Sustainable materials and metamaterials for acoustical applications

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In 1987, the World Commission on Environment and Development developed a definition of sustainability which became widely known as the **Brundtland Report**.

It stated that:

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

A product can be considered sustainable if its production enables the **resources** from which it was made to continue to be **available for future generations**.

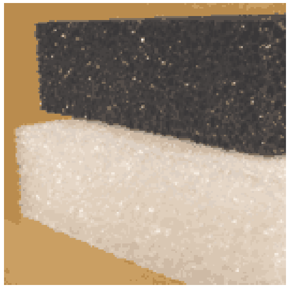
A sustainable product can thus be created repeatedly **without** generating **negative environmental effects**, without causing **waste products**, and without **compromising the wellbeing of workers or communities**.

Materials obtained from synthetic fibres are widely used for thermal and sound insulation, because of their good performances and low cost.

The European building insulation market of a value of approximately **3.3 billion euros** has been estimated to:

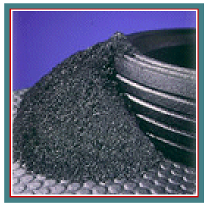
- mineral wool (glass) : 27%
- mineral wool (stone): 30%
- foam plastics: 40%
- other materials: 3%.





In the last years many new materials for noise control have been studied and developed as alternatives to the traditional ones, especially in the building sector:

- **natural materials**: cotton, cork, hemp, wool, clay, etc..
- **recycled materials**: rubber, plastic, carpet, cellulose, etc..


Environmental Assessment

Many commercial products are labelled as "green" just because they contain small percentages of natural or recycled materials or because they are not harmful for human health.

The real sustainability of a material should be evaluated through **Life Cycle Assessment** (LCA) procedures, which take into account the potential impacts that derive from the **life history** of a building product: **material extraction**, **production**, **transport**, **construction**, **operating** and **management**, **desconstruction and disposal, recycling and reuse.**

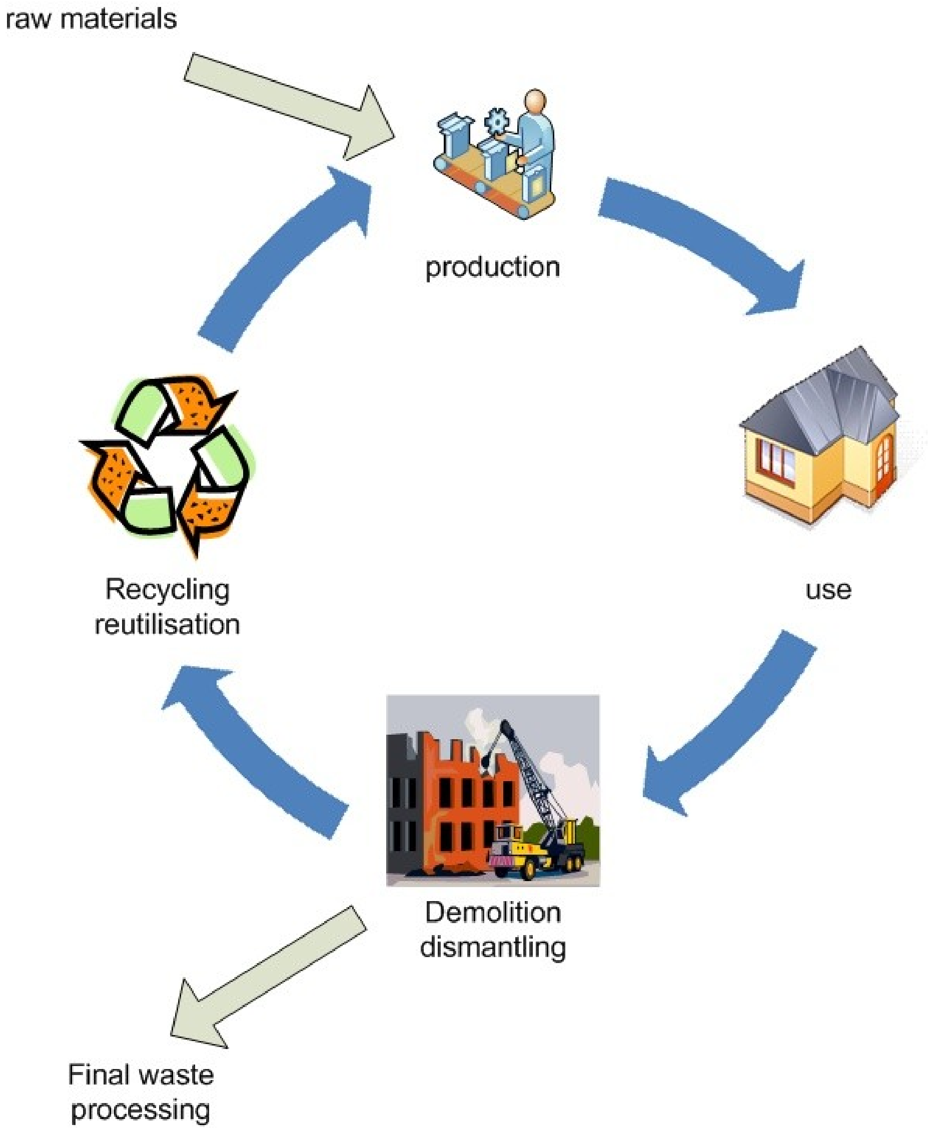
Environmental Performance Evaluation (EPE)

Methods for EPE

- Environmental Indicator Systems (EPI)
- Environmental Management Accounting (EMA)
- Environmental Management Systems (EMS)
- Life Cycle Analysis (LCA)
- Eco - labelling

Supportive ISO Standards

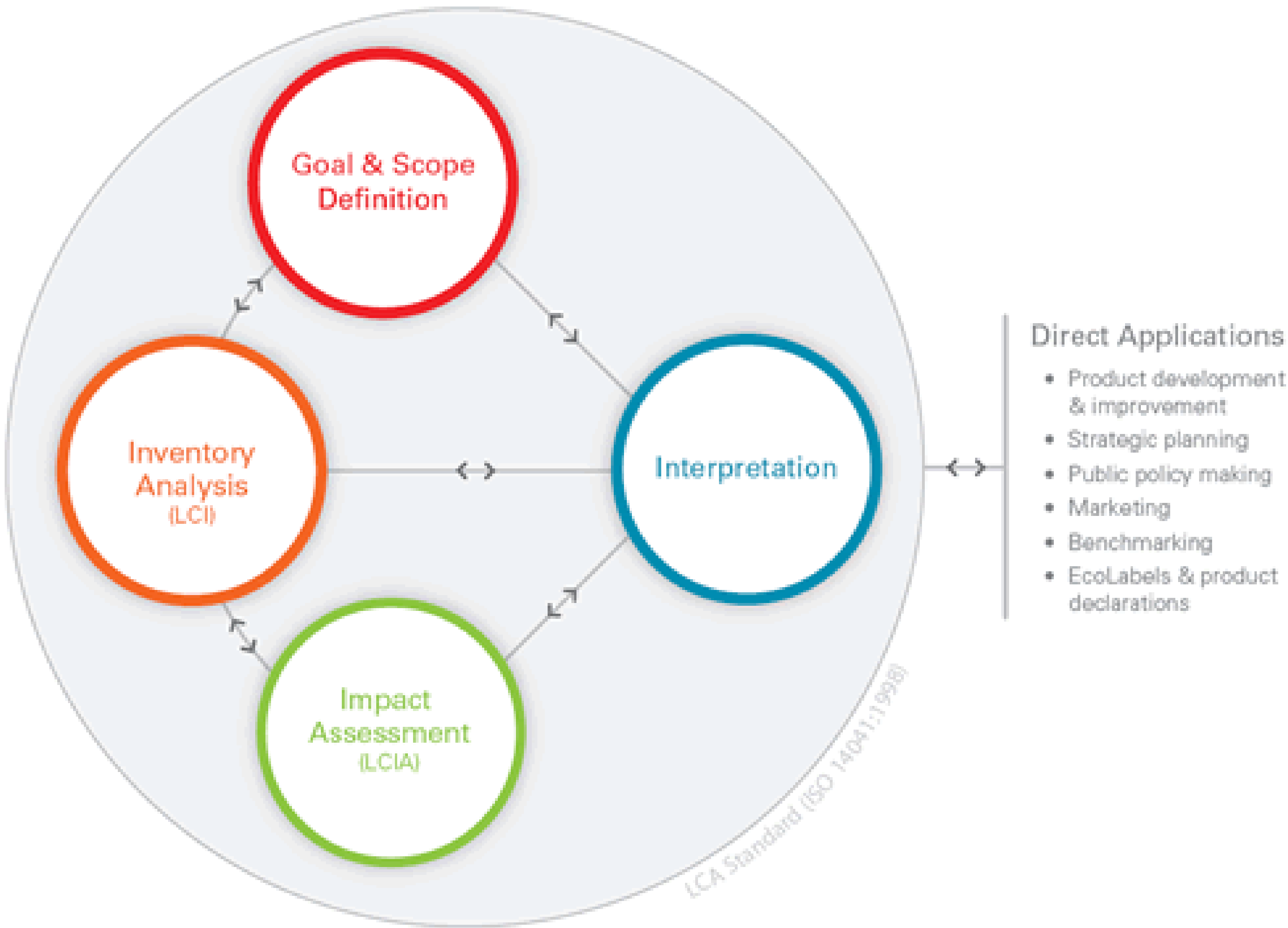
- ISO 14000 (EMS), includes general guidelines for
- principles, systems and tools for environmental
- management
- ISO 14001 (EMS), provides specific guidelines for
- environmental management system's implementation
- ISO 14010, includes general principles and guidelines
- for environmental auditing
- ISO 14020, refers to eco-labelling
- ISO 14031, refers to environmental performance
- evaluation and indirectly to environmental accounting
- ISO 14040, refers to Life Cycle Assessment (LCA)



The **concept of LCA** is based on:

- the consideration of the entire life cycle which includes raw material extraction and processing, production and use, up to recycling and disposal;
- the consideration of all environmental impacts connected with the life cycle such as air, water and soil emissions, wastes, raw material consumption or land use;
- the aggregation of the possible impacts of the environmental effects in consideration and their evaluation in order to give environmental oriented support to decisions made.

Life Cycle Assesment framework



Methods

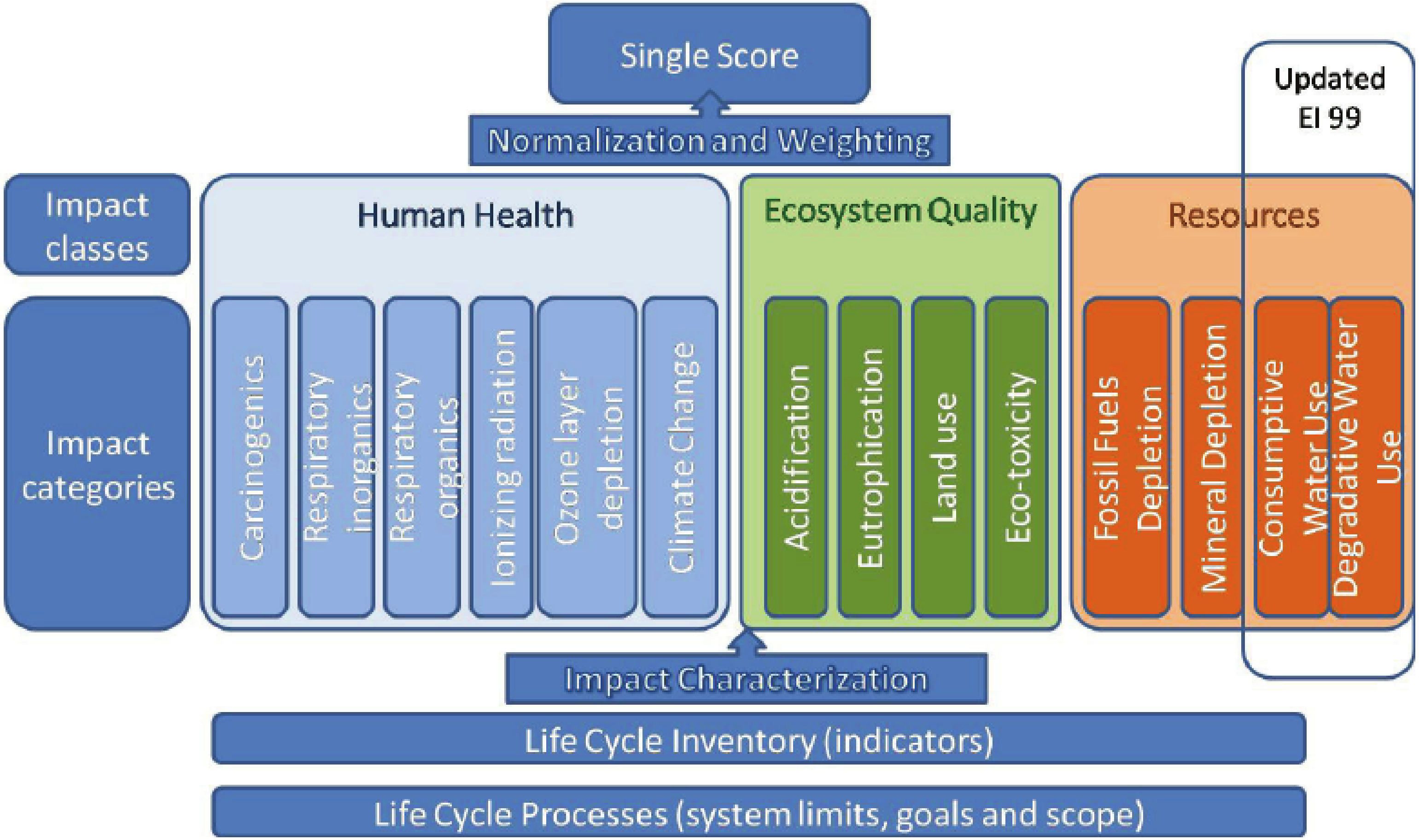
Cumulative Energy Demand (CED) method: calculates the amount of energy (MJ-eq) used during the entire life cycle of the building.

IPCC (International Panel on Climate Change) method: classifies the different emissions according to their contribution to greenhouse effect; the indicator is Global Warming Potential (GWP), the unit is kg CO2-eq.

Eco-Indicator 99 method: allows the evaluation of the emissions and the use of resources according to 11 impact categories (carcinogenic substances, respiratory diseases, climate changes, ozone depletion, radiation that causes ionisation, acidification/eutrophication, ecotoxicity, land use, mineral resource depletion and fossil fuels), grouped into three damage categories:

1. damage to human health, expressed as the number of years of human life lost or in suffering from diseases;
2. damage to the quality of ecosystems, expressed as the loss of living species in a certain area over a certain period;
3. damage to resources, expressed as the surplus of energy necessary for the further extraction of minerals and fossil fuels.

Eco-Indicator 99 method



Sustainable materials for thermal and sound insulation in buildings

Natural materials

•The more natural and less treated the materials are, the higher they perform in energy saving.

•It is preferable to adopt native materials in order to reduce energy consumption during transport.

•Vegetal fibres have the advantage that they contribute to the absorption of CO_2 helping against climate change.

•Vegetal fibres are more subject to fungal and parasitic attack and are less resistant to fire than mineral fibres.

•The toxicity of the chemical products used for cultivation must also be taken into account.

Recycled materials

Many recycled materials, such as waste rubber, metal shavings, plastic, textile agglomerates can be used to prepare thermal and acoustic materials.

It could be useful to mix various recycled materials of different granular sizes to obtain the desired performance; in these cases a binder or glue has to be added in the appropriate proportion.

Embodied Energy

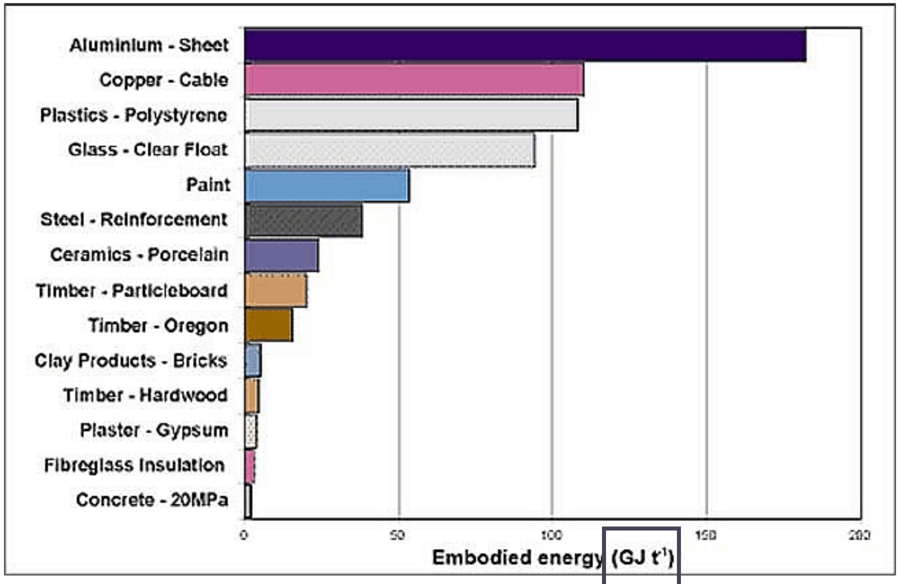
Embodied energy is defined as the available energy that was used in the work of making a product, including raw material extraction, transport, manufacture, assembly, installation, disassembly, deconstruction and/or decomposition.

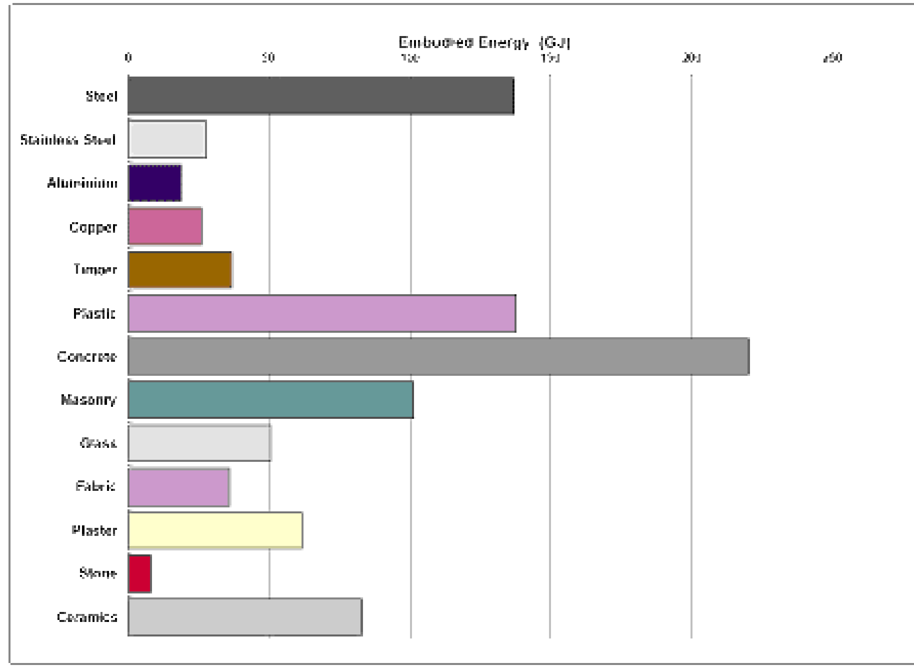
Different methodologies produce different understandings of the scale and scope of application and the type of energy embodied. International consensus on the appropriateness of data scales and methodologies is pending.

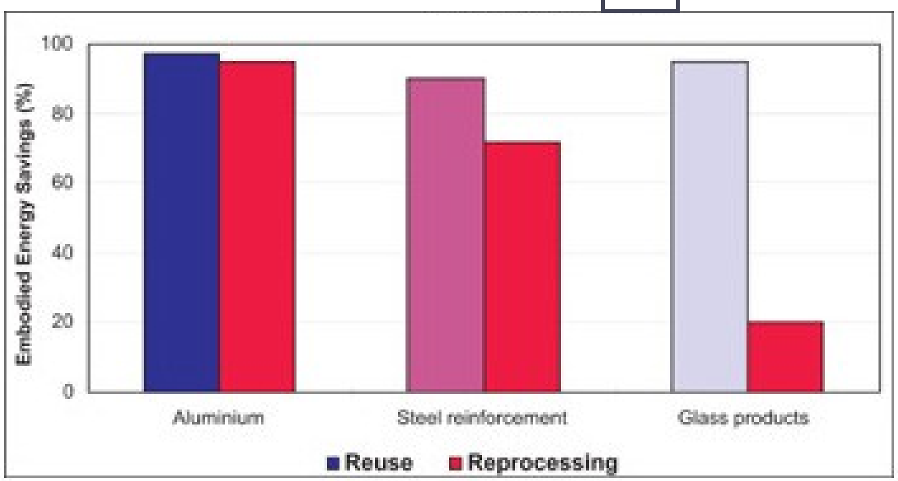
Embodied energy figures published for common building materials **vary enormously** and there is often little indication of how they have been obtained.

Furthermore, embodied energy data refers to the mass or volume unit of materials (Joule/kg or J/m^3), and **does not take into account the different performance as far as thermal or sound insulation**.

Embodied Energy



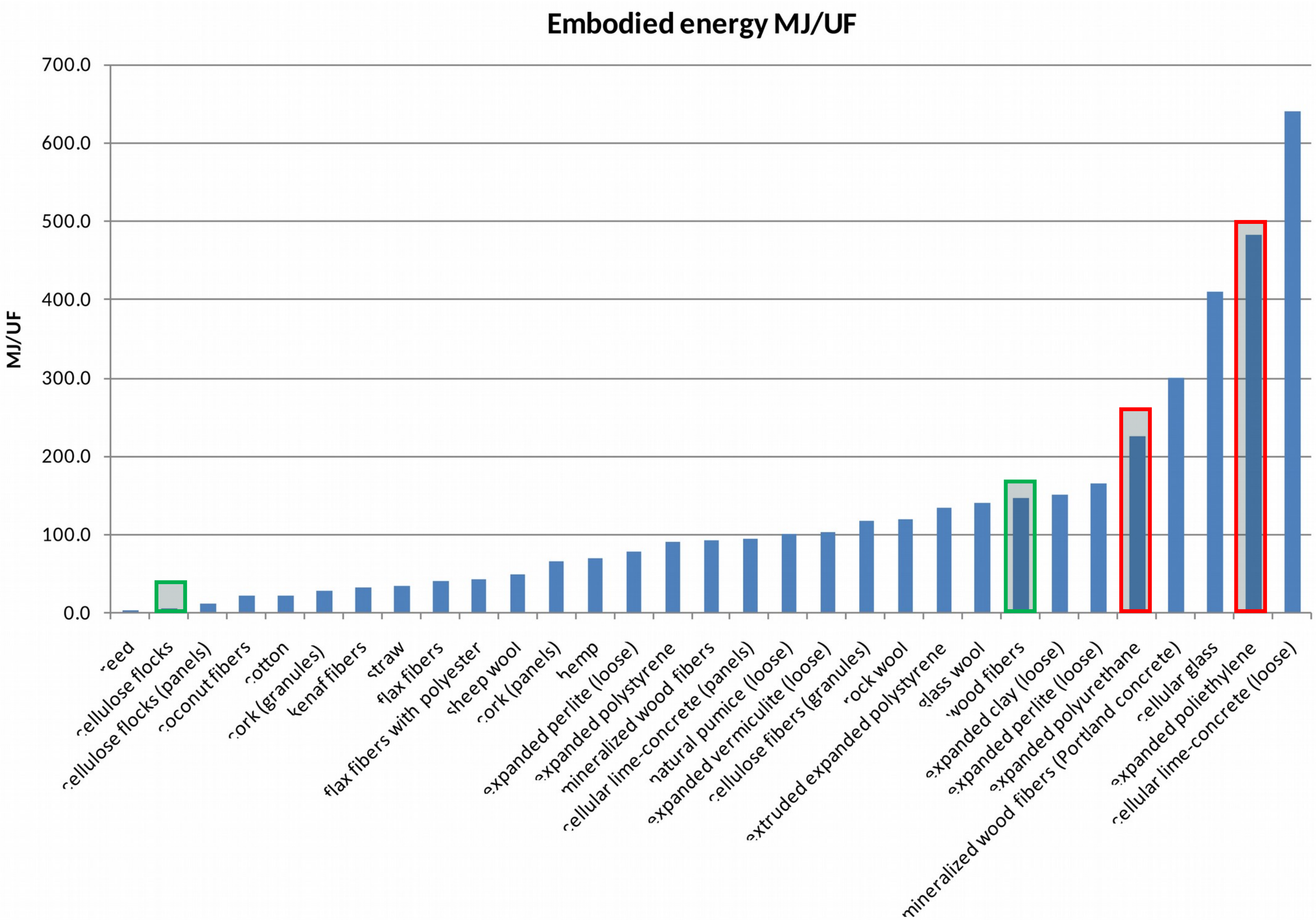




Total embodied energy of building materials

(from Tucker, Selwyn (2001). "The Embodied Energy in Buildings")

Thermal insulating materials

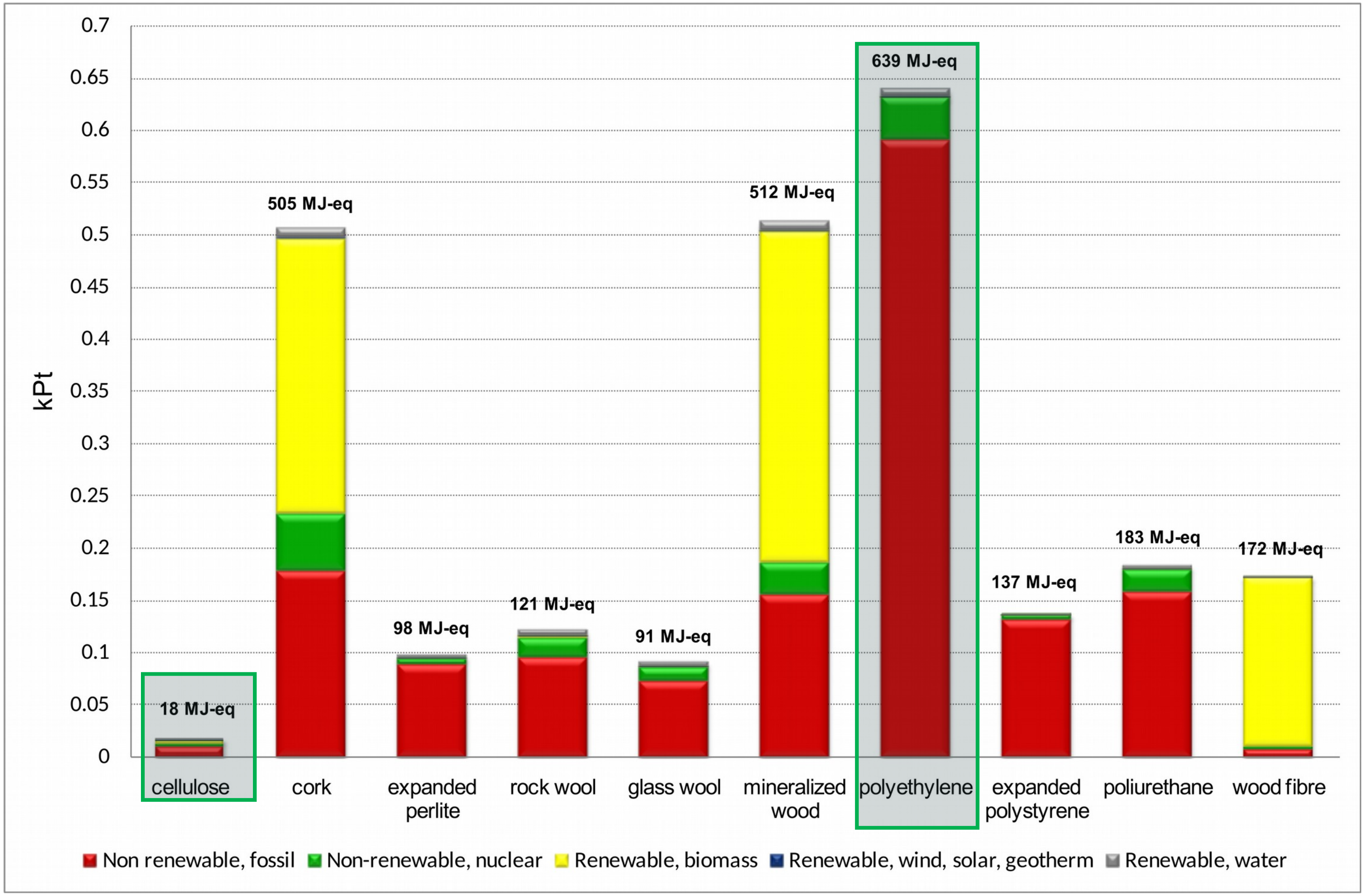


Some natural materials, such as *cellulose flocks* or *cotton*, show very low values of Embodied Energy, while *expanded polyethylene* or *polyurethane* exhibit the highest values.

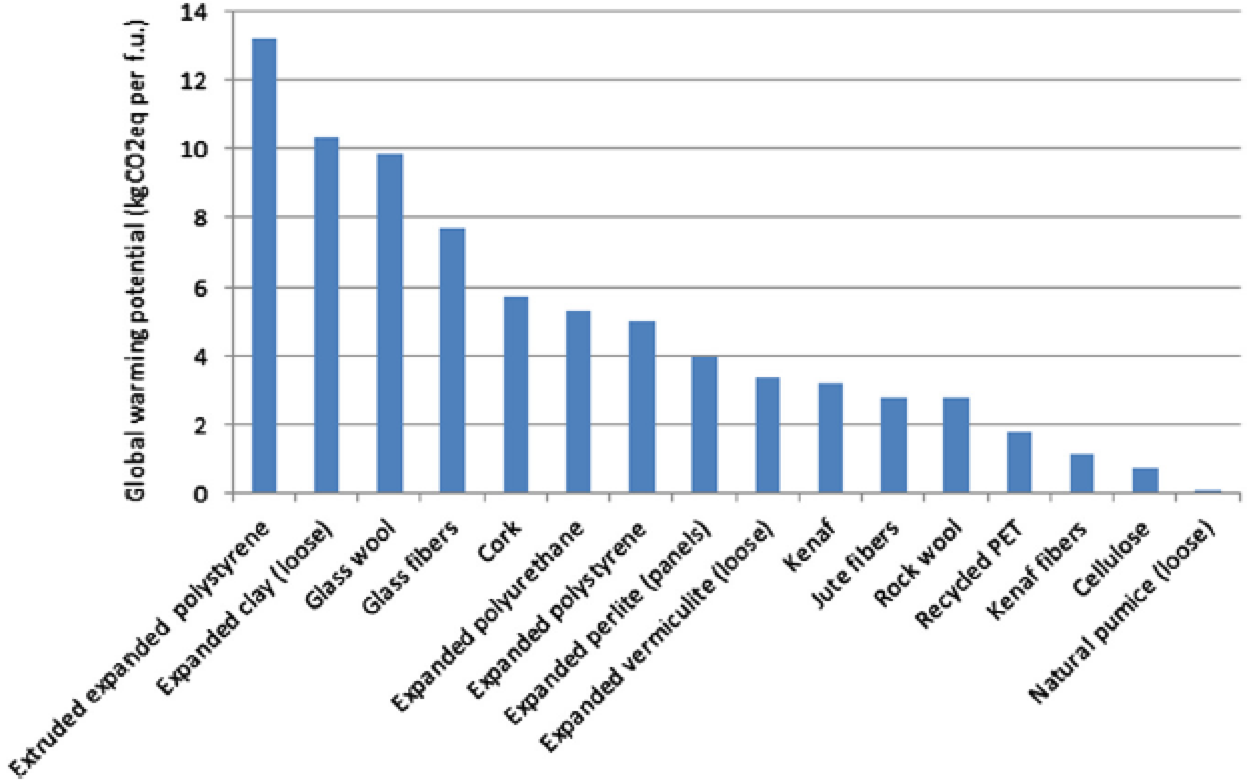
There are also some natural materials (*wood fibres*) whose embodied energy is as high as that of synthesised materials.

Functional Unit: quantity of material necessary to guarantee a thermal resistance of 1 m^2K/W for 1 m^2 of wall

Thermal insulating materials



Comparison of the entire Life Cycle Impact of various thermal insulating materials (Cumulative Energy Demand Method), for a given value of thermal resistance



Global warming, in terms of kg CO_{2eq} per f.u., potential of thermal insulation material (CTGA approach).

Sound insulating materials

	Absorption coefficient α_s at 500 Hz (-)	Index of reduction of impact noise ΔL_w (dB)	Embodied energy (MJ/kg)
Hemp	0.6 (30 cm)	-	15
Kenaf	0.74 (5 cm)	-	15
fiber	0.42	23	4,90
Sheep wool	0.38 (6 cm)	18	12,60
Cork	0.39	17	7,05
Cellulose	1 (6 cm)	22	4,24
Flax	-	-	33,12
Glass wool	1 (5 cm)	-	34,60
Rock wool	0.9 (5 cm)	-	22,12
Expanded polystyrene	0.5	30	99,20

Ecoprofiles

For designers and decision-makers, LCA analysis results are available as ***“ecoprofiles”*.**

Among these the most known are:

- Ecoinvent (CH)
- BRE Eco-profiles (UK)
- Eco-indicator ’99 (NL)

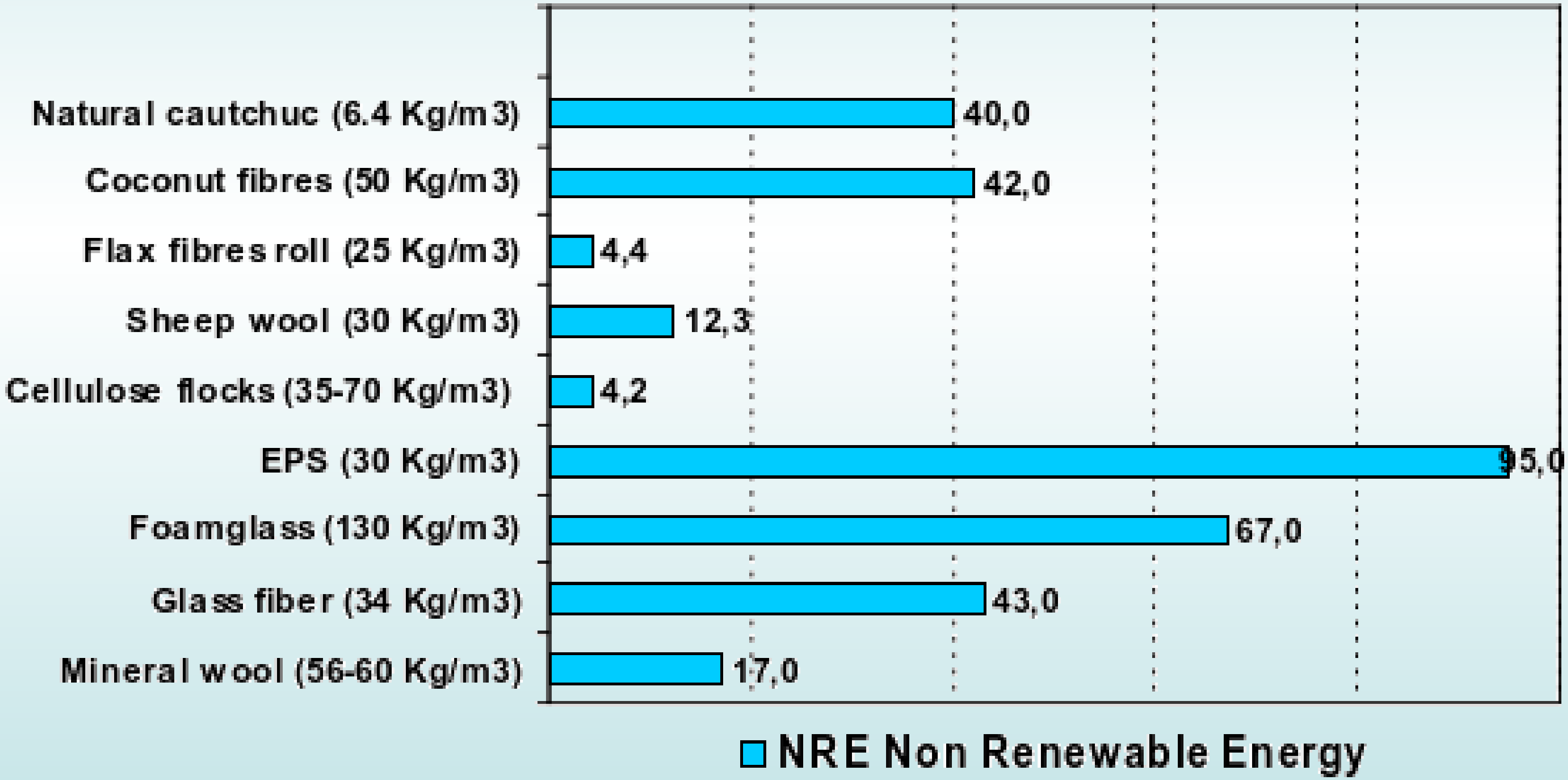
Ecoprofiles

ECOINVENT is a Swiss LCA database which takes into account:

- Cumulated Energy Demand,
- Non-Renewable Energy Sources fraction;
- Global Warming Potential;
- Acidification Power.

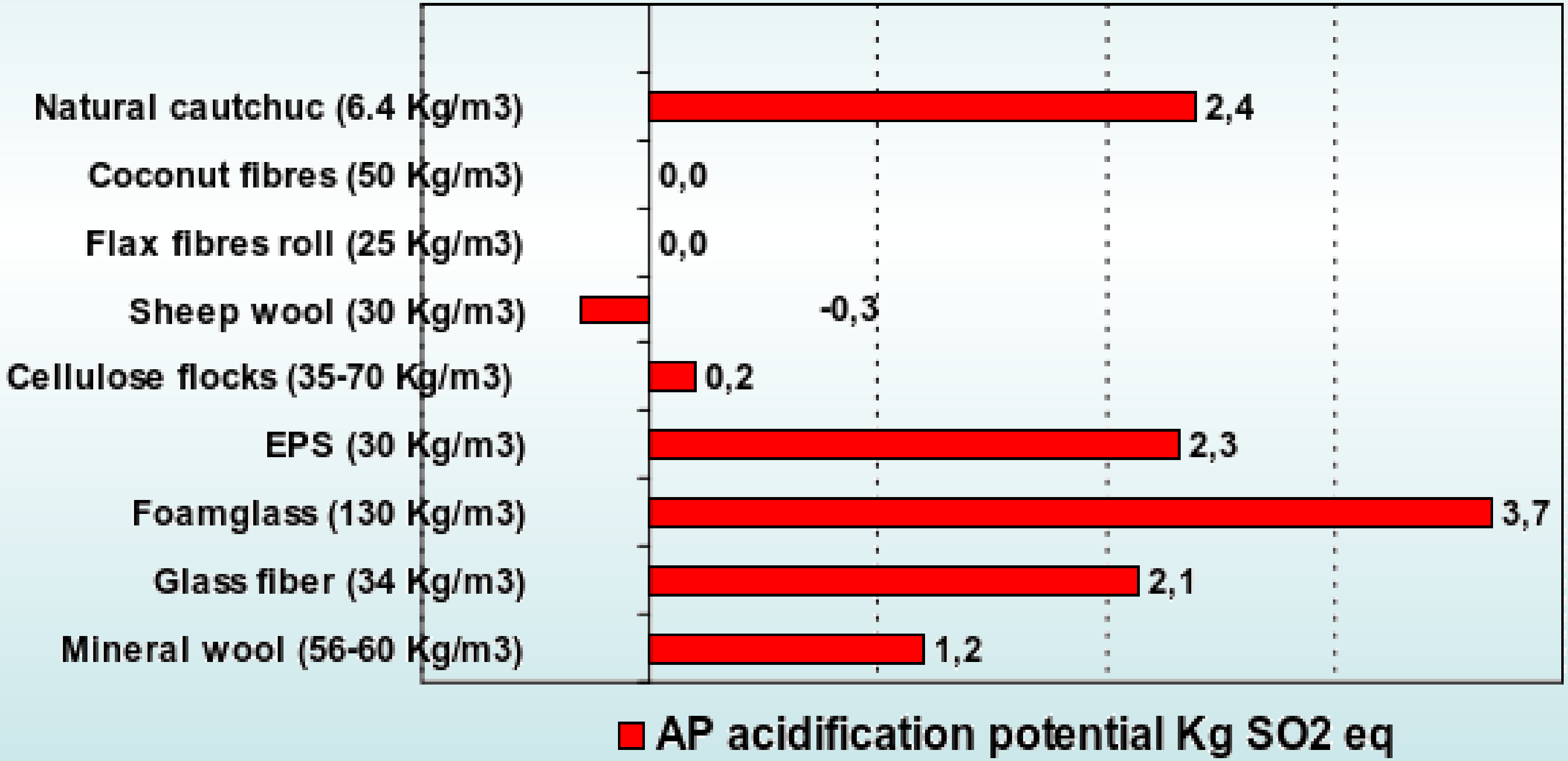
Ecoprofiles

Ecoinvent: Comparison of environmental impacts of traditional and natural insulations from “the cradle to the grave”.



Ecoprofiles

Ecoinvent: Comparison of environmental impacts of traditional and natural insulations from “the cradle to the grave”.



Ecoprofiles

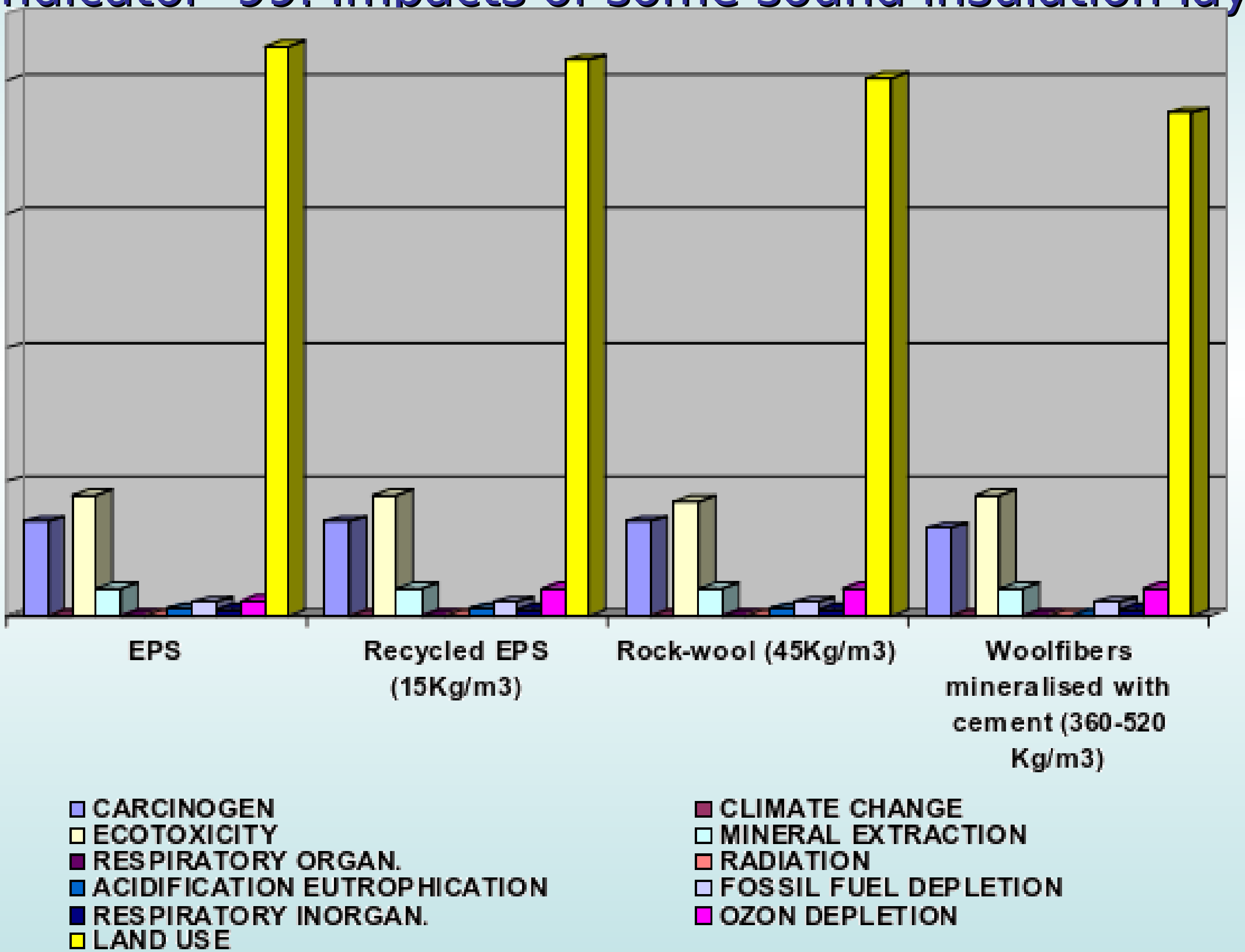
Eco-profile (UK):

Supplies a final score (**eco-points EPS**) by weighting normalized impacts on climated change, acid deposition, eutrophication, eco-toxicity, ozone depletion, mineral extraction, fossil fuel extraction, human toxicity, waste disposal, transport pollution.

- Expanded Polystyrene = 0.028 points
- Rockwool = 0.020 points
- Recycled newspaper cellulose = 0.002 points

Ecoprofiles

Eco-indicator ’99. Impacts of some sound insulation layers.



Other labels

Natureplus is a label for high-quality building products, construction materials, and home furnishings.

Products that carry this label have been produced in an environmentally friendly way, do not represent a health risk, and will perform their allotted functions trouble-free.

The natureplus seal of quality is only awarded to products that comprise a proportion of at least 85 % renewable and / or mineral raw materials, according to the principle of sustainability

The product must also carry a full declaration of all its input materials - to enable users to judge the product more clearly.

Other labels

ECOLABEL

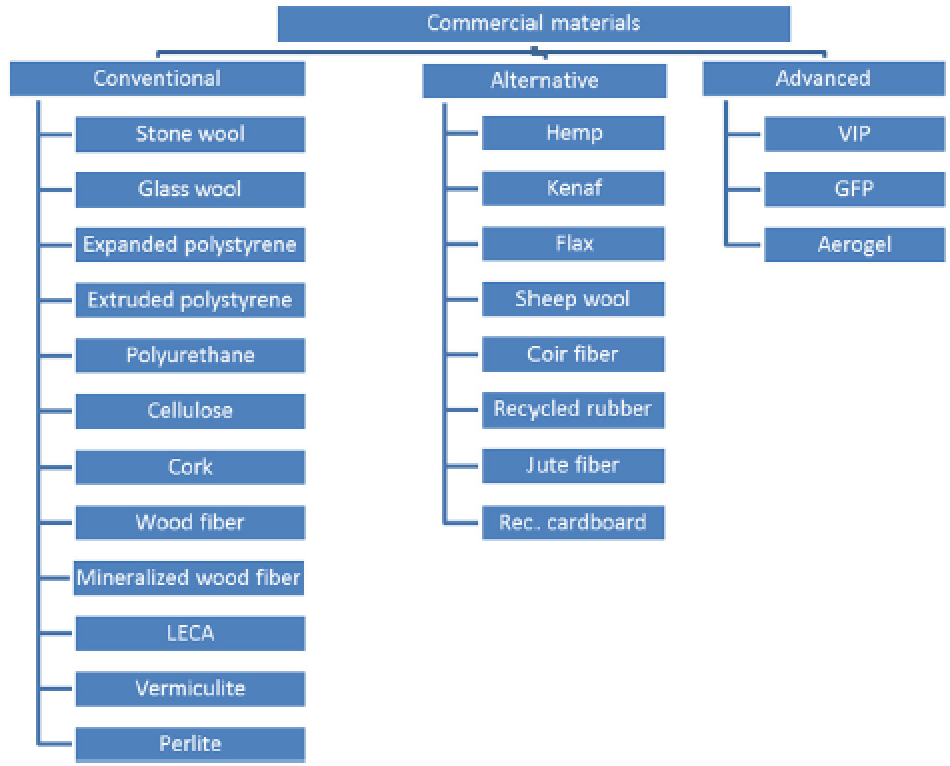
Over the past twenty years, the "Flower" has become a European-wide symbol for products, providing simple and accurate guidance to consumers.

All products bearing the "Flower" have been checked by independent bodies for complying with strict ecological and performance criteria

There are currently twenty-three different product groups, and already more than 250 licences have been awarded for several hundred products

The EU Eco-label is administered by the European Eco-labelling Board (EUEB) and receives the support of the European Commission, all Member States of the European Union and the European Economic Area (EEA).

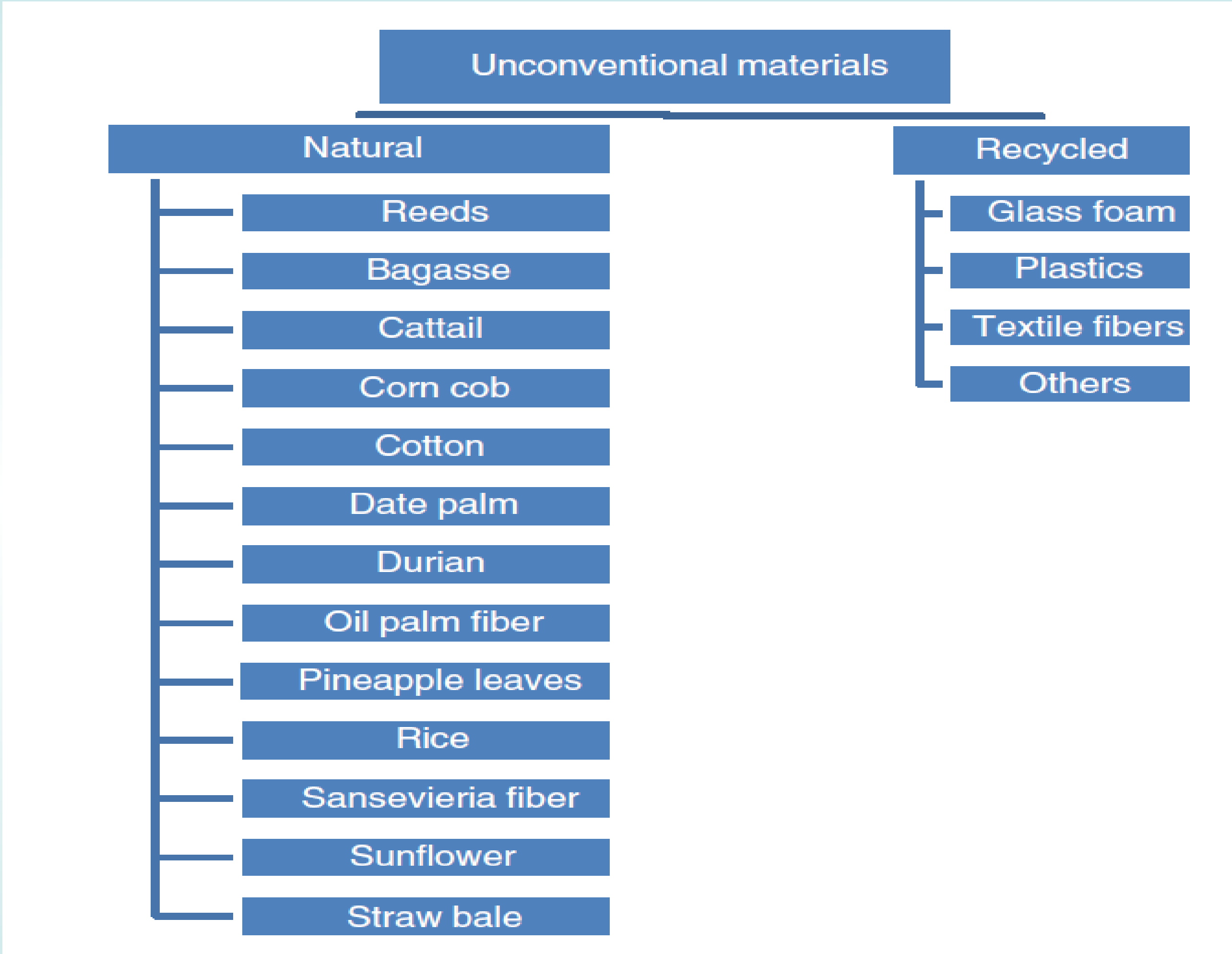
Commercial materials



List of the commercial insulation materials analyzed in the paper.

1. Reference: Schiavoni, S.,D'Alessandro, F.,Bianchi, F.,Asdrubali, F. : “*Insulation materials for the building sector: A review and comparative analysis*”, Renewable and Sustainable Energy Reviews (2016), 62, pp. 988-1011

Unconventional materials



Block diagram of the analyzed unconventional building insulation materials.

Reference: F. Asdrubali, F. D'Alessandro, S. Schiavoni: “A review of unconventional sustainable building insulation materials”, Sustainable Materials and Technologies, 4 (2015) 1-17.

Natural products

Acoustic and thermal properties and costs of some traditional and natural insulating materials.

	Thermal conductivity λ (W/mK)	Rel. resistance to vapour flux μ (-)	Absorption coefficient α_s at 500 Hz (-)	Index of reduct. of impact noise ΔL_w (dB)	Cost (€/m²)
Hemp	0.04	2	0.6 (30 cm)	-	14
Kenaf	0.044	2	0.74 (5 cm)	-	-
Coco fiber	0.043	18	0.42	23	12
Sheep wool	0.044	3	0.38 (6 cm)	18	14
Wood wool	0.065	5	0.32	21	16
Cork	0.039	12	0.39	17	23
Cellulose	0.037	2	1 (6 cm)	22	-
Flax	0.040	1	-	-	14
Glass wool	0.04	-	1 (5 cm)	-	6
Rock wool	0.045	-	0.9 (5 cm)	-	7
Expanded polystyrene	0.031	100	0.5	30	6

Natural materials for acoustic applications : examples (1)

Kenaf fibres

Kenaf is the name of a hibiscus plant related to cotton and okra.

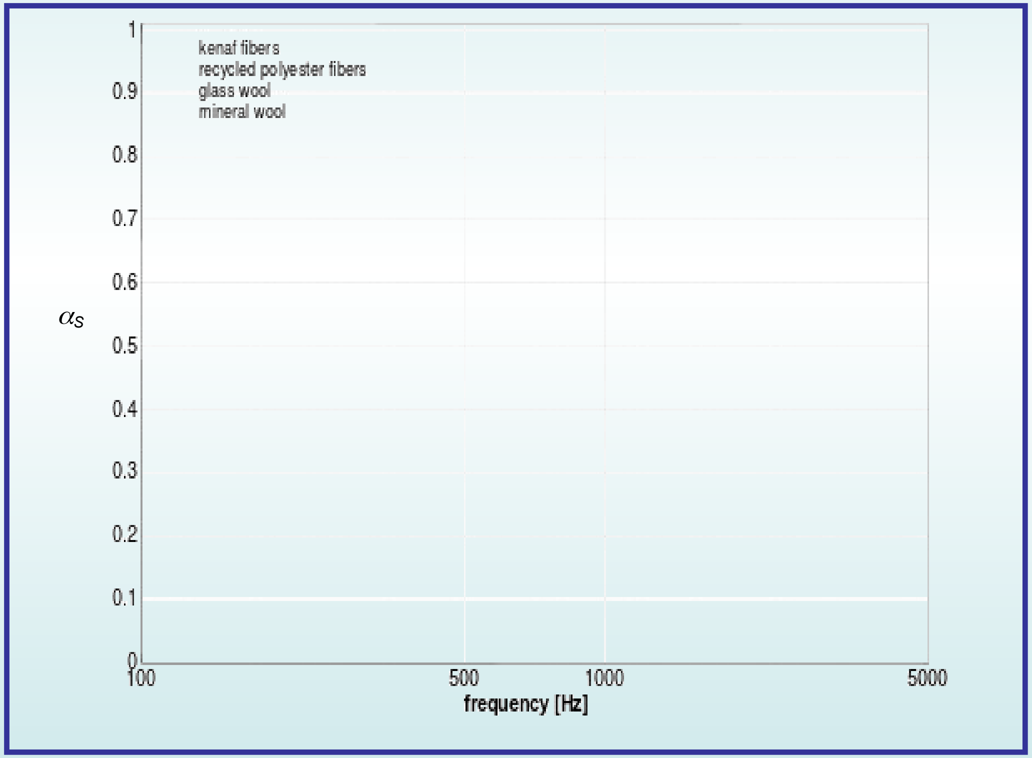
Today it is used especially for its cordage, canvas and sacking.

The stems produce two types of fibres, a coarser one in the “bast”, and a finer one in the “core”. Bast fibres (about 35 %) are suitable for paper, textiles and rope; core (about 65 %) is usually used as a biomass or it can be reduced to particles and bonded into panels similar to particleboard.

Reference: *Sound absorption properties of sustainable fibrous materials in an enhanced reverberation room*, F. D’Alessandro and G. Pispola, Proc. of Internoise 2005, Rio de Janeiro, Brazil.

Natural materials for acoustic applications : examples (1)

Kenaf fibres



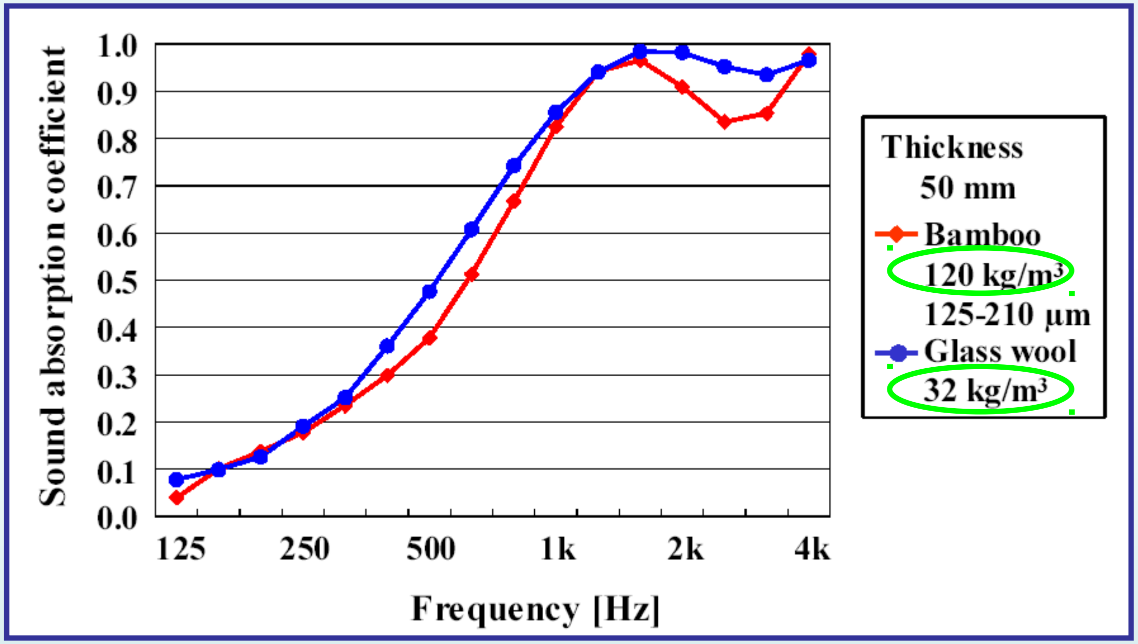
The kenaf samples show an averaged absorption coefficient equal to 0.85 in the 500-5000 Hz range and equal to 0.65 in the 100 – 5000 Hz range.

sample thickness: 50 mm
sample density: 50 kg/m^3

Reference: *Sound absorption properties of sustainable fibrous materials in an enhanced reverberation room*, F. D’Alessandro and G. Pispola, Proc. of Internoise 2005, Rio de Janeiro, Brazil.

Natural materials for acoustic applications: examples (3)

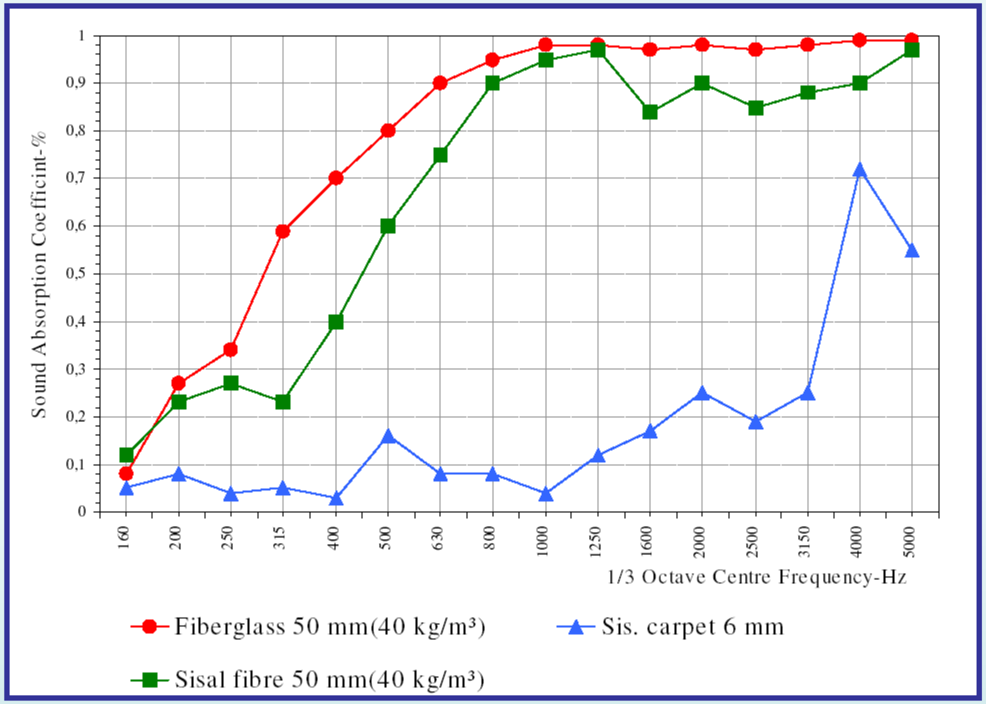
Bamboo fibres



Reference: *The development of sound absorbing materials using natural bamboo fibers and their acoustic properties*, T. Koizumi *et al*, Proc. of Internoise 2002, Dearborn, MI, USA.

Natural materials for acoustic applications : examples (4)

Sisal fibres



Reference: *Sound Absorption of Sisal Fiber Panels,* L. J. Azevedo *et al*, Proc. of Internoise 2005, Rio de Janeiro, Brazil.

Natural materials for acoustic applications : examples (5)

LECA (Lightweight Expanded Clay Aggregate)

LECA consists of small, lightweight, bloated particles of burnt clay. The thousands of small, air-filled cavities give LECA its strength and thermal insulation properties.

The relatively high open porosity (50 -70 %) assures high values of acoustic absorption.

Reference: *The acoustic properties of expanded clay granulates,* F. Asdrubali and K. V. Horoshenkov, Building Acoustics, Volume 9, Number 2, 1 June 2002.

Natural materials for acoustic applications : examples (5)

LECA (Lightweight Expanded Clay Aggregate)

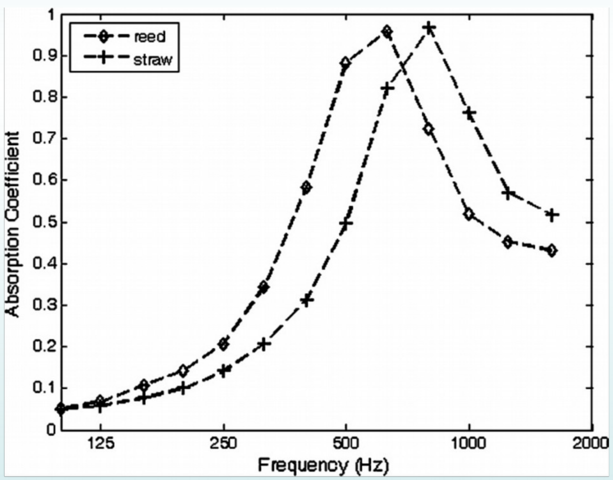
The absorption coefficient of the 50 mm LECA layer (0-2 mm grain mix) is close to or above 80 % in the frequency range 500-5000 Hz.

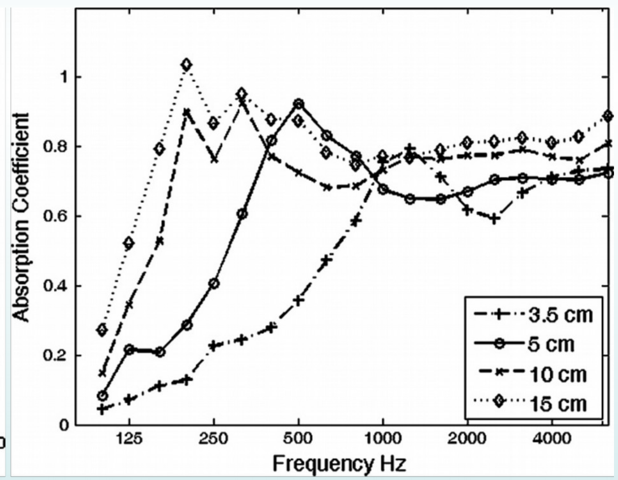
Reference: *The acoustic properties of expanded clay granulates,* F. Asdrubali and K. V. Horoshenkov, Building Acoustics, Volume 9, Number 2, 1 June 2002.

Natural materials for acoustic applications : recent developments

Reeds (Impedance tube)

The most absorbing specimen is the one with the longitudinal direction of the reed parallel to the incident sound [1] .





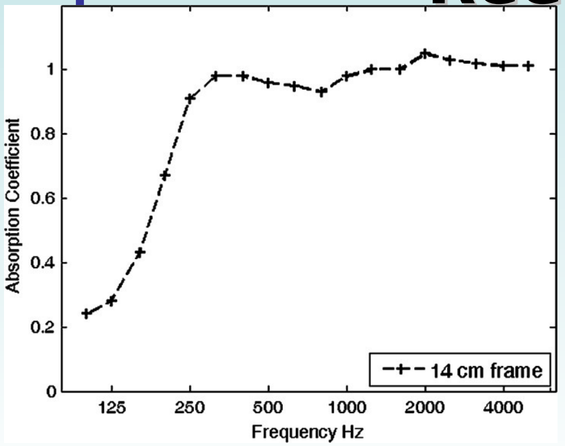
Absorption coefficient of samples made with reeds parallel (left) and transversal (right) to the incident sound. Reeds are able to provide up to 80% absorption in a relatively broad frequency [2].

References: [1] Chilekwa, V., Sieffert, G., Egan, C. A. & Oldham, D., The acoustical characteristics of reed configurations, Proceedings of Euronoise 2006, Tampere, Finland, 2006.

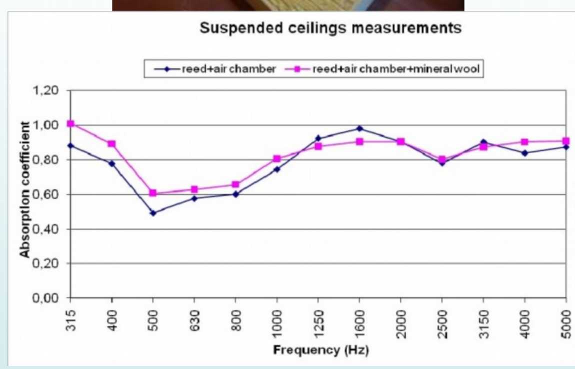
[2] Oldham, D. J., Egan, C. & Cookson, R., Sustainable acoustic absorbers from the biomass, Applied Acoustics, 2011 72, 350-363

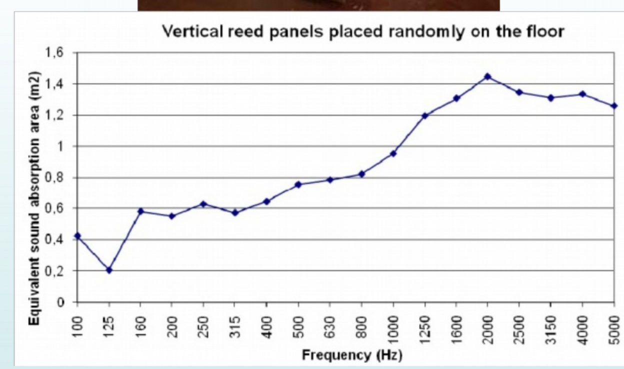
Natural materials for acoustic applications : recent developments (2)

Reeds (Reverberation room)



The reeds have also been tested in the front-end configuration in a reverberating chamber using a 12m² sample which was 14 cm thick . This test confirmed that >90% absorption can be attained at frequencies greater than 250Hz in the case of diffused sound field [1].





Another study evaluated the absorption properties of two test specimen made from reeds inside a reverberation room:

- a suspended ceiling (left, surface 4 m²)
- a vertical panel (right, 5 m²) [2].

References: [1] Oldham, D. J., Egan, C. & Cookson, R., Sustainable acoustic absorbers from the biomass, Applied Acoustics, 2011 72, 350-363;

[2] Jiménez-Espada, M. & Diaz-Sanchidrian, C., The use of reed panels in suspended ceiling and room dividers, Proceedings. of Internoise 2010. Lisbon, Portugal 13-16 June 2010

Natural materials for acoustic applications

Other natural materials which have been proposed for acoustic applications are:

- animal wool (sheep wool);
- latex – coco;
- flax;
- cork.

Recycled materials for acoustic applications

Recycled materials can even be regarded as a sustainable alternative, as they contribute to lower waste production and use of raw materials (Circular economy)

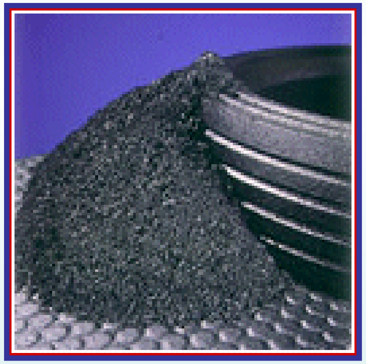
There are a lot of examples of materials belonging to this category, such as:

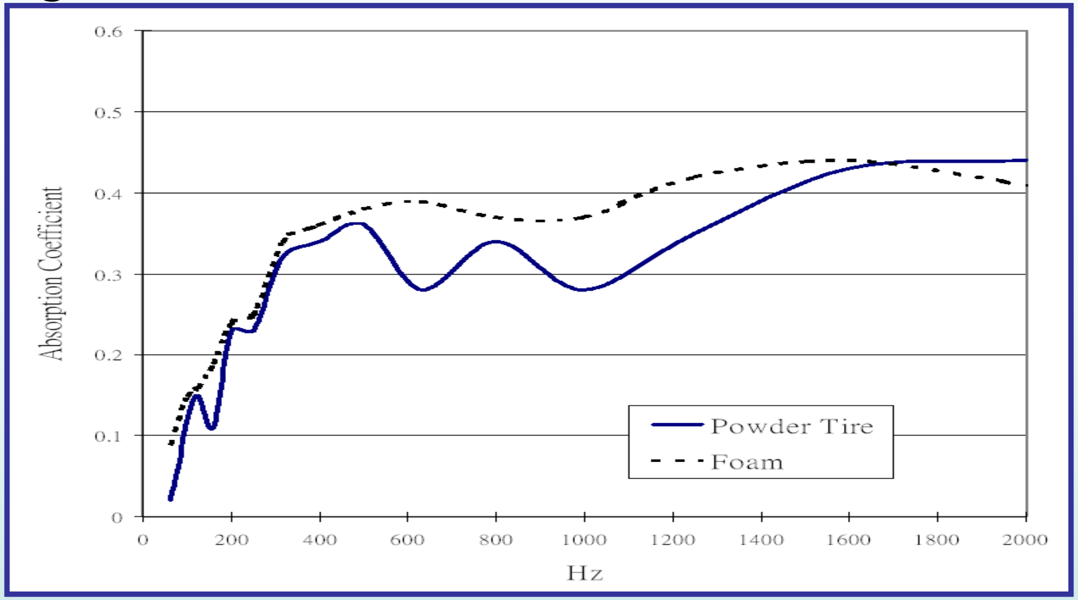
- Cellulose insulation from recycled newspapers (isofloc),
- Recycled rubber;
- Recycled plastics and polymers;
- Recycled textile fibres;
- Recycled urban solid waste.

Recycled materials for acoustic applications: examples (1)

Rubber powder tyres

Whole and powder forms of tyres are available at very low cost. The powder tyre can perform porous absorption while the whole tyre provide air gaps and damping effects.



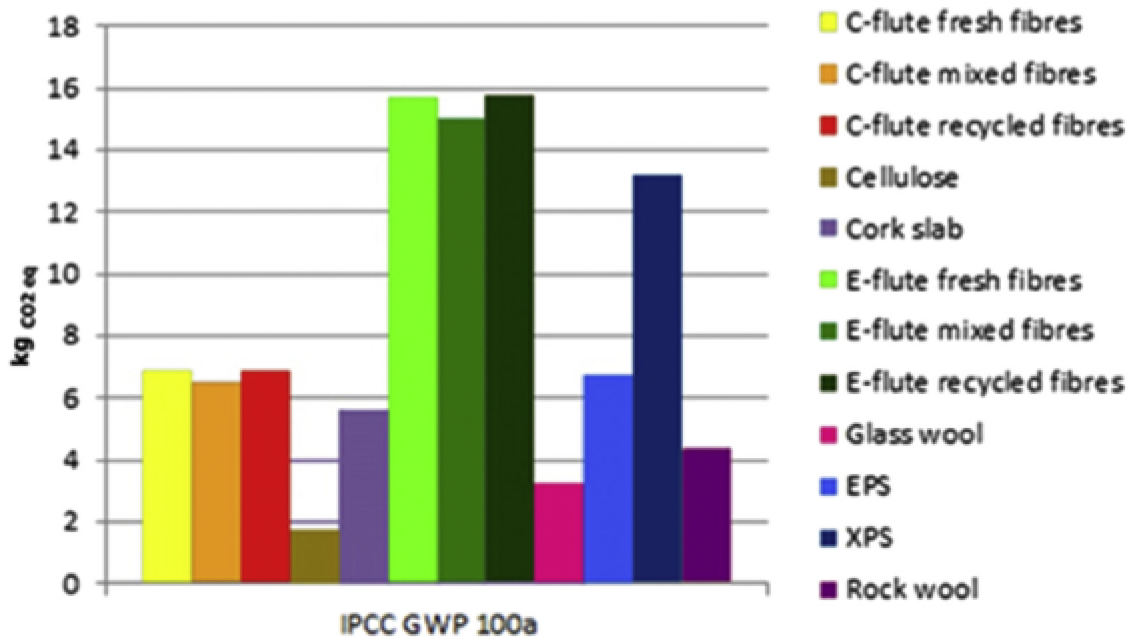


Comparison between α_s of powder tyre and of a foam often used in acoustic absorption treatment

Reference: *Waste rubber for noise reduction,* W. F. Cheng *et al*, Proc. of Internoise 2003, Seogwipo, Korea.

Recycled materials for acoustic applications: examples (2)

Examples of layers orientation in the considered samples.



. LCA results with respect to the IPCC method, of the different insulation materials.

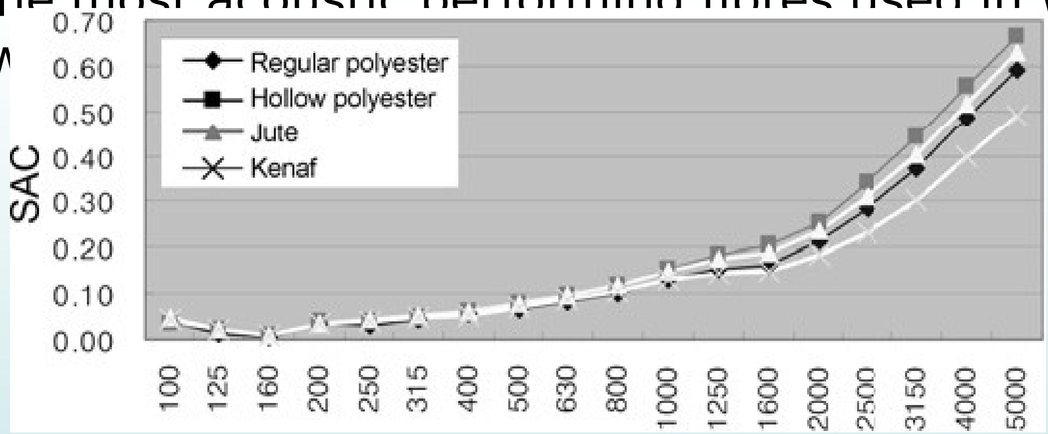
Secchi, S., Asdrubali, F.,Cellai, G., Nannipieri, E., Rotili, A., Vannucchi, I.:" Experimental and environmental analysis of new sound-absorbing and insulating elements in recycled cardboard". Journal of Building Engineering (2016), 5, 1-12.

Composite materials for acoustic applications

Wood plastic composites

The term Wood-Plastic Composite (WPC) is referred to any material made mixing plaint fibre (cotton, jute, kenaf etc) with thermosets or thermoplastics. Thermosets are plastic that once cured cannot be melted by reheating. An example of thermosets are the resins. Thermoplastics are plastics that can be repeatedly melted. Examples of thermoplastic are polypropylene, polyethylene and polyvinyl chloride [1].

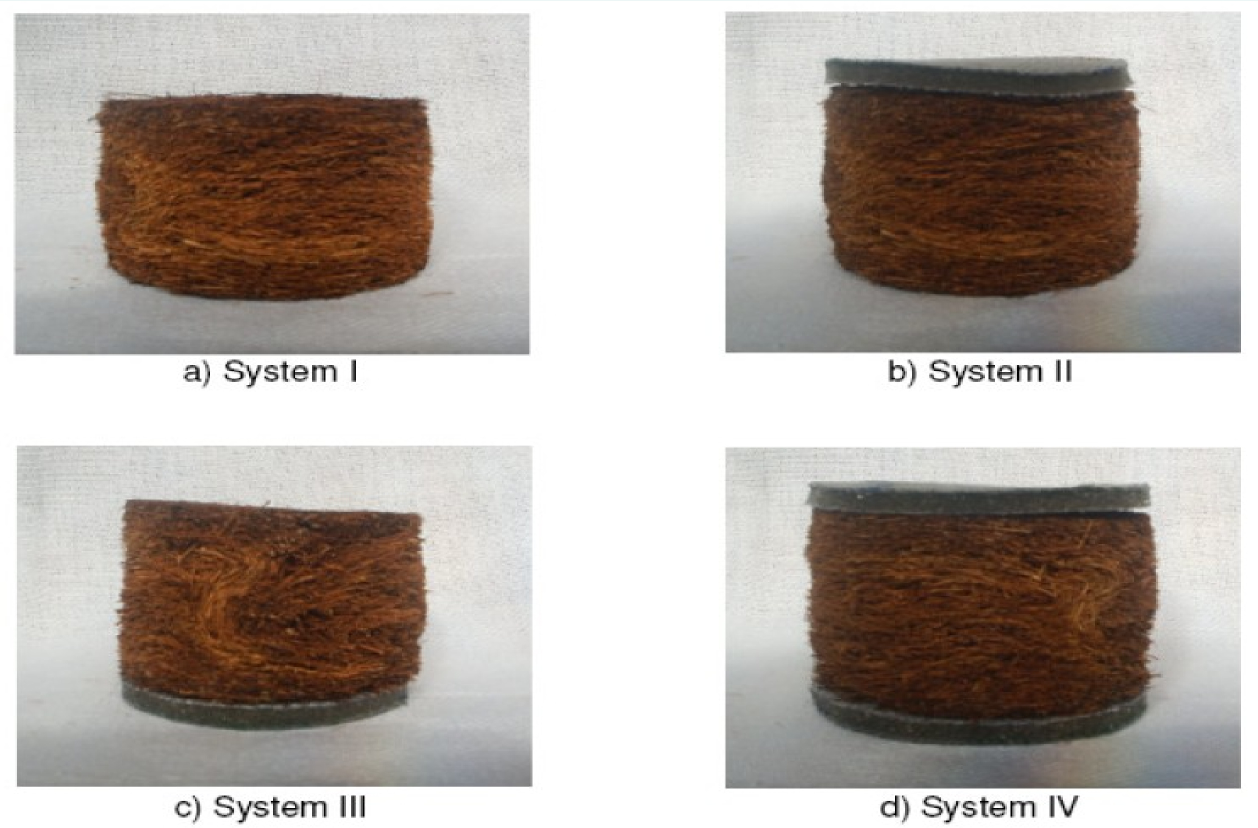
Kenaf is one of the most acoustic performing fibres used in WPC for the automotive nonw



Reference: [1] Ashori, A., Wood-plastic composites as promising green-compostites for automotive industries!, Bioresource Technology, 2008, 99, 4661-4667.
[2] Youngjoo, N. & Gilsoo, C., Sound Absorption and Viscoelastic Property of Acoustical Automotive Nonwovens and Their Plasma Treatment, Fibers and Polymers, 2010, .5(11), 782-789.

Composite materials for acoustic applications

Coconut and foam

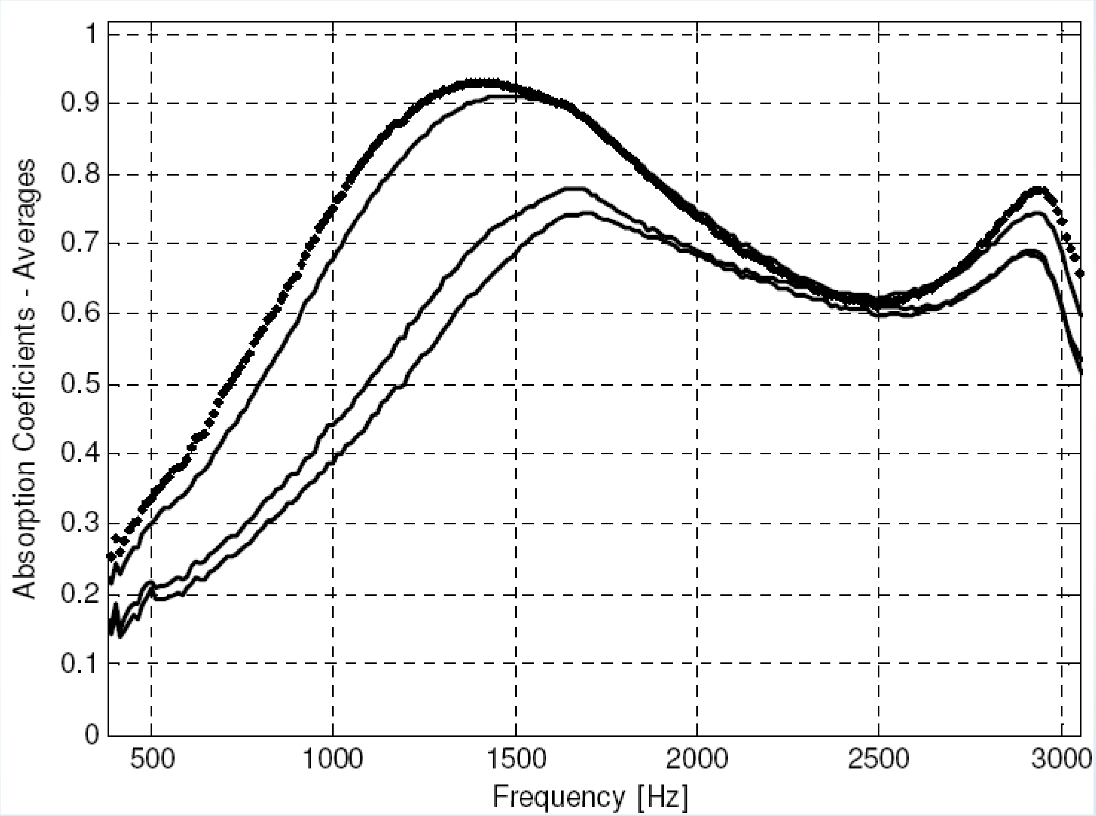


Tested systems: a) coconut fibre sample,
b) foam + coconut fibre,
c) coconut fibre + foam,
d) foam + coconut fibre + foam.

Reference: Moreira da Silva, G., de Castro Magalhaes, M. & Guerra, A., Comparative study of sound absorption systems composed of multylayered panels, Proeedings. of the 17th International Congress on Sound & Vibration (ICSV), Cairo, Egypt, 18-22 July 2010.

Composite materials for acoustic applications

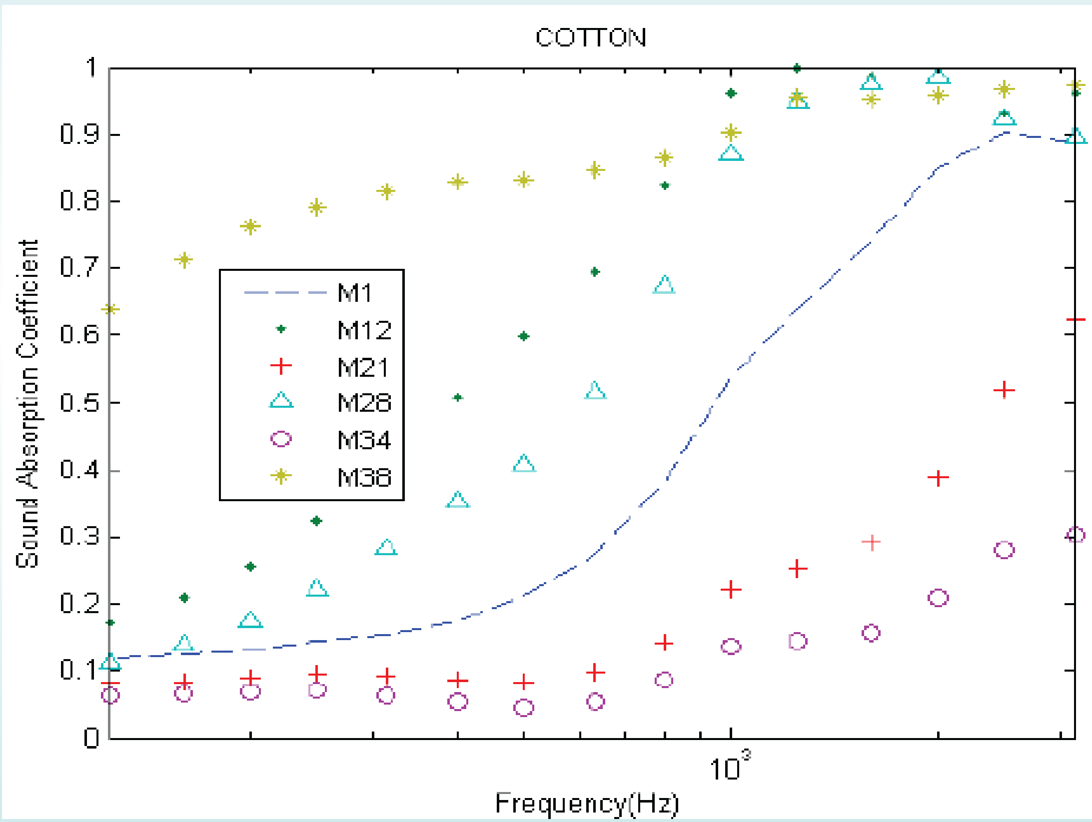
Coconut and foam



Reference: Moreira da Silva, G., de Castro Magalhaes, M. & Guerra, A., Comparative study of sound absorption systems composed of multylayered panels, Proeedings. of the 17th International Congress on Sound & Vibration (ICSV), Cairo, Egypt, 18-22 July 2010.

Composite materials for acoustic applications

Natural fibers and recycled polymers



Material	Composition	Thickness (cm)	Airflow resitivity (kpas/m²)
M1	70% cotton. 30% synthetic resin.	3	24
M2	75% acrylic/recycled wool. 25% PP	2	24
M3	80% recycled false ceilind. 20% Bico.	4	9
M4	85% recycled cotton and jute. 15% PP.	3	28
M5	85% PIM. 15% PES.	4	3
M6	64% wool. 16% acrylic. 20% PES Bico.	6	8
M7	85% wool. 15% PE Bico.	6	1
M8	85% remainder canvas. 15% PES Bico.	2	3
M9	80% cellulose. 20% PES Bico.	2	33
M10	80% recycled foam. 20% PET Bico.	3	14
M11	70% recycled cotton. 22% PES. 8% PES Bico.	1	112
M12	35% cotton. 35% Bico. 30% straw.	3	21
M13	50% wool. 30% jute. 20% Bico.	4	9
M14	40% PES. 40% recycled latex. 20% PES Bico.	2	3
M15	70% kenaf. 30% resin.	1	10
M16	50% hemp. 50% PP.	1	45
M17	70% feather. 30% PES Bico.	3	13
M18	15% recycled bottle. 35%	5	8

Reference: del Rey Tormos, R., Férnandez, J., Berto Carbo, L. & Sanchis Rico, V., Absorbent acoustic materials based in natural fibers, Proceedings of Forum Acusticum 2011. Aalborg, Denmark.

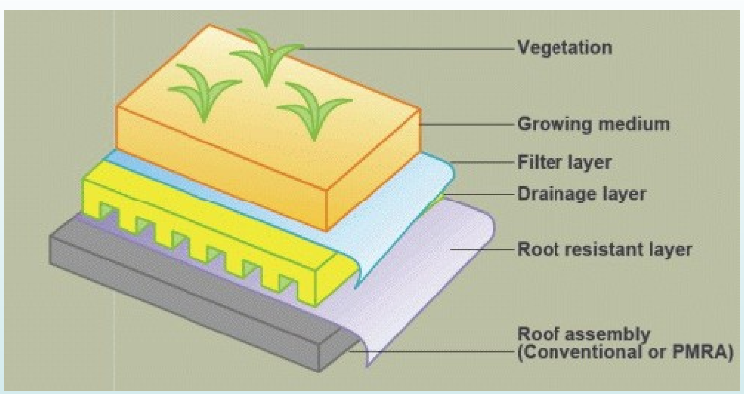
Green roofs and green walls

A “green roof” is a system based in the covering of the upper surface of a building with a layer of living vegetation. Usually the green roofs are classified in three types:

•intensive (substrate layer with a depth of more than 150 mm);

•extensive (substrate layer with a maximum depth of about 150 mm);

•semi-intensive (a combination of th



Reference: Kang, J., Huang, H. & Sorril, J., Experimental study of the sound insulation insulation of semi-extensive green roof, Proceedings of Internoise 2009. Ottawa, Canada.

Green roofs and green walls

The Green roofs technology contributes to:

- Reduce the energy demand of a building;
- Remove part of the air pollution
- Mitigate the heat island effect;
- Reduce the storm water runoff.

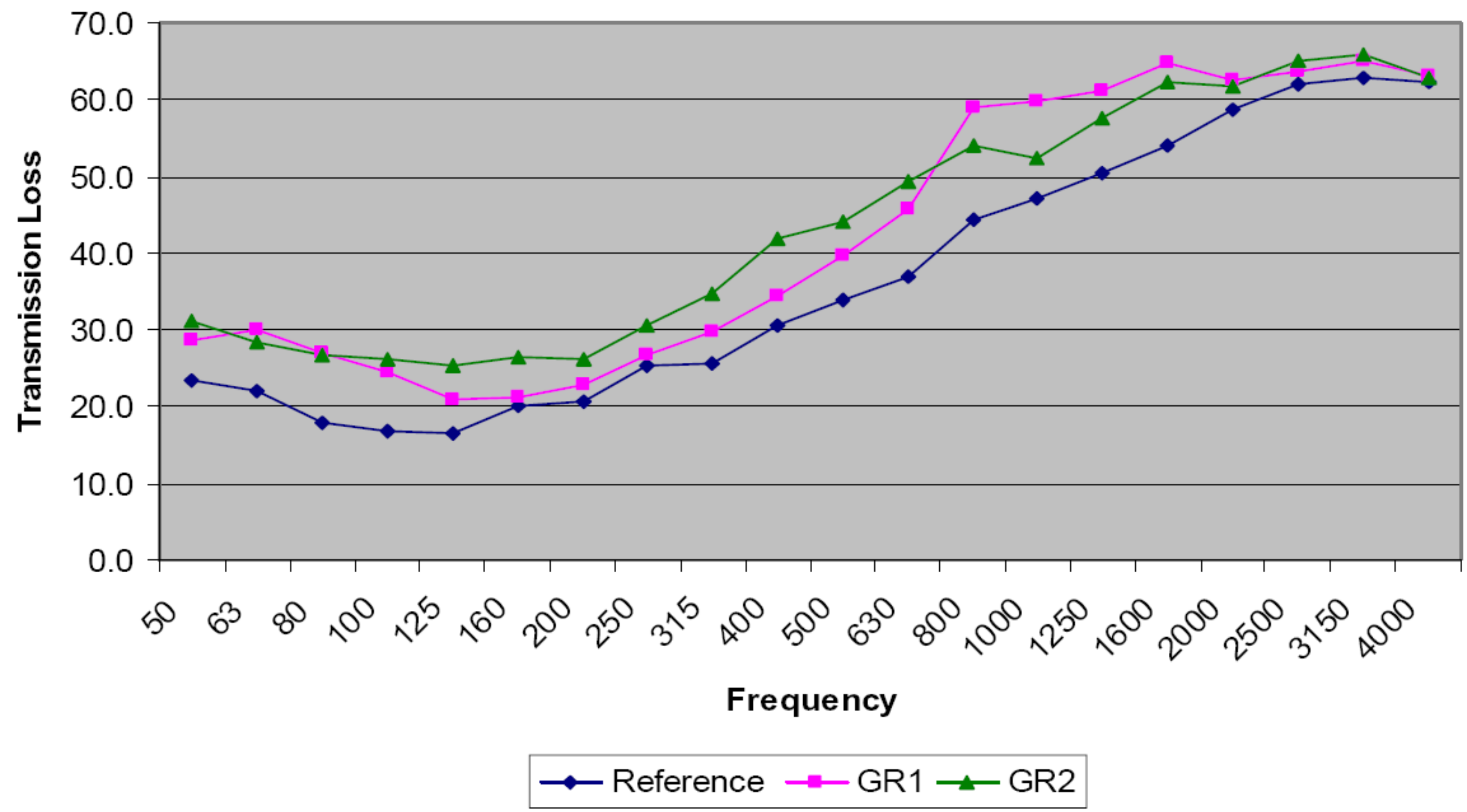
Concerning the acoustical aspects, there are two positive effects:

- an improvement of the sound insulation and absorption properties of the roof
- and a reduction of the diffracted noise component.

The first effect consists of a reduction of the sound level that could be observed inside the building.

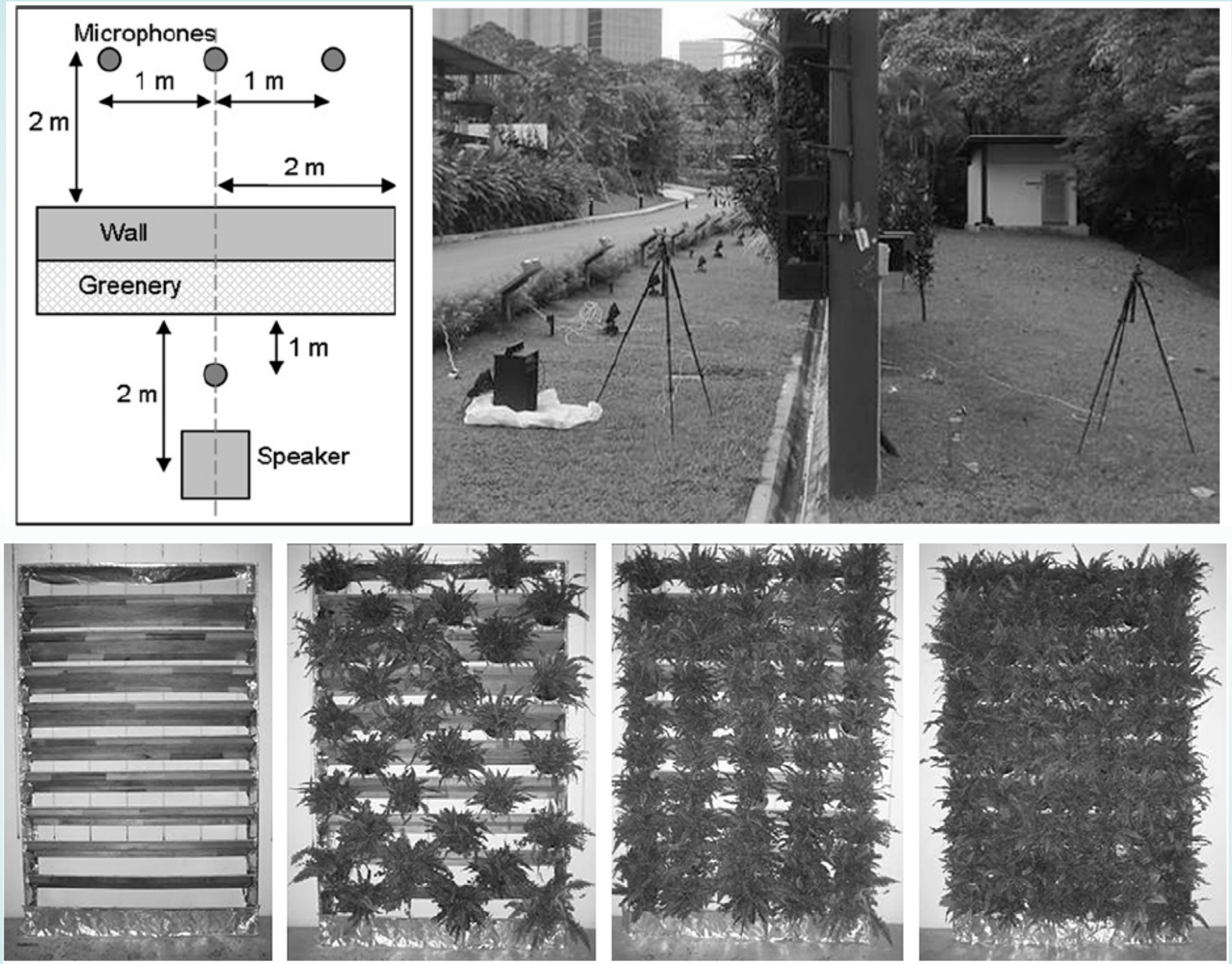
The second effect is the protection of quiet areas behind the building façades, since the greenery system has an acoustic absorptive surface that reduces the strength of the diffraction component for the noise propagated from a busy road.

Green roofs and green walls



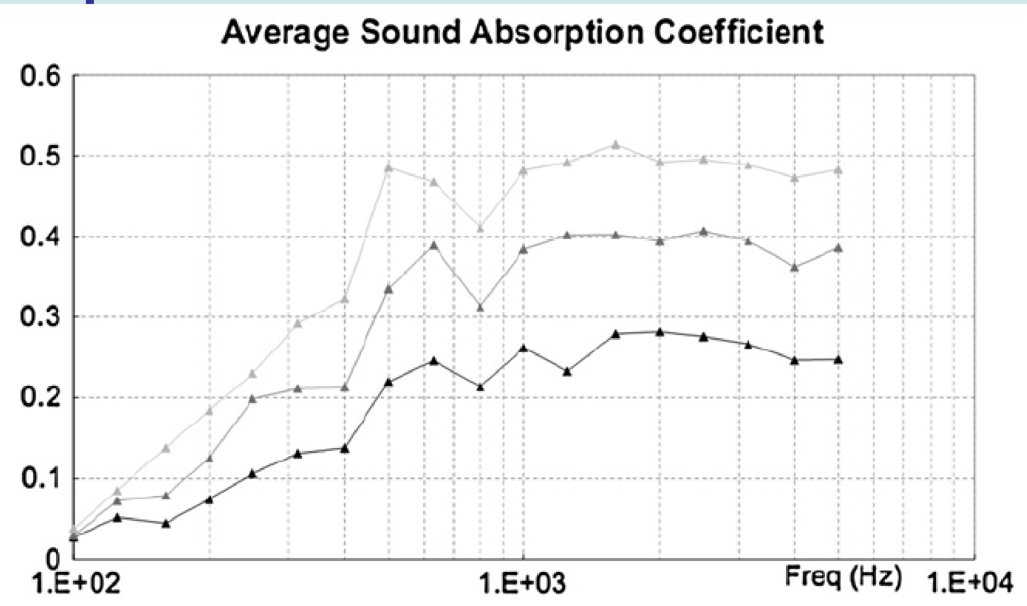
Reference: Connelly, M. & Hodgson, M., Sound trasmission loss of green roofs, Proceedings of Greening Rooftops for Sustainable Communitie, 2008, Baltimore, USA.

Green roofs and green walls



Reference: Wong, N.H. et al., Acoustical evaluation of vertical greenery systems for building walls, Building and Environment, 2010, 45, 411-420.

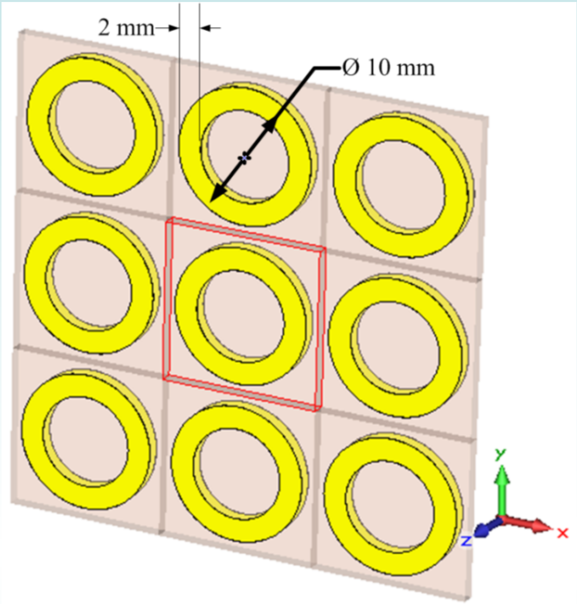
Green roofs and green walls



Vertical greenery system	Insertion loss (dB)			
	Zone B: 125–1250 Hz		Zone D: 4–10 kHz	
	Lowest	Highest	Lowest	Highest
2	−1.1	9.9	2.2	3.8
1	−2.5	5.6	−0.6	3.1
3	−4.5	2.2	−4.0	3.2
4	−1.5	4.0	−2.5	2.0
5	−3.3	7.0	0.3	2.8
6	−2.4	5.4	−1.6	3.2
7	0.3	8.4	0.0	3.9
8	−0.6	3.1	2.6	8.8

Reference: Wong, N.H. et al., Acoustical evaluation of vertical greenery systems for building walls, Building and Environment, 2010, 45, 411-420.

Metamaterials



Metamaterials are artificially constructed materials with unusual properties that cannot be found in nature.
One of the main advantages of using metamaterials, is the possibility of creating metasurfaces: arrays of very small elements with respect to the wavelength whose geometric characteristics determine the physical behavior.

The materials to be used and consequently their weight and their ability to reduce noise are a function of the frequencies of interest and the bandwidth.
Depending on the specific objective, it is possible to design both a single layer operating in a restricted frequency band and a multilayer structure acting on a wider range of frequencies.

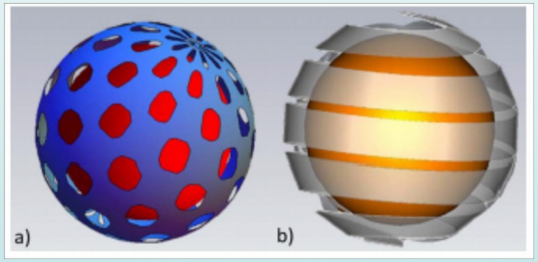
Metamaterials

By designing an acoustic metasurface it is possible to vary significantly the acoustic surface impedance of the structure.

It is therefore possible to check the T and R values and the relative sound-absorbing properties.

The variation of the transmission/reflection coefficient can be obtained by acting on the thickness of the metasurface, on the dimensions and shape of the inclusions and on the distance between them.

The metasurface is represented by a thin layer with a specifically defined acoustic impedance.



Metamaterials

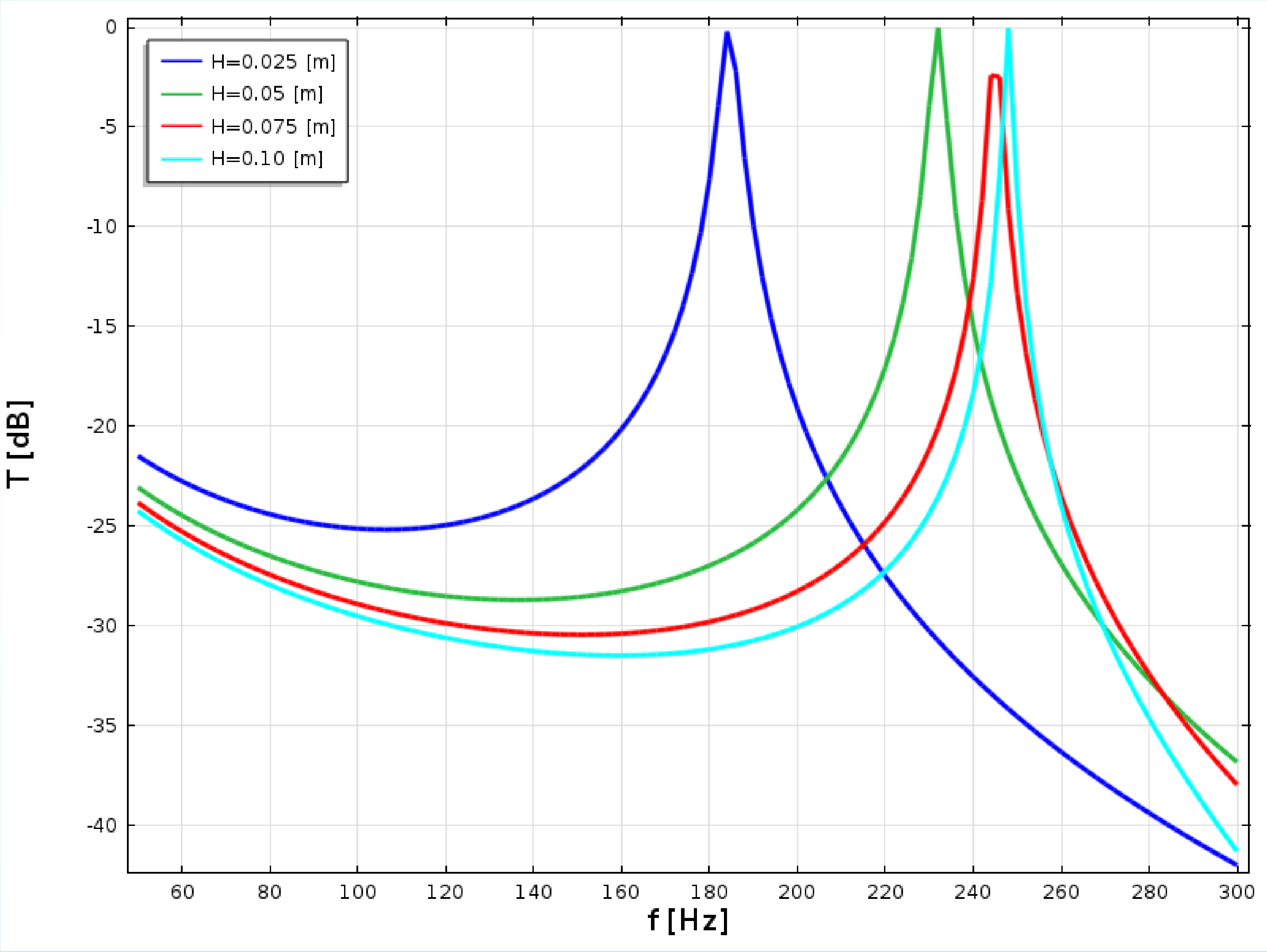
The effective possibility of controlling the transmission coefficient value through the design of an acoustic metasurface consisting of a two-dimensional array of cylinders or air spheres was demonstrated

It was also demonstrated the possibility to define its value and the desired range of operating frequencies by acting on the geometric parameters of the metasurface independently of the law of mass.

The advantages of using this technology are represented by the reduced thickness of the structure compared to traditional technologies and the possibility to choose an extremely flexible and light sustainable material as array matrix.

P. Gori, C. Guattari, F. Asdrubali, R. de Lieto Vollaro, A. Monti, D. Ramaccia, F. Bilotti, A. Toscano: *“Sustainable Acoustic Metasurfaces for Sound Control”*, Sustainability (2016) 8, 107-207.

Metamaterials



Conclusions

- Acoustical sustainable materials, either natural or made from recycled materials, are quite often a valid alternative to traditional synthetic materials.
- Airborne sound insulation of natural materials such as flax or of recycled cellulose fibers is similar to the one of rock or glass wool.
- Many natural materials (bamboo, kenaf, coco fibers) show good sound absorbing performances
- Cork or recycled rubber layers can be very effective for impact sound insulation.
- Some of these materials are currently available on the market at competitive prices, but many others are still at a prototypal stage.

Conclusions

- Composite materials, for example materials made of both natural fibers and recycled polymers, represent an interesting challenge
- Also research on green walls and green roofs received a boost in recent years. These systems have also other significant environmental benefits (visual aspects, air quality)
- Acoustic metamaterials can represent an innovative option for a taylor made material with desired properties and a sustainable matrix
- The production of these materials generally has a lower environmental impact then conventional ones, though a proper analysis of their sustainability, through Life Cycle Assessment procedures, has to be carried out. The concept of embodied energy is important.
- There is the need of a standard and unique procedure to evaluate the sustainability of green materials

Thank you for your attention!

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