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Mini Review
An Insight into the Composite Materials for Passive Sound Absorption

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Abstract
In the current scenario of fast growing industrialization sound pollution becomes a key concern that leads to the investigation of novel environmental friendly materials which can absorb sound frequencies in the audible range of 20 Hz to 20 kHz. However, design of passive sound absorbing materials in low frequency (below 500 Hz) regions are still challenging. In the past decade, low frequency noise has begun to be acknowledged as a public health problem. Health concerns lead to high intellectual investments on different types of cost effective, ecofriendly and efficient natural, synthetic as well as nanomaterial based composites to achieve strong wide band acoustic absorption in low frequency range. The composite making technology together with the advancement in nanotechnology paved strong foundation to engineer high performing acoustic materials. These investigations are also prime to the development of phononic crystals, acoustic metamaterials and sound absorbing composites. This review critically investigates the achievements and challenges in passive noise controlling with the help of novel acoustic composite materials.

Key words: Acoustic materials, passive sound absorption, sound absorbing composites, ecofriendly materials, nanomaterials

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INTRODUCTION

Noise and vibration control have got much relevance in the present situation of industrialization and the fast development of the modern society. It is important to have proper noise control in various areas of modern life as far as from the comfort and health point of view. Elevated sound can cause serious health issues such as hearing impairment, hypertension, ischemic heart disease, annoyance, sleep disturbance, changes in the immune system and birth defects[1-6] etc. The cause and effect of some of such health impacts are listed in Table 1. From the present serious concern of environmental pollution to the smooth functioning machineries in various areas of our life noise and vibration control is inevitable[7,8]. So passive and active noise control have higher priority at this juncture. The active and passive noise control mechanisms and their response frequency region are shown in Fig.1a and b, respectively[9]. Passive noise control is more economical and energy efficient technique compared to the active one since it doesn't need any external power consumption for its performance. It is clear from Fig. 1b that in the lower frequency level the acoustic absorption performance of the passive material is very weak compared to that of the active ones for which extra energy consumption is inevitable. Here comes the limitation of the passive noise controlling materials in the lower frequency domain where we need serious investigation for fine tunable sound absorbing materials, which can be realized through the use of different types of composite materials as the passive noise controllers. Recently developed nanomaterials and natural fiber based composites are promising candidates in this regard. These materials can be prepared by cost effective and simple material preparation techniques. These processing techniques also offer tunability in the relevant frequency region of importance. The choice of the material and preparation techniques also varies according to the problem of interest.

The three main classes of passive sound absorbers/acoustic materials existing are the porous absorbers, the non-rigid and non-porous panel absorbers and the micro perforated panels called resonators like the Helmholtz resonator[10-12]. These materials are having their own specific microscopic structures which enhance the different types of sound absorption mechanisms happening within them. In the case of the porous materials the different microscopic structures existing in them namely the tubular (cellular), the fibrous and the granular ones make them behaving as good acoustic absorbers in noise controlling applications in various fields[13,14]. The microscopic images and the schematic representation of the tubular, fibrous and granular structures of the passive porous acoustic

Table 1: Cause and effect of some of the noise induced health problems

Causes	Effects	References
Sound levels at 95, 110 and 125 dB of frequencies 6, 12 and 16 Hz for 20 min	Variation in diastolic blood pressure and systolic blood pressure	Danielsson and Landstrom[1]
Industrial infrasound at 100 and 135 dB of 5 and 10 Hz	Changes of EEG patterns, reduced heart muscle contraction strength, decreased respiration rate	Karpova *et al.*[2]
Lifelong exposure to industrial noise levels of 85-90 dB	Progressive hearing loss	Kryter[3]
50 noise events per night at 50 dB	Sleep disturbance	Ohrstrom[4]
Continuous noise exposure at 85 dB	Increased blood pressure	Zhao *et al.*[5]
Exposure to high intensity industrial noise	Raised levels of noradrenaline and adrenaline	Cavatorta *et al.*[6]

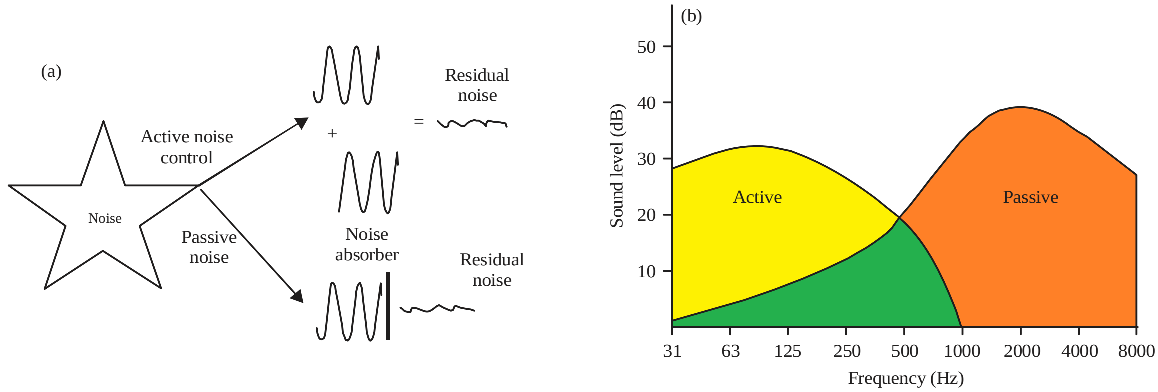

Fig.1(a-b): (a) Active and passive noise control mechanisms[9], (b) Frequency response region of the active and passive noise control methods[9]

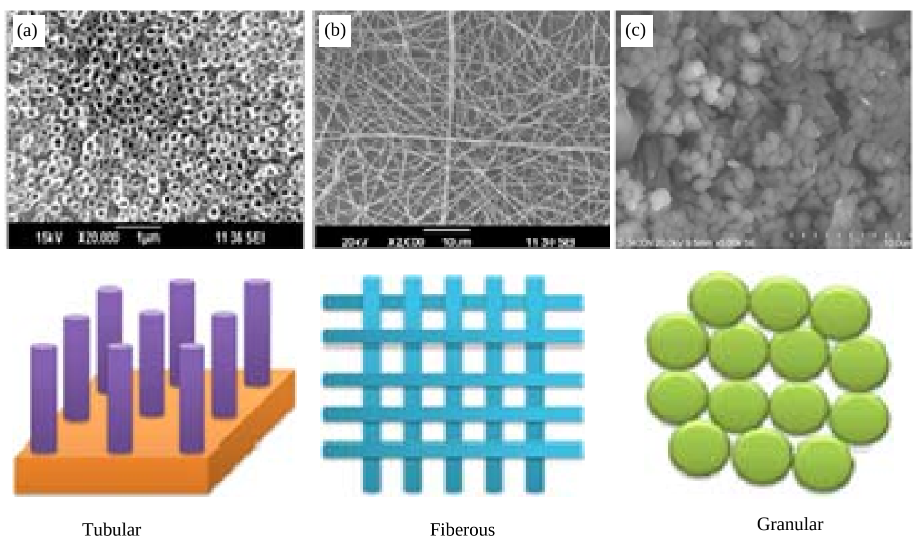

Fig. 2(a-c): Scanning electron microscope images and schematic representation of porous absorbers, (a) Tubular structure, (b) Fiberous structure and (c) Granular structure

absorbers are shown in Fig. 2a, b and c, respectively. These materials can be prepared easily by electro spinning[15] or electrochemical anodization method[16].

Natural as well as synthetic based materials can be used as passive acoustic absorbers in noise reduction applications. Coconut coir fiber, date palm fiber, bamboo fiber, cotton, kenaf, hemp, wood flax, bagasse, jute etc. are examples of some of the naturally existing passive acoustic materials. Different types of synthetic materials such as ceramics, mineral wool, fiber glass etc are also properly modified now a days for passive sound absorption applications as per the requirement and availability[17,18]. Nevertheless these materials are not still engineered properly for low frequency noise reduction applications. The recent introduction of the smart acoustic metamaterials with novel interesting properties like negative mass density and density-near-zero[19], negative bulk modulus[20], inhomogeneous and anisotropic mass density[21] make them suitable to be used as acoustic materials of interest. Understanding of such properties leads to the development of new acoustic devices like acoustic cloaks, acoustic hyper lenses[22], gradient index lenses[23] and acoustic black holes or sonic black holes in passive noise controlling[24]. However, limitations in scalability and high cost of production makes these materials unsuitable for large scale industrial noise reduction applications.

In this particular scenario there comes the relevance of the composite materials which stand as a unique promising material in the current fast growing technological world.

Composites can be exploited in various fields of daily applications and their inherent properties make them favorable to be used in passive noise controlling devices. A composite material is the one which contains a reinforcing stress/load carrying material enclosed in a weaker binding material known as the matrix[25,26]. The properties of the composite materials can be controlled and optimized based on the application of interest by adding different types of reinforcing materials. The different types of composite materials such as Metal Matrix Composites (MMC), Polymer Matrix Composites (PMC) and Ceramic Matrix Composites (CMC)[27-29] find wide applications because of their modified physical, mechanical and chemical properties compared to that of the individual components. The composite making technology also provides an opportunity for converting the hazardous waste products of the modern world to the useful ones as well as it helps in producing eco-friendly green composite materials for the purpose of interest[29,30]. Thus the useful incorporation and utilization of cheapest materials in superior performing appliances makes the composite making technology the most promising one. The recent development of nanomaterials through cost effective aqueous synthesis routs leads to the development of a new set of composite materials that makes high strength and easy tunability of material properties[30,31].

So in this present context the solution to noise pollution problems can be well addressed with help of these composite materials as passive sound absorbers. Thus passive acoustic materials made using composites play a crucial role in various fields such as automobile and aircraft industry, medical field and other comfort related applications where the noise pollution seriously affects the health of the human beings, the environment and the performance of the machinery parts of certain important sensitive instruments. In each particular case the acoustic frequency to be controlled will be different and it is possible to cover this wide frequency region with the help of different types of composite materials available presently. Each composite material absorbs sound at a particular frequency of interest which is characteristic of its intrinsic properties. Hence the composites serve as one of the superior passive noise controlling material[25-31]. This review critically analyzes the advances and the wide range of possibilities in using composites as sound proofing materials in comparison with the competing materials such as metamaterials and phononic band gap materials which prevents the acoustic phonons of selected ranges of frequencies from being transmitted through the material.

Natural and synthetic material based composites are proven to be efficient in absorbing wide range of sound frequencies. So particular emphasis has been paid to investigate the high frequency and low frequency noise reduction capability of natural and synthetic material based composites separately.

NATURAL FIBER BASED COMPOSITE MATERIALS AS PASSIVE ACOUSTIC ABSORBERS

In recent years natural fiber reinforced polymer composites are gaining more attention due to their cheap production cost, eco-friendly composition and their relevant properties related to the application of interest. Because of the overgrowing environmental concern and the existing possibility of tuning their response over wide range by the compositional variations these natural composite materials are emerging as spontaneous solutions for many of the threatening problems of the modern developing countries[32,33].

Now a days sustainable green and recyclable acoustic materials which leave low carbon foot print are preferred as sound absorbers. Different types of natural fibers like cotton, kenaf, hemp, wood flax, bagasse, jute, kapok, date palm fiber, coconut coir fiber, bamboo fibers etc. are investigated for their acoustic responses. The microscopic structure and the surface morphology of these lignocellulosic materials make them favorable to be used as acoustic absorbers by enhancing the sound absorption mechanisms happening within them[34-39]. The comparison of the frequency response of sound absorption coefficient of these natural bio friendly green sustainable materials is depicted in Fig. 3[40-47]. These promising results in combination with the recent advances in the composite making technology create wide opportunity for the replacement of synthetic and mineral fiber based acoustic materials with these type of natural material based composites. The operating acoustic frequency region of the material will vary depending on the nature of the material and the frequency region to be controlled depends on the application of interest. So in this particular context we can critically analyze the low frequency and high frequency noise controlling applications of these natural fiber based composites.

Acoustic absorbers in the frequency region below 2000 Hz: One of the main challenges to be addressed in passive noise controlling is that in the low frequency region below 500 Hz the active noise controlling is more efficient compared to the passive one[9]. This problem can be well addressed with the help of passive sound absorbing composites which are reinforced with the green sustainable natural materials. The

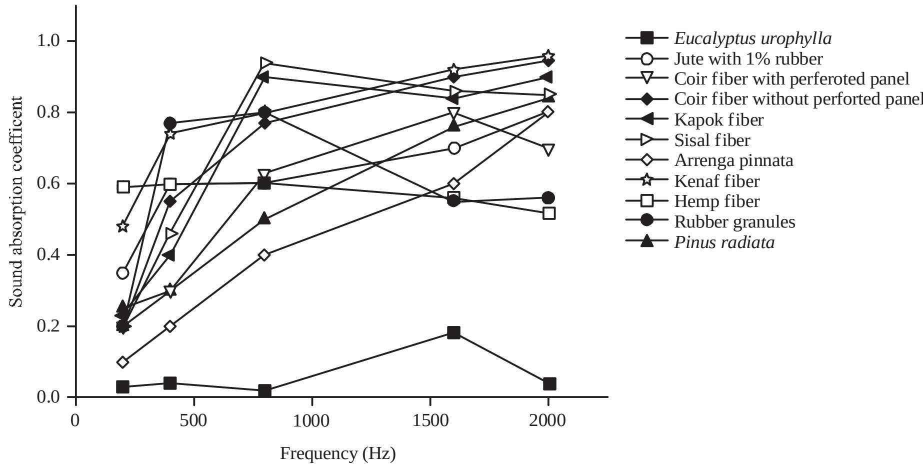

Fig. 3: Frequency response of sound absorption coefficient of certain natural bio friendly green sustainable materials[40-47]

agricultural waste material in raw form and their byproducts obtained during the industrial processing in powder or dust form are tested as reinforcing elements in making composites for low frequency passive noise controlling. Other green fibrous materials like coir, kenaf, hemp, kapok etc. are also proved to be good acoustic absorbers in bare and composite form in this low frequency region. The following section discusses advancements in the use of these bio friendly materials in low frequency passive noise controlling in the form of composites.

Rice hull is one of the major agricultural waste products obtained mainly from the rice cultivating paddy fields of the southern parts of India. It is used mainly for thermal insulation, for making tooth paste, for beer brewing etc. In addition it is used as a fuel and the remaining rice hull ash is used for making Portland cement. It finds many other industrial applications also[48]. Here rice hull is used in an entirely different manner as a reinforcement material in a composite which helps to enhance the sound absorbing property of the particular composite[49]. As a purposeful utilization of this agricultural waste material in the form of a useful product Wang *et al.*[49] incorporated Rice Hull (RH) as a reinforcing material in the polyurethane composite (PU-RH composite) which enhanced the physical, mechanical and acoustic properties of the material. So it finds application in many of the sophisticated modern appliances in automobile industry, in packing industry and even in aerospace industries. This environment friendly biodegradable cost effective light weight composite is proved to be an excellent passive sound absorber with very high absorption value in the lower frequency range below 500 Hz compared to the pure polyurethane foam. More than that the presence of this RH in this composite shifts its acoustic absorption response region from the higher frequency region above 1200 Hz to the lower frequency region below 500 Hz so that it can be used as an acoustic absorber in the low frequency appliances. Thus in the lower frequency region below 500 Hz where the active noise controlling mechanisms predominates over the passive ones the active noise controllers can be replaced by these types of passive ones[9]. Here the incorporation of RH enhances the different types of sound absorption mechanisms through the alteration of the porous cell morphology of this composite compared to that of the pure polyurethane foam without RH[50,51]. The acoustic frequency response region is entirely different when the rice husk is incorporated in a different composite as reported by Gonzalez *et al.*[52]. They reported the enhancement in the acoustic absorption coefficient of mortar composite when a slight amount of sand in this composite is substituted with waste materials like the residue of plywood resin form work, rice husk and thermoplastic shoe counters at different levels[52]. The mortar which is having a very poor acoustic performance having sound absorption just above 20% without these constituents showed an average enhancement of 50% in sound absorption in the frequency range of 200-2000 Hz with the incorporation of rice husk and ply wood. Thus the same material itself can be utilized in different composites to get different acoustic active region of importance reveals the potential of the composite making technology.

Agricultural wastes other than rice hull are also used in making sound absorbing composites for passive noise controlling. Saadatnia *et al.*[53] used acoustic insulation panel made of composites of aspen particles reinforced with Lignocellulosic agricultural fibrous materials such as wheat and barley straws with urea formaldehyde as the binder material and investigated its acoustic absorption response in the frequency range of 0 to 5000 Hz[53]. It is reported that both the barley and wheat straw samples behaved almost the same way and the noise reduction coefficient at first increased with respect to frequency and showed a maximum at the frequency of 2000Hz after that the response was poor[53]. Tiuc and Moga[54] also attempted in making composite which is both thermally insulating and acoustically absorbing. Here also the green waste materials are being converted to useful composite using polyurethane as the binder. Here the agricultural waste by products in the form of dust are used. The waste materials used for this particular case include fir sawdust, beech sawdust and particles of recycled rubber. Here different samples with different compositions of the constituents are analyzed. Out of the different samples the one containing fir sawdust particles with polyurethane concentration of 25% showed both good acoustic absorbing and thermal insulating property. The performance frequency range can be shifted by varying the type of the waste material[54]. But this particular composite is not a useful acoustic absorber in the low frequency region below 600 Hz. The maximum performance was observed near 1500 Hz. Thus waste materials can be purposefully converted to thermally and acoustically useful materials when they are incorporated properly in different composites.

With the help of composite making technology coir fibers can also be processed into more effective passive noise absorber for various industrial and domestic applications. Coir one of the strongest lignocellulosic materials finds an elegant role as a passive noise absorber in addition to its various potential applications in our daily life. It is evident from the acoustic response of certain natural fibers considered in Fig. 3 that the coir without perforated panels showed an acoustic absorption coefficient nearly above 0.7 in the frequency region above 1500-2000 Hz. So it is incorporated in making composites for acoustic absorption applications. Mahzan *et al.*[55] used coconut coir as reinforcing element, recycled rubber tyre particles as the secondary materials and polyurethane as the binder material for making composites to be used as acoustic panels. The optimized sample having maximum porosity value showed peak sound absorption coefficient near to 0.9 in the frequency region close to 1500 Hz[55]. Thus the transformation into the composite form clearly enhanced the acoustic response of the coir fibers. Here the acoustic absorption of this composite is enhanced as a result of the enhancement in the porosity when this coir is used as reinforcing element in this particular composite. Whereas, Zulkifli *et al.*[56] reported an acoustic absorption value near to 0.7 in the frequency region between 1000-2000 Hz for bare coir fibers sample. Thus coir fiber plays the role of reinforcement element in converting the waste rubber purposefully as a passive noise controller in this composite form. All these results lead to the necessity of further engineering of coir structures for industrial applications over wide range of frequencies.

In noise controlling process the crucial challenge faced is the problem of passive noise controlling in the low frequency region below 500 Hz. Even though passive acoustic filters are not that much effective in the lower frequency region compared to the active ones natural fibers like kenaf, hemp and rubber granules performs better in comparison with other natural fibers in this frequency region. Kenaf fiber of thickness 50 mm and density of 50 kg m^{-3} showed an absorption of 0.74 at 400 Hz[42,45]. Kapok fiber based composites are also proven to be effective in this low frequency region. Veerakumar and Selvakumar[57] reported that the kapok fiber/polypropylene nonwoven composite in the presence of air gap performed well in the acoustic frequency range between 250-2000 Hz. The noise reduction coefficient of this sample ranges from 0.72 to 0.87 for all the different samples tried by varying the compositions. In the lower frequencies 250 and 500 Hz the optimized sample showed sound absorption coefficient values of 0.93 and 0.80, respectively so that they can be used as passive acoustic absorbers in the low frequency region replacing the actives ones[57].

Acoustic absorbers in the frequency region above 2000 Hz: The composite making technology helps to use the above mentioned green ecofriendly sustainable materials in the high frequency noise controlling applications also when they are incorporated in different composites. For example kenaf one of the lignocellulosic micro fibrous natural materials has the potential to be used as a reinforcing element in composites for making both the low frequency and high frequency acoustic absorbers. Parikh *et al.*[58] reported the essentiality for the development of renewable, ecofriendly, biodegradable and cost effective natural fibrous lignocellulosic materials based composites as the interior noise controllers for automotive industry which enhances the passenger comfort offering competitive advantages to the manufacturer. They developed nonwoven floor covering based on the composites of kenaf, jute and cotton fibers in blend with polypropylene (PP) and polyester (PET). The sound absorption property of the prepared samples is studied separately with and without cotton and polyurethane under pad. The composite based on kenaf fiber with polyurethane under pad showed nearly 100% absorption at 3.2 kHz while that with cotton under pad showed 80% absorption and without under pads the efficiency was nearly 50% only. Thus the incorporation of kenaf in this particular case has a role in controlling the noise in the frequency region of 3.2 kHz whereas other kenaf based composites showed an acoustic response in the frequency region below 500 Hz[42,45,57]. Thus this acoustic material provides the opportunity for being used as an acoustic absorber covering a broad frequency range when it is incorporated in different composites. Other than the acoustic properties the mechanical properties can also be enhanced with the help of composite making technology when this kenaf is used in another composite. When Kenaf fiber is tried as a reinforcing element in Rubber based composites then also the frequency response region is close to 3 KHz but the product is mechanically stiff compared to the previous one discussed[59]. Suhawati *et al*.[59] did the sound absorption analysis of Foamed Rubber Composites made of natural rubber (ENR 50) and grafted natural rubber latex (MMA) reinforced with kenaf fiber and calcium carbonate instead of the commonly used reinforcing fillers like the carbon black and the silica. In this particular study the presence of the kenaf fiber helped in increasing the porosity of this composite which in turn enhanced the sound absorption mechanisms happening within it. The presence of calcium carbonate gave stiffness to the material. Thus the incorporation of naturally existing environmentally benign kenaf fiber and the calcium carbonate to a particular limit increased the noise reduction capability and stiffness of this sample. Out of the various tested specimens with varying ratios of the constituent materials the optimized sample gave the maximum absorption value near to 0.9 close to the frequency 3000 Hz[59]. Thus in the above specific cases discussed here different kenaf based composites showed peak sound absorption in the frequency region near to 3000 Hz but differing in their mechanical properties.

Even though kenaf based composites can be used for acoustic absorption below 500 Hz and in the frequency region near to 3 KHz[42,57-59] another micro fibrous eco material hemp find its application in the frequency region above 3 kHz[60]. Hemp fibers are widely used for making ropes, sack, building material, fabrics, wrapping paper etc. It is also used for waste water treatment and soil purification. It finds applications in thermal insulation appliances also because of its low value of thermal conductivity[61]. In addition to the above uses the hemp fibers are also proved to be a good lignocellulosic acoustic absorber like kenaf. Markiewicz *et al*.[60] investigated the effect of this lignocellulosic materials on the sound absorption characteristics of polypropylene composites. With the impedance tube measurement they reported that the pure polypropylene composites without the presence of this lignocellulosic fillers showed very poor sound absorption in the frequency range from 0 to 7000 Hz. It showed good acoustic response with hemp fillers but the response is favorable in the higher frequency range from 3000 to 6000 Hz. Below 3000 Hz there is practically no enhancement in the sound absorption characteristics compared to the pure polypropylene composites without these fillers. The effect of other lignocellulosic fillers like flax, rapeseed straw and beech wood is also attempted and which showed maximum performance at the frequency range of 3000-4000 Hz. The present study reported the hemp fillers as the efficient one because of its higher percentage of cellulose content (75 wt. %). Also it satisfies the compatibility conditions according to Biot[62-64] theory. Thus the incorporation of this bio friendly material has the capability of enhancing the acoustic response in addition to its capability of shifting the acoustic response frequency region from the range 3000-6000 Hz to the range 3000-4000 Hz. Here hemp helps to shift and enhance the acoustic response of this particular polypropylene based composite while the kenaf fiber played the role of doubling the acoustic absorption in the polypropylene based composite reported by Parikh *et al*.[58]. The high value of acoustic absorption makes this type of composites material useful in different interior parts of the automobiles.

In order to cover the acoustic absorption frequency above 4000 Hz coir based composites can be used. When the coir fiber is used properly for making a different composite as reported by Shiney and Premlet[65] the acoustic absorption peak is observed in the frequency region above 6000 Hz compared to the hemp based composite discussed above[60]. In addition to the potential use of coir-one of the hardest lignocellulosic fibers obtained from the husk of coconut having microns size in diameter-as erosion control blankets, mulch blankets, basket liners, bio-rolls, roof greening mats, grow sticks, coco logs etc. Shiney and Premlet[65] reported the use of composite coir mats as acoustic absorbers. They investigated the noise reducing capability of coir mats with different weaving patterns (Panama, Herringbone and Boucle weaving pattern) with and without latex under pad by varying the thickness of these mats. In all the samples the acoustic absorption was very low (<20%) in the frequency range 125-2000 Hz. Even though the acoustic response of this material was very low below 2000 Hz above 4000 Hz it showed a better performance. Usage of the latex under pad along with increasing the thickness of the samples enhanced the sound absorption prominently in the case of the panama weaved mat. In all the cases the response region was almost the same and maximum noise reduction greater than 0.9 was observed at 6300 Hz in all the cases. Acoustic comfort in the class rooms and auditoriums can be improved in an environmentally friendly manner by using these types of mats and curtains made of green sustainable materials like coir, bamboo, pine etc. This noise free environment will improve the efficiency of the teaching learning process[66,67].

In addition to the above mentioned natural fibers like hemp, kenaf, coconut coir other natural fibers can also be used for acoustic absorption applications in the higher frequency range above 2000 Hz. For example natural fibers like sisal fiber, fibers of arenga pinnata, rice straw fibers, jute fibers[40,43,68] are also used in making composites for the above purpose. Sisal fiber reinforced composites are also ecofriendly and cost effective with better noise absorbing capability compared to commercial plywood. Tholkappiyan *et al*.[68] optimized the acoustic absorption capability of the sisal fiber reinforced recycled paper pulp composites using experimental and theoretical analysis. Out of the sisal fiber reinforced recycled paper pulp composite samples the best one showed the averaged noise reduction coefficient of 0.58 in the frequency range of 125-4000 Hz[68]. Acoustic insulation panels made using the fibers of Arenga Pinnata also showed better performance in the high frequency range 2000-4000 Hz compared to those of palm fiber based ones[40]. Ismail *et al*.[40] investigated the acoustic performance of these cheap, low dense and biodegradable samples of varying thickness and the best sample showed an absorption coefficient greater than 0.85 in the wide frequency range of 2000-5000 Hz. Fatima and Mohanty[43] reported that the glass fiber reinforced rubber composites can be replaced by those of the natural jute fiber based ones but their higher sound absorption coefficient values in the high frequency range constrain their applications to domestic and automotive fields only. Jayamani *et al*.[69] investigated the acoustical, mechanical, physical, chemical and morphological properties of the polypropylene composites reinforced with rice straw fibers. They used the rice straw fibers treated with NaOH and the untreated ones for this particular study. They reported that the sound absorption of this composite is enhanced by this lignocellulosic rice straw fiber reinforcer. The study revealed that the treatment with NaOH, the fiber concentration and the thickness of the sample influence the sound absorption coefficient. But the sound absorption coefficient value of these composites is not so high compared to that of the other natural fiber reinforced polymer composites. In this particular composite samples the maximum absorption value is close to 0.15 in the frequency region close to 6000 Hz whereas for the rice hull reinforced Polyurethane composites (PU-RH composite)[49] the sound absorption coefficient value was very close to unity in the frequency region below 500 Hz. Another polypropylene based composite with kapok fiber as the reinforcing element reported by Veerakumar and Selvakumar[57] also performed as a good acoustic absorber compared to this particular polypropylene based one. Hence the reinforcing material can be used properly to tune and alter the acoustic property of the composites.

Thus with the help of composite making technology these ecofriendly materials can be used for passive noise controlling in a productive way by incorporating them in composites according to the application of interest by tuning their physical and mechanical properties. Here these materials are proved to be efficient in controlling the noise in a variety of appliances in the low frequency and high frequency region.

SYNTHETIC MATERIAL BASED COMPOSITES AS PASSIVE ACOUSTIC ABSORBERS

Synthetic materials are also proven as efficient acoustic absorbers even though some of them are not environmentally friendly compared to the natural green sustainable materials. Glass wool, rock wool, polystyrene, polyurethane, polyethylene and Polyester are some of the popular synthetic acoustic absorbers[13]. In the case of the synthetic materials the availability of the materials with known chemical properties and optimized physical properties make them comfortable to be used as acoustic absorbers. Recent advancement in the composite making technology allow it favorable to use the synthetic fibers like glass fibers and carbon fibers as reinforcing elements to alter the physical and chemical properties of the particular composite of interest[70]. For example the nylon fibers are proven to be a good reinforcing element in different types of rubber composites[71,72]. Now a days it is possible to develop low cost, fire resistant, cost effective, high temperature resistant and less polluting composites for acoustic applications[73,74]. With the recent introduction of nanomaterials, polymer based organic and inorganic nano composite materials are gaining wide acceptance in various applications compared to the conventional composite materials because of their improved mechanical, thermal, electrical and optical properties[75,76]. An additional advantage is that the structural properties of these types of composite materials can be modified in order to get the required composites with required properties with the help of the technique used to prepare them[77]. The recent introduction of metamaterials opened a new horizon in noise controlling[24]. Here this particular section mainly concentrate on the different synthetic composite materials developed which are having good acoustic absorption in the frequency range below 2000 Hz and above 2000 Hz.

Acoustic absorbers in the frequency region below 2000 Hz: As an impact of the modernization of the present industrial world sound of all frequency range which are present in the environment adversely affect the human well being physically, physiologically and psychologically. In particular low frequency noise control is predominantly significant because of its low attenuation by the walls and other structures. So they travel more with less energy loss[7]. In the present context it is relevant to consider the low frequency noise reducing smart materials. Different types of Aluminium based composites, cement composites, rubber composites, polyurethane and formaldehyde composites etc. are tested for their acoustic absorption in this particular frequency region. Hasan *et al.*[78] developed low frequency sound insulating materials with cement based composite material. It is proven to have good sound transmission loss in the frequency range below 500 Hz. Here the composite material tried is the closed cell cement foam known as Cement-based Syntactic Foam (CSF). The acoustic energy loss while transmission is tested in two types of CSF. One is CSF-CS and the other is CSF-CHS. The CSF-CS is the cement matrix embedded with in-house developed Cement Spheres (SC) and CSF-CHS is that with Cement Hollow Sphere (CHS). Both samples performed well in low frequency range below 500 Hz and the maximum Sound Transmission Loss (TL) was near to 300 Hz. In addition to this the developed smart materials showed excellent mechanical properties also.

Different types of composites of Aluminum are popularly used in noise controlling applications. Low density aluminum foam and its composites showed better acoustic absorption and transmission loss in the wider frequency region of 500-1200Hz while the high density foam showed better performance in the region 400-800 Hz[79]. Ko *et al.*[79] reported an increased sound absorption coefficient for the compressed aluminum foam than the uncompressed one. Here compression introduces sharp edged cracks and hence increases the air cavity length within this material. As a result of this the sound absorption mechanisms are enhanced more effectively irrespective of its density and the acoustic absorbing region is shifted to the lower frequency side. It is reported that these cellular metal composites are environmentally friendly compared to glass wool and polyurethane foam which are the commonly used synthetic passive noise controllers. For the acoustic absorption applications in the frequency region above 1000 Hz also the Aluminum based composites can be used. In the case of another Aluminum based composite a sound absorption peak value of 0.95 is observed at the frequency of 1500 Hz as reported by Baskar *et al.*[80] for the Al/cenosphere composite matrix. Thus the shifting in the peak acoustic absorption frequency is taking place when the elemental aluminum itself is incorporated in one composite to an entirely different one. This Al/cenosphere composite matrix produced by stir-casting technique is cost effective and less pollutant compared to the aluminum based ceramic materials[80]. The presence of the cenosphere micro-balloons with hollow space in between them within this material enhances the sound absorption mechanisms happening inside it. In the present context this particular composite material showed a very good acoustic response in the frequency range1000-2000 Hz with its peak absorption at 0.95 corresponding to 1500 Hz. Whereas, Cuiyun *et al.*[73] reported another Al based composite specimen which is having acoustic absorption greater than 0.9 in the frequency range 1500-2000 Hz. As a result of the difference in the particular composite making technology applied to prepare this particular Al based composite it is acoustically absorbing as well as high temperature resistant, low dens, fire resisting and cost effective compared to other Al based composites and ceramics. Cuiyun *et al.*[73] fabricated this macro porous zeolite (a ceramic material) by high temperature sintering method. Zeolites have their main component as aluminosilicate are made macro pours by adding pore forming polymer particles. The acoustic absorption properties of this composite are investigated for different samples of varying density and porosity and thus optimized the sample for its best acoustic performance. The optimized samples showed a noise reduction coefficient greater than 0.9 in the frequency range 1500-2500 Hz. The Allard[81] and Delany and Bazley[37] modeling studies are also done for characterizing the acoustic properties of these samples of which the Johnson Allard model almost match with the experimental observations. The aluminum foam A356/20SiCp prepared by infiltration technique having improved mechanical properties also showed good acoustic absorption with peak absorption coefficient close to 0.9 in the frequency region 1600-1800 Hz[82].

Other than these Al based materials the Nylon/PET/PU composite planks are also reported to be acoustically active in the frequency region near to 1000 Hz as reported by Lou *et al.*[74]. As the nonwoven materials are proven to be good sound absorbing materials with their inherent properties like high surface area, porous nature and the possibility for varying the fiber diameter improves the sound absorption mechanisms within them. Lou *et al.*[74] utilized recycled waste selvage fiber for reinforcing poly urethane based non-woven composites and acoustically characterized them. They tried with different samples by varying the composition and optimized the samples for their sound absorbing and fire retarding property. Out of the nonwoven nylon/PET/PU composite planks prepared the five best performed samples showed peak acoustic absorption coefficient in between 0.77 and 0.86 with the corresponding peaking frequencies in between 856 and 1028 Hz in each case making them favorable to be used as passive noise controllers in automobiles and buildings[74]. The ecofriendly, cost effective, light weight, flame retarding and other relevant tunable mechanical and physical properties of these composites make them useful in automobile, aerospace and building industries.

Like aluminum foam natural Styrene Butadiene Rubber (SBR) is also a good acoustic absorber in the low frequency region with peak acoustic absorption at 500 Hz. In this context the use of composites made by blending natural rubber with reclaimed rubber as noise absorbers serves as a remedy for both the noise pollution and waste disposal problems at a single stretch. Algaily and Puttajukr[83] developed a composite material by blending natural Styrene Butadiene Rubber (SBR) with Reclaimed Rubber (RR) with sodium bicarbonate as the blowing agent. Here this material is a strong acoustic absorber without the presence of RR itself having an absorption coefficient above 0.9 in the wide frequency range 20-2000 Hz with its peak absorption at 500 Hz. By the addition of RR its absorption peak is shifted to the higher frequency range above 500 Hz. Here the addition of RR not only enhances and shifts the sound absorption region but also improves the mechanical properties of this composite. The blowing agent sodium bicarbonate helps in producing microstructural open cells in the samples and hence helps in increasing the porosity and hence the sound absorption mechanism[83]. Thus the problems of the environmental pollution from rubber wastes as well as the noise pollution which became serious concern of the modern society are solved in single stretch by converting the rubber waste products as passive noise absorbers for the reduction of the industrial/automobile noise which are harmful to human beings.

Other than the synthetic materials already discussed the industrial waste materials can also be fruitfully converted into passive acoustic absorbers with the help of the composite making technology. The same technology itself is proved to be successful in the case of producing passive acoustic absorbers of natural composites using different types of agricultural wastes as reinforcing element[49,52-54]. For example waste materials like crushed glass from glass industry, waste wood particles from wood processing industries and the polypropylene from plastic wastes can be usefully utilized by converting them into acoustic materials[84]. Thus waste disposal problems and its hazardous effects are solved at the same time. Bratu *et al.*[84] developed different types of formaldehyde composite materials reinforced with crushed glass, waste wood particles and polypropylene plastic wastes respectively. They studied the acoustic absorption properties of the prepared samples using the Impedance tube. The size distribution of the used waste particles were analyzed using the laser particle analyzer and the porosity, the compressive strength and the water absorbing capacity of the composite samples are also quantified. The morphological analysis of the samples are done using the SEM. Out of the different composite samples prepared the best one was that containing wood particle waste and its acoustic absorption performance was above 70% in the frequency range 1300-2200 Hz. The peak acoustic absorption coefficient observed for this particular sample is 0.9 at 1600 Hz. Whereas for the polypropylene reinforced composite samples the acoustic absorption value peaked at 0.8 corresponding to the frequency 1600 Hz and the acoustic response range was narrower compared to the best performed sample. The porosity value of the optimized wood particle reinforced sample was the highest one (46.28%) compared to that of the other ones whereas its compressive strength was minimum and water absorption capacity was maximum. Thus the maximum value of porosity and minimum value of compressive strength help it to become a good passive noise controller. Here because of the weaker porous morphology of the crushed glass reinforced composite samples it is behaving as a poor acoustic absorber compared to the other ones. This sample showed a maximum absorption coefficient of 0.2 while the other ones reinforced with wood waste and polypropylene waste having higher porosity performed with their peak sound absorption values at 0.9 and 0.8, respectively.

Acoustic absorbers in the frequency region above 2000 Hz: The synthetic material based composites are also proven to be efficient absorbers in the acoustic frequency region above 2000 Hz. For example different types of aluminum composites

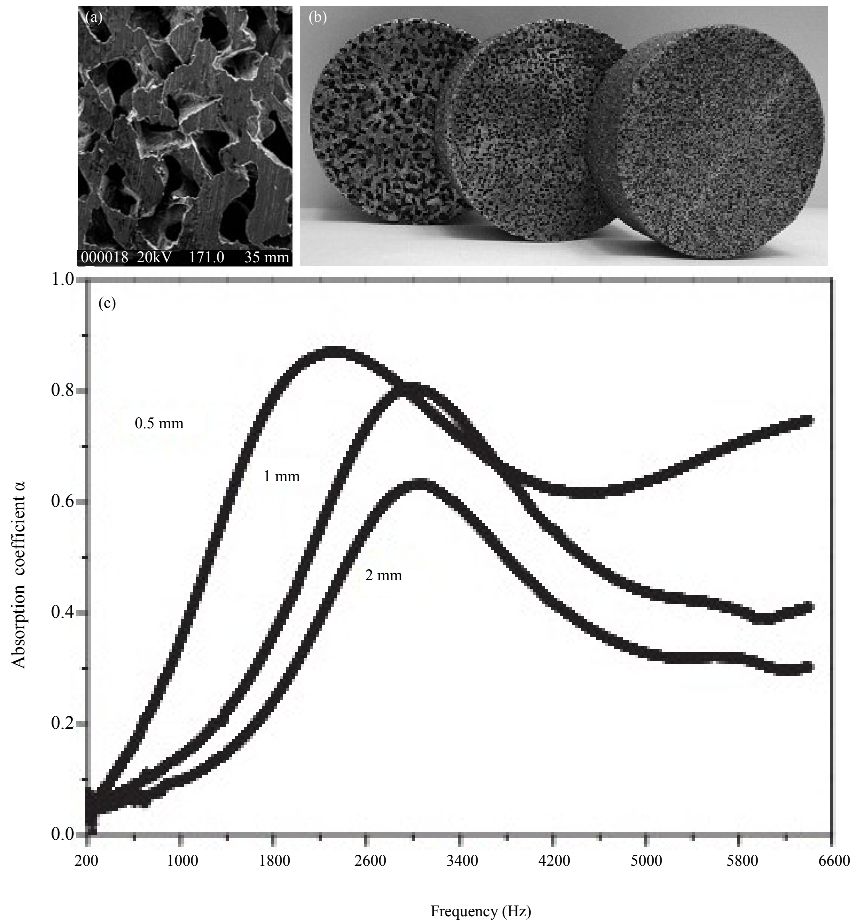

Fig. 4(a-c): (a) SEM image of the interconnected pores in AlSiMg alloy/NaCl composite[76-85], (b) Different samples with different pore size prepared by infiltration process[76-85] and (c) Dependence of pore size of the sample on the sound absorption coefficient[76-85]

can be used for noise controlling in this frequency region. Already it is seen that low density aluminium foam and high density Aluminium foam are proven to have acoustic absorption in the frequency region 500-1200 and 400-800 Hz, respectively[79]. While the aluminium/cenosphere and aluminium zeolite composite materials have their sound absorption peak at 1500 Hz and in the frequency region 1500-2500 Hz, respectively[80,73]. Eventhough these aluminium based composites are operating in the frequency region below 2000 Hz, Fernandez *et al.*[77] developed another aluminium based AlSiMg alloy/NaCl composite with its peak sound absorption in the frequency region between 4000 Hz and 5000 Hz. Here the structural properties of the pores which plays a major role in regulating the noise controlling properties of acoustic materials are optimized by the fabrication method used to prepare this particular composite material. Fernandez *et al.*[77] reported the effect of the infiltration technique in varying the morphological and dimensional properties of the pores structure of the AlSiMg alloy/NaCl composite. The inter-structural interconnection between the open pores existing inside this particular aluminum sponge composite as seen in the SEM image of this composite (Fig. 4a)[77,85] enhances the sound extinction mechanisms inside the material. It is reported that the decrease in pores size is helpful in improving the acoustic absorption property[37] which can be optimized using this particular infiltration technique in this cellular metal. The optimized samples with minimum pore size of 0.5 mm showed an acoustic absorption coefficient near to 0.9 for a sample of thickness 10 mm (Fig. 4b, c)[85]. In all the samples the absorption coefficient varies with respect to the variation in the in the pore diameter which can be controlled by the nature of the NaCl used in the infiltration technique. The other important achievement is that this particular composite of 45 mm thickness with 0.5 mm pore size showed a shifted acoustic absorbing region below 500 Hz when it is backed

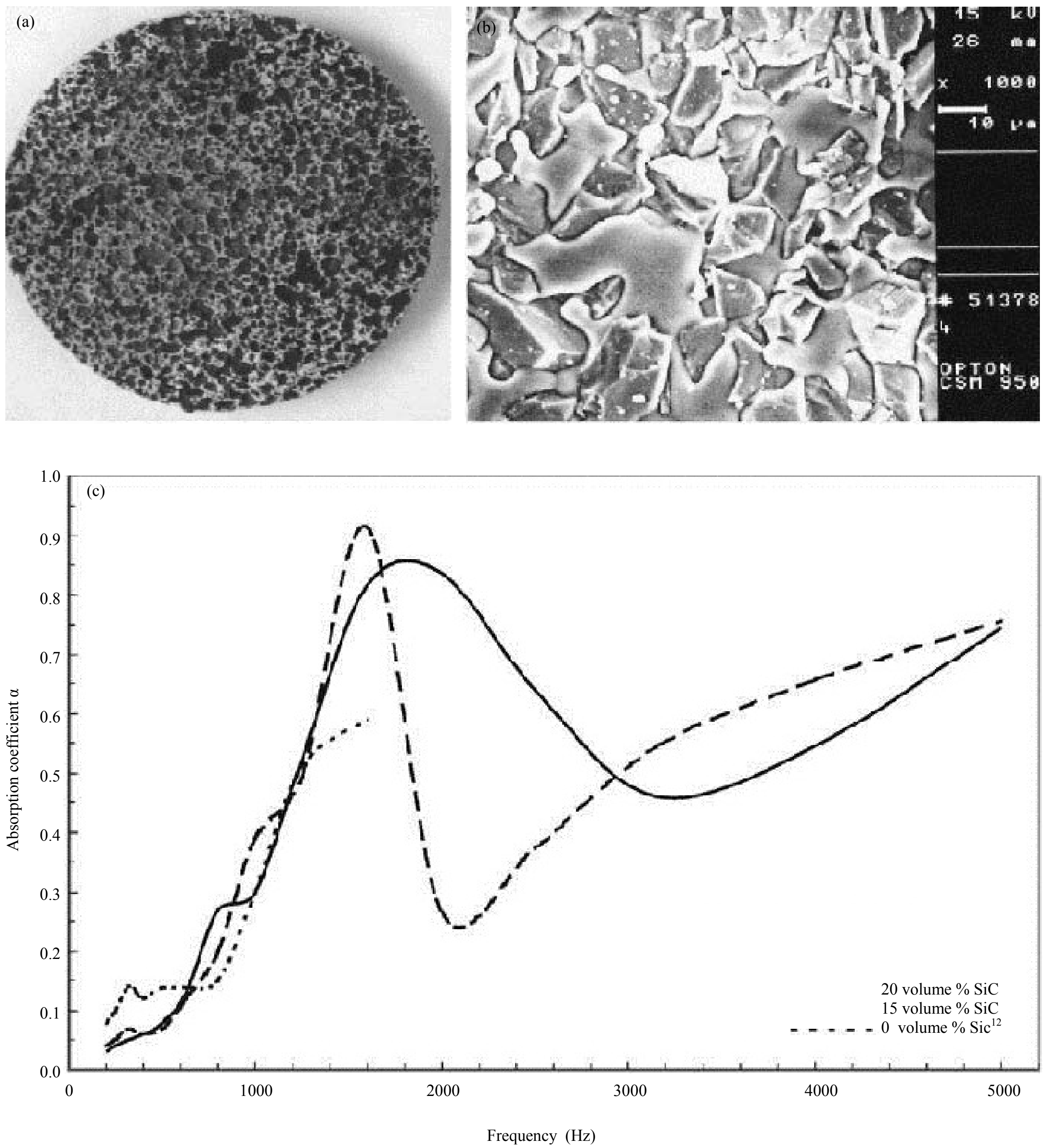

Fig. 5(a-c): (a) Typical macro graphic structure of A356/20SiCp composite foams[82], (b) SEM image of cell surface of A356/20SiCp composite foams[82] and (c) Influence of frequency and SiCp content on sound absorption coefficient[82]

with air gap of different thickness[85]. The macroscopic structure of the samples with different pore size prepared through the infiltration technique and the dependence of pore size on the sound absorption coefficient are shown in Fig. 4b and c, respectively[85]. While, Jiejun *et al.*[82] achieved in preparing a different Aluminum based composite foam (A356/20SiCp) with the infiltration technique itself with good acoustic absorption in the frequency region below 2000 Hz. Figure 5a and b show the macroscopic structure of the sample and its SEM image, respectively. The porous morphology of this specimen having interconnected pores is helpful in increasing its acoustic absorption which can be controlled with the technique of preparation of this composite. Figure 5c shows the shifting in peak absorption frequency for different percentage of SiC[82]. In the above cases the acoustic response of the sample is being tried to get enhanced and controlled within the frequency region of interest with the help of the composite making technology. Thus it is clear that the composite making technology is so powerful in altering the porous morphology of the passive absorber according to the problem of interest so that it is possible to produce efficient acoustic absorbers operating in different frequency regions from the same elemental material itself.

The recent advances in the field of nanotechnology and the introduction of different types of nanomaterials are helpful in improving the performance of the naturally existing acoustic materials. Thus composite making technology is being empowered with the introduction of nanotechnology. Trematerra *et al.*[86] reported that coating a layer of Nano fibrous materials on the surface of the acoustic materials improves their performance. It is also noted that the acoustic absorbing frequency region shifts when the nano fibrous layer is coated on different acoustic materials[86]. This Nano fibrous acoustic resonance membrane having very narrow Nano fibers with high surface to volume ratio enhances the different types of acoustic energy loss mechanisms like the frictional, thermal, scattering and momentum loss mechanisms[13,87,88]. In this particular case the incorporation of NY6 nano fibrous coating layer of thickness 10 m on the kenaf sample of thickness 40 mm increases the sound proofing capability slightly in the frequency region below 500 Hz and prominently up to 25% in the frequency region 500-1500 Hz and above that the effect of nano fibre layer coating is insignificant. While felt sample of 3 mm thickness with this coating showed an enhancement in the higher frequency region 3-6.5 kHz[86].

Like the natural and synthetic composites already discussed nano fibrous resonant membranes and textile materials are also used for making passive acoustic absorbers[89,90]. Textile materials find application in passive noise reduction due to their fibrous nature similar to that of the natural fibers like coir, kenaf, hemp etc. Na *et al.*[90] reported the efficiency of nano fiber webs compared to microfiber and ordinary fabrics in acoustic absorption applications. They used different types of micro fiber fabrics such as suede, waffle, queenscord mesh, terry and then used nano fiber fabric of the same materials containing different number of layers with similar weight for the acoustic absorption measurement. Even though it is revealed that increased number of nano layers improved the noise reduction mechanisms it is restricted only in the frequency range of 1000-4000 Hz and in the frequency region below this the effect was insignificant. The best efficiency of 85% at 4000 Hz is achieved by the addition of Nano fiber webs on regular fiber fleece which makes them ideal to be used as thin light weighted noise filters[90]. Asmatulu *et al.*[91] reported the sound absorption properties of the nano fibrous PVC and polyvinylpyrrolidone (PVP) which are prepared by the electro spinning method. These materials because of t heir fiber diameter in the nanometer range of 500-900 nm with high surface to volume ratio compared to natural micro fibrous martial showed better acoustic absorption in the frequency range of 2000-7000 Hz. So they can be used for aircraft interior noise reduction[91]. In such type of cases there is not that much wide opportunity for converting waste products of modern world to the useful green materials. So the possibility of useful incorporation of cheapest materials in producing novel materials for superior performing appliances is limited in this textile technology compared to the composite one.

Recent advances in the designing and development of acoustic metamaterials paved the way in using them as acoustic absorbers in different regimes where the noise control is relevant. Mei *et al.*[24] developed acoustic metamaterial capable of absorbing sound in the low frequency region between 100-1000 Hz which can be used as a perfect acoustic absorber in this frequency region. Instead of the commonly used traditional acoustic absorbers Jiang *et al.*[92] designed an acoustic metamaterial having acoustic absorption coefficient near to 1 in the wide frequency region of 100-10000 Hz and experimentally verified their theoretically predicted result. Li *et al.*[93] reported acoustic metamaterial with the capability for both sound absorption and energy harvesting which are active in the frequency region between 400 and 500 Hz. However, the high cost of production of these materials limits their applications compared to those of the above mentioned composites.

Thus the availability of synthetic materials with known physical, mechanical and structural properties make them comfortable to be used as acoustic absorbers in various applications. Therefore the incorporation of these particular ones for the acoustic application satisfying the required physical properties can be easily optimized. The active absorbing frequency region/the peak absorption frequency of some of the composites which are reviewed in this present article are shown in Table 2.

Table 2: Active absorbing frequency region/the peak absorption frequency of some of the composites

Composite materials	Active acoustic absorbing frequency region/peak absorption frequency	References
Coconut coir/recycled rubber tyre particles/polyurethane composite	Peak sound absorption coefficient close to 0.9 nearly at 1500 Hz	Mahzan *et al.*[55]
Arenga pinnata panels	Absorption coefficient greater than 0.85 in the wide frequency range 2000-5000 Hz	Ismail *et al.*[40]
Kapok fiber/polypropylene nonwoven composite	Frequency range 250-2000 Hz. Noise reduction coefficient in the range 0.73-0.87	Veerakumar and Selvakumar[57]
Kenaf/polypropylene/polyester (PET) composite with polyurethane under pad	Nearly 100% absorption at 3.2 kHz	Parikh *et al.*[58]
Kenaf/polypropylene/polyester (PET) composite with cotton under pad	80% absorption at 3.2 kHz	Parikh *et al.*[58]
Kenaf/polypropylene/polyester (PET) composite without under pads	Only 50% absorption at 3.2 kHz	Parikh *et al.*[58]
Pure polypropylene/hemp composites	Frequency range 3000-6000 Hz	Markiewiez *et al.*[60]
Coir mats with latex under pad	4000-6000 Hz. 90% absorption at 6.3 kHz	Shiney and Premlet[65]
Sisal fiber/recycled paper pulp composites	Noise reduction coefficient of 0.58 in the frequency range 125-4000 Hz	Tholkappiyan *et al.*[68]
Mortar/rice husk/ply wood composite	The frequency range of 200- 2000 Hz	Gonzalez *et al.*[52]
Natural rubber (ENR 50)/grafted natural rubber latex (MMA)/kenaf fiber/calcium carbonate composite	Maximum absorption coefficient value near to 0.9 close to 3000 Hz	Suhawati *et al.*[59]
Polyurethane/Rice Hull composite (PU-RH composite)	Lower frequency range below 500 Hz	Wang *et al.*[49]
formaldehyde/waste wood particles composite	Acoustic absorption above 70% in the frequency range 1300-2200 Hz with the Peak acoustic absorption coefficient value 0.9 at 1600 Hz	Bratu *et al.*[84]
Low density like aluminum foam	Frequency region 500-1200 Hz	Ko *et al.*[79]
High density foam	In the frequency region 400-800 Hz	Ko *et al.*[79]
AlSiMg alloy/NaCl composite	Greater than 0.9 in the frequency range 4000-5000 Hz	Fernandez *et al.*[77]
Kenaf sample with NY6 Nano fibrous coating layer of thickness 10 µm	Frequency region 500-1500 Hz	Trematerra *et al.*[86]
Felt sample with NY6 Nano fibrous coating layer of thickness 10 µm	Frequency region 3-6.5 kHz	Trematerra *et al.*[86]
Al/Cenosphere composite matrix	Frequency range of 1000-2000 Hz	Baskar *et al.*[80]
Rubber (SBR)/reclaimed rubber (RR)/sodium bicarbonate composite	Frequency range 20-2000 Hz	Algaily and Puttajukr[83]

CONCLUSION

This article elaborate the potential of using composite material as passive sound absorbers. Recent developments in composite making technology provides a wide opportunity in designing sound attenuators in required frequency range. Natural fiber composites has a wider prospective in this regards since it can reduce the global warming potential.

SIGNIFICANCE STATEMENT

Sound pollution is a serious health concern of the modern world. Composite materials have proven advantages in passive noise control. The physical, mechanical and structural properties of the composites can be engineered through proper choice of constituent materials in appropriate composition. Hence, it offers a wide range of acoustic frequency tuning for different industrial level applications. Natural fiber composites in sound pollution control is an emerging area of research, where more intellectual investment is required to overcome the limitations of thermal instability.

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