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Professional paper

COMPARATIVE ANALYSIS OF NANOMATERIALS FOR ENERGY EFFICIENCY IMPROVEMENT OF HISTORIC BUILDINGS

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Abstract

The scientific interest in nanomaterials in buildings'' energy efficiency has increased significantly in the last decade, especially after the application of the ambitious concept of nearly zero-emission building (NZEB). This also leads to an increase of conventional thermal insulation materials' thickness in order to improve their thermal performance. In some European countries, the thickness of the insulation has almost doubled. This restriction has important economic and technical consequences such as: reduction of internal space, increase of insulation costs and, above all, inadequate change of the original architectural design of existing buildings, i.e. jeopardizing cultural heritage. New buildings have a limited impact on the overall energy reduction because they represent only a small part of the existing building stock. It is estimated that only 1% of Europe annually belongs to the new building stock. Existing buildings therefore represent the greatest opportunity for improvements in energy efficiency. Moreover, new buildings use four to eight times more resources than renovated ones, which is a sustainable argument in favor of renovating existing buildings. The development of high-performance insulation with as low thickness as possible has become a technically and scientifically challenge. Not only the thickness of the material highlights the need for research and development of new materials, but more important factors, especially when it comes to historical buildings. This paper focuses on analyzing nanomaterials for buildings' energy performance improvement, especially in cultural heritage buildings, whose original architectural appearance should not be compromised during the renovation process. Firstly, extensive literature related to the general application of nanomaterials in the building sector is reviewed, where the most significant properties in terms of their thermal insulation characteristics are emphasized. Then, based on the obtained data, a comparative analysis of the researched nanomaterials was carried out and several criteria were established for the evaluation and selection of the most appropriated materials for historical buildings' renovation. Finally, conclusions for the selection of nanomaterials with best thermal properties and a minimal impact on the cultural heritage, emerge from the analysis.

Keywords: nanomaterials, energy efficiency, thermal insulation, cultural heritage

1. Introduction

Nanomaterials have a great potential in the building sector, especially when it comes to the building materials thickness which continually increases in order to solve the problems with the energy efficiency and climate changes. Most of the buildings, especially in Europe, are already existing historical building, some of them are of a great cultural and historical value, and their original appearance should not be changed during the renovation processes for better energy efficiency, thermal comfort and sustainability (Torgal, 2016). In this paper, different types of nanomaterials have been researched and analyzed in terms of energy efficiency improvement of existing buildings and at the same time protection and reservation of their original architectural appearance. Several criteria for nanomaterials selection have been established, in order to find the most adequate materials for solving this research problem.

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2. Types of nanomaterials and their use in the building sector

Nanomaterials or nanocomposites are materials that have at least one dimension (width, length, height) smaller than 100 nanometers. The nanometer is 1×10^{-9} m (Bozsaky, 2016). The physical, chemical and biological properties of nanomaterials are much different from conventional materials, which contributes, by incorporating nanocomposites into other materials, to give them unique and improved characteristics (Mohamed, 2015). In construction, materials based on nanotechnology can be structural and non-structural, depending on whether the modification of the physical and chemical properties of the material is in terms of load-bearing (mechanical properties) or in terms of protection (thermal, fire or waterproofing properties) of conventional materials. The application of nanotechnology in construction is wide and significant in many spheres (table 1), however, the most significant goals, which especially concern this paper, are: improvement of energy performance, energy saving, reduced costs and preservation of the existing buildings.

TABLE 1. APPLICATION OF NANOMATERIALS IN CONSTRUCTION

<table>
<tr><td rowspan="10">Nanotechnology in the building sector</td><td rowspan="5">Materials</td><td colspan="2">Structural materials</td><td>Non structural materials</td></tr>
<tr><td colspan="2">Cement, concrete</td><td>Glass (windows, curtain walls)</td></tr>
<tr><td colspan="2">Steel</td><td>Plastic and polymers (windows, curtain walls)</td></tr>
<tr><td colspan="2">Wood</td><td>Gypsum plaster, mortars (facades and interiors)</td></tr>
<tr><td colspan="2">New materials</td><td>Roof materials</td></tr>
<tr><td rowspan="5">Preservation</td><td colspan="3">Filtration, Air Purification</td></tr>
<tr><td colspan="3">Coating (self-cleaning facades (Lotus effect – photocatalysis, (ECT), Antibacterial)</td></tr>
<tr><td rowspan="3">Energy</td><td rowspan="2">Reduction in energy consumption</td><td>Lightning</td></tr>
<tr><td>Insulation (graphite EPS, VIPs, airgel, thin film coatings of ceramic or glass nano-spheres, PCMs)</td></tr>
<tr><td>Energy production</td><td>Electronics/ Sensors
Energy production systems</td></tr>
</table>

Table 1 shows the possible applications of nanotechnology in the building sector, as well as the use of nanomaterials as building materials (structural and non-structural materials). For example, adding silica as nanomaterial to cement increases its durability and compressive strength. It can also be used to improve the fluidity and water permeability of the concrete (Kexing, 2014). By adding nanotubes or nanofibers, the tensile and flexural strength of concrete can be improved (Bozsaky, 2016). Nanotubes and nanofibers can also be added to the composition of wood, and such products have almost twice load capacity comparing to the steel (McIntyre, 2012). Titanium dioxide (TiO_2) can be used as a nanoparticle in the creation of thin coatings, thanks to its sterilizing and anticorrosive properties (Abdelrahman, 2010). Coatings that have nanoparticles in their composition provide better adhesion, transparency, protection against corrosion, fire resistance and are self-cleaning properties (Mohamed, 2015).

3. Thermal isolation nanomaterials

In terms of energy efficiency, the following nanomaterials available on the market have been developed so far:

- Products based on expanded polystyrene with graphite powder as an additive – (graphite nanotubes or carbon particles are added to the granular structure of polystyrene (Berardi, 2018);
- Aerogel based products - wide range of products for insulating transparent or non-transparent surfaces;
- VIPs (vacuum insulation panels) - vacuum thermal insulation panels, based on nanoparticles, with high thermal insulation power and very low thickness (Mohamed, 2015);

- Nano ceramic thermal insulation coatings (extra thin film coatings) for insulating transparent or non-transparent surfaces (Bozsaky, 2017).

To regulate the temperature of the envelope elements and to maintain the thermal comfort in the interiors of buildings, the following materials are used:

• PCMs (Phase change materials) – materials based on paraffin nanoparticles and salt hydrate whose paraffin globules with a diameter between 2-20 nm are encapsulated in a plastic shell. They can be integrated into different building materials, whereby, with a concentration of about 3 million such capsules in one square centimeter, they change their aggregate state from solid to liquid when the temperature changes, and thus maintain the required temperature in buildings (Seong, 2013).

Thermal insulation materials based on nanotechnology generally have better thermal properties than conventional thermal insulation materials. The methods of heat transfer in conventional thermal insulation materials are: thermal conduction, convection and radiation. The reason that nanomaterials are so good in their thermal properties is because they block the common methods of heat transfer and the coefficient (U value) of the structural elements decreases. The formula for calculating the heat transfer coefficient is as follows:

$$U = \frac{1}{\frac{1}{h_i}+\sum_{i=1}^{n}+\frac{d_i}{\lambda_i}+\frac{1}{h_e}} \quad (1)$$

In (1) U heat transfer coefficient [W/m2K]; d_i is the thickness of each material/layer [m]; λ_i is the coefficient of thermal conductivity of each material / layer [W/mK]; h_i is the internal surface heat transfer coefficient [W/m^{2}K]; while h_e the external surface heat transfer coefficient [W/m^{2}K]. The U value can be reduced in two ways in nanomaterials for thermal insulation (Bozsaky, 2016). Some of them (for example, graphite EPS, aerogel based materials, and VIPs – vacuum thermal insulation panels) have a lower coefficient of thermal conductivity, due to the fact that heat transfer through their structure (conduction) is blocked. In products based on graphite EPS, there is a deceleration of thermal radiation. In the case of vacuum thermal insulation panels, the transmission through conduction and convection (heat flux) is also slowed down. In aerogel thermal insulation materials, all three modes of heat transfer are significantly slowed down (Bozsaky, 2017). Nano ceramic thermal insulation coatings are considered the most critical in terms of their thermal properties, due to the contradictory technical data on their characteristics, given by the manufacturers, but also in the scientific literature. So far, no common method has been established for the way of forming the insulating effect of nano ceramic coatings. According to the manufacturers of these materials, their excellent thermal insulation properties are due to the extremely low thermal conductivity coefficient. According to the scientific achievements in the field, based on the researched literature, thermal insulation coatings can significantly increase the thermal resistance of the insulated surface by reducing the surface coefficient of heat transfer through convection (h) (Bozsaky, 2019). Thermal energy cannot be transferred in the same way between air and an insulated surface. This process faces obstacles in the nanostructure and the transmission takes much more time. Convection heat transfer is more difficult to analyze than conduction heat transfer because no single heat transfer characteristic (coefficient of thermal conductivity) can be defined to explain the mechanism of operation. Convection heat transfer varies from situation to situation (depending on the state of the fluid flow). In practice, the analysis of heat transfer through convection is treated empirically (through direct observation)

4. Comparative analysis of characteristics of nanomaterials

Comparative analysis between the different nanomaterials have been conducted in terms of their thermal characteristics, based on the researched literature, and the state of the art is given in Table 2. The mechanical properties, aggregate state and method of application have been investigated. The values in the table are selected data obtained through extensive literature research for all materials. Although they refer to one nanomaterial, they can vary a lot in terms of their characteristics (thermal conductivity, strength, density, thickness) depending on the type of material, i.e. from the structure of its composition.

There are several types of aerogel materials (silica, carbon metal aerogel, etc.) (Collins, 2019). PCMs (hexadecane, hepadecane, dodecane, octadecane, etc.) that vary in terms of their properties. There are large variations in thermal conductivity with nano ceramic coatings. It is also due to the components of the nano composition of the material, and it is different for different manufacturers, i.e. products. In PCMs, the main constituent material is paraffin, but it has very weak mechanical properties, ie. its compressive strength is 3.2 MPa. PCMs don’t consist only of paraffin, but rather complex structures are formed with different properties that vary. If infiltrated with graphite foam, the compressive strength varies over 6.25 MPa, and if incorporated in concrete or cement mortar, the strength varies from 13.3-30 MPa for mortar and 8.2-30.5 for concrete with optimal strength 20-22MPa (depending on the percentage of PCMs) (Lecompte, 2015). The same applies to aerogel based materials. The optimal values are given in table 2, according to the researched literature.

Table 2. Thermomechanical characteristics of nanomaterials

Thermomechanical features of the nanomaterials	Graphite EPS	VIPs panels	Aerogel materials	Nano ceramic thermal coating	PCMs materials
Density ρ (kg/m³)	15-30	150-300	60-80	500-745 - ρwet 290-410 - ρdry	773-853
specific heat capacity c (kJ/kgK)	1350-1500	800	750-840	1080	1200-1550
Heat conductivity coefficient λ (W/mK)	0.03-0.032	0.005-0.01	0.013-0.021	0.001-0.003; 0.014;	0.39; 0.33; 0.28; 0.26
Water vapor resistance factor μ	20-100	∞	5	2	10-14*
Compressive strength σc (kPa)	60-150	140-250	2-100	/	3,2 -20*
Tensile strength σ_t (kPa)	80-100	60	16-200	200-300	/
Thickness (cm)	2-20	1-5	0,62-8	0,03	0,64
State	solid	solid	solid and liquid	liquid	variations
Method of application	panels	panels	different products	coatings / thin films	incorporated capsules in materials

Based on the data, four criteria have been established by which the most appropriate nanomaterials have been defined to solve the problem of improving the energy efficiency of the analyzed buildings:

1. Criteria for thermal conductivity;
2. Criteria for toxicity and environmental factors;

3. Criteria for thickness and methods of application;
4. Criteria for cultural heritage preservation.

According to the first criteria, nano ceramic coatings, aerogel materials and VIP panels have the lowest thermal conductivity (best thermal properties). According to the toxicity criteria, it is known that polystyrene has negative consequences to the environment (Torgal, 2016), and in some literature some of the PCMs materials contain toxic elements in their composition. According to the thickness criteria, nano ceramic coatings, aerogel materials and VIP panels are also preferred. Although PCMs materials also have very small dimensions and can be incorporated into different materials, they act differently on the energy characteristics of the building. In fact, they are substances that are able to store and release thermal energy, converting it into latent energy. Because the amount of absorbed or released latent energy is much higher than the sensible (comfortable) energy, the use of PMCs has great potential in reducing energy consumption in buildings. However, because each PCMs as its own "phase" of temperature change, which is the temperature at which latent heat is absorbed or released, it is very important to use a suitable PCM for insulating the building envelope (Seong, 2013). This indicates the fact that, according to the fourth criteria, they are more difficult to use PCMs in existing historical buildings, and according to the researched literature, they are not the most adequate materials for use in cultural heritage buildings (Bernardi.2013). There is also a lack of literature on the application of these materials in historic buildings. The criteria of cultural heritage is the most important because of the problem with the preservation of the original appearance of the building when it is isolated from the outside. This criteria completely eliminates graphite polystyrene and VIP panels. Despite the improved thermal properties with the addition of nanomaterials, graphite polystyrene needs a greater thickness (over 5 cm) to be effective enough. Also, If a completely different type of facade material is applied, it will completely destroy the authentic appearance of the building. As for VIP panels, despite the fact that they have a much lower λ and thickness, they have certain disadvantages. With VIP panels, all joints and details should be carefully designed so that during installation, the covering of the panels is not damaged, which, in case of minor damage, lose their thermal properties. This means that architects and contractors should be aware of the special requirements of VIP materials, early in the design process, which make them very difficult to adapt to existing buildings.

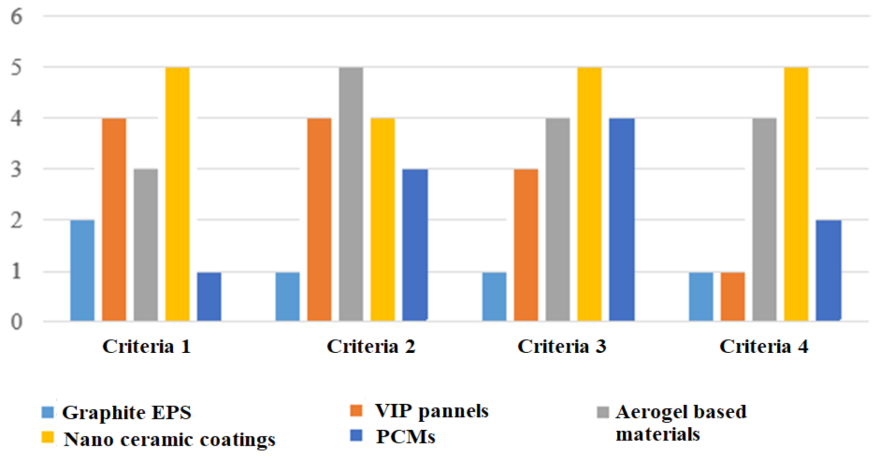

Figure 1. Evaluation of nanomaterials according to their characteristics and set criteria

Each of the nanomaterials is evaluated with a rate from 1-5 in relation to the established criteria, according to the data from the researched literature (shown on the diagrams in Figure 1). Nano ceramic coatings and aerogel materials have the best properties in terms of established criteria. It can be summed up that these materials are the most adequate ones for future in situ applications on existing buildings which require renovations for improving their energy efficiency and in the same time keeping their original architectural look.

Conclusion

This paper focuses on analyzing nanomaterials for buildings' energy performance improvement, especially in cultural heritage buildings, whose original architectural appearance should not be compromised during the renovation process. Firstly, extensive literature related to the general application of nanomaterials in the building sector is reviewed, where the most significant properties in terms of their thermal insulation characteristics are emphasized. Then, based on the obtained data, a comparative analysis of the researched nanomaterials was carried out and several criteria were established for the evaluation and selection of the most appropriated materials for historical buildings' renovation. Finally, conclusions for the selection of nanomaterials with best thermal properties and a minimal impact on the cultural heritage, emerge from the analysis, where it can be concluded that the most appropriate nanomaterials for solving the problem are the aerogel based materials and the nano ceramic coating materials.

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