Use of municipal, agricultural, industrial, construction and demolition waste in thermal and sound building insulation materials: a review article

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Abstract

Production and usage of green and sustainable building materials realizes the desire to integrate more biodegradable, natural, recycled, and renewable resources into the construction industry. The aim is to replace traditionally available construction industry materials due to their environmental impacts through air emissions and waste generation. An observed trend is the production of insulation materials by recycling of industrial, agriculture, construction and demolition (C&D), and municipal solid wastes, thus reducing the environmental burdens of these wastes. While thermal insulation is important in saving energy, sound insulation has drawn much attention in recent years. There are various waste materials that have good thermal and sound properties, enabling effective replacement of traditional materials. This review investigates the use of industrial, agricultural, C&D, and municipal solid wastes to produce innovative thermal and acoustic insulating building materials. The performance of these insulating materials, and the influence of several materials parameters (density, thermal conductivity, sound absorption coefficient) on thermal and acoustic performance are reported after a brief description of each material.

Keywords Solid wastes · Recycling · Thermal and sound insulation · Building materials

Introduction

Usage of environmentally friendly materials has significantly increased due to greater attention and awareness of society about the environment, and in particular the impact of the

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construction industry on it [1]. The application of thermal insulation is an important factor for energy savings in buildings [2]; effective building insulation can reduce greenhouse gas (GHG) emissions by over one hundred times versus the emissions incurred in manufacture of these materials. The European Commission's target is to reduce greenhouse gas (GHG) emissions by 20% by 2020 versus a baseline fig. [3]. Production of insulation materials from recycled waste can be the solution to this problem [4, 5]. At the same time, noise pollution is one of the major concerns in building design because of its impact on human health [6]. With increasing demand for building materials, development of products that can provide better sound and thermal insulation has been become more popular [2].

Building materials that are produced from recycled wastes are now considered as green materials, as opposed to low quality or inexpensive materials according to traditional views. Thus, the production of thermal insulation materials by recycling of industrial, agriculture, construction and demolition (C&D), and municipal solid waste has drawn a lot of attention [7]. It is important to analyze and characterize the recycling of wastes as construction materials [8–10] for thermal or acoustic insulation. Researchers have investigated the potential use of agricultural by-products as thermal and sound

insulation [9, 11–13]. Different wastes have been studied as raw material sources to obtain lightweight bricks [14], panels [15–17], or as concrete reinforcement [18, 19]. Table 1 summarizes the waste materials that can be used to improve insulation properties.

In buildings, all of the mentioned wastes (Table 1) can potentially replace synthetic thermal and sound insulation materials in the main and partition walls, ceiling, and roofs, leading to savings in virgin materials and cost reduction in the building industry. This

review paper reports the current state of research on the conversion of municipal, agricultural, C&D, and industrial wastes into innovative thermal and acoustic insulating building materials. After a brief description of each material taken into account, and the required characteristics of insulation materials, the review reports and assesses how the materials' properties (density, thermal conductivity, and sound absorption coefficient) influence thermal and sound insulation performance.

Table 1 Waste materials that can be used to improve insulation properties

Waste type	Materials	References
Municipal waste	Recycled concrete with cores of textile waste	[15]
	Recycled cardboard based panels	[16]
	Textile fiber waste	[20]
	End-of-life rubber waste particles have been made from the mechanical shredding of rubber	[21]
	Olive seeds after the separation and extraction of oil added to ground PVC and wood chips (from wood industry)	[22]
	Recycled-PET fiber based panels from end consumer of plastic bottle	[17]
	Recycled polyester fibers from recycled plastic	[23]
	Recycled foam from packaging materials	[24]
	Various plastics in municipal waste, such as recycled end-use carpet waste	[7, 24]
	Cellulose sound absorbers produced by using extracted cellulose from recycled paper	[25]
Agricultural waste	Glass waste	[26]
	Maize husk after separation of the corn	[27]
	Maize cob after separation of the corn	[27]
	Coconut pith with groundnut shell	[27]
	Sheep's waste wool	[1]
	Sunflower stalks after the separation and extraction of oil	[28]
	Corn peel after separation of corn seed	[29]
	Wheat straw board composed of coconut coir and durian peel	[27]
	Kenaf binderless board	[27]
	Expanded vermiculite and perlite	[27]
	Stubble fiber after harvesting of wheat and barley	[30]
	Bagasse after extracting sugar	[31]
	End-of-Life Tires (ELTs) from cars	[32]
Industrial waste	Recycled fillers including fly ash and bottom ash	[33, 34]
	Composite from coal fly ash and scrap tire fiber	[13]
	Steel slag from the steel production plant	[35]
	Cardboard-based panels with recycled cardboard from packaging	[16, 36]
	Composite of onion skin and peanut shell fibers, perlite, fly ash, pumice, cement, barite	[37]
	Rice husk ash and volcanic ash	[38]
	High calcium fly ash concretes with recycled foam	[39]
	Elastomeric waste residues consumed in the packaging industry	[40]
	Composite of cotton waste, fly ash and barite	[41]
	Wood processing by-products waste	[42]
C&D waste	Lightweight expanded clay, crushed bricks, and aggregates foam polystyrene and its waste	[43]
	Recycled blocks containing C&D	[44]
	Construction waste wood used in cement-bonded particleboards	[45]
	Recycled concrete blocks and recycled aggregate concrete	[46]

Fig. 1 Textile waste types studied by Briga-Sa et al. (2013) [63]. Reused with permission from Elsevier (4546730816186)

Characteristics of insulation materials

Thermal insulation

Thermal insulation materials are designed to reduce the transmission of heat flow through building walls. A building's internal ambient temperature can be controlled with air conditioning. Application of thermal insulation in buildings is the main technique for reducing the use of air conditioning, therefore saving in energy consumption [9]. The thermal insulation performance of single or combined materials is usually evaluated by thermal conductivity and thermal transmittance. Thermal conductivity defines the heat flow passing through a unit area of the material, 1 m thick, with 1 K difference of temperature between the two sides of the material ($\text{Wm}^{-1} \text{K}^{-1}$). Moreover, it is measured according to EN 12664 [47] and EN 12667 [48], or also ASTM C518 standard [49]. Thermal insulator materials are

characterized by having a conductivity lower than $0.07 \text{ Wm}^{-1} \text{K}^{-1}$ [4]. Insulator materials having thermal conductivity under $0.05 \text{ Wm}^{-1} \text{K}^{-1}$ can be considered to be high performing [50]. Multi-layer thermal properties are usually characterized by thermal transmittance [51], which is the heat flow that passes through a unit area of a complex component or inhomogeneous material with a unit of $\text{Wm}^{-2} \text{K}^{-1}$ [52].

There are comparable thermal properties between the corn's cob, which is an agricultural by-product, and that of extruded polystyrene. Researchers have also carried out studies to produce new insulating material from jute, flax, and hemp. The application of a combination of these natural materials is comparable with conventional thermal and sound insulation materials [11]. Another study showed that bagasse fibers enhance the thermal properties of cement composites [53]. There are several other agricultural by-product materials, such as coconut coir and rice husk, that have shown lower thermal conductivity [54].

Fig. 2 Sections of test pieces classified regarding their percentage of rubber weight and rubber size graduation [32]. Reused with permission from Elsevier (4546731141780)

Acoustic properties

Sound insulation is expressed by measuring sound reduction index R_w , which can be done according to the ISO 717-1 standard [55]. R_w is the ability of a material to prevent the passage of sound through itself, and it is expressed in dB. The lower the sound reduction indicated, the lower the sound insulation of the structure. The amount of sound insulation by a wall in buildings is evaluated through the standard ISO 10140 [56]. The R_w is measured on real-sized samples, such as windows, partitions, doors, etc. [57].

Sound absorption coefficient (α) is the portion of the absorbed sound from the incident sound to the wall. The sound power absorbed by a material is usually evaluated by Eqs. (1) and (2).

$$W_a = W_i - W_r - W_t \quad (1)$$

$$\alpha = W_a W_i^{-1} \quad (2)$$

Fig. 3 **a** Recycled cellulose fibers. **b** Recycled cellulose aerogel. **c** FE-SEM image of recycled cellulose aerogel Nguyen et al. (2014) [72]. Reused with permission from Elsevier (4546731300473)

where: W_i : the incident sound power; W_r : sound power reflected by the analyzed material; W_t : the sound power that passes through the material; and W_a : the absorbed sound power.

For small samples, the sound power absorbed by a material is measured by using an impedance tube in compliance with ISO 10534-2 in a laboratory setting [58], while for larger ones (at least 10 m²), this parameter is measured in a spatial reverberation room by ISO 354 (ISO 2003) or by ASTM C423-09a [59].

Open porosity and air movement are the key parameters to absorb sound [60]. Therefore, an interconnected structure is a vitally important parameter to reduce noise and absorb them [40]. As well as, the mass and density of the acoustic insulation materials have a strong relationship with this characteristic. Hence, the ability of sound insulation of heavier components is better than that of lightweight materials.

Wastes converted into building thermal and sound insulation materials

Municipal solid waste into building insulation materials

It is anticipated that by 2025 cities will produce about 2200 million tons per year of solid waste globally (Schiavoni et al. 2016). There are various materials in municipal waste that can be converted to insulation material.

Textile fiber waste, which is composed of 28% C₂S, 38% portlandite and 21% of calcite, has been added to natural lime. The textile waste fibers were 4–82 cm long and 0.05–0.4 mm thick. In the sample with lime to water ratio of 1:2, thermal conductivity was 0.25 Wm⁻¹ K⁻¹, and sound absorption

coefficient (α) was 0.25 [20]. Thermal property of converted textile waste was 0.033–0.039 Wm⁻¹ K⁻¹ for tablecloth and linter; linter are short fibers clinging to cotton seeds after ginning [61]. The composite materials made up of polyurethane foam and textile fiber have better sound absorption properties compared to pure polyurethane foam [62]. The woven fabric waste and woven fabric sub-waste (Fig. 1) have thermal conductivity of 0.04–0.103 Wm⁻¹ K⁻¹ [63]. In one study that investigated the influence of proportion and particle size of rubber from ELTs, the insulation property was enhanced. The best results were for the finest particle size (0–0.6 mm and water/plaster = 0.77 and plaster/rubber = 0.6) (Fig. 2) [32].

The thermal conductivity of wood-gypsum-newspaper sandwiched concrete panel, and cement-wood were 0.233, 0.45, and 0.08 Wm⁻¹ K⁻¹, respectively [64–66]. The thermal conductivity of cement composites containing rubber with the density of 430 kg m⁻³ was 0.47 Wm⁻¹ K⁻¹ for a lightweight insulation panel containing 50% rubber particles [67]; as a result, the cement thermal conductivity was decreased about 60% [21]. The thermal conductivity of expanded shale-based concrete with a density of between 1100 and 1300 kg m⁻³ was 0.70 Wm⁻¹ K⁻¹ [67]. In cases where crumb rubber was used in concrete panels, these were lighter and had a higher sound absorption and lower heat transfer. Crumb rubber concrete (CRC) panels must have a thermal conductivity less than 0.303–0.476 Wm⁻¹ K⁻¹. Concrete that contains 30% and large-sized crumb rubber No. 6 (3.36 mm) have the lowest value of heat transfer rate. With 20% of No.6 crump rubber, sound absorption coefficient was 0.37. With increasing the rubber content and rubber particle size heat transfer decreases while the sound absorption increases [68], unlike rubber-gypsum composite [67].

Fig. 4 Processing steps for manufacturing wool insulation batts Corscadden et al. (2014) [1]. Reused with permission from Elsevier (4546740124625)

Fig. 5 Insulation boards made from sunflower stalk, textile waste and stubble fibers Binici et al. (2013) [30]. Reused with permission from Elsevier (4546740391584)

Fluff is derived from the shredding of tires and contains ground tire rubber elastomer, metal fibers, and textile. The fibrous layer enhances the sound absorption coefficient (α). Resin causes a reduction in open porosity, which decreases the sound absorption properties. The best acoustic performance has been obtained for a sample with a thickness of 2.28 cm, density of 441 kg m^{-3} , and compaction preset of 0.003 MP. In 2000 Hz, the sound absorption coefficient was 0.99 [69]. The thermal conductivity of composite of concrete containing plastic waste (20% PE) with the density of 606 kg m^{-3} was $0.663 \text{ Wm}^{-1} \text{ K}^{-1}$, and samples with 20% PVC waste with the density of 715 kg m^{-3} had a thermal conductivity of $0.769 \text{ Wm}^{-1} \text{ K}^{-1}$ [70]. Moreover, the thermal conductivity of another sample with 10% PE and 10% PVC, which had a density of 624 kg m^{-3} , was $0.774 \text{ Wm}^{-1} \text{ K}^{-1}$.

In the study on various cardboards as sound insulation materials, which was made up of two honeycomb panels filled with cellulose fibers, and having a thickness of 15 mm and 10 mm cells, the sound absorption coefficient (α) was 0.85. On the other hand, in panels

made of cylindrical cardboard with a density of 80 kg m^{-3} and 20 mm total thickness, α was 0.95. This amount is higher than conventional gypsum panel's sound absorption coefficient (0.5–0.7), with cell diameters from 6 to 10 mm, and thickness of 60–200 mm, which are filled with wool or polyester fibers [71]. Recycled cellulose aerogels of recycled paper have thermal conductivity of $0.032 \text{ Wm}^{-1} \text{ K}^{-1}$, and can be an alternative to silica aerogel and sheep wool, which possess thermal conductivity of 0.026 and $0.03\text{--}0.04 \text{ Wm}^{-1} \text{ K}^{-1}$, respectively (Fig. 3) [72]. The thermal conductivity value can be decreased to $0.029 \text{ Wm}^{-1} \text{ K}^{-1}$ after being coated with methyltrimethoxysilane, for enhancement of hydrophobic properties [58]. Cellulose obtained from the paper is a sound absorbing material, and can be formed to obtain adequate noise reduction coefficient (NRC). The thermal conductivity of cellulose with a density of 55 kg m^{-3} is reportedly $0.039 \text{ Wm}^{-1} \text{ K}^{-1}$. NRC of such sound absorber with thickness of 60 mm and density of 36 kg m^{-3} has been measured to be 0.75 [25].

In a survey on the performance of insulation panels made up of 38% ground PVC, 33% epoxy, 19% wood chips, and 10% olive seed, the thermal conductivity was lower than other samples with a higher amount of olive seed. Low thermal conductivity coefficients were obtained in those sample groups having more air gaps in the samples. Ultrasonic penetration speed was decreased in samples made up of 0.76 parts plaster and 0.24 parts water [22].

Table 2 Characteristics of the samples tested for the determination of the intrinsic properties of the materials and maximum sound absorption coefficient (α) and the frequency, density and thickness of the specimens tested Arenas et al. (2017) [79]

Material	Particle size (mm)	Specimen code	Thickness	Density (kg m^{-3})	frequency	α
Bottom Ash	$7 > D_p > 2.5$	E2.1.1.1	40.30	765	1241	0.93
		E2.1.1.2	40.25	773	1278	0.93
		E2.1.1.3	80.55	780	1241	0.94
		E2.1.2.1	80.95	783	603	0.94
		E2.1.2.2	80.95	781	606	0.93
		E2.1.2.3	81.10	803	563	0.91
		E2.1.3.1	121.55	771	356	0.94
		E2.1.3.2	121.50	796	356	0.92
		E2.1.3.3	120.30	799	356	0.91
		E2.2.1.1	41.65	1242	106	0.50
		E2.2.1.2	41.30	1259	128	0.53
		E2.2.1.3	41.10	1236	106	0.45
		E2.2.2.1	82.20	1245	118	0.34
		E2.2.2.2	82.05	1263	97	0.34
Bottom Ash	$D_p < 2.5$	E2.2.2.3	81.90	1244	118	0.36
		E2.2.3.1	123.25	1250	128	0.27
		E2.2.3.2	122.70	1255	128	0.31
		E2.2.3.3	122.35	1255	128	0.39

Fig. 6 Cardboard samples tested: (a) E-flute; (b) C-flute; (c, d, e, f) Concordant, orthogonal 1 × 1 and 2 × 2, and sandwich (4E-10C-4E) samples Asdrubali et al. (2016) [16]. Reused with permission from Elsevier (4546770023990)

In the case of composites prepared with sand/cement ratio of 2, and 5% coarse sawdust, thermal conductivity was lower than in a sample with greater sand fraction and containing fly ash [42]. The effectiveness of silica-based wastes, rice husk ash, and volcanic ash powders, in thermal isolation, has also been assessed. Thermal conductivity decreases to $0.15 \text{ Wm}^{-1} \text{ K}^{-1}$ with an increase in the concentration of the blowing agent. Adding a rice husk ash or volcanic ash to the inorganic polymer composites increases the Si/Al ratio in the pore solution, which reduces the sodium silicate content to produce a suitable porous structure [38].

Using 50/50 proportions of waste wool fibers and RPET fibers, best sound insulation and thermal properties have been achieved. Sound absorption confiscation (α) in this mat is reported to be 0.70 in the frequency range of 50–5700 Hz, and thermal conductivity of this materials was $0.032 \text{ Wm}^{-1} \text{ K}^{-1}$ [23]. Recycled carpet pieces have shown adequate acoustic insulation performance, when converted into a granulated mix of industrial carpet waste. Optimum proportion of grain to fiber in this study was 60:40 [7].

Agricultural solid waste into building insulation materials

In the agricultural industry, harvesting and post-harvesting activities generate large quantities of solid waste [73]. Agricultural waste can offer a good alternative to conventional insulation materials: they are renewable annually and compostable, and they naturally have low thermal conductivity [74]. Total yearly agricultural by-product that has been produced in EU-27 in 2000–2002 was 457 million tonnes, about half of which (215 million tonnes) was accepted as by-product [75]. One study has shown only a small difference in thermal insulation values and material density between the samples tested. The performance of wool insulation was comparable to values reported in the literature for other materials such as polystyrene, fiberglass, and cellulose insulation (Fig. 4) [1].

The thermal conductivities of the paddy-straw board and coconut pith board, with urea formaldehyde resin as the binding material (6% w/w), were 0.0861 and 0.062, respectively [73]. In a study on an insulating composite made from sunflower stalks particles and chitosan with composition ratio of 4.3% (w/w), thermal conductivity

Table 3 Physical, thermal and sound properties of onion skin and peanut shell fibers, fly ash, pumice, perlite, barite, cement and gypsum samples [37]

Sampl	FA50PE50C	BA100C	PE100C	PU100C
Composition	FA (50 g) W (25 g) C (50 g) OSPS (150 g)	BA (100 g) C (50 g) W (25 g) OSPS (150 g)	PE (100 g) C (50 g) W (25 g) OSPS (150 g)	PU (100) C (50) W (25) OSPS (150)
Density (kg m^{-3}) (CB)	1150 (L)	3450 (H)	1330	1590
Sound penetration (kl s^{-1}) (CB)	0.69	1.25 (H)	0.16 (L)	0.16 (L)
Termal coductivity ($\text{Wm}^{-1} \text{ K}^{-1}$) (CB)	0.081	0.313 (H)	0.062 (L)	0.078
Sample	PE100G	BA100G	FA15PU15G	
Composition	PE (100) G (100) W (25)		FA (15) PU (15) G (50) W (25)	
Density (kg m^{-3}) (GB)	1040 (L)	3330 (H)	1500	
Sound penetration (kl s^{-1}) (GB)	0.1 (L)	0.7	0.81 (H)	
Termal coductivity ($\text{Wm}^{-1} \text{ K}^{-1}$) (GB)	0.058 (L)	0.223 (H)	0.103	

FA Fly ash, PE Perlite, C Cement, OSPS Onion skins and peanut shells, W Water, BA Barite, PU Pumice, G Gypsum, CB Cement base, GB Gypsum base

Fig. 7 **a** Closed cell structure observed with tire shred residue compounded with the low molecular weight PU₂ binder. **b** Open cell structure observed with tire shred residue compounded with the high molecular weight PU₂ binder [40]. Reused with permission from Elsevier (4546770206236)

was $0.056 \text{ Wm}^{-1} \text{ K}^{-1}$, and α was 0.2 at frequency range of 2500–4000 Hz, which is lower than 0.5 for insulating materials.

A composite material made up of sugarcane waste fibers and polyester has been reported to have a coefficient of absorption greater or equal to 0.5 [76]. Therefore, the acoustic performance of this bio-based composite was considered too low [28]. The thermal conductivity coefficient of an insulation building material made up of sunflower stalk fibers, the spongy parts of sunflower stalks, textile waste, cotton waste, stubble fibers, and epoxy, was $0.1642 \text{ Wm}^{-1} \text{ K}^{-1}$. Such value is greater than 0.1; as a result, this material could not be considered as an insulation material according to TS 805 EN 60155 (Fig. 5) [30]. The thermal conductivity values of narrow-leaved cattail fibers, combined with a binder having a density of $200\text{--}400 \text{ kg m}^{-3}$, were $0.0438\text{--}0.0606 \text{ Wm}^{-1} \text{ K}^{-1}$; this is less than comparable fibrous and cellular materials [27].

Fig. 8 2D and 3D display of the waste-fiber/glass-fiber/perlite-concrete specimens and their components [15]. Reused under CC BY 3.0 license

In one study, hemp fibers were bound through the use of polyester bio component fibers. For hydrophobic treatment of these samples, H₆: Hexadecyl trimethoxysilan (HDTMS), T₆: Tris (2-methoxy ethoxy) (vinyl) silane (TMEVS), and LUK: Lukofob 39–hydrophobic agent were used for hydrophobization of silicate materials. DR: Draxil 153–hydrophobic agent was used for wood-based materials, and TG: Tagal–impregnation agent was used for textiles. In this study, the samples show satisfactory thermal property (lower than $0.07 \text{ Wm}^{-1} \text{ K}^{-1}$) under wetting conditions after hydrophobic treatments with any of the materials mentioned above [6].

Particleboards made from a mixture of Tissue Paper Manufacturing (TPM) waste and corn peel were investigated as thermal and sound insulation layers. Results show that with increasing amount of corn peel the density of the particleboards decreases, which leads to a decrease in thermal conductivity. In the cases where TPM to corn peel ratio was 25 to 75, thermal conductivity was $0.13 \text{ Wm}^{-1} \text{ K}^{-1}$; therefore, these materials could be considered as thermal building insulation [29].

Industrial solid waste into building insulation materials

Today's varied industries produce a significant amount of wastes; as a result, there is urgent need to develop suitable routes to treating or disposing them. Vast amounts of fly ash and bottom ash are generated by burning coal in power plants [77]. The insulation materials that have been made from fly and bottom ash could be not only considered as one option for the sanitary point of view, but also have attractive economic benefits [78].

Table 4 Water/solid ratio, physical, sound, and thermal properties of samples [44]

Mixture	Water/ solids ratio	density	PC ^{*a}	FRA	FA ^{*b}	CRA	CA ^{*c}	Conductivity (Wm ⁻¹ K ⁻¹)	Sound absorption (α)
H ₀ ^{*d}	0.09	2088	20	0	50	0	30	—	0.1 (H ₀) in 1500 Hz and 0.25 (H ₀) in 5000 Hz
H-FRA20	0.12	1790	20	20	30	0	30	—	—
H-FRA40	0.18	1750	20	40	10	0	30	—	—
H-FRA50	0.20	1710	20	50	0	0	30	—	—
H-CRA20	0.14	1820	20	0	50	20	30	—	—
H-CRA30	0.16	1500	20	0	50	30	30	—	—
HR ^{*e}	0.18	1590	20	50	0	30	30	0.66 (30–70 ° C)	0.15 (H ₁) in 1500 Hz and 0.5 (H ₁) in 5000 Hz

^{*a} = Portland cement (PC); ^{*b} = fine aggregate (FA); ^{*c} = coarse aggregate (CA); blocks without recycled waste (H₀)^{*d}, and with fine and coarse recycled aggregates (HR)^{*e}

In a study on coal bottom ash as sound insulation, the designed methodology consisted of determining the intrinsic acoustic properties (tortuosity, open porosity, and static air-flow resistivity) of bottom ash-based concretes with different particle sizes. The acoustic absorption coefficient measurements were obtained in an impedance tube and through mathematical equations in the software CARAM. This model describes the acoustic behavior of porous materials. Ash to cement ratio was fixed at 4:1. Moreover, the bottom ash was

sieved using 2.5 mm mesh size, generating two fractions. The first one was coarse, E2.1 (7 mm > D_p > 2.5 mm), and the other was fine, E2.2 (D_p < 2.5 mm). The sound absorption was higher in the coarse sample. Table 2 shows the characteristics of the samples tested and their acoustic properties [79].

In a survey on cardboard-based insulation panels, two types of flutes (C and E) with thicknesses of 4.1 and 1.9 mm, respectively, were investigated. Samples with C-flutes showed a thermal conductivity of 0.053 Wm⁻¹ K⁻¹

Fig. 9 Recycling of construction waste wood into noise and thermal insulation cement-bonded particleboards. Adapted from Wang et al. (2016) [45]

Table 5 Composition, physical and thermal characteristic of samples [46]

Groups	Water	Cement	Recycled coarse aggregate 5–10 mm	Natural coarse aggregate 5–10 mm	Recycled fine aggregate 0–5 mm	Natural fine aggregate 0–5 mm	Natural aggregate >10 mm	Recycled concrete aggregate >10 mm	Thermal conductivity ($\text{Wm}^{-1} \text{K}^{-1}$)	Density (kg m^{-3})
RAC-1	130	325	395	592	263	395	—	—	1.0568	1955
RAC-2	130	289	706	303	471	202	—	—	0.8336	1794
RAC-3	130	260	1036	—	684	—	—	—	0.7392	1619
RAC-4	140	350	676	290	644	—	—	—	0.8262	1768
RAC-5	140	311	989	—	264	396	—	—	0.8464	1868
RAC-6	140	280	403	605	470	202	—	—	0.9358	1903
RAC-7	150	375	945	—	441	189	—	—	0.7350	1788
RAC-8	150	333	388	582	647	—	—	—	0.9300	1832
RAC-9	150	300	693	297	—	396	—	—	0.9348	1871
RbC-1	130	325	—	—	658	—	987	—	1.0114	1981
RbC-2	130	325	—	—	658	—	494	494	0.7678	1760
RbC-3	130	325	—	—	658	—	—	987	0.8148	1617
LRC-1	130	325	592	395	395	263	—	—	1.3990	2195
LRC-2	130	325	296	691	197	461	—	—	1.0848	2094
LRC-3	130	325	—	987	—	658	—	—	1.0114	1981

while the thermal conductivity of E-flute was $0.058 \text{ Wm}^{-1} \text{K}^{-1}$. Thermal conductivity for the E and C-flute are similar to each other despite the significant difference in the percentage of cardboard mass. The E-flute panels with higher density had better sound insulation behavior than the C-flute panels (Fig. 6). Such recycled cardboard panels cannot be considered as the sound insulation material due to the low acoustic absorption [36]. Porous sound absorbers require high open porosity, interconnected pores, and air movement inside [16].

In another study, gypsum, vermiculite, fly ash, and polypropylene fibers used to produce insulation board. In the thickness range of 2 and 4 mm, the sound absorption coefficients were 0.3 and 0.8 in the frequency of 1000 to 2000 Hz, respectively, and thus could be considered as sound absorbing the material. On the other hand, these board present low thermal conductivity ($0.3 \text{ Wm}^{-1} \text{K}^{-1}$) [34]. Coal fly ash and scrap tire fiber (FA-STF) have also been considered as wall insulation in buildings. The mass ratios for the final mixture design consisted of 66% of fly ash, 8% of tire fiber, and 26% of water. The measure value of thermal conductivity for this insulation material was $0.035 \text{ Wm}^{-1} \text{K}^{-1}$ [13].

Recycle foam (RF) is a type of discarded packaging from household electrical appliances. Thermal conductivities of crushed foam used an aggregate in concrete at added ratio of 0.95, 1.00, and 1.05% were 0.30, 0.29, and $0.27 \text{ Wm}^{-1} \text{K}^{-1}$, respectively [39]. The thermal conductivity values of another lightweight aggregate foamed geopolymer concrete was reported to be $0.47\text{--}0.58 \text{ Wm}^{-1} \text{K}^{-1}$ [80]. In a survey on chipboards,

which is produced with cotton waste, fly ash, and barite, natural white epoxy resin is used as a binder, and a thermal conductivity of $0.0022 \text{ KWm}^{-1} \text{K}^{-1}$ is achieved. Thermal conductivities of all samples prepared were lower than 0.060, and these samples resisted against sound transmission [41].

In the insulation material production from onion skin and peanut shell fibers, fly ash, pumice, perlite, barite, cement, and gypsum, the results which were presented in Table 3 were notable. The thermal conductivity of pumice (PU) and perlite-added samples and the ultrasonic sound penetration velocity were lower than the others. The thermal conductivity of samples made with onion skins and peanut shells were 3.5–5 times smaller than those of the control, which resulted from the fiber ratios [37].

In panels made from waste residue particles and foaming binder, a mix of PVC grains and nylon fibers from PVC-backed carpet and tire shredded residue was used (Fig. 7) [40]. PU foam adhesive was used as a binder. Shredded residue samples showed good sound absorption coefficient with the low open porosity (67%) and binder loading of 10%, and had thermal conductivity of $0.06 \text{ Wm}^{-1} \text{K}^{-1}$ and high density (495 kg m^{-3}). Moreover, the sound absorption was 4 DLa and sound impact insulation was 135 dB. There is a direct relationship between open porosity and sound absorption. On the other hand, there is an adverse relationship between the polyol and open porosity. For example, with increasing amount of polyol, with molecular weight 2000 Da, in the binder and an increase in density (334 kg m^{-3}), open porosity was decreased to 75% and the thermal conductivity was $0.043 \text{ Wm}^{-1} \text{K}^{-1}$.

Table 6 Thermal and sound properties of insulation materials made from municipal solid waste

Type		Density (kg m ⁻³)	Conductivity (Wm ⁻¹ K ⁻¹)	Sound Absorption (α)	sound absorption frequencies (Hz)	Composite	Particle board	Reference
MSW	Textile fiber waste blundered with natural hydraulic lime	716	0.14	0.25	500–4500	—	1	[20]
	Cement composites containing rubber	1150	0.47	NA	—	1	—	[21]
	Recycled cellulose aerogels	40	0.032	NA	—	—	1	[71]
	Gypsum with olive seed and wood chips	.	0.074	0.023 kl s ⁻¹	50–60	1	—	[22]
	Plaster–rubber mortars	653	0.14	85 dB	1000	1	—	[32]
	Woven fabric waste	440	0.04	NA	—	—	1	[63]
	Rice husk ash and volcanic ash powders	NA	0.16	NA	—	—	1	[38]
	50% Wool and 50% recycled polyester	62.50	0.032	0.71	50–5700	—	Mat	[23]
	Recycled PET	66.66	0.033	0.69	50–5700	—	Mat	[23]
	Recycled wool	62.5	0.032	0.61	50–5700	—	Mat	[23]
	10% PE + 10 PVC + mortar	624	0.774	NA	—	1	—	[70]
	Recycled carpet (grain/fiber = 60:40)	277	NA	55 dB	1000	—	Mat	[7]
	Recycled cardboard 50 mm thick	50	NA	0.85	100–600	—	Panel	[16]
	Cardboard tube (slit = 4 mm, distance = 20 mm)	80	NA	0.95	100–600	—	Panel	[16]
	Crumb rubber (30%) concrete panel	2030	0.29	NA	—	1	—	[68]
	Crumb rubber (20%) concrete panel	2110	0.27	0.37	1000	1	—	[68]
	50% recycled polyurethane +50% textile	65	NA	0.6	250–2000	—	1	[62]
	Cellulose from recycled paper	55	0.039	NA	—	—	1	[25]
	Cellulose from recycled paper	36	NA	0.75	>500	—	1	[25]
	Rubber particles and fluff	441	NA	0.9	2000	—	1	[69]

N.A. not available

Moreover, the sound insulation and sound absorb were 128 dB and 2 DLa, respectively. In the samples with carped shredded (40:60 fiber: grain) at a binder loading of 10%, the density, open porosity, thermal conductivity, sound insulation, and sound absorb were 366 kg m⁻³, 75%, 0.06 Wm⁻¹ K⁻¹, 134 dB, and 2DLa, respectively. The sound absorption was improved due to the increase of binder, causing a decrease of the density and an increase of the open porosity. By increasing the ratio of fiber-to-grain, the open porosity and sound absorption were decreased, while the thermal conductivity was increased. Moreover, increasing the fiber size led to an increase in tortuosity; therefore, the open porosity, thermal conductivity, and sound absorption were increased. Sound absorption was increased due to the general increase in open porosity. On the other hand, with decreasing the open porosity, the thermal conductivity was decreased [40].

Cotton fibers are classified as natural fibers and they represent a vast amount of waste in the textile industry, but also possess low thermal conductivity, low density, and low cost. Glass fiber mesh was used in order to keep the waste fibers in

a central layer within lightweight concrete. In this investigation, all the specimens were constructed using perlite concrete, and had thermal conductivity in the range of 0.1–0.3 Wm⁻¹ K⁻¹, which is lower than 0.3 Wm⁻¹ K⁻¹ in previous studies (Fig. 8) [15].

C&D waste into building insulation materials

C&D management is one of the major sustainability issues worldwide [81]. Some of the environmental impacts are the contamination of water resources and soil, which result in environmental and economic impacts due to unsanitary waste disposal [82]. Yet, the recycling rate of C&D reaches as high as 75% in some European countries [83]. Two types of recycled aggregates have been obtained from construction waste, which have been classified according to their size: fine recycled aggregate (FRA) (0–10 mm) and coarse recycled aggregate (CRA) (10–80 mm). Table 4 is a water/solid ratio and physical, sound and thermal properties of samples. Blocks with fine and coarse recycled aggregates (HR) have a low

Table 7 Thermal and sound properties of insulation materials made from agricultural solid waste

Materials	Density (kg m ⁻³)	Conductivity (Wm ⁻¹ K ⁻¹)	Sound absorption (α)	sound absorption frequencies (Hz)	composite	Particleboard	Reference
Maize husk	310	0.095	NA	—	—	1	[73]
Maize cob	320	0.096	NA	—	—	1	[73]
Paddy straw	190	0.062	NA	—	—	1	[73]
Coconut pith	290	0.0861	NA	—	—	1	[73]
Groundnut shell	540	0.15	NA	—	—	1	[73]
Cereal straw	100	0.055	NA	—	—	Bales	[75, 86]
Hemp	44	0.045	0.6 (30 cm)	> 150	—	1	[75, 86]
Jute fiber	35	0.05	NA	—	—	1	
Wood fiber	150	0.045	NA	—	—	1	[75]
Cork	130	0.05	NA	—	—	1	[87]
Cork	130	0.049	NA	—	—	1	[87]
Cork	151	0.039	0.39	—	—	*a	[75]
Coconut	95	0.045	NA	—	—	1	[75]
Flax	50	0.041	NA	—	—	1	[75]
Cellulose	70	0.037	1 (65 cm)	5000	—	Loose fill ^a	[86]
Cellulose	30	0.04	NA	—	—	Loose fill ^a	[88]
Cellulose	138	0.047	NA	—	—	Loose fill ^a	[75]
Sheep wool (Romanov)	22.1	0.0072	NA	—	—	Mat	[1]
Sheep wool (Suffolk)	22.7	0.0068	NA	—	—	Mat	[1]
Sheep wool (North Country Cheviot)	23	0.0066	NA	—	—	Mat	[1]
Sheep wool (commercial 1)* _b	21.9	0.006	NA	—	—	Mat	[1]
Sheep wool (commercial 2)	22	0.0065	NA	—	—	Mat	[1]
Sheep wool	58.82	0.0315	0.75 (1.7 cm)	50–5700	—	Mat	[25]
Sunflower stalks particles and chitosan	175	0.057	0.2	—	1	—	[28]
TPM/corn (100:0)	980	0.25	NA	—	—	1	[29]
TPM/corn (75:25)	969	0.19	NA	—	—	1	[29]
TPM/corn (50:50)	789	0.14	NA	—	—	1	[29]
TPM/corn (25:75)	726	0.13	NA	—	—	1	[29]
FEF (hemp 100% without treatment)	38	0.062	NA	—	—	1	[6]
H6 with HDTMS (85%), C = 6%	39	0.058	NA	—	—	1	[6]
T6 with TMEVS (98%),	38	0.061	NA	—	—	1	[6]
LUK with Lukofob 39,	40	0.064	NA	—	—	1	[6]
DR with Draxil 153	29	0.062	NA	—	—	1	[6]
TG with Tagal 100	29	0.067	NA	—	—	1	[6]
Cattail fiber	300	0.052	NA	—	—	1	[27]
SSFCTSE ^c	143	0.1642	NA	—	—	1	[89]
Rice husk	162.5	0.051	NA	—	—	1	[90, 91]
Rice husk	170	0.070	0.87	3600	—	1	[92]
Coconut coir	325	0.066	NA	—	—	1	[53, 90]
Bagasse	115	0.048	NA	—	—	1	[9, 90]
Corn cob	315	0.097	NA	—	—	1	[90, 91]
Durian peel	637.5	0.107	NA	—	—	1	[90, 93]
Oil palm leaves	900	0.179	NA	—	—	1	[94]
Cotton stalk	300	0.07	NA	—	—	1	[95]
Durian peel and coconut coir	583.5	0.1	NA	—	—	1	[86, 90]
Kenaf board	100	0.054	0.95 (4 cm)	2000	—	1	[17]
Linen fibers	35	0.038	NA	—	—	1	[73]
Corn cob	—	—	0.153–0.450	125–2000	1	—	[96]
Shredded sunflower stalks	—	—	0.139–0.481	125–2000	1	—	[96]
Sheep wool balls	—	—	0.107–0.456	125–2000	1	—	[96]

N.A. not available

^aData from existing NFI materials (Spanish)^btwo different commercial breed mixes^cspongy parts of sunflower stalks, cotton waste, textile waste, stubble fibers, and epoxy

Table 8 Thermal and sound properties of insulation materials made from industrial solid waste

Type	Materials	Density (kg m ⁻³)	Conductivity (Wm ⁻¹ K ⁻¹)	Sound absorption (α)	sound absorption frequencies (Hz)	Composite	Particleboard	Reference
Industrial waste	Fly ash board ^a	850	0.3	0.8 (4 cm)	1500		1	[34]
	Fly ash board with tire fiber	—	0.035	NA	—	1	—	[13]
	Bottom ash-based concretes (1) ^b	765–779	NA	0.93–0.91	356–1241	1	—	[79]
	Bottom ash-based concretes (2) ^c	1242–1255	NA	0.50–0.39	106–128	1	—	[79]
	Recycled cardboard	—	0.053–0.058	60 dB	900–1600	—	1	[16, 36]
	Shredded tire (90%) with elastomeric waste (10%)	495	0.06	4 DLa	100–5000	—	1	[40]
	Shredded carpet (90%) with elastomeric waste (10%)	366	0.06	2DLA ($\alpha > 0.9$ in fiber length > 6 mm)	100–5000	—	1	[40]
	Chipboards (cotton waste, fly ash and barite)	—	2.2	NA	—	1	—	[41]
	Onion skin and peanut shell fibers, fly ash, pumice, perlite, barite, cement (C) and gypsum (G)	1040 (G)-13-30 (C)	0.058 (G)-0.062 (C)	0.16 (C)-0.1 (G) (kl s ⁻¹)	—	1	—	[60]
	Light weight concert with Cotton waste	1050	0.2	—	—	—	1	[15]
	Paper Mill Waste	—	0.4	—	—	—	1	[97]
	perlite wastes	408–476.5	0.076–0.095	—	—	—	1	[98]
	polystyrene	—	—	0.123–0.447	125–2000	1	—	[96]
	PET	—	—	0.108–0.496	125–2000	1	—	[96]

N.A. not available

^a fly ash board contain vermiculite, Gypsum, and fiber^b 7 mm > diameter of particle > 2.5 mm^c diameter of particle < 2.5 mm

thermal conductivity ($0.66 \text{ Wm}^{-1} \text{ K}^{-1}$), which is not lower than a medium-weight concrete. The recycled aggregates increase α to 0.5 at 5000 Hz [44].

A huge amount of waste wood formwork from construction sites is disposed of in landfills every day [84]. Construction waste wood has been investigated for conversion into thermal and noise insulating particleboard. These wastes were granulated and sieved to 2.36–5 mm and 0.3–2.36 mm as coarse aggregates and fine aggregates, respectively. Thermal conductivity was $0.29 \text{ Wm}^{-1} \text{ K}^{-1}$, which represented 19% of the thermal conductivity in a concrete board ($1.52 \text{ Wm}^{-1} \text{ K}^{-1}$) [45]. This amount was comparable with that of solid wood panel ($0.24 \text{ Wm}^{-1} \text{ K}^{-1}$ at 1.0 g cm^{-3}) [85], but higher than that of waste wood ($0.07 \text{ Wm}^{-1} \text{ K}^{-1}$) (Fig. 9) [45].

In one study, recycled concrete aggregate (RCA) with particle size of 0–10 mm was used to determine thermal conductivity of RAC, and these RCA were used to make recycled concrete block. Recycled coarse aggregates, with particle size over 10 mm, was used to determine the thermal conductivity of large particle recycled concrete (LRC). Crushed waste brick slag was screened to <10 mm, and used to test the thermal conductivity of recycled brick concrete (RbC). Table 5

presents the composition, physical, and thermal characteristic of samples in this study. The amount of recycled aggregate has a high effect on the density and thermal conductivity. Greater density led to greater thermal conductivity. The thermal conductivity of LRC was reduced with increasing amount of the recycled aggregate. The thermal conductivity of RBC was less than that of RCA [46].

Comparative analysis of the thermal and sound performance of unconventional insulation materials

Tables 6, 7, 8, and 9 are thermal and sound properties of insulation materials made up municipal solid, agricultural, industrial, and C&D waste, respectively.

From MSW, the recycled cellulose aerogel, recycled PET, recycled wool, and woven fabric waste have good properties on thermal conductivity [104]. From the agricultural waste category, cellulose, sheep wool, kenaf board, cork, hemp, and wood fiber have good properties on thermal conductivity and hemp, kenaf fiber, and cellulose have good sound

Table 9 Thermal and sound properties of insulation materials made from C&D and municipal solid waste

Materials	Density (kg m ⁻³)	Conductivity (Wm ⁻¹ K ⁻¹)	Sound absorption (α)	Composite	Particleboard	Reference
Recycled mixed concretes	NA	0.66 (H1)	0.1 (H ₀), 0.15 (H ₁) in 1500 Hz and 0.25 (H ₀), 0.5 (H ₁) in 5000 Hz	–	1	[44, 99]
Construction waste wood cement composite	1540	0.29	NA	–	1	[45]
Recycled aggregate cement composite	1619	0.73	NA	1	–	[46]
Cement with wood byproduct (coarse sawdust 5%)	NA	0.62	NA	1	–	[42]
plaster and Wood Shavings (10%)	1166	0.17	0.218 (500–2000 Hz)	1	–	[100]
plaster and Wood Shavings Perforated (10%)	<1166	NA	0.435 (500–2000 Hz)	1	–	[100]
plaster and Wood Shavings (20%)	954	0.16	0.255 (500–2000 Hz)	1	–	[100]
plaster and Wood Shavings Perforated (20%)	<954	NA	0.439 (500–2000 Hz)	1	–	[100]
plaster and Sawdust (10%)	1187	0.21	0.255 (500–2000 Hz)	1	–	[100]
plaster and Sawdust Perforated (10%)	<1187	NA	0.447 (500–2000 Hz)	1	–	[100]
plaster and Sawdust (20%)	1044	0.17	0.360 (500–2000 Hz)	1	–	[100]
plaster and Sawdust Perforated(20%)	<1044	NA	0.473 (500–2000 Hz)	1	–	[100]
Marble powder (0, 5, 10, 15, 20, 25, 30, and 35%)	1590–2050	0.4	NA	1	–	[101]
Glass powder (20–35%) and palm oil fly ash (20–35%)	338.7–1628	0.39	NA	1	–	[102]
Sawdust (5–20 vol%), wood ash (5–15 vol%), and lime mud (5–15 vol%)	1380–2080	0.55–1.12	NA	1	–	[103]

N.A. not available

absorption properties. From industrial waste category, composite of fly ash, tire fiber, recycled cardboard, shredded carpet, tire, and recycled elastomeric waste have good properties on thermal conductivity, while fly ash and fiber tire, bottom ash based concrete, shredded tire, and elastomeric fiber have good sound absorption properties [105]. From C&D waste category, construction waste wool cement composite has a good property on thermal conductivity and recycled mixed concrete has a good sound absorption property in high frequency.

Conclusion

In this overview, it can be concluded that many wastes in the various categories and production source including municipal, agricultural, industrial, and C&D can be used as a thermal and sound insulation material. A common observation has been that with decreasing the density, thermal performance of materials generally increases. Moreover, with increasing the density, sound insulation property generally increased. Improved thermal conductivity, sound absorption and sound insulation properties resulted from the use of dense double walls filled with the porous materials. In general, increasing the open porosity leads to increase in sound absorption but in the cases that the open porosity was decreased, thermal conductivity

decreased as well. It appears that utilization of two layers, one of which has open porosity and another having closed porosity with low density can improve thermal and sound absorption properties. In the majority of cases, thermal conductivity and sound absorption properties were improved with increasing the thickness of materials. As a result, it should be noted that the production of low thickness materials with better insulation properties could be considered as a research priority.

It is essential to conduct more investigation about the feasibility of utilizing municipal, agricultural, industrial, and C&D wastes as alternative materials in place of high cost synthetic raw materials, such as aggregates and synthetic insulation layers in buildings. Research can be done to enhance the physical and chemical properties of these alternative insulation layers. The different insulation layers must be made in a way that the disassembly and recycling of them be made more practical. Considering the environmental aspects, the combined use of natural and green materials in the future must attract more attention, in order to develop green buildings and promote recycling and re-utilization of all kinds of wastes.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

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