahic et. al. (2012) discuss that the experiments show that raw sand pumice and lime mixture is a promising binder. They discuss that pumice/lime ratio of 9:1 in weight obtains a compressive strength larger than 8 MPa after 28 days.

2.4.4. REED

Reed is a perennial grass of the Gramineae (Poaceae) family growing in humid and both moderate and hot climates. Some of similar reed family names are phragmites australis and scirpus lacustris. It's height ranges from 1.5 to 4 m and up to 2 cm thickness having many closed pores with density of roughly 160 kg/m^3. It includes 42.5-45% cellulose, 22-24% lignin, 24-27% pentosan, 1.5-6% wax, fat and resin and 4.7-5.6% minerals. Its thermal conductivity λ is 0.055 $w/m.K$ in Central Europe. It has been used in construction industry for centuries due to its mechanical and tensile strength, water resistance and durability. Reed also can be combined with plaster, lime or clay (Diaz *et al.*, 2012).

Reed grows in wet areas like lake and river sides in Turkey. The local communities make baskets and ornaments with reed and use it in floors and ceilings for local buildings such as sheds. Vast majority of the reed is exported to USA and other countries (Tapan *et al.*, 2008). Turkey has very significant wetland areas due to geographic location. On the other hand, Turkey has lost half of the wetlands (1.200.000 ha) because of drying, filling and various water area disturbances. Turkey has signed International Convention for the Protection of Wetlands in 1994 (Ramsar). 12 wet areas have been protected as Ramsar Area since then. According to this contract, Wetlands Protection Regulations in Turkey has some restrictions and rules about cutting and collection of reeds. The significant rules about the reed are that cutting is forbidden during breeding period of animals living in that habitat and only 30 % of reeds can be cut in that season (Orsam, 2011).

Espada *et al.* (2007) describe the properties of reed as organic, cheap, good thermal and structural behavior and low impact on environment. They add that hollow tubes with knots are good for sound absorption. Their work is on measurement of sound absorption properties of reed with reverberation chamber method. As for reverberation chambers the edges of the materials may affect the results, they measure both with and without covered edges. They use 5 cm thick layers of reed in 1, 2 and 3 layered configurations and the results are promising, 1 layer reed absorption coefficients are the best in medium frequencies, on the other hand the α increases while the thickness increases for low frequencies and the thickness does not affect the higher frequencies. The results are given both with covered edges and uncovered edges in Figures 2.42 and 2.43. Also they simulate reverberation time of a room with two walls covered with 5 cm reed and the RT decreases 2 seconds to below 0.5 seconds which means reed is a good absorptive material for room acoustics.

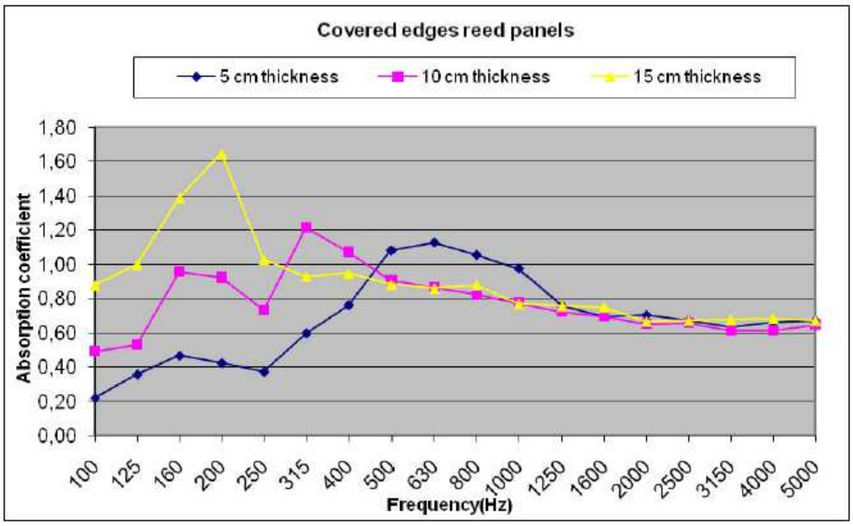


Figure 2.42. "Effect of the reed thickness in sound absorption coefficient. Covered edges" (Espada et al.,2007).

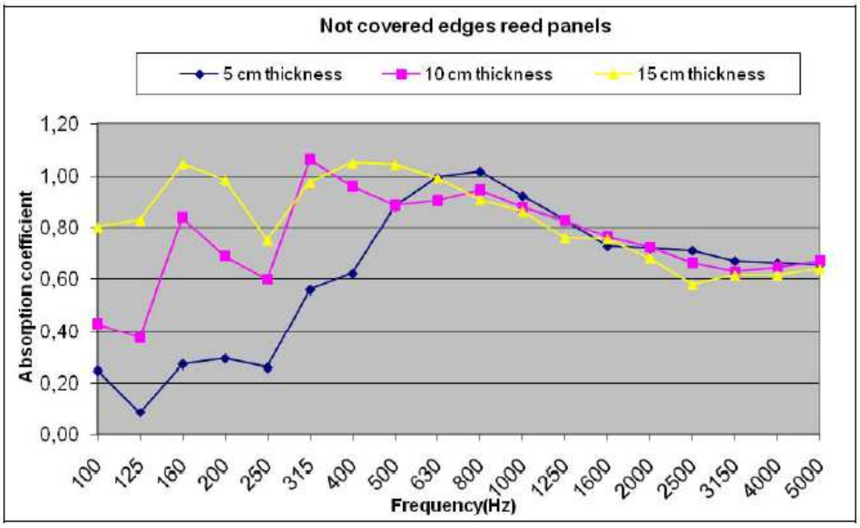


Figure 2.43 "Effect of the reed thickness in sound absorption coefficient. Not covered edges" (Espada et al.,2007).

Diaz *et al.* (2012), measured the sound absorption coefficients of reed in perpendicular configuration in a $65m^3$ reverberation chamber. They measured the 5, 10 and 15 cm

samples, similar with Espada *et al.* (2007).'s work and results are similar, as well. They also made measurements of the reed panel as a suspended ceiling application simulation with 20 cm airspace behind. The results are shown in Figures 2.44 and 2.45.

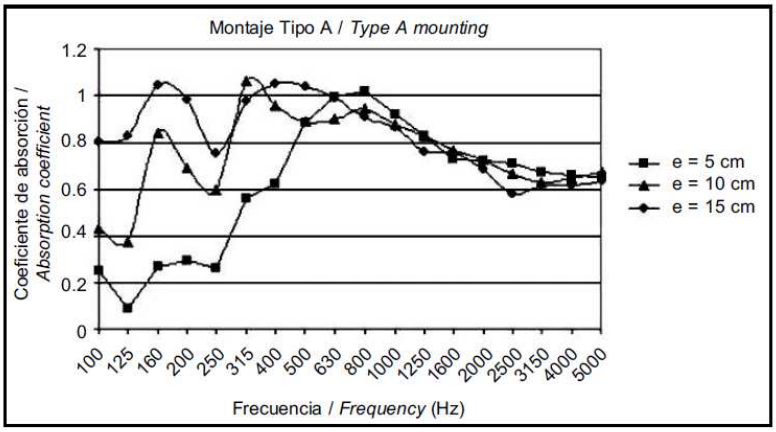


Figure 2.44 Effect of panel thickness on the sound absorption coefficient (Diaz et al., 2012)

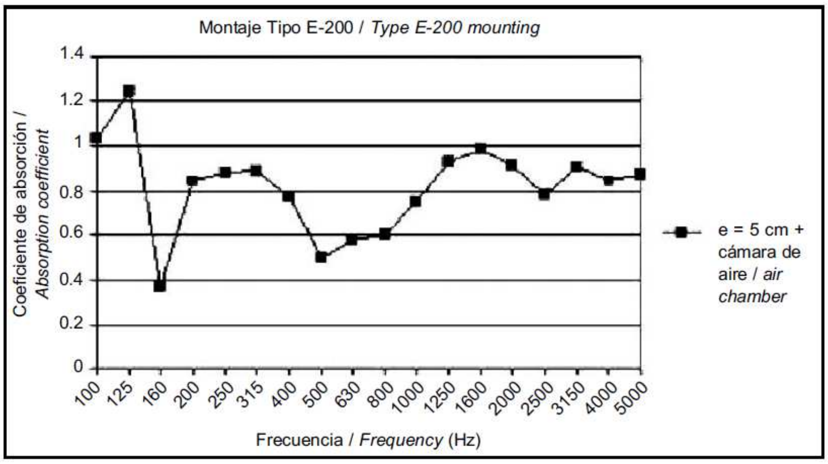


Figure 2.45 Sound absorption coefficients for reed panels simulating a suspended ceiling (Diaz et al., 2012).

The Figure 2.45 shows that the 200 mm air space behind 5 cm thick reed panel increases the low frequency sound absorption and provides a sound absorption performance that is similar to 15 cm thick reed panel.

Chilekwa *et al.* (2006), introduces the sound absorption characterization of reed in different configurations with impedance tube method. Besides they make predictions on configurations and compare the results. The results are shown in Figures 2.46, 2.47, 2.48.

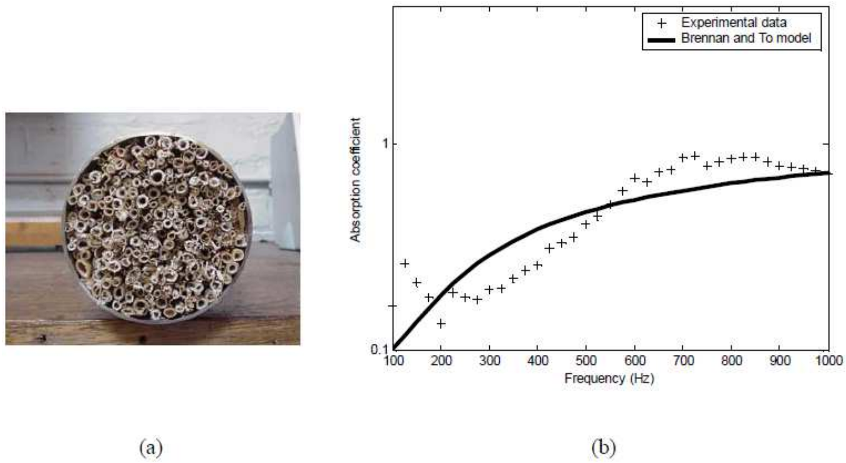
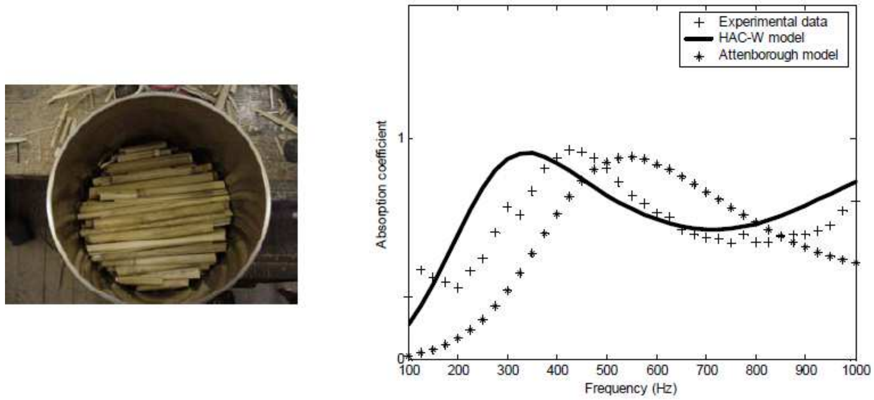
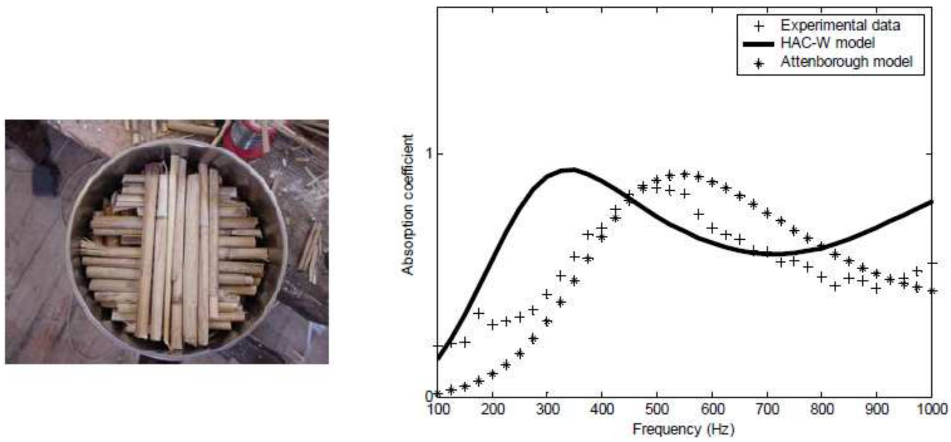


Figure 2.46 Acoustic performance of the parallel reed configuration. (a) reeds in sample holder (b)comparison of experimental data and predictions (Chilekwa et al., 2006).



(a) (b)

Figure 2.47 Acoustic performance of the perpendicular reed configuration. (a) reeds in sample holder (b)comparison of experimental data and predictions (Chilekwa et al., 2006).



(a) (b)

Figure 2.48 Acoustic performance of the cross reed configuration. (a) reeds in sample holder (b)comparison of experimental data and predictions (Chilekwa et al., 2006).

As seen in the figures the prediction and experimental results are different but the slope characteristics are similar. It can be derived that the parallel reed configuration, has a stable increase from low to high frequencies, conversely, sound absorption characteristics are increasing in perpendicular configurations for low frequencies.

The work of Oldham *et al*. (2011) as previously described in previous chapter, analyses the reed configurations and compares the results with straw sound absorption coefficients. The picture of the samples is given in Figure 2.49. Besides, they examine a composite made of reed and hemp. The results are given in Figures 2.50 to 2.51.

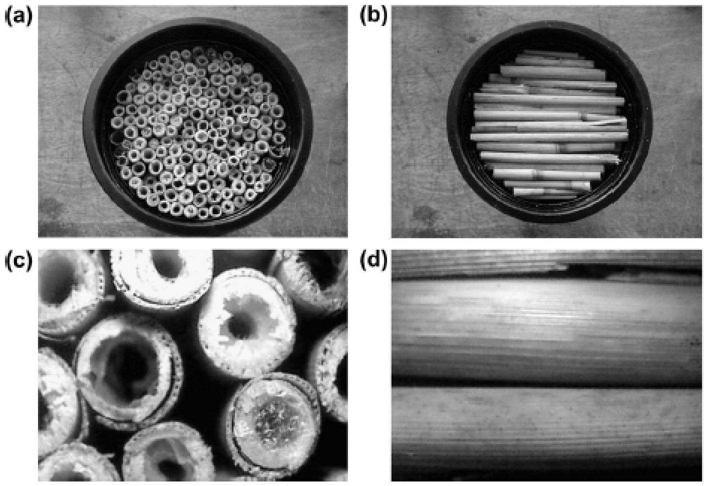


Figure 2.49 (a) End-on reeds in large sample holder. (b) Transverse reeds in large sample holder. (c) Magnified view of end-on reeds showing pitch in reed tubes and gaps between reeds. (d) Magnified view of transverse reeds showing gaps between aligned reeds (Oldham et al., 2011)

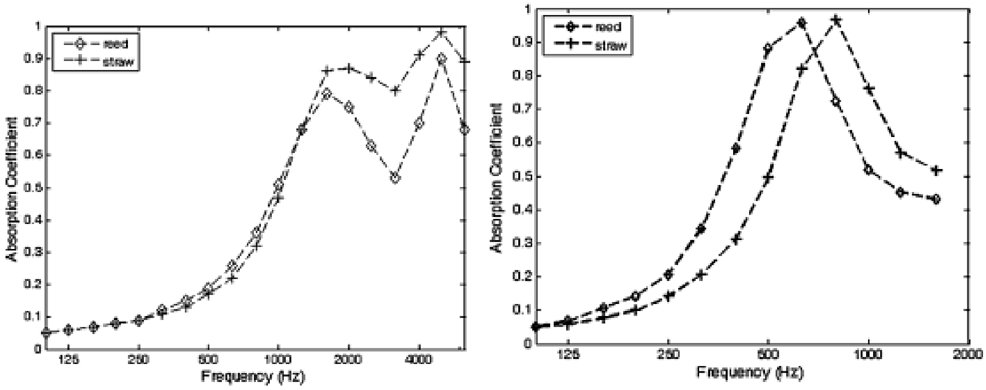


Figure 2.50 Normal incidence absorption coefficient of straw and reeds in end-on configuration measured using small and large impedance tubes (left figure). Absorption coefficient of transverse straw and reeds (aligned perpendicular to the incident sound) measured using large impedance tube(right figure) (Oldham et al., 2011)

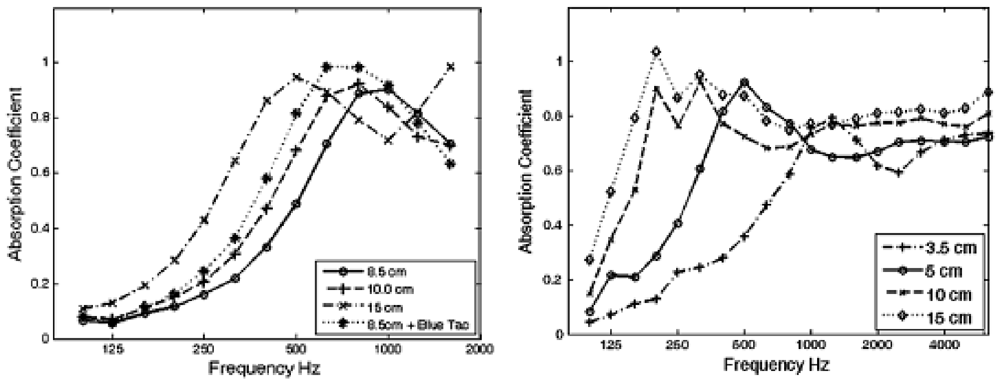


Figure 2.51 Normal incidence absorption coefficient of end-on reeds of different lengths measured using large impedance tub. (left figure). Absorption coefficient of aligned reeds of different thickness measured in reverberation room (right figure) (Oldham et al., 2011)

The Figure 2.50 shows that reed with parallel to incident sound configuration has weak sound absorption performance both at low and high frequencies. On the other hand, perpendicular to incident sound configuration has significantly better sound absorption performance for both low and high frequencies. Besides, the thickness of the reed results in better sound absorption for both configurations.

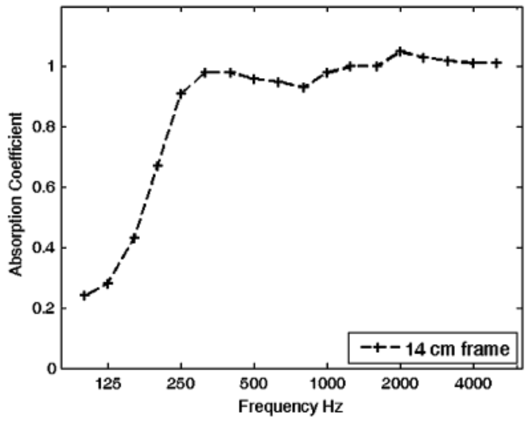


Figure 2.52 Absorption coefficient of end-on reeds of nominal length 14 cm measured in reverberation room (Oldham et al., 2011).

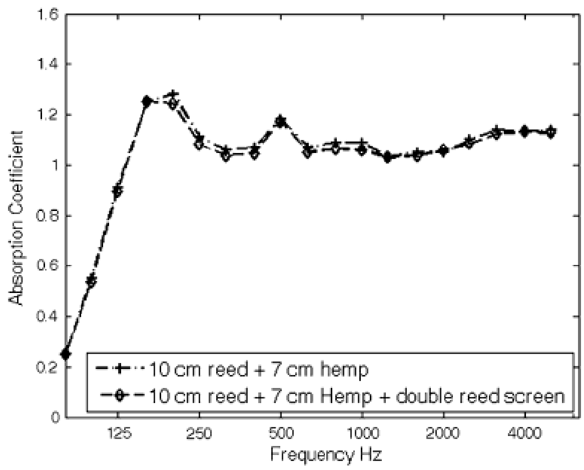


Figure 2.53 Absorption coefficient of composite system composed of 10 cm thick reed underlay, 7 cm hemp batt and thin double reed surface measured in reverberation room (Oldham et al., 2011).

Figures 2.52 and 2.53 show that larger thickness of reed, results in better sound absorption, even for low frequencies. On the other hand, addition of hemp and extra reed layers do not result to a significant change in sound absorption.

Figure 2.53 shows that decrease in reed thickness for reed and hemp layered configuration, results in reduction at low frequency sound absorption.

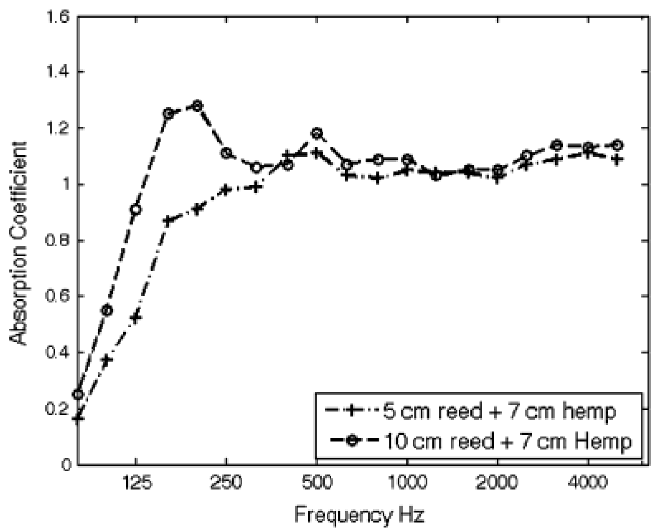


Figure 2.54 Absorption coefficient of broadband composite sound absorber consisting of reed underlay with hemp batt on top measured in reverberation room (Oldham et al., 2011).

2.5. EVALUATION OF LITERATURE

The survey of literature of this thesis research is based on green building design, architectural acoustics, the relationship between the two topics, ecologic sound absorbers in literature and the survey on the materials used in this study.

It is obvious that emphasized acoustical requirements in green building design criteria are very limited as mentioned in literature (Muehleisen, 2010, Şan *et. al.*,2011, Field, 2008) and should be improved according to sustainability parameters. Especially, the relationship between natural lightening, air conditioning and acoustical requirements should be analyzed carefully. The material selection is a very important issue for indoor air quality and sustainability, nevertheless, if the acoustical requirements are not considered, these subjects can cause worse acoustical conditions in green buildings.

Acoustical comfort requirements are very important for healthy indoor environments. However, the materials used for acoustical precautions are not healthy materials at all. Most of the sound absorptive materials are mineral wool based materials or perforated materials supported with mineral wools. This is a very significant problem for healthy environments, as these wools have bad effects on health, furthermore, these synthetic fibers are not energy efficient as described by Astrubali (2006). Whereas, variety of natural fibers exist that are more ecologic and economic in nature as illustrated by Mahzan *et. al.* (2009). The materials used for acoustical precautions both for building acoustics and room acoustics should be commentated in terms of health and energy efficiency and new materials should be discovered and promoted to be used in construction industry.

In the literature there are varieties of natural materials that are worked on in terms of sound absorption (Gle *et al.* 2011), (Oldham *et al.*,2011) , (Saadatnia *et al.,* 2008), (Mohd *et al.,* 2004), Bastos, *et. al.* (2012). Most of these materials have very good acoustical performances. Barely, only one herb, jute is commercialized in construction industry as a natural sound absorber with fine finish. Also reed panels are commercialized not because of its sound absorption capacity but as a ceiling material. These materials that are in research base should be developed in terms of constructability requirements and natural and healthy sound absorptive materials in construction industry should be diversified.

The architects’ choice is another significant point on the selection of interior surfaces. Most of the architects do not prefer perforated finishes because of aesthetical deficits. They prefer fine seamless finishing. Besides, perforated surfaces are not desired on wall surfaces because of the location which people can reach and damage. However, most of the sound absorptive materials are perforated with mineral wool backing and the ones that are unperforated are import and expensive sound absorbers.

In this thesis research, a sustainable sound absorber is intended to be developed which is also local and economic. The inspirations of the ideas, covering the information in literature, that are the occasions to construct such a configuration with three layers are given in this section.

The inspiration of the idea of fine finishing surface for the desired sound absorber in this study is the preference of the architects. Most of the commercialized sound absorbers in construction industry with fine finishing are layered systems made of glass particles and cement plasters with glass or rock wool backings. The basic of idea to design a fine plaster finish sound absorber configuration with fibrous backing material is this kind of materials’ being import and expensive.

In Turkey, generally gypsum and cement products are used as plaster surfaces, whereas, pumice is a natural porous stone that is used as a plaster for centuries which is also a good sound absorber having a large reserve in Turkey. Also, lime, which is used as a binding agents for pumice plaster has a great puzzolanic activity together with pumice (Nozahic *et al.*, 2012). Besides, Thomas (2012) work on pumice and lime expresses the conformity of pumice and lime in terms of strength and health. Furthermore, Cotana&Goretti (2008) describe the lime as energy efficient and optimum in terms of biologic qualities and availability. Although lower energy is consumed in production of lime as described by Spencer (2012) and better sound absorption performance is examined in the work of Gle *et al.* (2011) compared to cement, the lime content is intended to be used as little as possible since the binding agent may cause to lower sound absorption performance.

The two layered system for the plaster is desired to get a more porous plaster media at the bare coat and a fine finishing surface which is intended to be smooth as much as possible and thin to transfer the sound to the bare coat easily. In addition, the two layered plaster surfaces are more durable and clear if the rough and fine plaster is illustrated. In this study granular pumice particles are desired for bare coat as a more porous media as given in Table 2.6 and likewise pumice powder is selected to get a fine plaster coat.

The plaster surface which is desired to be a porous media as a plaster needs porous backing to have a higher sound absorption performance especially in medium frequencies. One objective of this thesis study is to develop an ecologic sound absorber with natural materials. The survey on natural sound absorbers gives very useful information about natural sound absorbers. Reed, which is natural herb that is rapidly renewable is a perfect selection in terms of sustainability, durability and acoustical performance if the works of Espada *et al.* (2007), Diaz *et al.* (2012), Chilekwa *et al.* (2006) and Oldham *et al.* (2011). This herb also is used as a construction material for centuries in the world. Turkey has a large wetland area where the reed finds essential habitat to grow spontaneously. In fact, the cutting rules and times of the reed is described in the Wetland Protection Regulations in Turkey as mentioned in the work of Orsam (2011). The breathing structure of lime, in addition to porous media of pumice can help the reed to get dry and resistant to fungal attracts and water vapor. The breathing media of pumice and lime plaster can transmit the sound to the reed layer and the reed can absorb the transmitted sound in its structure and convert it to heat energy.

In the light of the wide information of both the topics of the thesis and the materials that are intended to be used in this thesis study, a three layered configuration made of local and ecologic materials, pumice, lime and reed, is examined. The experiments according to parameters that affect the acoustical properties are conducted to improve the sound absorption properties of the configuration which are reported in detail in the following chapters.

CHAPTER 3

MATERIAL AND METHOD

3.1. MATERIAL

The scope of this work is to develop a sustainable and local sound absorptive material with a smooth surface finish. The materials are selected according to such properties; ecological, economical, appropriate to Turkey's natural resources with good acoustical properties.

The basic materials that are used for this composite are pumice, stone and reed. Lime, which is more energy efficient that have better sound absorptive properties compared to cement and gypsum products is used as a binding agent for the layers of pumice plaster.

Pumice is a significant raw material that has large amount of reserves in Turkey. The material is a volcanic lightweight aggregate that has porous structure and have good acoustical properties as described in İlter (2010) and Sarıışık&Sarıışık (2012). Asidic pumice is selected for the experiments in the light of the information that acidic pumice has higher puzzolanic reaction which makes it more useful for construction and more porous media compared to basaltic pumice. (İlter,2010).Besides, pumice has a large use area in construction that has good fire resistivity and water resistance. The pumice content of acidic type is acquired from Nevşehir Region which has the 35% of the pumice reserves in Turkey. The chemical and physical properties of pumice from Nevşehir region are given in Table 2.4 in the previous section. The dry unit weight and real porosity of the pumice according to particle diameter are given in Table 2.5 and Table 2.6, respectively.

Reed is a natural material that grows spontaneously on the shores of rivers and lakes in Turkey. This natural herb is in tubular configuration which is a significant property in terms of acoustics as mentioned in the work of Espada *et al.* (2007). Besides, reed has been used in traditional buildings as well as rural areas and holiday villages as a ceiling material. The resistance of fungal attacks and water makes the reed a natural material that is appropriate for construction industry. The direction of the reed layer that is perpendicular to incident sound is selected in the light of Espada *et al.* (2007), Diaz *et al.* (2012), Chilekwa *et al.* (2006) and Oldham *et al.* (2011) ‘s works mentioned in literature. In these studies that are realized both reverberation chamber measurement method and Impedance tube method show that the sound absorption performance of the reed is better for low and medium frequencies. Furthermore, application of reed is easier as a panel in construction industry. The layer of reed in varying diameters in configurations is obtained from METU Campus. The reeds for the measurements are collected in between October to November when it is legal to harvest them according to Regulations on Wetland Areas in Turkey.

Lime is a binding agent that has been widely used in construction for centuries. The popular production of cement with higher strength for structural elements has reduced the usage of lime in construction sector. On the other hand, lime binder with pumice aggregate has well compressive strength according to Nozahic *at al.* (2012), besides, energy efficiency and breathing properties of lime is significant for indoor air quality. Using lime as a binding agent for pumice helps to keep the pumice structure porous and efficient for sound absorption. Besides, the harmony of lime and pumice is very well that are used for centuries since ancient times as described in Nozahic *et al.* (2012)’s work. Besides, the structure of lime is more efficient in terms of sound absorption (Gle *et al.*, 2011) and with the breathing activity lets the reed keep dry and helpful to use it as a construction material. The lime content that is used in this research is a local product.

The configuration of the materials are given in Figure 3.1.

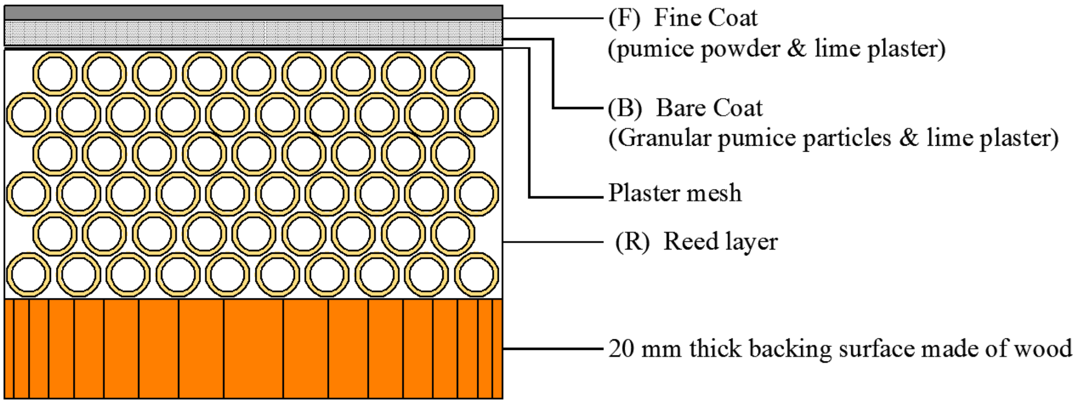


Figure 3.1 Configuration of layers.

The pumice plaster that is used as the fine coat with lime binder (F) is powder of pumice with a width varying between 0 to 0.5mm. The granular pumice plaster (B) with granular pumice particles with biding agent lime is used as a bare coat. For the 1st Experiment, 3 to 7mm wide raw pumice and for the rest of the research, 0.5 to 2mm wide pumice is used for undercoat. For the first experiment hydraulic lime (CaO) is used. Nevertheless, as the slaking of lime is difficult to control, thus, hydrated lime (lime putty ($CaOH_2$)) is used for the all subsequent experiments. The reed layer is aligned perpendicular to incident sound with the thickness of 40 mm. The reed layer treats as a cavity behind the pumice plaster and expected peak frequencies are calculated according to Equation 2.4.

The selection of thickness for the reed layer is basically the effective sound absorbers in construction industry for medium frequencies being in the range of 50 mm thickness in total. This approximate thickness is also desired for easier application for sound absorbers. Most of the perforated absorbers with mineral wool backing such as perforated metal, gypsum and wood products, besides, fine finish sound absorbers with mineral wool backings in construction industry are mostly in the thickness of approximately 50 mm.

The plaster mesh to provide connection between reed and pumice aggregates is added to configuration after the first experiment to provide a connection media between reed layers and plaster.
The investigations are performed with four basic experimental configurations in four phases. The material properties are given below.

3.1.1. Experiment I

For the Experiment I, the material configuration that the measurements are performed is given in Table 3.1.

Table 3.1 Material configuration for Research Question 1.

F1B1R1			
Code	**Layer**	**Thickness**	**Content**
F1	Fine Coat	2 mm	0-0.5 mm wide pumice (pumice powder), lime (Pumice:Lime:2:1 by mass) and water
B1	Bare Coat	10 mm	3-7 mm wide raw pumice stone, lime (Pumice: Lime: 2:1 by mass) and water.
R1	Reed	40 mm	40 mm thick Reed (⌀: 2 to ⌀:5 mm tubes)

3.1.2. Experiment II

For the Experiment II, the material configuration that the measurements are performed is given in Table 3.2.

Table 3.2 Material configuration for Research Question 3

F2B2R2			
Code	**Layer**	**Thickness**	**Content**
F2	Fine Coat	2 mm	0-0.5 mm wide pumice (pumice powder), lime putty (Pumice:Lime:2:1 by mass)
B2	Bare Coat	5 mm	0.5-2 mm wide pumice, lime putty (Pumice:Lime:2:1 by mass)
R2	Reed	40 mm	40 mm thick Reed (⌀: 4 mm to ⌀: 7 mm tubes)

3.1.3. Experiment III

For the Experiment III, the material configurations that the measurements are performed are given in Table 3.3.

Table 3.3 Material configurations F3B3R3, F3B3R4, F3B3R5

F3B3R3			
Code	**Layer**	**Thickness**	**Content**
F3	**Fine Coat**	3 mm	0-0.5 mm wide pumice (pumice powder), lime putty (Pumice:Lime:3:1 by mass)
B3	**Bare Coat**	7 mm	0.5-2 mm wide pumice, lime putty ((Pumice:Lime:4:1 by mass)
R3	**Reed**	40 mm	40 mm thick Reed (⌀: 3 mm to ⌀: 4 mm tubes)

Table 3.3 continued…

F3B3R4			
Code	**Layer**	**Thickness**	**Content**
F3	**Fine Coat**	3 mm	0-0.5 mm wide pumice (pumice powder), lime putty (Pumice:Lime:3:1 by mass)
B3	**Bare Coat**	7 mm	0.5-2 mm wide pumice, lime putty ((Pumice:Lime:4:1 by mass)
R4	**Reed**	40 mm	40 mm thick Reed (⌀: 5 mm to ⌀: 6 mm tubes)
F3B3R5			
Code	**Layer**	**Thickness**	**Content**
F3	**Fine Coat**	3 mm	0-0.5 mm wide pumice (pumice powder), lime putty (Pumice:Lime:3:1 by mass)
B3	**Bare Coat**	7 mm	0.5-2 mm wide pumice, lime putty ((Pumice:Lime:4:1 by mass)
R4	**Reed**	40 mm	40 mm thick Reed (⌀: 8 mm to ⌀: 10 mm tubes)

3.1.4. Experiment IV

For the Experiment III, the material configurations that the measurements are performed are given in Table 3.4.

Table 3.4 Material configuration F4B4R4

F4B4R4			
Code	**Layer**	**Thickness**	**Content**
F4	**Fine Coat**	2 mm	0-0.5 mm wide pumice (pumice powder), lime putty (Pumice:Lime:7:3 by mass)
B4	**Bare Coat**	5 mm	0.5-2 mm wide pumice, lime putty ((Pumice:Lime:7:3 by mass)
R4	**Reed**	40 mm	40 mm thick Reed (⌀: 5 mm to ⌀: 6 mm tubes).

3.2. METHOD

In this thesis research, sound absorption performances of the configurations mentioned in previous chapter are investigated.

The main hypothesis of the research:

"A three layered configuration made of a fine coat with pumice powder plus lime, bare coat made of granular pumice particles plus lime and a porous backing layer made of reed works well as a sound absorber."

is investigated.. Variations of configurations according to various parameters that affect the sound absorption, referring the literature information given in 2.1.3 are investigated to improve the configuration. The investigated parameters are summarized below:

a. Granular sizes of pumice particles
b. Thicknesses of pumice plaster layers
c. Percentage of binder content (lime)
d. Diameters of reed
e. Porosity

The first experiment is performed to understand the behavior of the materials and forecast if the hypothesis can be verified or not. According to first experiment results, sub-hypothesizes are constructed and experiments are performed to understand the effects of variables and achieve better results. Four basic sample configurations are investigated as given in the material section.

The experimental analysis of the sound absorption properties of the configurations is performed with the Impedance Tube Method that is described in literature survey. The experimental setup of this impedance tube measurement system is shown in Figure 3.2.

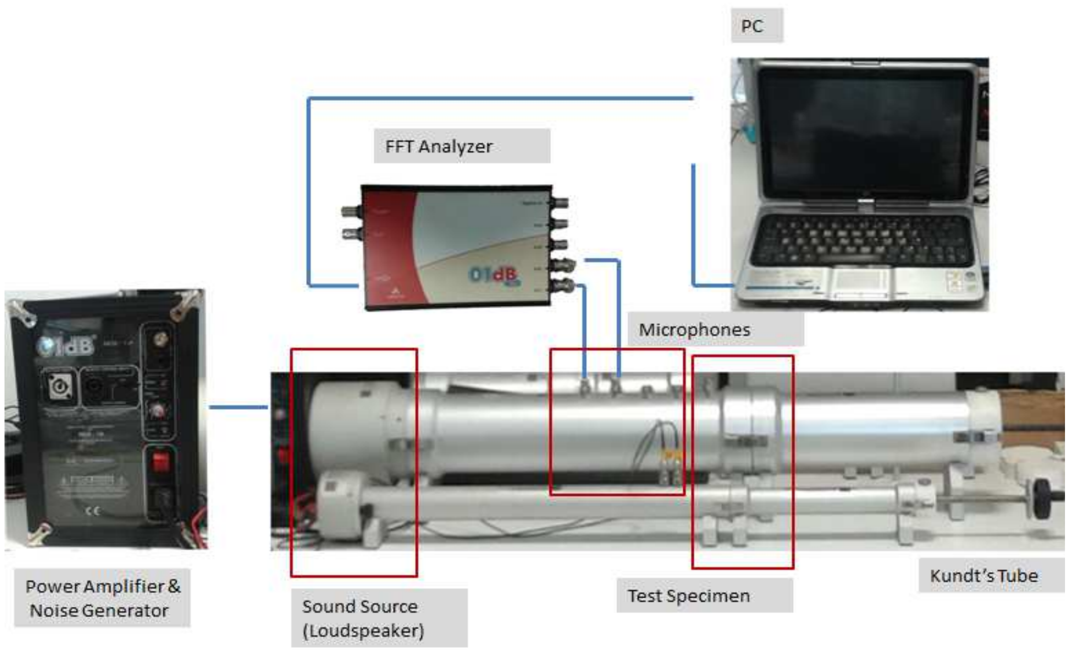


Figure 3.2 The experimental setup of impedance tube measurement system.

Pumice aggregate, mixed with lime as a binding agent is used to obtain plaster layers in this study. Reed is used as a sound absorptive porous media for backing layer. Samples are prepared in 100 mm and 28 mm diameters to be examined by small and large impedance tubes, respectively, for the ranges of low-to mid and high frequencies. All the experiments are realized at room conditions, in approximately 22 ºC and 25% of relative humidity.

The production methods for the configurations mentioned in the material section are given below.

3.2.1. Experiment I

For the first experimental investigation, the layers of the plasters F1 and B1 are prepared in separate pieces and dried for 3 days. The percentage of the lime content is set according to recommended pumice/lime ratio of Grasser & Minke (1990). The reed layer (R1), with diameter ranging from 2 mm to 5 mm aligned perpendicular to incident wave with 40 mm thicknesses. The samples of materials are given in Figure 3.3.

Figure 3.3 Layers of the configuration: left: reed (R1), center: small diameter pumice aggregate (F1) and right: wider pumice aggregate (B1).

Firstly, the three layered configuration (F1B1R1) is measured. Subsequently, the bare coat (B1) is subtracted from the configuration and the **sub-hypothesis 1:** “The sound absorption performance of the configuration is better without granular pumice plaster layer.” is investigated.

3.2.2. Experiment II

For the second experiment the **sub-hypothesis 2:** "Decrease of granule sizes of pumice plaster results in increase of sound absorption performance of the three-layered configuration."
is investigated. The picture of the configuration is given in Figure 3.4.

Figure 3.4 F2B2R2 Configuration

Reed layer (R2) is formed perpendicular to incident sound as in the first experiment. The lime (CaO)'s being very difficult to prepare, quicklime ($CaOH_2$) is used for this configuration and the following investigations. A plaster mesh is inserted on the reed layer and a bare coat of pumice plaster (B2) is applied on this mesh. The fine coat of the pumice plaster (F2) is applied on the configuration after about a twelve hour desiccation.

The first measurement is realized after three days of drying and the measurements are repeated in 13th, 33rd and 60th day after the configuration produced to investigate the **sub-hypothesis 3:** "The sound absorption performance of the three layered configuration increases with time."

3.2.3. Experiment III

For the third experiment, firstly the **sub-hypothesis 4:** "The sound absorption performance of the configuration differs with variations in reed diameters." is investigated primarily with B3R3, B3R4 and B3R5 configurations. Subsequently, the measurements are repeated after the application of F3 on the configurations to investigate the **sub-hypothesis 5:** "Increase in thickness of pumice plaster layers and decrease in percentage of lime content results in similar sound absorption results." is investigated. Besides, with the results of the two measurements with and without F3 the **sub-hypothesis 6:** "The sound absorption performance of the configuration without fine coat is higher than the three layered configuration." is analyzed. With the additional samples of B3 and F3B3, **sub-hypothesis 7:** "The sound absorption performance of granular pumice plaster is higher than the two layered plaster with granular and fine coat." is explored.

The third phase experiments are performed with 3 discrete configurations with varying reed diameters. The picture of the configurations is illustrated in Figures 3.5, 3.6 and 3.7. The fine coat (F3) is applied to the configurations after the measurements of B3R3, B3R4 and B3R5 configurations, thus, various sub-hypotheses could be analyzed with the same samples.

Figure 3.5 Experiment III, Reed samples (Left: R3, Middle: R4, Right: R5)

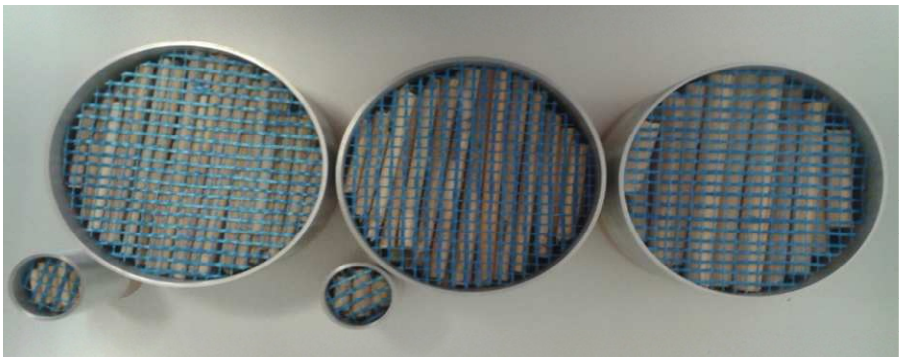


Figure 3.6 Experiment III with plaster mesh (Left: R3, Center: R4, Right: R5).

Figure 3.7 Experiment III complete samples (Left: F3B3R3, Center: F3B3R4, Right: F3B3R5).

Reed layers (R3, R4 and R5) are generated perpendicular to incident sound as in the previous experiments. The diameter of the reeds for R5 is not applicable for 28mm diameter impedance tube, thus, the configuration F3B3R5 could be investigated only with low frequency measurements. A plaster mesh is inserted on the reed layer as in the previous experiment. The bare coats of pumice plasters (B3) are applied on this mesh. After three days of drying the plaster, sound absorption measurements are realized. Because of the proportion of the lime content's espied insufficient for B3, the proportion of the lime for F3 is increased from pumice: lime 4:1 to 3:1. The fine coats of the pumice plasters (F3) are applied after the measurements are realized. The fine coats of the samples are dried for 3 days and the measurements are executed to get the answer for research question 5. At the same time with the measurements on the configuration samples, the pumice plaster layers are produced and measured with three days of drying for each layer of plaster.

3.2.4. Experiment IV

The fourth experiment is performed to investigate the **sub-hypothesis 8:** “The sound absorption performance of the configuration increases with the decrease of thickness of the pumice plaster layers.” Additionally, the **sub-hypothesis 9:** “The porosity of the pumice layers has a significant effect on the sound absorption performance.” is examined.

Reed layer R4 that is prepared for the previous experiment is used. A plaster mesh is inserted on the reed layer as in the previous experiment. The bare coat of pumice plaster (B4) is applied on this mesh. After three days of drying the plaster, sound absorption measurements are realized to make comparison with the previous measurement results. The fine coat of the pumice plasters (F4) is applied after the measurements are completed. The fine coat of the sample is dried for 3 days and the measurement is executed to investigate the sub-hypothesis 8.

For the porosity calculations, separate samples of pumice plasters used for B4 and F4 are prepared and dried for 3 days. The dry volume of the samples are calculated and recorded then the samples are smashed into dust and the volume of the samples are measured with water. Last, the volume of the samples in water is calculated and subtracted from the dry volume of the layers. Subsequently, porosity calculations are performed with the calculated results using the equation given in Equation (2.5) taken from the literature survey.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. RESULTS

4.1.1. Experiment I

Measurement results of F1B1R1 and F1R1 configurations are given in Figure 4.1.

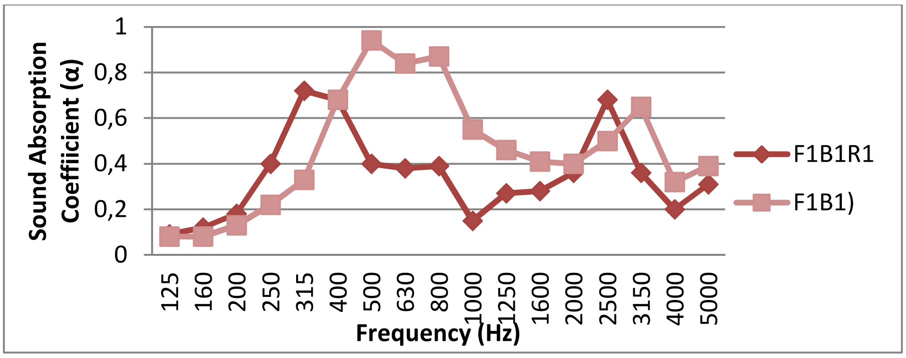


Figure 4.1 Measurement results of F1B1R1 and F1R1

The first measurement results show that the three-layered configuration F1B1R1 is found to be promising in terms of sound absorption. The results of the initial experiment show that three-layered configuration F1B1R1 has a good sound absorption performance between 250 Hz to 500 Hz. Nevertheless, the sound absorption decreases in the range of medium frequencies (500 Hz to 2000 Hz). The first peak frequency of the configuration is around 315 Hz and the second peak frequency of the configuration is around 2500 Hz. The desired characteristic is that the peak frequency should lie in the range of 500 Hz to 1000 Hz to get better results in medium frequencies. This figure is not an insufficient sound absorber; yet, higher sound absorption at medium frequencies is intended.

The second measurement performed with the configuration F1R1 show that the sound absorption performance of the configuration increases without B1. The configuration's sound absorption performance is found to be satisfactory between 400 Hz to 1000 Hz, in the range of intended higher sound absorption performance. The first peak frequency is around 500 Hz and the second peak frequency is around 3150 Hz which shows a better sound absorption performance compared to F1B1R1 configuration results. However, the fine coat 'F1' has a very thin thickness (3mm) which is accepted as an insufficient thickness for a plaster to be used in construction, in other words, the plaster is not durable enough for construction.

4.1.2. Experiment II

Measurement results of F2B2R2 configuration on 3rd, 13th, 33rd, and 60th day are given in Figure 4.2.

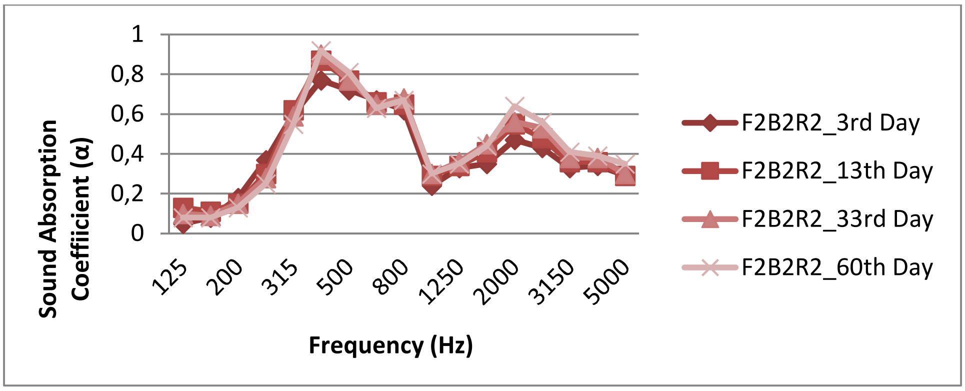


Figure 4.2 Measurement results of F2B2R2

The results of the second experiment with the configuration F2B2R2 show that increasing the sound absorption performance of the three layered configuration is possible by changing the bare coat with smaller granules of pumice content. The sound absorption performance of the configuration is well in the range of 300 Hz to 800 Hz and the first peak frequency of the configuration is around 500 Hz which is a desired characteristic. Besides, the second peak frequency is around 2000 Hz which fits to the purpose as well. Nevertheless, a sharp decrease in sound absorption performance of the configuration at 1000 Hz is unfavorable and should be prevented. The reason for this may be attributed to the thickness ratios of the layers.

The comparison on the sound absorption performance measurements on the 3rd, 13th, 33rd and 60th day after the production date of the configuration show that the sound absorption performance of the configuration generally increases somewhat at frequency base. Especially higher percentage of increase in peak frequencies is significant. Still, it can be mentioned that the general sound absorption performance of the configuration does not change significantly with time, that is, by ageing.

4.1.3. Experiment III

Measurement results of B3R3 and B3R4 configurations for full frequency performance are given in Figure 4.3.

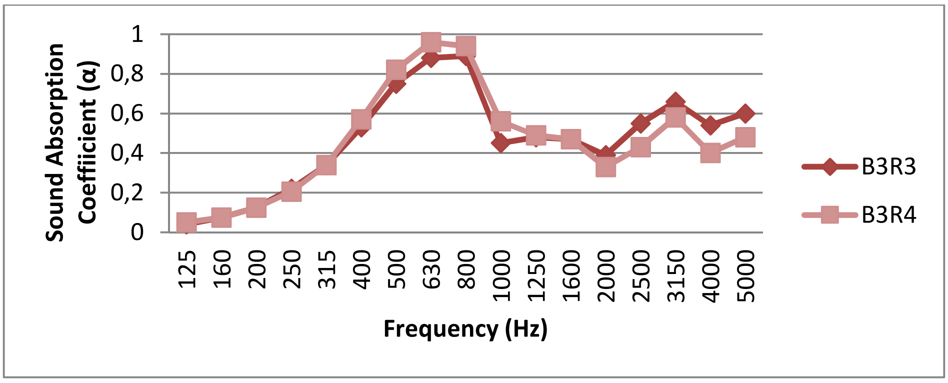


Figure 4.3 Full frequency measurement results of B3R3 and B3R4

Measurement results of B3R3, B3R4, B3R5 configurations for low frequency sound absorption performance are given in Figure 4.4.

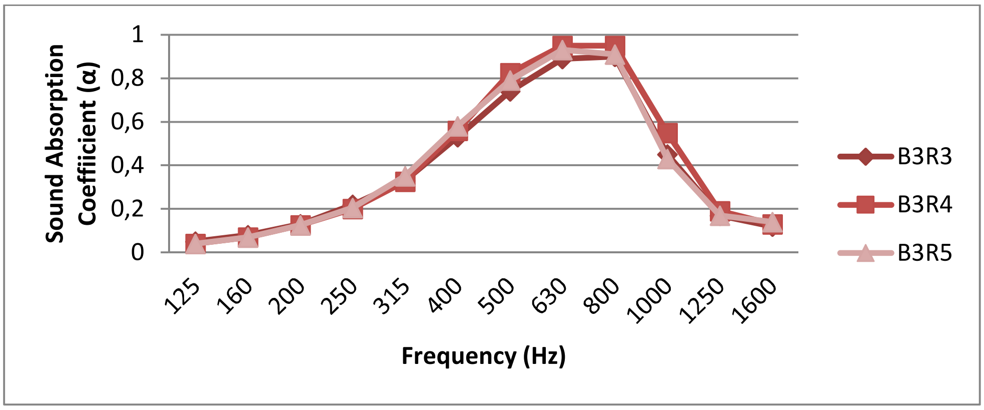


Figure 4.4 Low frequency measurement results of B3R3, B3R4 and B3R5

The results of the measurements of the configurations B3R3, B3R4 and B3R5 without fine coat ‘F3’ show that there are differences between three types of configurations with different diameters of reed. The configuration with R4 has better sound absorption at medium frequencies and R3 has better sound absorption at high frequencies. Nevertheless, the differences cannot be considered as significant. In other words, the general performances of the configurations in frequency base are similar.

The results of the configurations without fine coat ‘F3’ show that two layered configurations B3R3, B3R4 and B3R5 have a good sound absorption performance. The configurations’ sound absorption performances are found to be satisfactory between the frequencies 315 Hz to 1000Hz which is in range of intended sound absorption performance with respect to the frequency band. The first peak frequency is around 630 Hz and the second peak frequency for B3R3 and B3R4 is around 3150 Hz. The sharp decrease around 1000 Hz is still present, however the status is better compared to the previous experiment, especially for the configuration B3R4.

Measurement results of F3B3R3 and F3B3R4 configurations full frequency performance are displayed in Figure 4.5.

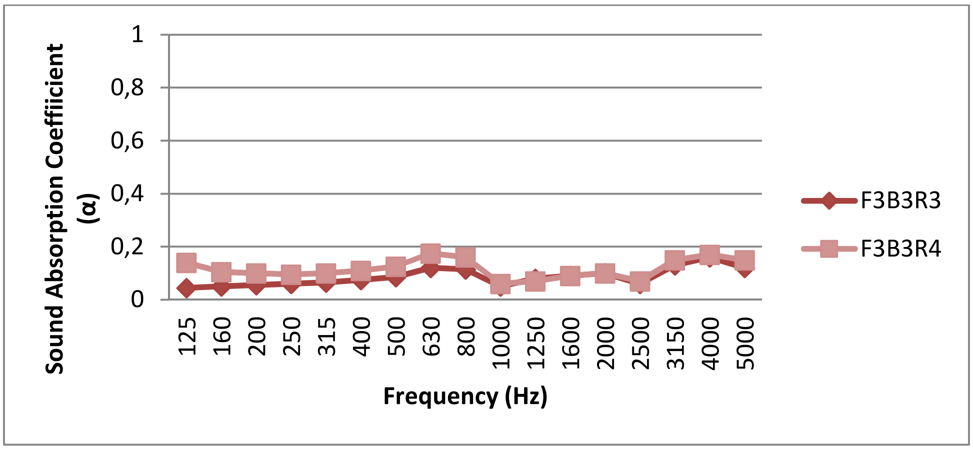


Figure 4.5 Full frequency measurement results of F3B3R3 and F3B3R4

Measurement results of F3B3R3, F3B3R4, and F3B3R5 configurations for low frequency sound absorption performance are given in Figure 4.6.

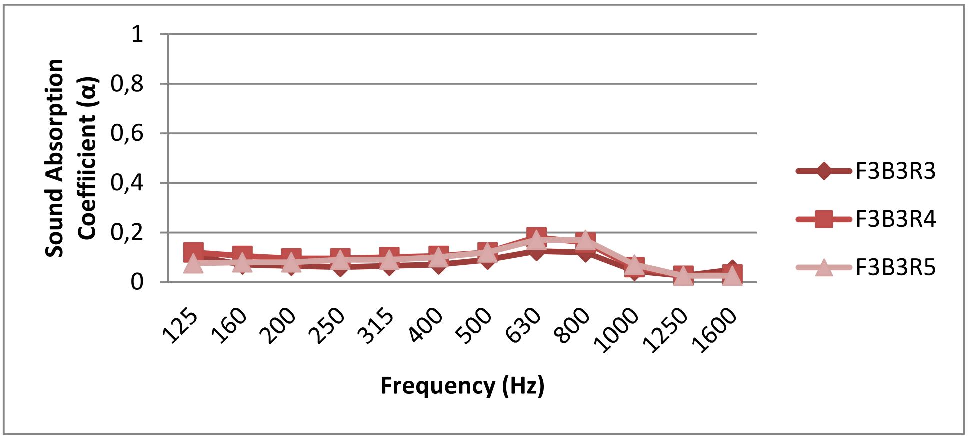


Figure 4.6 Low frequency measurement results of F3B3R3, F3B3R4 and F3B3R5

The results of the measurements performed with F3B3R3, F3B3R4 and F3B3R5 show that the sound absorption performance of the configurations decreases sharply with the increase of the thicknesses of pumice plaster layers. Any statement on peak frequencies is unnecessary because of the values of the sound absorption coefficients being very close to each other besides being low. Referring the measurements without fine coat F3, it can be expressed that the application of fine coat results in a reflective configuration instead of a sound absorber. The reason for this situation may be speculated to the increase of the thickness of the fine coat F3, or the total increase of the pumice plaster layers.

Measurement results of B3 and F3B3 pumice plaster sound absorption performance are given in Figure 4.7.

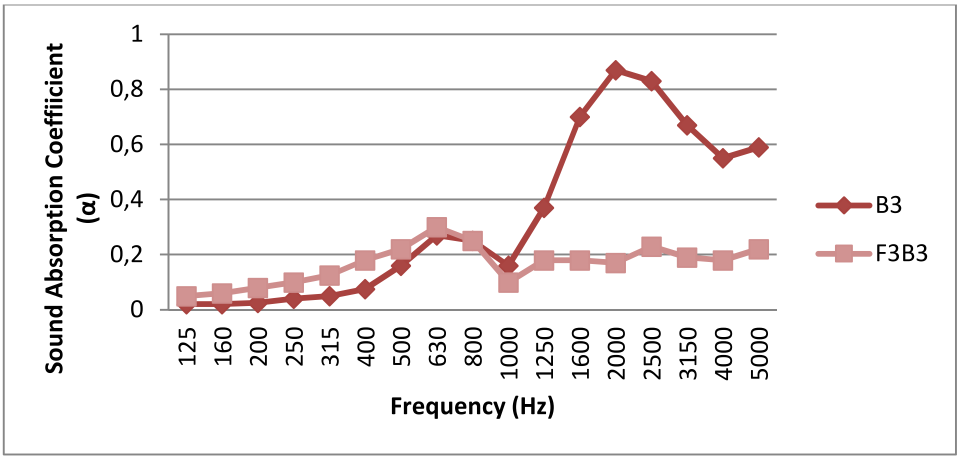


Figure 4.7 Measurement results of B3 and F3B3

The results of the measurements performed with the pumice plaster samples B3 and F3B3 show that pumice plasters have quite good sound absorption performance compared to common plasters made of gypsum or cement products in construction. Especially the high sound absorption performance of the pumice plaster B3 without fine coat F3 is very significant. However, pumice plaster layers cannot be considered as sound absorbers if applied on surfaces without a sound absorber backing material.

4.1.4. Experiment IV

Measurement results of B4R4 and F4B4R4 configuration for sound absorption performance are given in Figure 4.8

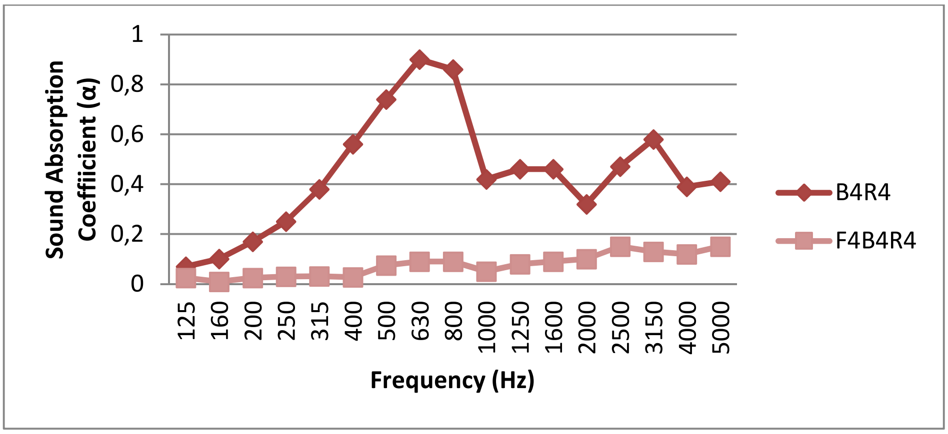


Figure 4.8 Measurement results of B4R4 and F4B4R4

The results of the experiment 4 show that despite the decrease of pumice plaster thickness the results are similar with the previous experiment. In fact, it can be mentioned that the comparison results of configuration B4 with increased lime content and decreased thickness have similar sound absorption performance with the configuration B3R4. For the configuration F4B4R4, the sound absorption performance of the configuration decreases somewhat compared to the previous experiment. This situation is assessed as the idea that the thickness alone has a significant effect on the sound absorption performance of the configurations is wrong. The other parameters (stated in heading 2.1.3) together with the thickness should be investigated to make a more accurate assessment.

The porosity calculations of F4 and B4 are given in Table 4.1

Table 4.1 Porosity calculations

F4B4R4		
Code	**Content**	**Porosity**
F4	0-0.5 mm wide pumice (pumice powder), lime putty (Pumice:Lime:7:3 by mass)	0.597
B4	0.5-2 mm wide pumice, lime putty ((Pumice:Lime:7:3 by mass)	0.637

The porosity calculations of the F4 and B4 show similar values. Besides the values in literature stated in Table 2.7 (İlter, 2010) are similar with the calculated ones. This shows that lime content does not affect the total porosity of the pumice plaster. However, the results of the configuration B4R4 and F4B4R4 show that the application of B4 has a significant effect on the decrease of the sound absorption performance of the configuration although the thickness of the pumice plaster layer F4 is lower than B4. The reason for this outcome might be attributed to the different pore structures of F4 and B4. The pumice plaster B4 is estimated as an open pore structure for the pumice granules' being large and the integration with lime would result in an open pore structure. Conversely, the pumice powder particles in F4 are available to form a close pore structure with lime. This estimation should be investigated with alternative methods of porosity measurements as a future study.

4.1.5. Comparison graph of the results

Comparison graph of the selected measurement results of each experiment is given in Figure 4.9.

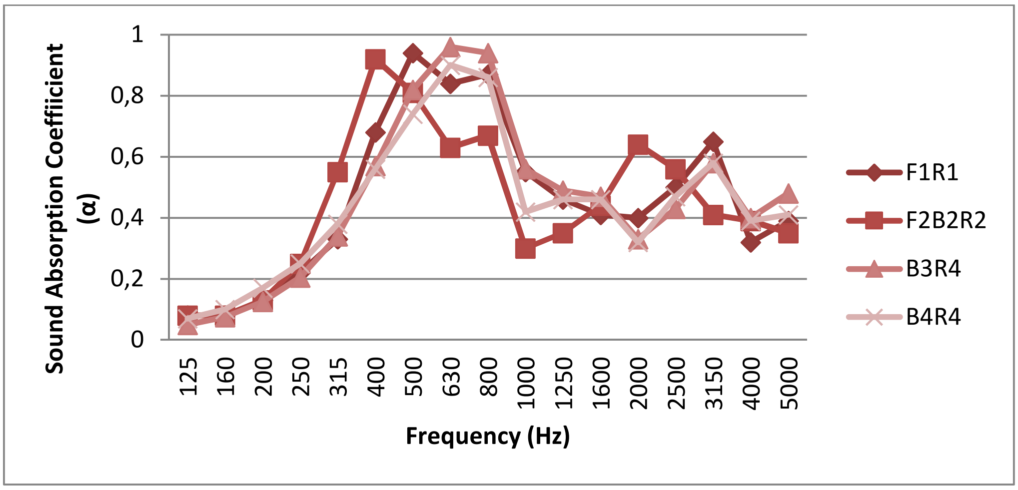


Figure 4.9 Comparison of the better results of the experiments

The comparison graphic of the measurements for the better results of the experiments show that the configurations have promising sound absorption performance. Peak frequencies of the configuration considering a 40 mm cavity behind the pumice plaster according to equation (2.4):

$$0.04m = h, \quad n = 1, \quad fmax = 2125\ Hz$$
$$0.04m = h, \quad n = 2, \quad fmax = 6375\ Hz$$

The reed layer's effects on peak frequencies are around 500 Hz and 3000 Hz, instead of a cavity behind the pumice plaster. This situation is assessed positive as the maximum sound absorption performance is intended to be around 500 Hz and 1000 Hz. The cavity depth can be arranged to lie between 160 mm to 80 mm to make fmax to fall in 500 Hz and 1000 Hz octave bands, respectively. The optimum configuration and sound absorption performance combination is F2B2R2.

4.2. DISCUSSION

In this section, the results of measurements are discussed according to the parameters investigated with the main and sub-hypotheses.

Basically, the **main hypothesis**: “A three layered configuration made of a fine coat with pumice powder plus lime, bare coat made of granular pumice particles plus lime and a porous backing layer made of reed works well as a sound absorber.” is true. The sub-hypotheses that are forecasted are assessed with the results of the experiments and the literature information to make clearer decisions with the finding.

Sub-hypothesis 1: “The sound absorption performance of the configuration is better without granular pumice plaster layer.”

The comparison results of the F1B1R1 and F1R1configurations show that the sub-hypothesis 1 is true. The reason for this result is basically the total decrease of pumice plaster. The result of the experiment shows that decrease in thickness results in an increase at especially medium frequencies. The results also verify that the hypothesis of İbrahim *et al.* (1978) in Seddeq (2009) that the sound absorption performance in low frequency range increases with the increase of thickness of the material if the better sound absorption performance of F1B1R1 at low frequencies is interpreted.

Sub-hypothesis 2: “Decrease of granule sizes of pumice plaster results in increase of sound absorption performance of the three-layered configuration.”

The results of the second experiment compared to first experiment results shows that the sub-hypothesis 2 is true. The reason for this result is basically the harmony of the smaller pumice granules with lime and fine coat, as well. The results of sound absorption properties with respect to frequency show a similar behavior with F1B1. The peak frequencies and the quantitative results are similar although the number of layers and plaster thicknesses of the configurations is different. This situation can be explained with the qualified integration of the fine coat and bare coat layers of

F2B2R2. Besides, the production method with short period of drying the bare coat could be effective on this result.

Sub-hypothesis 3: "The sound absorption performance of the three-layered configuration increases with time."

The results of the second experiments conducted with F2B2R2 at different times after the first measurements show that the sub-hypothesis 3 is true especially for the peak and incidence frequencies. The reason for these results could be the change in the porosity of the plaster layers whereas the drying process of lime content results in an increase in pore sizes. If the information in literature that the compression strength of pumice-lime plasters increases with time (Nozahic et al., 2012) is considered, more sound absorptive and more durable plaster is obtained with time.

Sub-hypothesis 4: "The sound absorption performance of the configuration differs with the variations of reed diameters."

The measurement results of B3R3, B3R4 and B3R5 show that the sub-hypothesis 4 is false. There is not a significant difference between the third experiment-first measurement results without F3. The results do not observe the hypothesis of Koizomi et al. (2002) in Seddeq (2009) that the increase in fiber size results in decrease in sound absorption. The reason for this result might be the effect of the bare coat of the pumice plaster above the reed layers.

Sub-hypothesis 5: "Increase in thickness of pumice plaster layers and decrease in percentage of lime content results in similar sound absorption results."

The measurement results of the three layered configurations experiment 3 compared to experiment 2 results show that the sub-hypothesis 5 is false. The reason for the result can be explained with the thickness of fine coat's decreasing the sound absorption performance sharply if the results of the configurations' being very well without fine coat F3 is considered. Besides, the reason for the result might be the different cellular structures of fine coat and bare coat which affect the porosity, consequently the sound absorption performance. Besides, different production methods and drying period of pumice plaster layers may contribute to the result.

Sub-hypothesis 6: "The sound absorption performance of the configuration without fine coat is higher than the three-layered configuration."

The measurement result of the configuration B3R3, B3R4 and B3R5 show that the sub-hypothesis 6 is true. In fact, a decrease in sound absorption is expected because of the effect of the thickness, nevertheless, the sharp decrease is considered very problematic and the parameters that cause this result should be investigated. The reason for this result might be cellular structure of the plasters affecting the porosity, in turn the sound absorption.

Sub-hypothesis 7: "The sound absorption performance of granular pumice plaster is higher than the two layered plaster with granular and fine coat."

The measurement result of the B3 and F3B3 without reed shows that the sub-hypothesis is true for high frequencies. For low and medium frequencies, the results are low and similar for the samples. The reason for this result is the ragged surface of bare coat causing an increase in the high frequency sound absorption.

Sub-hypothesis 8: "The sound absorption performance of the configuration increases with the decrease of thickness of the pumice plaster layers."

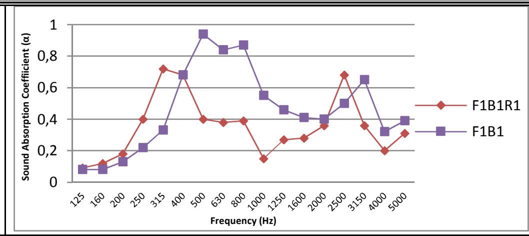
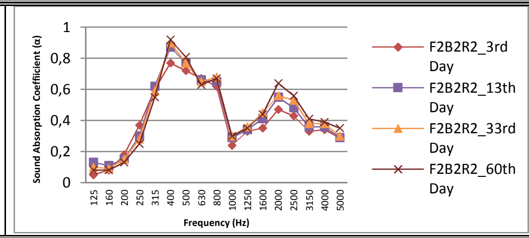
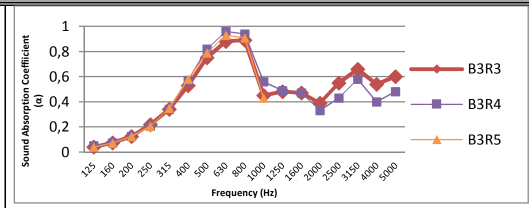
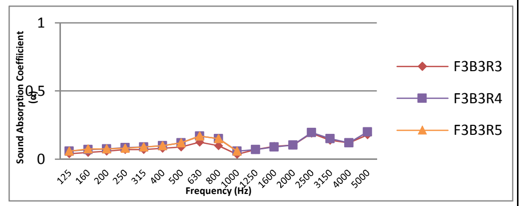
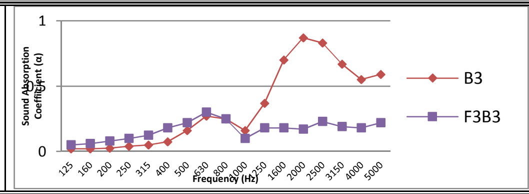
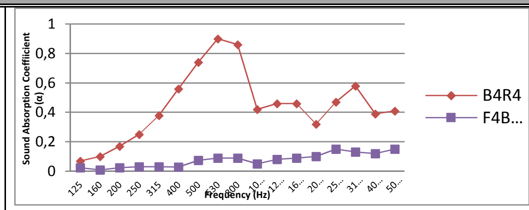
The measurement result of B3R3 and F3B3R3 compared to the results of B4R4 and F4B4R4 show that sub-hypothesis 8 is false. The configurations have similar sound absorption performances although the layer thicknesses are decreased in experiment 4. The reason for the similar results of B3R3 and B4R4 can be explained with the percentage of lime content. The reason for the similarity of three-layered configurations can be explained with the surface impedances of the pumice plasters fine coats being similar.

Sub-hypothesis 9: “The porosity of the pumice layers has a significant effect on the sound absorption performance.”

The calculation results of F4 and B4 compared to measurement results of the B4R4 and F4B4R4 show that the sub-hypothesis 9 is false. However, the result is not clear enough as the porosity calculations are conducted only for total porosity and the cellular structures of the plasters are not investigated. Different pore structures (open pore or close pore) might be effective on the sound absorption performances.

The comparative table of the configurations, measurement results and hypothetical assessments are summarized in Table 5.1.

Table 5.1 Configurations, results and discussions

Code	Layer	Thickness	Content	Hypotheses	Result	Discussion
				F1B1R1, F1R1		
F1	Fine Coat	2 mm	0-0.5 mm wide pumice (pumice powder), lime (Pumice:Lime:2:1 by mass) and water	**Main Hypothesis:** "A three layered configuration made of a fine coat with pumice powder plus lime, bare coat made of granular pumice particles plus lime and a porous backing layer made of reed works well as a sound absorber." **Sub-hypothesis 1:** "The sound absorption performance of the configuration is better without granular pumice plaster layer."		True. Yet, it is possible to improve the sound absorption performance of the configuration. True: The sound absorption performance of the configuration is better especially at medium frequencies.
B1	Bare Coat	10 mm	3-7 mm wide raw pumice, lime (Pumice: Lime: 2:1 by mass) and water.			
R1	Reed	40 mm	40 mm thick Reed (⌀: 2 -5 mm tubes)			
				F2B2R2		
F2	Fine Coat	2 mm	0-0.5 mm wide pumice (pumice powder), lime putty (Pumice:Lime:2:1 by mass)	**Sub-hypothesis 2:** "Decrease of granule sizes of pumice plaster results in increase of sound absorption performance of the three-layered configuration." **Sub-hypothesis 3:** "The sound absorption performance of the three layered configuration increases with time."		True. Smaller granule sizes of pumice plaster results in increase of sound absorption performance. True. The sound absorption properties of the configuration increase especially at peak frequencies with time.
B2	Bare Coat	5 mm	0.5-2 mm wide pumice, lime putty (Pumice:Lime:2:1 by mass)			
R2	Reed	40 mm	40 mm thick Reed (⌀: 4 -7 mm tubes)			
				B3R3, B3R4, B3R5		
B3	Bare Coat	7 mm	0.5-2 mm wide pumice, lime putty ((Pumice:Lime:4:1 by mass)	**Sub-hypothesis 4:** "The sound absorption performance of the configuration differs with the variations of reed diameters."		False. The variation in diameters of reed does not have a significant effect on sound absorption.
R3,4, 5	Reed	40 mm	40 mm thick Reed R3: ⌀: 3 -4 mm tubes R4: ⌀: 5 - 6 mm tubes R5: ⌀: 8 - 10 mm tubes			
				F3B3R3, F3B3R4, F3B3R5		
F3	Fine Coat	3 mm	0-0.5 mm wide pumice (pumice powder), lime putty (Pumice:Lime:3:1 by mass)	**Sub-hypothesis 5:** "Increase in thickness of pumice plaster layers and decrease in percentage of lime content results in similar sound absorption results." **Sub-hypothesis 6:** "The sound absorption performance of the configuration without fine coat is higher than the three layered configuration."		False. The sound absorption performance of the configuration decreases dramatically with the increase of pumice plaster thickness. True. The sound absorption performance of the configuration decreases dramatically with the application of fine coat.
B3	Bare Coat	7 mm	0.5-2 mm wide pumice, lime putty ((Pumice:Lime:4:1 by mass)			
R3	Reed	40 mm	40 mm thick Reed (⌀: 3 - 4 mm tubes)			
				B3, F3B3		
F3	Fine Coat	3 mm	0-0.5 mm wide pumice (pumice powder), lime putty (Pumice:Lime:3:1 by mass)	**Sub-hypothesis 7:** "The sound absorption performance of granular pumice plaster is higher than the two layered plaster with granular and fine coat."		True. The results show that the sound absorption performance of granular plaster is at high frequencies is better; however, the low and medium frequencies are similar.
B3	Bare Coat	7 mm	0.5-2 mm wide pumice, lime putty ((Pumice:Lime:4:1 by mass)			
				B4R4, F4B4R4		
F4	Fine Coat	2 mm	0-0.5 mm wide pumice (pumice powder), lime putty (Pumice:Lime:7:3 by mass)	**Sub-hypothesis 8:** "The sound absorption performance of the configuration increases with the decrease of thickness of the pumice plaster layers." **Sub-hypothesis 9:** "The porosity of the pumice layers has a significant effect on the sound absorption performance."		False. The sound absorption performance of the configuration is similar despite the decrease in pumice plaster thicknesses. False. The calculated porosity for F4 (0.597) and B4 (0.637) are similar, however α dramatically decreases with the F4.
B4	Bare Coat	5 mm	0.5-2 mm wide pumice, lime putty ((Pumice:Lime:7:3 by mass)			
R4	Reed	40 mm	40 mm thick Reed (⌀: 5 mm to ⌀: 6 mm tubes).			

CHAPTER 5

CONCLUSION

This study intends to develop a new sound absorptive material composition that is economic, ecologic, local and aesthetically preferable. The materials that are used to construct the composition are basically reed and pumice. Pumice is proposed for its porous structure which is advantageous for sound absorption and having a large reserve in Turkey. Reed is proposed as an alternative sound absorptive fibrous backing material to mineral wool based materials which are used extensively in Turkey. The advantage of reed as per mineral wools is basically its being more energy efficient, natural and healthier. Besides, reed has an excellent sound absorption capacity due to its tube in tube structure. Lime, which is used as a binding agent for pumice plaster is a binder that is more energy efficient than gypsum and cement products and has a perfect conformity with pumice as a plaster. Besides, lime has a breathing structure that helps to keep the reed behind the plaster.

One of the inspirations of the study is that the architects prefer seamless, fine finish surfaces in contrast to common sound absorbers that are commercialized in Turkey. Also, energy efficiency issues are very significant recently in contrast to commonly used unhealthy and high carbon footprint sound absorbers such as rock wool and glass wool inclusive sound absorbers. The other basic inspiration of this study is to use local, natural and economic materials which may contribute to territorial economy.

The research firstly tends to discover the potential of a selected configuration in terms of sound absorption capacity. The sound absorption performance of reed is measured is various studies in literature Espada *et al.* (2007), Diaz *et al.* (2012), Chilekwa *et al.* (2006) and Oldham *et al.* (2011). The direction of the reed is selected in light of these studies and ease in application. The sound absorption potential of the pumice does not exist in literature, together with the binding agent lime, but the harmony of pumice and lime is mentioned in Nozahic *et al.,* (2012)'s study. The potential of the pumice in terms of sound absorption performance is disclosed in this study.

This study is conducted with four basic experimental configurations. The layers of the configuration subtracted or changed systematically for some measurements to understand the effects of parameters affecting the sound absorption performances of the configurations. A main hypothesis is asserted covering the objective of the study and 9 sub- hypotheses are put forward to analyze effects of the variables of the sound absorption performance on the configuration.

The main hypothesis is: "A three layered configuration made of a fine coat with pumice powder plus lime, bare coat made of granular pumice particles plus lime and a porous backing layer made of reed works well as a sound absorber." The general assessment according to the various measurement results is that the main hypothesis is true. The assessments on the effects of the parameters, that are given in material section, according to proposed sub-hypothesizes and the measurement results are as follows:

Granular sizes of pumice particles: The granule sizes of pumice plaster are found to have significant effect of sound absorption

Thicknesses of pumice plaster layers: The comparative results of the investigations show that thickness of the pumice plasters are effective on sound absorption performance of the configurations. Nevertheless, the experiments are conducted to analyze effects of various parameters with each samples, thus, the experiments that focus only on the thickness of a single layer might give clearer response for this parameter.

Percentage of binder content (lime): The comparative results of experiment 2 and experiment 3 show that decrease of lime content and increase of pumice content in pumice plaster result in similar results. This situation might be expressed as the percentage of binder content has an effect on sound absorption.

Diameters of reed: The comparison of the results of various reed diameters in experiment 3 shows that with the pumice plaster above the reed layer, the diameter variations of reed does not have a significant effect on sound absorption performance of the configuration.

Porosity: The calculation results of porosities of plaster samples in experiment 4 shows that the porosities of the granular and fine finish plasters are similar. Nevertheless, there is a dramatic difference between the configurations in terms of sound absorption performances with and without fine coat. This can be explained that the porosity does not have a significant effect on sound absorption. However, the open pore-close pore structures of the plaster layers are not investigated and a clear assumption for this parameter is unavailable for this investigation. For a future study, the open pore and close pore structures of the pumice plaster layers should be investigated.

As a brief evaluation, the experiments on various configurations with pumice plaster and reed show that the proposed composition forms a promising sound absorptive material which is local, natural, economic and ecological. The sound absorption behavior of the compositions is similar in terms of characteristic in frequency base. Still, the pumice layers should be improved for better sound absorption performance and constructability with further investigations focusing on the pumice thicknesses, lime content, porosity and production method of the plaster layers. Besides, technologies to apply reed layers and pumice plaster should be worked on in- depth. The fire resistance can be provided by pumice layer which works as a shell on the reed; still, the effect of thickness on fire resistance should be investigated. The constructability issues and fire resistivity of the configuration are intentionally kept out of contents of this thesis.

Finally, this study is believed to lead new researches and experiments on ecologic materials that can be used in construction industry. Such materials are free from chemicals and toxic materials that are insanitary, in addition to being energy efficient and economic. The nature has a limited capacity and human being should create alternative processes to construct a sustainable living environment. New ways to provide healthier and energy efficient living spaces should be discovered avoiding damaging nature and living standards of future generations.

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