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A review of the properties of recycled and waste materials for energy refurbishment of existing buildings towards the requirements of NZEB

Alessandro Tallini[a], Luca Cedola[a] *

[a]*Dipartimento di Ingegneria Meccanica e Aerospaziale, "Sapienza" Università degli studi di Roma, Roma, Italia*

Abstract

In Europe buildings account for 40% to 50% of total energy consumption and the largest greenhouse gases emitters and urgent measures and valid instruments are therefore required to improve energy saving, use of renewable sources in moving towards a sustainable materials management where waste becomes a "resource". In this context, there is an increase in research into development and manufacturing of new eco-friendly building envelope components from recycled and waste materials as high value-added good circular economy practice. Waste management may have significant effects in the sector of sustainable building the ultimate objective being the alternative construction materials replacing traditional materials: the development of innovative techniques aims to incorporate wastes into the production of building materials – for examples rubber, fly ash and sludge, etc. – to enhance thermal insulation properties. An effort in the sustainability in building design process is to develop researches aimed at enhancing thermal performance of components using materials capable of reusing a high waste content. The goal of this paper is to examine the technical feasibility of using inert waste materials from the combustion of municipal solid waste or solid recovered fuel and highlight changes in thermal characteristics (thermal conductivity, specific heat and density) by adding recycled and waste materials to the construction materials. The paper explores the potential of the use of thus obtained materials for the energy-refurbishment of existing buildings or with the challenge of meeting stringent energy consumption limits which are typical of a NZEB (net-zero energy building).

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* Corresponding author. Tel.: +39-06-44585734; fax: +39-06-484854.
E-mail address: luca.cedola@uniroma1.it

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1. Introduction

The building sector is responsible for approximately 40% of total energy consumption in some developed countries, with a related emission of 40% of total greenhouse gas emissions (GHG). This sector is a key area for reducting energy consumption and GHG, which carries a high exploitation of resources such as materials, energy and water. Thus, it is essential to adopt more efficient actions during all stages of the construction process, including the use of more sustainable materials. Hence, it is necessary to improve the energy efficiency of buildings and concepts like "passive houses" and "net-zero energy buildings" (NZEB) are being introduced. The reuse of different types of waste in the construction and refurbishment projects of buildings can contribute significantly to sustainability. To meet the demands of improved energy efficiency, the thermal insulation of buildings plays an important role. A proper use of thermal insulation in buildings contribute in reducing the annual energy costs. Thus, the aim of the paper is to carry out a review of state-of-the-art on use of waste materials to enhance thermal performance of building materials. According to a literature review, a good insulation in building could save about 65% in domestic energy consumption [1-4]. Thermal insulation is a material or combination of materials that when properly applied retard the rate of heat flow into or out of a building (by conduction, convection, and radiation) due to its high thermal resistance [5]. Insulating materials are produced in different forms as follows: mineral fiber blankets: batts and rolls (fiberglass and rock wool); loose fill that can be blown-in (fiberglass, rock wool), poured-in, or mixed with concrete (cellulose, perlite, vermiculite); rigid boards (polystyrene, polyurethane, polyisocyanurate, fiberglass); foamed or sprayed in-place (polyurethane, polyisocyanurate); boards or blocks (perlite, vermiculite); insulated concrete blocks; insulated concrete form; reflective materials (aluminium foil, ceramic coatings) [5]. In addition to using the current traditional insulation materials in ever increasing thicknesses in the building envelopes innovative insulation materials and solutions with low thermal conductivity (TC or λ) values have been and are being developed, to achieve the highest possible thermal insulation resistance [6]. However, very thick building envelopes are not desirable due to several reasons. Recent studies point out that energy efficiency measures are the most cost-effective ones, whereas measures like e.g. solar photovoltaics and wind energy are far less cost-effective than insulation retrofit for buildings [6]. TC values of building materials (Table 1) are normally considerably higher than those of the most common thermal building insulation materials as mineral wool (MW), expanded polystyrene (EPS), extruded polystyrene (XPS), cellulose, cork, polyurethane (PUR) and other building materials (Table 2).

Table 1: Thermal conductivity of main building materials

Material	Thermal conductivity (W/mK)
Wood	0.10-0.20
Concrete	0.15-2.50
Lightweight aggregate	0.10-0.70
Brick	0.40-0.80
Glass	0.80
Stone	1-2
Steel	17-55
Aluminium	220

Table 2: Thermal conductivity of common building insulation materials

Material	Thermal conductivity (W/mK)
Stone wool/glass wool	0.033-0.040
Mineral wool	0.030-0.045
Expanded polystyrene (EPS)	0.031-0.037
Extruded polystyrene (XPS)	0.035
Polyurethane (PUR)	0.022-0.040
Polyisocyanurate (PIR)	0.018-0.028
Cellulose	0.037-0.042
Cork	0.037-0.050
Wood fibers	0.038-0.050

State-of-the-art thermal building insulation materials as follows (Table 3): vacuum insulation panels (VIM), gas filled panels (GFP), aerogels and future possibilities like vacuum insulation materials (VIM), nano insulation materials (NIM) and dynamic insulation materials (DIM) [6].

Table 3: State-of-the-art of thermal building insulation: thermal conductivity of advanced materials and systems

Material	Thermal conductivity (W/mK)
Vacuum insulation panels (VIP)	0.0035-0.008
Gas filled panels (GFP)	0.010 (Krypton)-0.035 (Air)
Aerogel (rolls, panels)	0.013-0.015
Aerogel (granular)	0.022
Vacuum insulation materials (VIM)	< 0,004
Gas insulation materials (GIM)	< 0.004 (Argon, Krypton, Xenon)
Nano insulation materials (NIM)	< 0.004 (nano pore 0,1-100 nm)
Dinamic insulation materials (DIM)	controllable within a desiderable range

Currently there exist no single thermal building insulation material or solution capable of fulfilling all the requirements with respect to the most crucial properties: TC, perforation vulnerability, building site adaptability and cuttability, mechanical strength, fire protection, fume emission during fire, robustness, climate ageing durability, resistance towards freezing/thawing cycles, water resistance, costs and environmental impact [6]. Thermal resistance of insulation materials is the most important property that is of interest when considering thermal performance and energy conservation issues [5]. The main factors for choosing insulating materials are: thermal performance (thermal resistance, thermal bridging, thermal storage); costs; ease of construction; safety and health issues; durability; acoustical performance; air tightness; environmental impact; availability [5]. Enhanced thermal insulation materials are the most cost-effective way in the construction and renovation projects with proper energy consumption, satisfactory thermal comfort and low operational costs [7].

2. Addition of waste materials in the production of thermal building insulation

2.1. Concrete

Concrete is a construction material widely used in building and infrastructural applications. However, its widespread use has affected the reduction of natural resources. Hence, many approached have been made by researchers to study the incorporation of waste materials in concrete as a substitution for natural resources besides reducing waste disposal problems. Recently, waste materials also known as by-product aggregate is widely used in concrete production that is blast-furnace slags, fly ash (FA), plastic and many others. It is usually used as lightweight aggregate (LWA, very low densities 0.8÷1.0 $g \cdot cm^{-3}$) by replacing fine aggregate, coarse aggregate or as addition mixture [8]. When mass concrete is used in external walls, thermal insulation is needed. TC of plain concrete is mainly dependent on the moisture content in the pores and on the volume fraction (VF) of the aggregate, as well as on the water cement ratio and the admixture types. TC of concrete can be reduced through the addition of an air-entraining admixture (aerated concrete, AC), or through LWA (lightweight concrete). These LWA can be natural or synthetic or also polymers such as wood-derivatives, expanded polystyrene, rubber, PET, combined or not. Some of these aggregates, as crumb rubber (CR), come from recycling processes. CR also may have a significant effect on concrete mix air entrapment, which also reduces TC of concrete. Researches aim to develop sustainable non-structural concrete with a high amount of recycled rubber [13]. The physico-mechanical properties of concrete are: strengths, permeability, shrinkage, durability, thermal properties, etc. In various thermal properties of concrete TC, which depends upon the composition, is very important in building insulation to measure the ability of a material to transfer heat. TC of concrete depends on several parameters: density, porosity, temperature, amount or volume percentage of materials, type of materials, degree of hydration, water cement ratio, micro-environment relative humidity and mineralogical characteristics of aggregate [8-9]. Several works suggest that TC is directly proportional to the material's density. A comparative analysis allows concluding that the λ-values of concrete mixes with recycled aggregates (RA) increases with increasing density. Many researchers have investigated TC of concrete utilizing waste materials: RA, FA, rubber, expanded perlite, oil palm shell, palm oil fuel ash, recycled glass, plastic waste, sawmill waste, polyamide [8]. Zhu et al. [10] obtained a similar conclusion when evaluating TC of concrete mixes with RA (fine and coarse) justifying the results with the porosity increase stemming from rising RA contents in the concrete mixes. The other parameter that affects TC of concrete is porosity. TC of the concrete mixes with RA from construction and demolition waste (CDW) were also evaluated, and it was concluded that the use of RA causes a decrease of TC coefficients of the concrete mixes. This decrease was quite significant (17%÷42%) when all the natural aggregates (NA) were replaced with fine or coarse RA. The analysis of the thermal behaviour showed that the use of RA improves the thermal performance of the concrete mixes. The extent of this change was shown to be quite variable depending on the origin of RA used [9]. In addition, the choice of the size of the RA used does not seem to significantly influence the quality of the concrete mixes regarding their thermal performance. The replacement of NA with RA reduces the λ-values of the concrete mixes, therefore improving their thermal and energetic performance for use in building applications where insulation is important. That improvement is quite significant in concrete mixes in which 100% of the coarse and fine NA are replaced, reaching decreases in λ of 42% and 23%, respectively significantly depending on the constitution of the RA used. The different types of RA have quite varied compositions, with different contents of concrete, ceramics, glass, wood, among other materials [9].

2.2. Rubber-added bricks

Recent studies of potential use of crumb rubber–concrete combination for producing a low cost and lightweight composite brick with improved thermal resistance are carried out. The physico-mechanical and thermal insulation performances of these rubber-added bricks shown that compressive strength, flexural strength, splitting strength, freezing–thawing resistance, unit weight and water absorption values satisfy with the relevant international standards. Thermal insulation performance is improved by introducing various amount of CR into the ordinary cementitious mixes. The percentage-wise improvements in thermal insulation performance varied nearly between nearly 5÷11%, depending on the amount of CR used. The rubber-added bricks show an environmental-friendly building material feature showing great potential as low cost lightweight building materials, which may offer significant savings. Due to their being thermally conservative, they can be used in forming exterior/interior walls and concrete board substitutes for energy thrifty buildings, and they are also economically alternative to the conventional concrete blocks, ceiling panels, and sound barrier panels [11].

2.3. Lightweight cement composite based rubber waste particles

Test results undertaken to investigate the physico-mechanical properties of aerated cement composite with rubber waste particles to produce usable materials in cellular concrete applications have shown many attractive properties, such as improvement in thermal insulation. The considered shredded rubber waste originates from mechanical shredding of rubber automotive industry waste that comprises rubber particle size <1 mm and contains approximately 20% by volume of polypropylene fibers as well, absolute density of rubber waste particles 430 kg/m^3. This demonstrates the feasibility of using shredded rubber waste as an aggregate in cement composite, to develop usable materials in cellular concrete applications. The idea is to use rubber waste particles, as a raw material, to develop new lightweight cement composite-based rubber waste particles. AC provide a high degree of thermal insulation due to their porous structure. Depending upon their physico-mechanical characteristics, these concretes can be employed as a suitable material for insulated loadbearing walls [12]. The results of experiment by Medina et al. [13] have shown that the larger the amount of rubber used as aggregate in concrete, the lower TC value is achieved. Measurements were carried out in a dry state using a transient plane source (TPS) technique to determine the effect of the rubber particles ratio on TC of a lightweight construction material containing rubber waste particles (10%, 20%, 30%, 40%, 50% rubber particle ratios by volume as replacement to cement). The addition of rubber particles reduces the material unit weight improving TC of the composite. The thermal insulating effect of rubber particles is most attractive and indicates a high and promising potential for development [14].

2.4. Fibers fixed to crumb rubber from tyre recycling

Plastic fibres partially coated with rubber (FCR) consists of fibres partially coated with crumb rubber recovered from the tyre recycling process, during granulation and before the total separation of rubber. An analysis of the mechanical and thermal properties of a sustainable concrete incorporating CR and steel or FCR that is a new type of aggregate was carried out [13]. Concrete with FCR aggregate presents the same or even better mechanical behaviour than conventional rubberized concrete. TC of rubberized concretes is reduced with FCR aggregates. TC of concrete with FCR as aggregate is comparable to TC of concrete with CR, and it is also lower than the reference concrete. Concretes CR and FCR with low TC and light weight can be used in rehabilitation of traditional flat-roofs [13].

2.5. Lightweight aggregate based on fly ash

A study of physico-chemical properties of LWA based on FA obtained in the continuous production line using specific granulation process (extrusion and pelletization), in which LWA pellets were fired at three different temperatures (1,100°C-1,150°C-1,200 °C) and uni-modal particles (d=16 mm) were produced, shows that the obtained value of the TC of LWA fired at 1,150°C (λ=0.0872 W/mK) is suitable to produce structural concrete blocks with improved thermal insulating properties. Because of their high-porosity and compressive strength values, designed LWA could be used instead of the conventional aggregates in the production of concrete blocks [15].

2.6. Plastic waste

Plastic bottles (PET) can be utilized as building units, replacing traditional concrete blocks. Tests were conducted after filling PET bottles with either dry sand, saturated sand, or air, bound by cement mortar to produce stable masonry walls of reduced TC. Thermal wise, air filled bottles showed better thermal insulation than the tradition block construction, which could act as thermal insulation material. Therefore, using plastic bottles as an infill building material, not only relieves the burden of their waste disposal, but is considered an acceptable thermal insulation material, that is structurally stable and achieves environmental awareness [16]. Researches on change in insulation property of the ordinary concrete due to adding polymeric based waste material (waste PET bottle and tyre rubber) are conducted [17]. The results reveal that proper addition of selected waste materials into concrete can significantly reduce heat loss or improve thermal insulation performance. The degree of improvement in thermal insulation is found to vary with the added waste material and geometry of shredded-pieces [17]. The results show that waste PET and rubber pieces remarkably lower thermal transmittance (or improve insulation property) of ordinary concrete. It is found that the insulation performance is improved as much as 18.52% by addition of square rubber matrix into the ordinary concrete. The corresponding percentages for PET bottle pieces vary between 10.27% and 18.16%, depending on the geometries of added pieces. Both waste, PET bottles and tyre rubber, used here abundantly exist in environment and can be obtained with almost no cost. The reuse of these materials in concretes seems to be good choice for contributing to cleaner environment and lower insulation cost [17].

2.7. Textile waste

In the European Union (EU) around 5.8 million tonnes of textiles are discarded by the consumers per year. Only 1.5 million tonnes (25%) of these textiles are recycled whereas the remaining 4.3 million tonnes are landfilled or incinerated. Adding to this type of waste, there is also the textile waste from the textile industry. A recycled textile material was thermophysically characterized in terms of TC and diffusivity. Several researches are being conducted on enhancing TC of textile reinforced composite for insulation applications. Previous work is based on the use of textile waste in the production of bricks and lightweight materials more particularly using cotton combined with other materials, such as limestone powder, FA, barite, and paper, and TC are studied. Studies are developed to investigate the use of woven fabric waste (WFW) and a waste of this residue, named woven fabric subwaste (WFS) (both materials are 100% acrylic), as an alternative solution to commercial insulation materials, such as XPS or EPS products. Experimental work was carried out to examine the thermal insulation benefit resulting from reinforcing thermally external double walls with WFW and WFS in the air-box [18]. The determined heat transmission coefficient (U) values of the double wall with the air box filled with these types of waste are used to calculate the value of TC of WFW and WFS. The obtained results from experimental work have shown that feeling the air-box with WFW and in the external double wall increases its thermal behaviour in 56% and 30%, respectively, when compared to the double wall with the air-box empty. The density of the WFW and the WFS products was specifically quantified and the respective approximate values are 440 kg/m^3 and 122.5 kg/m^3, respectively [18]. The potential of that innovative sustainable solutions for non-structural applications (thermal insulation) using these two types of textile waste as an alternative thermal insulation solution for external double walls is evident in the building industry application context. This result leads to the conclusion that the WFW has better insulation characteristics than the WFS. The λ-values of the WFW is like the values obtain for EPS, XPS and MW. The value of λ obtain for the WFS is approximately equal to the values for granules of clay, vermiculite or expanded perlite. Therefore, applying these wastes as a possible thermal insulation material seems to be an adequate solution [18]. Research results on applicability of a recycled textile material based on acrylic spinning waste (AS), as thermal insulation is conducted show that TC is found to be 38.27 mW/mK. The obtained results show that the AS is a competitive thermal insulation material and can increase the thermal performance of the building walls. Depending on its cost, the developed insulation based on acrylic spinning waste can be a good challenger for building thermal insulation [19]. Studied properties of samples waste linter (WL) and table cloth (WT) produced by shredding and mixing were compared to other usual building insulating materials. Results show that TC of WT and WL were 0.033 W/mK and 0.039 W/mK, respectively. In addition, the thermal diffusivity was found to be about $5.8 \cdot 10^{-3}$ m^2/h in the case of WT and about $3.8 \cdot 10^{-3}$ m^2/h for WL sample. Therefore, the recycled textile materials have competitive thermal properties and could be used in the building insulation materials [20]. Thermal insulation bio-based composite panels from Tetra Pak waste and wool fiber waste with different ratios and other sandwich bio-based composite panels manufactured using Tetra Pak waste as a core material with glass woven fabric and jute wove fabric as skin materials shown a significant improvement on thermal insulation properties that (TC, thermal resistance) of the developed biocomposite panels compared to the control samples made of plain Tetra Pak. Tetra Pak waste/glass fiber showed 8.5% reduction in TC compared to 6.5% reduction when jute fabric used as skin material to Tetra Pak waste composite. All the above results indicate that Tetra Pak waste can be recycled and converted into composite material that can be reused as an insulator material for buildings [21].

2.8. Polyester

Polyester waste is the dominant component of the clothing industry waste stream, yet its recycling in this industry is rarely addressed. One of the main environmental problems in the clothing industry is the production of remnant waste derived from cutting processes. Researchers propose to use polyester cutting waste as an insulation blanket for roofing and buildings' internal walls to reduce environmental pollution. The designed textile structures used waste cuttings from different polyester fabrics without opening the fabric to fibre. Thermal insulation, acoustic insulation, fire resistance and biodegradation of the new insulation structure were investigated and compared to commercial insulation materials. The coefficient of TC ranged between 0.0520 and 0.0603 W/mK. Thermal insulation from polyester fibers and bi-component fibers has comparable characteristic with mineral/rock wool [22].

2.9. Wood waste

Current insulation materials in the construction market, which are predominantly inorganic materials, have a high performance in relation to heat transfer, i.e. high R-values, but environmental impacts in their production processes are significant. The use of bio-based natural fibre materials such as cork, cotton, wood fibre with their lower embodied energy, moisture buffering capacity and improved Indoor Environmental Quality have received increasing focus in both research and application, particularly amongst environmentally-conscious clients and designers. A natural fibre material in the form of wood waste from primary production sources using untreated material is suitability for use as a thermal insulation material, without the addition of any binder, within a timber frame wall construction. TC values of wood waste with different densities, ranged from 0.048 to 0.055 W/mK. These values are slightly higher than commonly used inorganic based insulation materials, although comparable to other natural insulation materials in the market but have the economic advantage of being a low-cost by-product [23].

2.10. Fly ash

FA and waste polystyrene foam are two major killers of the environment. Experimental study on the building materials with FA modified insulation was carried out [24]. Lime and gypsum are used to stimulate the potential activity of FA and cement, thus making up for the loss of the strength of insulation mortar caused by FA and modified EPS. The innovation is in the following aspects: first, based on the mechanism of lime and gypsum to stimulate FA, the optimum blending ratio of FA was obtained; second, the synthesis performance experiment and the EPS modification experiment were carried out. The comprehensive performance of EPS modified mortar was studied under the action of additive. In summary, the durability weather resistance and thermal insulation properties of the new building insulation materials are very good. The utility model belongs to the environmental protection and new energy saving material, and has the advantages of low cost, high efficiency and simple construction. There is a broad potential market for developing the new type products as green products which have high economic, social and ecological effects [24]. It is also possible to increase the thermal efficiency of light-frame residential structures through addition of a fly ash-scrap tire fiber composite (FA-STF) to traditional fiberglass insulation in light-frame wood residential construction (more than 80% of the building stock in North America). FA are produced by coal burning power plants. FA-STF provides a sustainable supplement to traditional insulation that not only increases the efficiency of traditional insulation but can also help significantly reduce environmental issues associated with disposal of these waste products. The use of this recycled-composite material would prove to be an efficient and cost-effective supplement to standard fiberglass insulation in these structures [28].

2.11. Bottom ash

Municipal Solid Waste Incineration (MSWI) is estimated to increase in Europe, where the accessibility of landfill is restricted. Bottom ash (BA) is the most significant by-product from MSWI as it accounts for 85÷95 % of the solid product resulting from combustion. BA is a mixture of calcium-rich compounds and other silicates enriched in iron and sodium. In addition, it is categorized as non-hazardous waste which can be revalorized as secondary material in construction or civil engineering fields, previous weathering stabilization during 2÷3 months. Residual agricultural biomass has attracted attention in preparation of advanced materials for various applications, due to their low cost, abundance, and environment friendliness. Rice husk (RH) is a by-product of rice milling industry which has high content of silica and has been widely used in buildings as natural thermal insulation material. Weathered bottom ash (WBA) with a particle size <30 mm was milled under 100 μm, mixed with 2.0÷5.0 mm RH, formed into ball-shaped pellets and sintered by different thermal treatments, which remove the organic matter content generating a large porosity. It has been formulated a new lightweight material composed by municipal solid waste incineration WBA and RH as biomass. The obtained results of physico-chemical analysis and mechanical behaviour of the manufactured lightweight aggregates provide a suitable physico-mechanical formulation using WBA as silica source, as well as a common crop by-product [25]. New kind of porous thermal insulation materials with low TC can be prepared by foaming and slip casting method, using industrial wastes coal FA as main raw material. TC of the sintered thermal insulation material, measured by the transient plane source (TPS) at room temperature, could reach as low as 0.0511 W/mK. As an environmental friendly material, it is suitable for wall application to save energy showing promise in application of wall insulation materials [26].

2.12. Glass foam

Due to their unique properties, glass foams could have several applications such as acoustic and thermal insulation, catalyst supports, lightweight aggregate materials in concrete (Qu et al. [30]). An innovative powder-foaming process able to produce thermal and acoustic insulating foams obtained by sol-gel and a subsequent freeze-drying process was developed. Foams were also subjected to a thermal process to better fix powders into the final glass structure. SEM analysis pointed out an open cell structure improving thermal insulation properties [27].

2.13. Solid waste

New composite boards with low-TC produced from a mixture of solid wastes from tissue paper manufacturing (TPM, solid waste) and corn peel have been developed. The effects of solid waste TPM/corn peel ratio on the properties of the boards were investigated and the possibility of using recycled polystyrene packaging foam as a laminating agent to improve the quality of the boards was also evaluated. Results show that the density of the particle boards decrease with increasing the amount of corn peel added in the mixture, leading to a decrease in TC of the final product. The mixture of solid waste TPM and corn peel has the potential to be used as new materials to produce of new particle boards with low TC. TC, physical and mechanical properties of the boards depended on board density and solid waste TPM/corn peel ratio [29].

Table 4: Thermal conductivity of waste materials and composite materials for thermal insulation applications

Material	**Thermal conductivity (W/mK)**	**Material**	**Thermal conductivity (W/mK)**
Glass foam	0.045	Linters textile waste (WL)	0.039
Concrete with 100% of CR (as aggregate)	0.27	TetraPack (TP)	0.06 (thickness 5.68 mm)
Concrete with 100% of FCR (as aggregate)	0.34	Recycled cotton	0.036-0.044
Recycled glass fiber	0.031-0.05	Wood waste	0.048-0.055
Recycled PET	0.034-0.039	Lightweight 50% rubber waste particles	0.47
Recycled textile fibers	0.041-0.053	Lightweight WBA+RH	0.05
Wooven fabric waste (WFW)	0.044	Lightweight based on FA	0.087
Woove fabric subwaste (WFS)	0.103	Solid waste TPM/corn peel ratio	0.14 (25:75) - 0.25 (100:0)
Tablecloth textile waste (WT)	0.033	Linters textile waste (WL)	0.039

3. Discussion and conclusive remarks

The main objective is to perform a survey of the state-of-the-art of new thermal building insulation solutions using waste materials and by-products, which support the development of good practice of circular economy. The review considers the use of the main waste materials for the production or research of high thermal performance products and systems. The aim is to incorporate wastes materials – e.g. rubber waste, textile fibers, FA, etc. – into building materials to enhance thermal insulation properties and, therefore, reduce energy consumption of buildings. For the examined materials for non-structural applications (thermal insulation) the addition of waste generally improves thermal performance e.g. in terms of reduction of TC (Table 4) and increase in thermal resistance that is the most important property that is of interest when considering thermal performance and energy conservation issues. The results reveal that proper addition of selected waste materials can significantly reduce heat loss or improve thermal insulation performance. Furthermore, it can also increase the mechanical strength. The results of experimental research confirm the feasibility of using waste materials in the production of high-performance thermal insulation systems and highlight changes in thermal performance. These systems are therefore suitable for the energy retrofit of a building improve energy performance toward NZEB requirements. Studies shown that it is possible to reduce primary energy demand and associated emissions up to 40% from the current values by adopting market-available and well-proven technological solutions for retrofit. Moreover, exploiting on-site renewable energy sources, net energy consumption can be near zero and the thermal insulation of the building is key factor in successful retrofit.

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