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Review

Application of Wall and Insulation Materials on Green Building: A Review

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Abstract: The construction materials utilized in the building sector have accounted for a large amount of natural resource and energy consumption. Green building, which has developed over three decades, can be regarded as a management and technical approach for building and construction sectors to achieve resource and energy sustainability in building sectors. Therefore, the development and deployment of green construction materials play an important role in the green building field due to the contribution of sustainable resources and energy. To realize the barriers of energy and resources utilization on green building, the development trend, application, and some case studies on wall materials and thermal insulation materials are described. A summary of plant fibers, recycled wastes, and photochromic glass is developed to show applications of green construction materials, which contributes to sustainable development. The challenges and barriers from business, technical, and policy aspects are also reviewed. Finally, perspectives and prospects of green construction material life-cycle framework are illustrated. This paper presents a snapshot review of the importance of wall materials and thermal insulation materials from the point of view of energy and resources consumption.

Keywords: green construction material; wall material; thermal insulation material

1. Introduction

The construction industry provides quantities of employment opportunities directly or indirectly and promotes the development of the national economy and urbanization process in a country [1]. Buildings will cause more than 40 billion tons of carbon emissions and consume roughly one-third of the global energy and water every year in the 2030s [2–6]. Therefore, buildings have already had a negligible impact on the environment and resources [5]. However, the construction of buildings and production of materials will lead to 40% of all pollution emissions [5] and around one-third of black carbon emissions [6].

The numbers of commercial and institutional buildings in 2050 will be three times that of 2010 [7]. The building sector accounts for 65% and 42% of energy consumption in the United State (US) and European Union (EU) [8], respectively. In addition, according to the Environmental Information Administration, 2008, carbon dioxide (CO_2) emissions from the building sector accounted for roughly 35% to 40% of total GHGs emissions, both in the US and EU [8]. The building sector consists of not only a multitude of products, but also technical and biological nutrients, which have an important and extensive impact on water and energy cycles, air quality (indoor and outdoor), and fauna and flora, as well as on social and economic factors. The increase in construction resources may lead to pollution and emissions, and emphasize the need for energy and resource conservation to achieve sustainable development [9]. With the impact of building activities on the environment becoming more and more obvious, the action of green building is more and more frequently implemented [10,11]. Green building saves resources to the maximum extent, including energy saving, land saving, water saving, and material saving, so as to protect the environment and reduce pollution in the whole life cycle of the building [1,12]. In addition, green building is also used in terms of sustainable building and high-performance building in some fields [2,13].

After the emergence of green buildings, many countries all over the world have set up relevant certification standards in order to better standardize the development of green building and better improve the living environment of human beings. According to evaluation systems, green buildings are designed with the new characteristics of green energy saving. These evaluation standards also promote the development of recyclable materials and indoor-air-improvement materials [14]. Thus, green construction materials should produce minimal emissions and waste, consume less energy, and be beneficial to humans while maintaining high quality [15–19].

In the building, construction materials are the most important part and directly exposed to people. The source and quality of the construction material will influence the indoor environment and also the cost of a building [20]. The use of green construction material is an innovative solution for energy and resource saving during construction progress [21]. Wall materials and thermal insulation materials are the main components of the building and cost a large number of resources [1]. Most of the research aimed at green buildings, but is less concerned with green construction materials. The use of green construction materials involves all aspects of the building, but the previous researches mainly include waterproof seal materials and decorative materials. Wall materials and thermal insulation materials are important construction materials in a building, but they are rarely reviewed by scholars.

In this article, wall materials are reviewed from two aspects of cement reinforcement and recycled waste construction materials. Different plant fibers are introduced and their mechanical properties and construction waste are reviewed with different recycling ratios. Insulation materials are divided into natural insulation materials and photochromic glass, which are innovative technologies in the construction field. The article integrates information in terms of material properties and conditions of use, and furthermore, perspective and prospects are summarized and discussed.

2. Development of Green Building and Origin of Green Construction Materials

An analysis of the search results on Web of Science was carried out on 7th July 2018, using the word "green construction material". The database listed 3555 records (mainly articles, meetings, and reviews) from 1904 to 2017. 3536 of the records distributed from 1981 to 2017 were chosen to be studied. As shown in Figure 1, the researches related to "green construction material" increased quickly after 2000, especially for 2009 and 2016. More than 200 relevant papers were published every year after 2000. English, Chinese, and Korean are the three main languages of the publications.

The top 20 journals with most publications are listed in Table 1. Advanced Materials Research, Applied Mechanics and Materials, and Construction and Building Materials are the top three journals with more than 100 records for each.

The embryonic form of green buildings can be traced back to the 19th century, as shown in Figure 1, the architects completed constructions containing the idea of green. The concept of "ecological architecture" was developed in 1969 by Paolo Saleri who is an American architect from Italy. Meanwhile, the book "Design with Nature" in 1969 was written by Ian L. McHarg who is regarded as a pioneer of ecological architecture and the green building concept. The oil crisis in the 1970s pushed people to face the threat of the largest natural resources consumption from construction industries. That made people consider putting forward sustainable development in construction industries. Habitat I was concluded at the seminar on human settlements held by UN in Vancouver in 1976. In the 1980s, as the energy-saving building system gradually improved, the indoor environment problems of buildings were prominent, and the research on building health environment has become a new hot spot of the architectural field in developed countries.

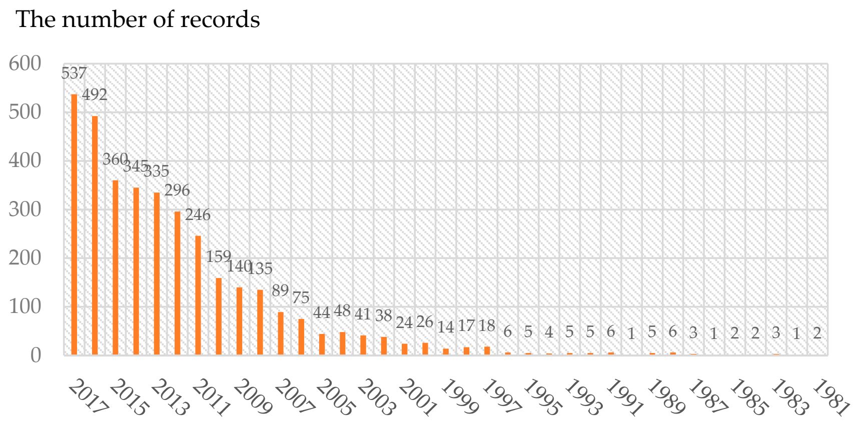

Figure 1. Total number of papers published from 1981 to 2017.

Table 1. Top 20 publishing sources for relevant papers.

NO.	Source Publication	Records	Percentage
1	Advanced Materials Research	141	3.966
2	Applied Mechanics and Materials	114	3.207
3	Construction and Building Materials	104	2.925
4	Journal of Cleaner Production	80	2.25
5	Energy and Buildings	62	1.744
6	Procedia Engineering	52	1.463
7	Journal of Green Building	32	0.9
8	Matec Web of Conferences	31	0.872
9	Energy Procedia	30	0.844
10	Journal of Materials in Civil Engineering	29	0.816
11	IOP Conference Series Materials Science and Engineering	26	0.731
12	Journal of Clinical Rehabilitative Tissue Engineering Research	25	0.703
13	Key Engineering Materials	24	0.675
14	Renewable Sustainable Energy Reviews	24	0.675
15	International Multidisciplinary Scientific Geoconference SGEM	22	0.619
16	Sustainability	19	0.534
17	AIP Conference Proceedings	18	0.506
18	Building and Environment	18	0.506
19	Frontiers of Green Building Materials and Civil Engineering pts 1 8	18	0.506
20	Environmental Science Technology	17	0.478

Green building refers to both a structure and the application of processes that are environmentally responsible and resource-efficient throughout a building's life-cycle: from planning to design, construction, operation, maintenance, renovation, and demolition [22,23]. The architects proposed the 3R (Reduce, Recycle, Reuse) principle: to reduce the use of non-renewable energy and resources to save energy or reduce the impact on the environment, to reuse building components or building products as far as possible, and to strengthen the restoration of old buildings and to reuse some of the components. Green building research has become significant to take into account for environment and comfort.

Many countries have implemented practices and promotion of green building, which plays an important role in architectural development.

On the other hand, the Kyoto Protocol was proposed in 1997 and initiated from 16th February 2005. That was the first time in human history greenhouse gases (GHGs) emissions were regulated. The protocol proposed methods to control anthropogenic GHGs emissions from global industrialized countries from the aspects of raw material development, manufacturing, and energy consumption. GHGs emissions had been expected to decrease by 5.2% from those in 1990 from 2008 to 2012.

To reduce GHGs emissions globally, the contribution of COP 15 held at Copenhagen, Denmark in December 2009 was encouraging the developed countries to provide financial support to developing countries and formulate policies. The Copenhagen agreement came into force on 1 January 2010.

In order to make the concept of green buildings practical and operable, developed countries established the green building rating systems which can adapt various characteristics around the world from 1990 to 2005 (As shown in Figure 2). The rating systems can quantitatively describe energy-saving and water-saving efficiency, environmental impact on GHGs emissions reduction, environmental performance evaluation of 3R materials and economic benefits, and provide a decision-making basis for policymakers and designers.

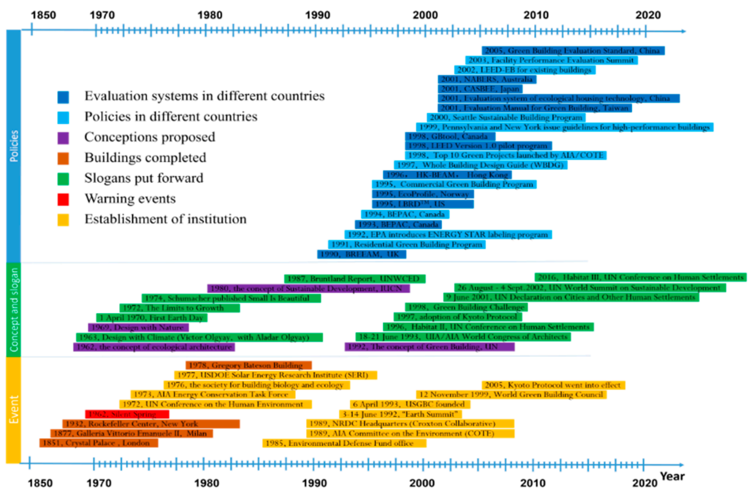

Figure 2. Development of green building [9,20,24–62].

As shown in Table 2, furniture, carpet, coating, adhesive, and floor are included in most of the evaluation systems, while the items that need to be paid more attention are filling material, surface material, wallboard material, equipment, textile, hard pavement, doors, windows, insulation material, sound-absorbing material, ceiling, caulking agent, concrete, and ceramic.

The controversy over the environmental impacts of building materials is inevitable, but it could guide sustainability standards in order to reduce the overall impact [63]. The most general criteria for evaluating building materials includes resources management, pollution, or indoor environmental quality, and comfort performance [64]. Khoshnava modified Lynn Froeschle's suggested model considering resource efficiency, indoor air quality, energy efficiency, water conservation, and affordability [65]. At present, there are LEED (Leadership in Energy and Environmental Design, US), CASBEE (the Comprehensive Assessment System for Building Environmental Efficiency, Japan), BREEAM (Building Research Establishment Environmental Assessment Method, UK), LNB (Germany), NABERS (Australia), EcoProfile (Norway), and ESCALE (France) all over the world. The use of materials is based on sustainability criteria and can directly reduce the environmental loads from construction materials [66]. Meanwhile, the selected material with lower embodied energy, waste production, energy consumption, and pollution discharged will also affect economic and social dimensions for sustainability [67,68]. Therefore, the utilization of green construction materials is regarded as a potential pathway to minimize both environmental impacts [69,70].

Table 2. Evaluation items of green construction material labels in different countries [42,44,45,47–49,51–57].

Country	Label	FU	CA	CO	AD	FL	FM	SM	WM	EQ	TE	HP	DW	IM	SA	CE	CA	CC
Germany	Der Blaue Ebgel	√	√	√	√													
	GUT		√															
	Gev-Emicode Plus				√	√	√	√										
Finland	M1 Finish Label		√		√	√			√	√								
France	Émissions Dans l'Air Intérieur		√		√	√			√									
Danemark	The Indoor Climate Label	√	√	√		√												
EU	EU-Flower	√		√							√	√						
America	Green Seal			√	√	√							√					
	Green Guard	√		√		√					√			√	√	√		
	Floor Score		√			√												
Canada	EcoLogo	√	√	√	√	√								√	√			
Japan	Eco-Mark	√		√														
South Korea	Korea Eco-Label			√		√								√	√			
	Healthy Building Material			√	√	√			√								√	
China	China Environmental Labelling	√		√	√	√					√		√					
Singapore	Green Label		√	√	√	√											√	√
	Singapore Green Building Product	√		√	√					√								
Thailand	Green Label		√	√		√												√

FU: Furniture; CA: Carpet; CO: Coating; AD: Adhesive; FL: Floor; FM: Filling material; SM: Surface material; WM: Wallboard material; EQ: Equipment; TE: Textile; HP: Hard pavement; DW: Doors and windows; IM: Insulation material; SA: Sound-absorbing material; CE: Ceiling; CA: Caulking agent; CC: Concrete and ceramic.

3. An Overview of Wall and Insulation Materials on Green Building

Green construction material is a kind of building material which needs to meet the following points: the use of clean production technology; no or less use of natural resources and energy; a large amount of use of industrial, agricultural, or municipal solid waste production with the features of free-pollution, recyclability, environmental protection, and human health. In this review, wall materials and thermal insulation materials are discussed. The wall materials refer to cement reinforcement materials and solid waste materials.

3.1. Wall Materials

Walls are the main structure of a building and bear the weight, but walls also act as some sound insulation and heat insulation. Wall materials lead to a huge cost during the construction of the whole building, but will save a lot in a green way. In this part, wall materials for weight bearing function are introduced in two aspects: green materials for cement reinforcement and recycled waste construction materials.

3.1.1. Natural Fibers for Concrete Reinforcement

Concrete is a general term for engineering composite materials cemented by cementitious materials. Generally speaking, concrete is obtained by cementing material (cement), aggregates (sand, stone), and water under stirring conditions. As an important engineering material, cement concrete has many advantages, such as low cost, high compressive strength, good plasticity, durability, and so on. At the same time, the production and use of concrete consume a large number of mineral resources, which has brought serious side effects to the living environment of human beings. Concrete materials have brought a severe test to sustainable development. The use of mineral admixtures has been very popular at home and abroad. Grinding slag, fly ash, silica fume, and recycled aggregates are mixed into concrete to replace part of cement, which could decrease the pollution of the environment. At present, there are many investigations and studies on plant fibers used as cement reinforcement materials in the world [71].

Brazilian curauá fiber was made into strain-hardening cementitious composites that promote distributed microcracking and strain-hardening behavior [71]. The satisfactory performance of piassava fibers with good mechanical properties (Table 3) proved their potential use in WPC (Wood plastic composite) [60]. Water-retted kenaf fibers were used as reinforcement in mortar composites [72].

Table 3 shows the mechanical properties of some cement reinforcement materials. Natural fibers have a similar specific modulus but a higher specific strength than glass fiber [46]. The density of these plant fibers distributes from 1.3 g/cm^3 to 1.6 g/cm^3, while the tensile strength and Young's modulus vary among different fibers. Plant fiber wall material has less thermal conductivity than other materials and has a good thermal insulation effect. Shrinkage is a major characteristic of concrete and has a great influence on the performance of concrete. As a reinforcing material of concrete, plant fiber can inhibit the development of concrete cracks, and its crack width is 1/3 narrower than that of ordinary concrete. There are different degrees of micro-cracks in the concrete, which has a great influence on the splitting tensile strength and flexural strength of concrete. When the plant fibers are evenly added to the concrete, the existence of fibers will reduce the development of micro-cracks and improve the internal defects of concrete. When the concrete receives an external force, the plant fiber and the matrix work together to improve the tensile strength, bending strength, and fatigue strength of the concrete. When the concrete is solidified, the fiber wrapped in the cement becomes a dense and disorderly distributed network reinforcement system, which enhances the toughness and overall strength of the concrete. Under the action of load, the fiber across the cracks can bear a certain pressure, thus enhancing the ultimate strain capacity of the concrete. When the concrete is impacted, the fiber absorbs a lot of energy, thus effectively reducing the effect of the concentrated stress, effectively preventing the extension of the cracks, and thus enhancing the impact resistance of the concrete.

There are also several problems to be solved. At present, the research into plant fiber mainly focuses on its mechanical and physical properties, but the corrosion problem of plant fibers in a cement alkaline environment cannot be ignored. At present, the study of corrosion is simply to process fibers before adding fibers. Soaking in acid solution, replacing part of cement with fly ash or silica fume are two commonly used methods. There is a problem of expansion when wet and shrinkage when dry for plant fibers, which will affect the degree of bond between fiber and concrete. Better bonding materials need to be found to make fibers with better function. Plant fiber easily absorbs water in the process of concrete mixing. How to distribute fibers uniformly in concrete is another problem.

Although there are still some problems in plant fiber concrete, plant fiber concrete has been applied to some projects and achieved good results. It can be popularized and applied in a wide range of fields. Plant fiber as a reinforced concrete substrate has broad prospects.

3.1.2. Recycled Waste Construction Materials

As far as building materials are used in the construction process, traditional materials are mainly composed of sand, burnt products, wood, and concrete. Therefore, in the process of building construction or building demolition, much waste of bricks, wood, and concrete is often produced. If these traditional building materials could be used again effectively, we can effectively reduce the construction site garbage and reduce the pollution of the environment.

In order to realize the recycling of traditional building materials, the builders can collect burnt products in the process of disassembling the building, and then apply the collected materials to the outside wall of the building so that the recycling and reuse of the old materials can be effectively realized. In addition, a constructor can also recycle wood materials during construction, which can be used for making furniture or for building decoration.

The surplus earth and stone of construction, industrial sludge, reservoir sludge, and harmless inorganic waste (Material A) are the most common waste materials for buildings. For the use of green materials, they could be recycled in different ways (Table 4) and the utilization ratio of recycled materials ranges from 15% to 90%. The recycled ratio in wooden recycled materials is roughly 90% (including particle boards, medium density fiberboard and wooden furniture) and 15~80% in other recycled materials (mainly stone materials).

Recycled wood is one of the recycled materials with great potential for recycling. Wood plays a very important role in the construction of urban infrastructure, family, and enterprise, such as boards, wooden doors and windows, building components, chair stools, floors, shelves, and so on.

At present, there are mainly four ways to deal with waste wood:

1. Wood-based panel processing. The artificial wood board made from building waste wood can have good economic benefits. The processing of 1 m^3 man-made boards requires roughly 4 m^3 of waste wood and 1.8 m^3 of logs. Therefore, the processing of plywood, particleboard, MDF (Medium Density Fiberboard), and other wood-based panels can save a lot of timber supply.
2. Carpenter board manufacturing. Carpenter boards, such as big core boards, can be used as building decoration materials and can be manufactured by using waste wood in simpler procedures. In the United States, the research in this area is very thorough, and they can maintain the edge angle of the fine wood by using waste wood in the condition of the strength of the original wood. The obtained wood edge has high compressive strength, is not easy to crack, and has a low manufacturing cost.
3. Composite material processing. The wood glue composite material can be produced by the combination of building waste wood and rubber. The wood glue composite material is high in strength and good in economic benefit. It can replace traditional packing and paving material to a certain extent. It is widely used in door and window frames, floors, auto parts, and traffic guardrails.
4. Transformation of combustible materials. The waste wood is transformed into a combustible material (Wood charcoal, wood vinegar, and wood gas) through heat equipment (Earth kiln, mechanical furnace, and continuous retort). Charcoal, wood vinegar, and wood gas can be obtained from waste wood. At present, technology to turn waste wood into ethanol has been applied in Japan.

Table 3. Properties of green materials for cement reinforcement.

	Density (g/cm^3)	Tensile Strength (MPa)	Young's Modulus (GPa)	Pectin (wt.%)	Moisture Content (wt.%)	Waxes (%)	Micro-Fibrillar Angle (°)	Lignin (w %)	Hemi Cellulose (%)	Cellulose (%)	Reference
Kenaf	1.4	1019 ± 188	30.8 ± 5.13	3~5	NA	NA	NA	8~13	21.5	45~57	[46,72,73]
Curauá	1.42 ± 0.047	620 ± 132	41.7 ± 9.9	NA	NA	NA	NA	13.0 ± 0.18	10.0 ± 0.12	69.0 ± 0.39	[71]
Piassava	1.57 ± 0.05	61 ± 18	1.82 ± 0.46	NA	NA	NA	NA	50.05 ± 0.51	8.34 ± 0.27	43.23 ± 0.18	[71]
Coir	1.15	83 ± 22	3.5 ± 1.5	3~4	8	NA	30~49	35.36~45.00	0.15~12.99	32.00~45.46	[46,71]
Sisal	1.42 ± 0.001	344 ± 94	7.9 ± 2.8	10	10~22	2	10~22	10~14	10.00~20.72	61~78	[71]
Flax	1.4~1.5	850~1500	27.6	2.3	8~12	1.7	5~10	2.2	18.6~20.6	71	[46,74]
Hemp	1.48	52	70	0.9	6.2~12	0.8	2~6.2	3.7~5.7	17.9~22.4	70~74	[46,75–78]
Jute	1.3~1.45	51	13~26.5	0.2	12.5~13.7	0.5	8	12~13	13.6~20.4	61~71.5	[46,79,80]
Ramie	1.50	400~938	61.4~128	1.9	7.5~17	0.3	7.5	0.6~0.7	13.1~16.7	68.6~76.2	[46]
Nettle	NA	NA	38	NA	11~17	NA	NA	NA	NA	86	[46]
Henequen	NA	NA	NA	NA	NA	NA	NA	13.1	4~8	77.6	[46]
PALF	NA	413~1627	34.5~82.5	NA	11.8	NA	14	5~12.7	NA	70~82	[46]
Abaca	NA	430~760	NA	1	5~10	NA	NA	12~131	NA	56~63	[46]
Oil palm EFB	NA	248	3.2	NA	NA	NA	42	19	NA	65	[46]
Oil palm mesocarp	NA	NA	0.5	NA	NA	NA	46	11	NA	60	[46]
Cotton	1.5~1.6	NA	5.5~12.6	0~1	7.85~8.5	0.6	NA	NA	5.7	85~90	[46]

NA: Not Available.

Table 4. Utilization ratio of recycled green construction materials.

Green Construction Materials	Recycled Material Available	Utilization Ratio of Recycled Materials	Reference
Particle boards	Waste wood or wood waste from wood plant waste	More than 90%	[81]
Medium density fiber (MDF) board	Waste wood or wood waste from wood plant waste	More than 90%	[61]
Wooden furniture	Recycled particle boards, recycled MDF, or recycled materials from waste furniture, desks and chairs	More than 90% of the wooden parts	[82]
Concrete aggregates	**(Material A)**	More than 80% of fine aggregates More than 50% of the coarse aggregates	[55,83]
Ceramic tile	**(Material A)**	15~25%	[84]
Gypsum board	Gypsum recovered after use, harmless gypsum in plant process	More than 50%	[85]
Common bricks	**(Material A)**	More than 40%	[54,86]
Hollow concrete blocks	**(Material A)**	20~50% (except for cement)	[55,87]
Compressed concrete paving units	**(Material A)**	20~50% (except for cement)	[52,55]
Regenerated fiber cement boards	Waste concrete materials, harmless inorganic waste, waste ceramics, glass and stone	50% (except for cement)	[88]
Lightweight concrete panels	**(Material A)**	More than 50%	[82]
Blended hydraulic cement	Waste blast furnace slag, blast furnace dust, fly ash	More than 40%	[52]
Granulated aggregate for decoration	Recycled glass, ceramic pellets	More than 70%	[89]
Permeable concrete paving blocks	**(Material A)**	More than 50%	[8]
Rubber paving block	Reclaim rubber and all kinds of macromolecule material	More than 80%	[90]
Synthetic stone	**(Material A)**	More than 60%	[8]
Concrete tile	Coal ash, furnace dust, recycled aggregate and so on	More than 25%	[55,91]
Green concrete	**(Material A)**	20~50%	[92]
Autoclaved lightweight aerated concrete blocks	**(Material A)**	More than 60%	[93]
Terrazzo blocks and terrazzo tiles	**(Material A)**	More than 50%	[91]
Wood-plastic recycled composite	Recycled plastic and wood materials	More than 50%	[82,94,95]
Plastic floor	Recycled plastic materials	More than 30%	[82]

Material A: The surplus earth and stone of construction, industrial sludge, reservoir sludge, harmless inorganic waste, such as waste ceramics, waste glass, furnace powder, fly ash, stone waste, and so on.

Glass tiles can be fired at high temperatures of 1100 degrees, with waste glass, ceramic waste, and clay as the main raw materials. Waste glass can reduce the firing temperature by creating glass phases inside the tiles. This kind of glass fired brick has been widely used and paved on urban roads, which can prevent rainwater collection and beautify the environment and make waste change into treasure.

3.2. Thermal Insulation Materials

In a building, the thermal insulation part is of vital importance for cold and heat resistance. Thermal insulation distributes widely in a building, and thousands of materials could be used for the insulation function. In this part, natural insulation materials and photochromic glass are specially reviewed because of their great potential for sustainability.

3.2.1. Natural Insulation Materials

General building insulation materials come from petrochemical products. The production process of these materials will cause pollution to the environment. There are also many problems in the recovery and reuse of industrial materials. Although some of the industrial materials have good performances—these include foamed polystyrene board (EPS), extruded polystyrene board (XPS), rock wool board, glass wool board, and other materials—natural insulation materials show a better prospect.

The materials of the building's insulation and reinforcement structures could be replaced by locally available fiber and other agricultural waste composites [96]. There are various situations in which cork was used for insulation, abrasion resistance, and durability as a raw material for sustainable construction. As shown in Figure 3, paddy straw, coconut pitch, maize husk, and groundnut shell have the lowest thermal conductivity among most natural insulation materials and lower than foamed polyurethane (0.024 W/(m·K)). Fibers of pineapple and pineapple leaves have a lower thermal conductivity than foamed glass insulation board (0.045 W/(m·K)). Twenty natural materials have lower thermal conductivity than the phase change material (PCM) (0.080 W/(m·K)). Most of the natural materials (except for durian, sansevieria fiber, corn peel, and rice hulls) have a lower thermal conductivity than foamed ceramic plate (0.1 W/(m·K)). As shown in Figure 4, hemp, flax, and jute have the lowest density of less than 50 kg/m^3. Sansevieria fiber and banana bunch have a density of greater than 1000 kg/m^3. The density of most natural materials is lower than that of cement (1200~1300 kg/m^3). Natural bark panels were found to have low formaldehyde emissions and appropriate thermal conductivity as thermal insulation materials instead of being burnt [97,98]. Coconut husk and bagasse could be made into low-density thermal insulation boards without the use of chemical adhesives [33]. Cotton stalk fiberboard can be used as wall and ceiling materials with little use of binder and energy [99]. Insulation materials based on natural fibers, especially hemp, flax, and jute, can be applied to the construction of external plant walls and roofs [100]. Date palm wood manufacture of thermal insulation for buildings [101], corn cob particleboard [102], oil palm, coconut, and sugarcane fiber [103] showed acceptable properties for building insulation structure.

Particleboards manufactured with tropical fruit peels [104] could be utilized for specific applications as in insulating ceiling and walls. Durian peels and coconut coir fibers acted as a component of construction panels with low thermal conductivity [104]. Rice hulls, crushed pecan shells, and pineapple leaves were found to have extreme potential for use as thermal insulation [105,106].

3.2.2. Electrochromic and Thermochromic Glass

The smart windows were originally proposed by the Swedish Grangrist. It is a light adjusting intelligent device composed of glass or other transparent materials such as substrate and dimming material. Under certain physical conditions (such as light, electric field, temperature), the device changes its color state by coloring or fading reaction. Therefore, it can selectively absorb or reflect the heat radiation of the outside world and prevent the internal heat diffusion, so as to achieve the purpose of energy saving by adjusting the light intensity and indoor temperature.

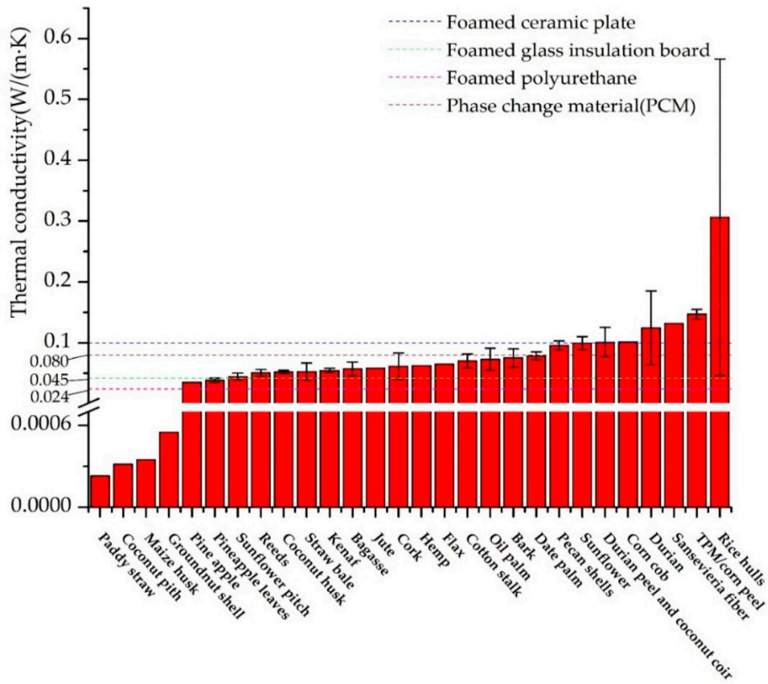

Figure 3. Thermal conductivity of different ecological materials [29,49,88,97,99–104,106–118].

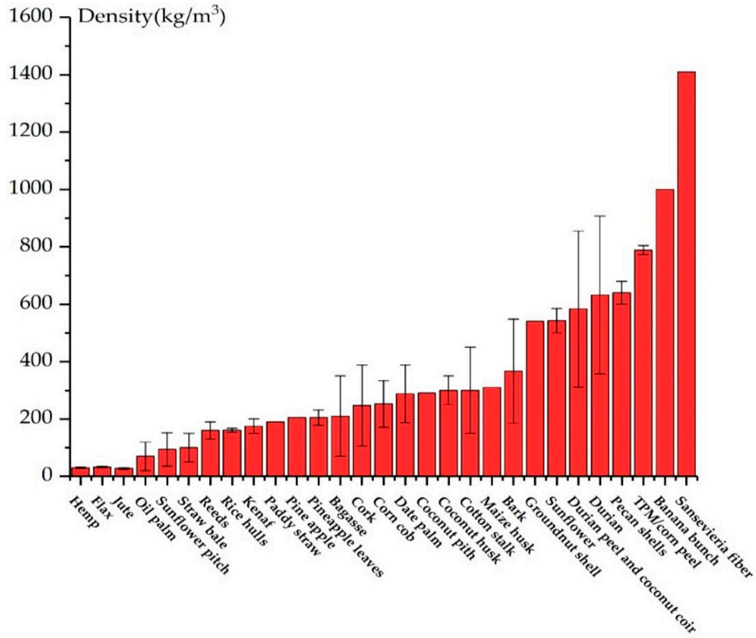

Figure 4. Density of different natural insulation materials [44,64,73,88,98,100,106,109,119–122].

As shown in Table 5, and according to the different excitation methods, it can be divided into electrochromism, thermochromism, photochromism, and gas chromism, of which electrochromism has a broad market prospect. For the inorganic-based window solutions, the functional materials in the smart window are generally VO_2, WO_3, and TiO_2. Besides, water with dye and aerogel could be applied into smart windows as well. The NIR (Near Infrared) reflectance of inorganic material based windows is roughly 20%, and the maximum reflectance can reach 80%. The main materials of the organic windows are dye and the liquid crystal, as shown in Table 5, and the NIR reflectance could reach 45%.

The advantage of an electrochromic window is that it usually requires only a low conversion voltage (0 V~10 V, AC), which can be kept transparent throughout the conversion range and can be adjusted to any intermediate state between transparent and complete coloring. This device, consisting of a basic glass and electrochromic system, takes advantage of the tunability of the transmittance (or absorption) of the electrochromic material under the action of an electric field. It can realize the purpose of adjusting the illumination according to a person's wishes. At the same time, the electrochromic system selectively absorbs or reflects the external heat radiation and prevents internal heat loss. Diffusion can reduce the amount of energy that buildings need to consume in the summer to keep cool and warm in winter. At present, most of the glass materials with this function are liquid crystals and electrochromic materials.

Like electrochromic glass, photochromic glass can be divided into two categories: organic and inorganic according to the different materials used. For electrochromic materials, there are some development directions. Conductors with electrochemically stability and stretch-ability still need to be studied. In the energy storage smart window, the trade-off between large optical modulation and high charge density needs to be solved carefully. Electrolyte systems that require strong cycling and fast switching of windows are also needed.

The inorganic photochromic glass is composed of optically sensitive material and matrix glass, and it is added to matrix glass with a small amount of sensitive material. After heat treatment, it is precipitated as a photosensitizer in the glass melt. The optical sensitive materials are mainly silver, copper, and cadmium halide or rare earth ions. The base glass is generally considered to use alkali metal borosilicate glass as the substrate, and the photochromic properties are the best.

Inorganic photochromic materials are more widely used in some fields than organic photochromic materials because of their high thermal stability, long duration of discoloration, and strong oxidation resistance.

Thermochromic glass can change the transparency according to the temperature. The thermochromic glass is coated with a thermochromic material on the glass, which can adjust the transmittance of glass with the change of ambient temperature. Thermochromic materials usually have a phase transition temperature. The material exhibits different optical properties above or below the phase transition temperature. In order to use thermochromic materials for building energy efficiency, the phase change temperature should be around the room temperature (around 28 T). Although there are many kinds of thermochromic materials, there is little room to choose.

Reversible thermochromic materials can be divided into three categories: inorganic materials, liquid crystals, and organic materials. Thermochromic materials usually have a phase transition temperature. The material exhibits different optical properties above or below the phase transition temperature. This kind of window is suitable for blocking the solar radiation when the air conditioning load is too high to block the heat transfer. It is very practical in the control of the passive solar heating device. The temperature of the glass is a function of solar radiation intensity and indoor and outdoor temperature. Thermochromism can adjust the total solar energy into human thermal storage equipment. Because its opaque state can affect the field of view, thermochromism is especially suitable for skylights.

Because of the long time and mature technology of electrochromic materials, the developed areas such as Europe and America have invested a lot to study and develop electrochromic glass and put it into the market. Thus it has been widely used and some products have been commercialized.

Because of the unique characteristics of photochromic materials, thermochromism materials, and gas chromism materials, they can be applied in many fields, but the development and application of these discoloration materials are still in the primary stage.

Table 5. Properties of smart window materials.

Classification	Materials	Function Chemicals	Effect of Light Adjustment	Advantages	Limitations	Reference
Inorganic materials based window	Metallic based reflective layers	Randomly dispersed silver nanodisks	20~80% (thickness: 2.5~20%) of NIR Reflectance	Ultra-thin and flexible	Low visible light scattering	[123]
	Photocatalytic material	F-TiO_2-KxWO_3 nanocomposites coatings	20~50% of NIR reflectance	Low-cost and eco-friendly; Property of outstanding NIR, UV light shielding performance; Degradation of harmful organic pollutants Excellent hydrophilic capacity; Excellent stability;		[124]
	Electrochromic	A porous tungsten oxide (WO_3)	19~21% of NIR reflectance	• Dynamically adjustment; • Daytime privacy protection; • Energy storage;	• Electrochemically stable and reliable conductors; • Suitable electrolyte systems;	[125]
	Thermochromic	Vanadium dioxide (VO_2)		Total energy needs decrease by 25% in hot climates.	In cold climates, the savings are below 10%	[126]
	Plasmonic nanoparticles	Mg_4Ni alloy and Pd thin films		It reduces the required cooling power by more than 30%.	The cost to implement this technology has been prohibitive	[127]
	Aerogels glazing	Monolithic silica aerogel	20~24% (solar energy and daylight); The thermal conductivity of 0.010~0.017 W/(m K);	High solar energy transmittance and good optical quality.		[128]
	Trapped gas in fluid membranes	Glycerin, colored water and metallic dye	A reduction in total annual energy consumption of approximately 140 kW h/m^2 per year in comparisonwith the single and double glazing windows	• Utilizing low-cost materials and simple system; • No electricity supply for both switching and maintaining the particular shade; • Low installation cost;	The opacity level and the color of the liquid cannot be manually controlled.	[129]
Organic materials based window	Transparent luminescent solar concentrator (LSC)	NIR fluorescent dyes (especially phthalocyanines, cyanines, and squaraine dyes)	Transparent power conversion efficiencies >0.4%.	Theoretically, about 75~80% of the luminescence could be trapped.		[130]
	Cholesteric liquid crystalline (Ch-LC) material	Nematic liquid crystals; chiral molecules	Rejection of 8 to 45% of the total incident infrared energy	More than 12% of the total energy saved compared to a standard double glazing window	Inherent narrowband nature and limited impact on indoor temperature	[130]

4. Perspectives and Prospects

4.1. To overcome the Challenges and Barriers

For wall materials and thermal insulation materials, there are still some challenges and barriers to overcome. Barriers can be classified as business related, technology related, and legal policy related, as illustrated in Table 6. For the business-related barriers, a major obstacle is the lack of public awareness and acceptance, and also the lack of full understanding of the designer of the green building, which will affect market demand. Green building may lead investors interested in wall and insulation material technology to investment risk and uncertain factors. Because the new technology of the green materials often involves the application, which may have a higher technical cost and income uncertainty. Despite policy support, unready photochromic glass technology will lead to consumer distrust. For the use of plant fibers in wall materials and cement reinforcement, more active laws and regulations are needed.

Table 6. Challenges and barriers for the development of green construction material.

Items	Challenges and Barriers
Business-related barriers	• The innovative technology products are more expensive • The market demand for the products is not high • The choice of building materials is usually decided by price rather than environmental benefits • The popularity of smart windows is still low because of the nature of windows products and consumers' consumption habits • There is no good connectivity between different products
Technology related barriers	• The instability of source and quality of raw materials • The innovation of technology is not perfect • The lack of complete information disclosure on technology innovation
Legal policy-related barriers	• The lack of implementation of education to promote innovative technology or advocacy work • The limitations of the statute for innovative technology application • Not in accordance with the construction or building regulations • The lack of incentives for innovative technology supplier

4.2. Establishment of Green Construction Materials Life-Cycle Framework

In the development process of wall materials and thermal insulation materials, the main aim is saving resources and minimizing the use of existing energy and resources. At the same time, researchers should look for industrial solid wastes that can meet the actual needs instead of the existing resources and energy resources or treat the domestic garbage and construction waste through technical measures to meet the needs (as shown in Figure 5). According to the essential requirements of green building materials, energy conservation should be embodied in the whole process of production, use and waste disposal of green building materials. Accordingly, we must constantly optimize the manufacturing process of materials and reduce the energy consumption of materials in the production process. Besides, the cost of building materials should also be reduced, including transportation costs and heat preservation cost.

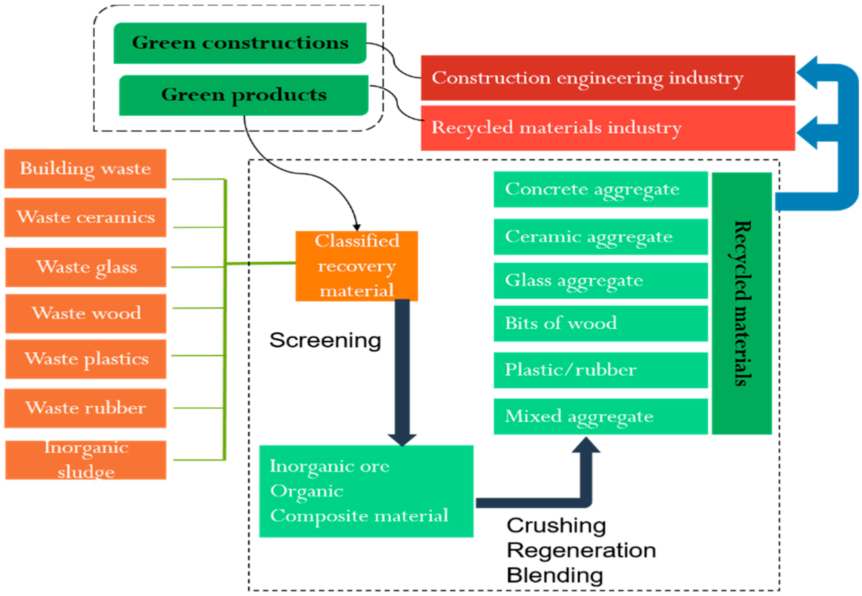

Figure 5. Life cycle of recycled materials.

5. Conclusions

In this paper, the development of green building and the origin of green construction materials are introduced in detail, and the green construction materials with development prospects are reviewed from two aspects of wall materials and thermal insulation materials. Green concrete replacement material is a new energy-saving material, which has been widely used in the construction industry. The recyclable building material is a recycling of waste resources, providing an environmentally friendly solution for construction waste. The natural insulation material is a good solution for agricultural waste and has excellent performance. Photochromic glass has broad prospects for energy saving in cities and provides a good solution for indoor environmental health. Although the development and application of green construction materials are still facing many challenges, the development and application of green construction materials have a great impetus to sustainable development and urban ecological protection. The conclusions of this research plan include:

1. Green materials for cement reinforcement and recycled waste construction materials are two promising green construction materials for their saving amounts of energy and natural resources. As the basic structure of a building, wall materials could create huge perspectives in a greenway.
2. Natural insulation materials have been widely used in some areas on the earth, which decrease the cost of wall construction through saving wall structure materials. The electrochromic and thermochromic glass is an innovative technology, which faces technology and cost barriers before wide application.
3. Compile the international promotion of innovative technology of green building common obstacles and challenges, including the lack of public awareness and acceptance, the designer of green building is also a lack of full understanding, leading investors for green building technology related industries with investment risk and uncertain factor, because the innovative technology of green building will generate high technology costs and benefits the uncertainty.
4. Green building development strategy of countries have been organized as four directions, including perfecting the policy system, the implementation of basic education, strengthen the partnership as well as the development of economic incentives to promote the objectives and implementation strategy.

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