INNOVATIVE MATERIALS CONTRIBUTIONS TO THE SUSTAINABLE DEVELOPMENT OF CONSTRUCTIONS

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ABSTRACT

Sustainable building development involves the use of environmentally friendly materials to reduce carbon footprint, energy consumption and costs. This paper presents natural, customary and innovative materials used in construction. Breathe brick used to filter air from existing pollutants into the atmosphere, Ferrock concrete absorbing carbon dioxide from the atmosphere, nanoparticle thermal insulating materials and metamaterials used in acoustic insulation are future solutions for sustainable development.

Keywords: Breathe brick; Ferrock concrete; nanoparticle insulating materials; metamaterials

REZUMAT

Dezvoltarea durabilă a clădirilor implică utilizarea de materiale ecologice pentru a reduce amprenta de carbon, consumul de energie și costurile. Această lucrare prezintă materiale naturale, obișnuite și inovatoare utilizate în construcții. Cărămida Breathe utilizată pentru a filtra aerul de poluanții existenți în atmosferă, betonul Ferrock care absoarbe dioxidul de carbon din atmosferă, materialele termoizolante cu nanoparticule și metamaterialele utilizate în izolația acustică reprezintă soluții viitoare pentru dezvoltarea durabilă.

Cuvinte-cheie: cărămida Breathe; betonul Ferrock; materiale izolante cu nanoparticule; metamateriale

1. CONTEXT

Energy consumption in the construction sector can reach up to 40% of the total energy demand of an industrialized country. For this reason, environmentally friendly building strategies can be extremely effective in saving fossil fuels and reducing greenhouse gas emissions. Sustainable materials can play an important role because, in general, less energy is required for their manufacture, use, re-use and / or recycling than the amount required for conventional materials. According to the definition of sustainability given by the Brundtland Report, "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Asdrubali *et al*., 2012). Therefore, a material can be considered sustainable if its production allows the resources used to create it to remain available to future generations and if it has the least possible impact on human health and the environment. In recent years, a lot of attention has been paid to "green" materials, especially in the construction sector. Many research centers have developed new, durable materials with improved properties.

This paper aims to give an overview of the innovative materials developed, researched and used in sustainable construction. For achieving this goal, we used the study and synthesis of the information existing in the current specialized literature.

2. RESULTS AND DISCUSSIONS

2.1. Breathe Brick

Pollution-absorbing bricks, which can clean the atmosphere, are some of the latest innovations in the construction industry.

Breathe Brick (Fig. 1) has been developed by Carmen Trudell, associate professor at the

Cal Poly San Luis Obispo College of Architecture (California Polytechnic State University, College of Architecture & Environmental Design, San Luis Obispo, CA, USA) and a group of MIT (Massachusetts Institute of Technology) students (Trudell, 2014).

Currently, these bricks are not widely available on the market, but are being tested in India - a country suffering from strong pollution - to study their long-term impact.

Breathe Brick is designed to form a part of a building's regular ventilation system, with a double-layered facade of the specialized bricks on the outside, complemented by a standard internal layer providing insulation (Trudell, 2014). At the center of the Breathe Brick's function is the cyclone filtration, an idea borrowed from modern vacuum cleaners, which separates out the heavy pollutant particles from the air and drops them into a removable hopper at the base of the wall. The Breathe Brick modules are connected by a coupler which helps collect particles, protect the filter system and facilitates the alignment of the module during construction (Fig. 1).

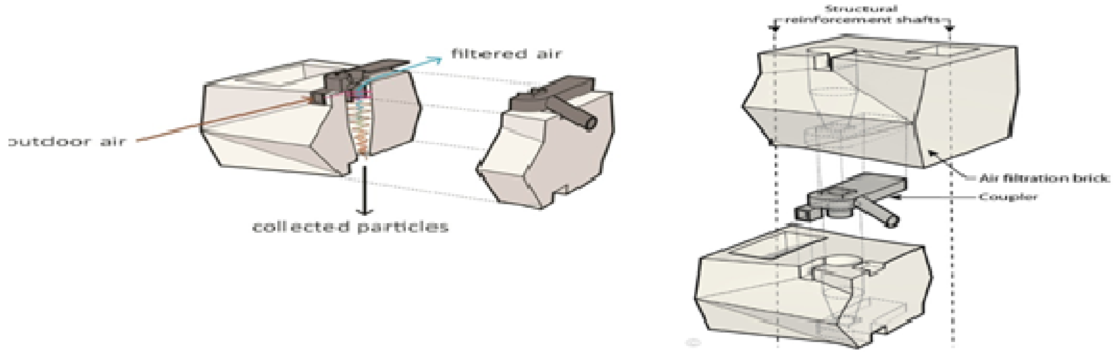
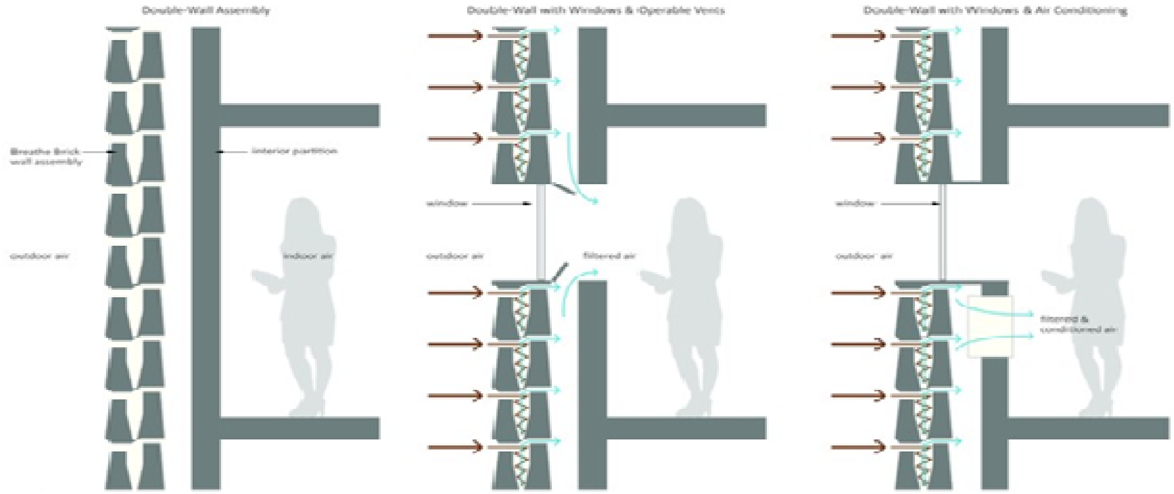


Fig. 1. Section of Breathe Brick and assembling module

The system consists of two key parts: concrete bricks, and a recycled plastic coupler, which both helps to align bricks and create a route from the outside into the brick's hollow center. The concrete bricks themselves feature a faceted surface which helps to direct airflow into the system, and a separate cavity for inserting the steel structure.

There are three possible configurations of the Breathe Brick walls (Fig. 2), starting with simple double-walled constructions (a), where the inside wall provides insulation, while the outside wall provides filtered air in the space between the two walls; the double wall with one window (b), where the filtered air can be introduced inside the building through vents ordered by the users; respectively a third version (c), which uses mechanical heating / cooling equipment to condition the filtered air before it is introduced into the living space.



a) b) c)

Fig. 2. Possible configurations of Breathe Brick walls (Trudell, 2014)

The tests performed revealed that the system filters 30% of fine particles (such as air pollutants) and 100% coarse particles, such as dust (Trudell, 2014). Since the entire system is relatively inexpensive, Trudell places Breathe Brick as a way to reduce pollution levels in developing countries, where rapid industry expansion and less stringent environmental regulations often cause problems (Trudell, 2014).

2.2. Ferrock Concrete

Ferrock concrete was discovered by David Stone while he was doing his PhD in environmental chemistry at the University of Arizona in Tucson.

Metallic iron reacts with carbon dioxide (CO_2) under controlled conditions (Equation 1) and forms complex iron carbonates having binding capacity. Additives containing silica and alumina were added to facilitate the dissolution of iron and to obtain beneficial rheological properties.

$$Fe + CO_2 + H_2O \rightarrow FeCO_3 + H_2 \uparrow \qquad (1)$$

One of the unique properties of the Ferrock concrete is that its hardness increases in salt water environments, making it ideal for construction projects in marine areas. Also, instead of emitting large amounts of CO_2 as it dries, the Ferrock concrete absorbs CO_2. This results in a carbon-negative process that actually helps capture greenhouse gases (Das *et al.*, 2014).

The chemical composition obtained using the X-ray emission of the iron powder used to produce Ferrock concrete is presented in Table1.

Table 1. *Chemical composition of the iron powder (Das et al., 2014)*

Fe [%]	Cu [%]	Mn [%]	Cr [%]	Ca [%]	K [%]	O [%]
88	0,2	0,8	0,3	0,1	0,04	10

The Ferrock concrete manufacturing process involves the initial mixing of all materials (iron powder, fly ash, limestone powder, metakaolin and organic reducing agent). Then water was added and mixed to obtain a uniform cohesive blend. The water - total mass ratio varied between 0.22 and 0.25. Samples were stored in a CO_2 medium for three days and then allowed to mature for two days in open air at 23 ± 2°C (Das *et al.*, 2014).

Fig. 3. Corrosion resistance of Ferrock concrete (3 days in CO_2 and 2 days in open air), compared to various blends of Portland cement 7 days after casting (processed by the authors, based on Das *et al.*, 2014)

Samples containing 20% fly ash were significantly more compressive resistant (these mixtures have the lowest porosity) (Fig. 3).

The duration of exposure to air influences compressive strength over longer carbonation times. The compressive strength of Ferrock concrete based on the duration of exposure to air for 4 days of carbonation is presented in Fig. 4.

Possible applications of Ferrock concrete are in pavements, tiles, other modular small units, walls, slabs, roofs and columns, structural panels, thin shells and other prefabricated products (Garcia *et al.* 2017).

The "green" features of Ferrock concrete are: it recycles iron powder as a source of iron and fly ash as a source of silica, captures CO_2 during curing and releases hydrogen as a by-product.

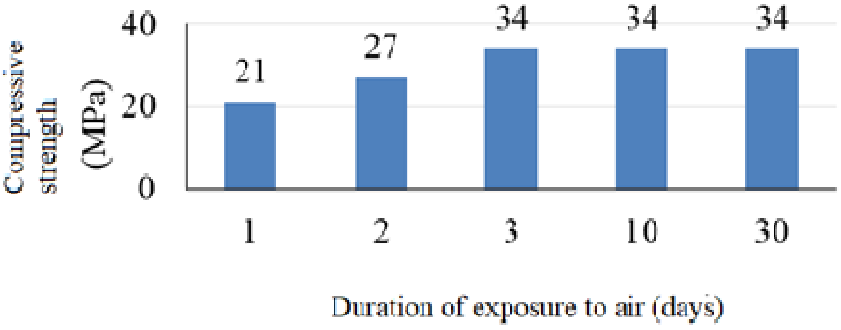


Fig. 4. The effect of exposure to air on compressive strength (processed by the authors, based on Das *et al.*, 2014)

2.3. Materials Used for Thermal Insulation

The most common traditional thermal insulation materials of today's buildings have a relatively low thermal conductivity. These are: mineral wool, expanded polystyrene, extruded polystyrene, cellulose and polyurethane. The average thermal conductivity typical for traditional thermal insulation materials is presented in Table 2.

Table 2. Typical thermal conductivity for traditional thermal insulation materials (Jelle et al., 2011)

Thermal insulating material	Thermal conductivity [mW/mK]
Mineral wool	30÷40
Expanded polystyrene	30÷40
Extruded polystyrene	30÷40
Cellulose	30÷50
Polyurethane	20÷30

Thermal conductivity of insulating materials varies with temperature, humidity and density. Table 3 presents the change in thermal conductivity for traditional thermal insulating materials due to increased humidity

Table 3. Thermal conductivity of thermal insulation materials depending on humidity (Jelle *et al.*, 2011)

Thermal insulating material	Thermal conductivity [mW/mK]	Relative humidity%
Mineral wool	37÷55	0÷10
Expanded polystyrene	36÷54	0÷10
Extruded polystyrene	34÷44	0÷10
Cellulose	40÷66	0÷5
Polyurethane	25÷46	0÷10

Innovative materials that are considered to be thermal insulation with the lowest thermal conductivity today are: vacuum insulated panels (VIP), gas-filled panels (GFP) and aerogels.

Vacuum insulated panels (VIP) consist of a porous, open porosity, silicon core, coated in several laminated layers of metallized polymer, Fig. 5.

The VIPs represent today's state-of-the-art thermal insulation with center-of-panel thermal conductivities ranging from as low as 2 to 4 mW/(mK) in pristine non-aged condition to typically 8 mW/(mK) after 25 years of aging due to water vapors and air diffusion through the VIP envelope and into the VIP core material, which has an open pore (Jelle *et al*., 2011).

GFPs contain a gas less thermally conductive than air, such as argon (Ar), krypton (Kr) and / or xenon (Xe), instead of vacuum, as in VIPs Conductivity coefficients for GFP prototypes are high, such as 40 mW/(mK) (Jelle *et al*., 2011).

Commercially available last generation aerogels have thermal conductivity between 13 and 14 mW / mK at normal atmospheric pressure. Production costs for aerogels are still very high. Aerogels have a relatively high compressive strength but are very fragile due to very low tractive forces (Jelle *et al*., 2011).

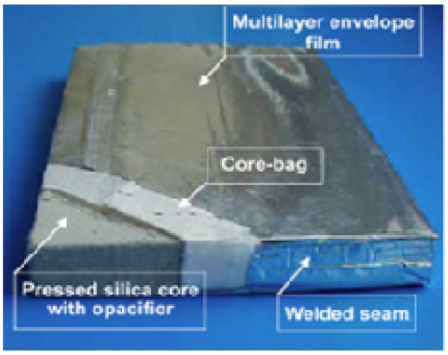


Fig. 5. Vacuum insulated panel (Jelle *et al*., 2011)

Future solutions for thermal insulation of buildings are provided by vacuum insulating materials (VIM), gas insulating materials (GIM), nanoparticle insulating materials (NIM) and dynamic insulating materials (DIM) (Jelle *et al*., 2011).

A vacuum insulation material (VIM) is basically a homogenous material with a closed small pore structure (Fig. 6), filled with an overall thermal conductivity of less than 4 mW/(mK). The VIM can be cut and adapted with no loss of low thermal conductivity. Perforating the VIM with a nail would only result in a local heat bridge. A gas insulation material (GIM) is basically a homogenous material with a closed small pore structure filled with a low-conductance gas like e.g. Ar, Kr or Xe, with an overall thermal conductivity of less than 4 mW/(mK). That is, a GIM is basically the same as a VIM, except that the vacuum inside the closed pore structure is substituted with a low-conductance gas (Jelle *et al*., 2011). The development from VIP to nano insulation materials (NIM) is depicted in Fig. 7.

In NIM the pore size within the material is decreased below a certain level, i.e., 40 nm or below for air, in order to achieve an overall thermal conductivity of less than 4 mW/mK. That is, NIM is basically a homogenous material with a closed or open small nano pore structure with an overall thermal conductivity of less than 4 mW/mK. The low thermal conductivity of the gas in NIM is caused by the Knudsen effect, where the mean free path of the gas molecules is higher than the diameter of the pores. That means that a gas molecule located inside the pore will hit the wall of the pores and not another gas molecule (Jelle *et al*., 2011).

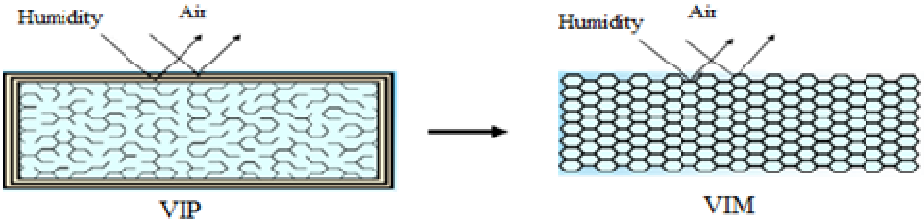


Fig. 6. Structure of the vacuum insulation material (Jelle et al., 2011)

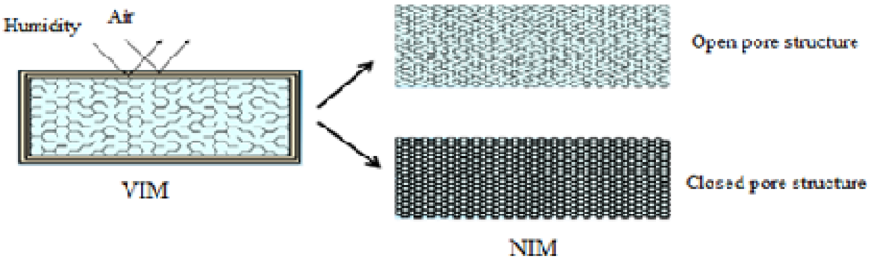


Fig. 7. The development from vacuum insulation panel to nano insulation material (Jelle et al., 2011)

A dynamic insulation material (DIM) is a material where the thermal conductivity can be controlled within a desirable range. The thermal conductivity control may be achieved by being able to change in a controlled manner the inner pore gas content or concentration, including the mean free path of the gas molecules and the gas-surface interaction, the emissivity of the inner surfaces of the pores and the solid state thermal conductivity of the lattice. (Baetens *et al.*, 2011).

2.4. Sound Insulation Materials

The use of natural materials contributes to achieving greater durability of buildings. The more natural and less processed the materials, the better they are in terms of energy savings (Asdrubali *et al.*, 2012). A number of materials with acoustic insulation properties are shown in Table 4.

Sound attenuation has been conventionally done by applying acoustic barriers, reflecting or absorbing the incident acoustic energy. While broadband attenuation can be achieved, low frequency (<500 Hz) attenuation using such approaches is difficult and requires a greater thickness of the acoustic barrier. Such sound attenuation methods eliminate air flow, which excludes their functionality for applications that require ventilation (Ghaffarivardavagh *et al.*, 2019).

Table 4. Acoustic and thermal properties of natural insulating materials (1-8) and traditionally sintered (9-11)

Material	Thermal conductivity (W/mK)	Absorption coefficient at 500 Hz	Impact Noise Reduction Index
Hemp	0,04	0,6 (30 cm)	-
Kenaf	0,044	0,75 (5 cm)	-
Coconut fiber	0,043	0,42	23
Sheep wool	0,044	0,38 (6 cm)	18
Wood fibers	0,065	0,32	21
Cork	0,039	0,39	17
Cellulose	0,037	1 (6 cm)	22
Flax	0,040	-	-
Glass wool	0,04	1 (5 cm)	-
Mineral wool	0,045	0,9 (5 cm)	-
Expanded polystyrene	0,031	0,5	30

Ultra-open metamaterials (UOM) (Fig. 10) composed of subwavelength unit cell structures with an open area provide adequate functionality when sound attenuation is required, but ventilation also needs to be provided (Ghaffarivardavagh *et al.*, 2019).

Fig. 10 (a) shows the bilayer UOM structure, the first open-center ($r < r_1$) and the outer area in the second, featuring six channels coiled in the form of helix ($r_1 < r < r_2$).

Fig. 10 (b) shows the internal structure of the UOM with an acoustic wave traveling through the channels and essentially following the helical pathway.

Fig. 10 (c) shows the acoustic transmittance resulting from the impedance tube experiment - the dotted-line with a triangular marker demonstrating that near 460 Hz, the transmittance is reduced to the minimum value of approximately 0.06. Sound transmission loss for the wave passing through the UOM is also shown. The solid line represents the predicted behavior using the Green's function method by modeling the UOM structure as a transverse bilayer metamaterial (Ghaffarivardavagh *et al.*, 2019).

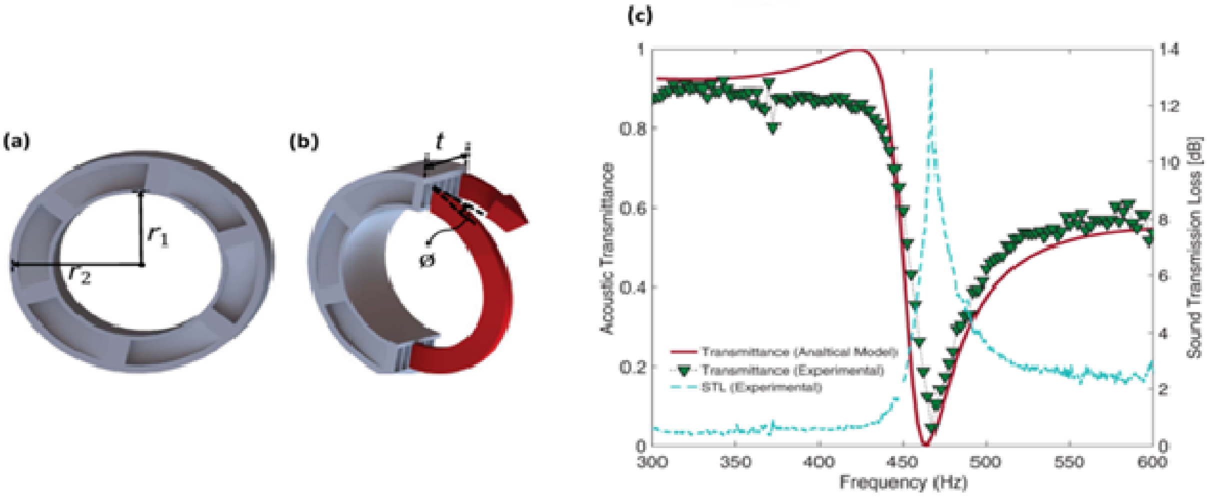


Fig. 10. (a) UOM structure (b) Internal structure of the UOM is shown with an acoustic wave traveling through the channels. (c) Acoustic transmittance resulting from the impedance tube experiment, sound transmission loss for the wave passing through the UOM and the predicted behavior using the Green's function method by modeling the UOM structure as a transverse bilayer metamaterial. (Ghaffarivardavagh *et al.*, 2019)

3. CONCLUSIONS

Based on the analyzed data, we can say that currently there is a variety of innovative materials that allow for the construction of buildings to meet the sustainability concept in the Brundtland Report.

Waste iron powders in combination with raw materials commonly used in the preparation of concrete and fly ash, limestone powder and metakaolin (as minor components) can be used to produce a binder with acceptable but carbon-negative properties for a wide range of construction applications.

There is currently no single insulating material or solution that meets all the requirements in regard to the most important properties. Therefore, it is important to choose the most appropriate solution by combining the use of traditional and modern materials.

Sound insulation made with natural materials, such as flax or recycled cellulose fibers is similar to mineral or glass wool. Many natural materials (bamboo, kenaf, sisal, coconut fiber) have good sound absorption performance. The tested "green" walls and the recycled rubber layers are effective for impact sound insulation.

These materials also have good thermal insulation properties. They are often lightweight and may be less harmful to human health. Composite materials, such as materials made of natural fibers and recycled polymers, are an interesting challenge. Also, research on "green" walls has received strong impetus in their development in recent years.

Metamaterial-based methodology allows the design of a breathable acoustic buffer. Using this method, the subwavelength structures can be designed to cut out the specific frequency bands of unwanted sound along with their harmonics.

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