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Review

Sustainable Non-Metallic Building Materials

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Abstract: Buildings are the largest energy consumers and greenhouse gases emitters, both in the developed and developing countries. In continental Europe, the energy use in buildings alone is responsible for up to 50% of carbon dioxide emission. Urgent changes are, therefore, required relating to energy saving, emissions control, production and application of materials, use of renewable resources, and to recycling and reuse of building materials. In addition, the development of new eco-friendly building materials and practices is of prime importance owing to the growing environmental concerns. This review reflects the key tendencies in the sector of sustainable building materials of a non-metallic nature that have occurred over the past decade or so.

Keywords: sustainability; sustainable buildings; construction; building materials

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1. Introduction

Almost twenty years ago, following the publication of Brundtland's report entitled "Our Common Future" [1] and the 1992 Rio "Earth Summit", the term sustainable development (SD) has gained great attention worldwide. This concept had been defined as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. SD was given a further prominence in the context of the 2002 World Summit on Sustainable Development held in Johannesburg. It became clear that the environment can no longer exist separately from the development of other associated sectors. The idea of SD involves enhancing the quality of life, thus allowing people to live in a healthy environment, with improved social, economic and environmental conditions [2]. In recent years, climate change, air pollution, depletion of natural resources and biodiversity, waste generation, depletion and pollution of water resources and deterioration of the urban environment became global issues that require urgent actions to be taken. Climate change and global warming resulting from carbon dioxide (CO_2) and other greenhouse gases (GHG) emissions pose a huge threat to human welfare. To contain that threat, the world needs to cut the emissions by about 50% below current levels by 2050 [3,4].

A great quantity of CO_2 is emitted to the atmosphere through the whole life-cycle of a building. This includes the production of building materials (BM), the construction of a building itself, the exploitation, renovation, possible rehabilitation and its final demolition [5]. Construction industry is intensively growing and actively developing worldwide. Only in Europe, construction is the largest industrial employer, accounting for 7% of total employment and 28% of industrial employment at least in fifteen EU countries [6]. On the other hand, this sector is responsible for such environmental burdens as high energy and water consumption, solid waste generation, global GHG emissions, external and internal pollution and depletion of natural resources. Annually, building construction in the world consumes: 25% of the global wood harvest; 40% of stone, sand and gravel; and 16% of water. It generates 50% of global output of GHG and agents of acid rains. Furthermore, almost 3 billion tons of raw materials are turned into foundations, walls, pipes and panels [7]. Generally, energy is used for the extraction, transportation, processing of the BM and assembling of the structures. The CO_2 emissions are derived from the combustion of fossil fuels, the land-filling activities and the reactions taking place in the industrial processes [8]. Some authors estimate that almost 50% of total energy costs in the developed countries are a consequence of intensive construction and building practices [4,9,10]. To achieve the goals of SD in building construction, a combination of factors must be considered, such as energy saving methodologies and techniques (use of renewable energy resources), improved use of materials, their further reuse/recycle and emissions control.

A sustainable building is designed, built, renovated, operated or reused in an ecological and resource efficient manner [7]. It has a minimal negative impact on built and natural environment. Sustainable building should meet a number of certain objectives: resource and energy efficiency; CO_2 and GHG emissions reduction; pollution prevention; mitigation of noise; improved indoor air quality; harmonization with the environment [11]. “An ideal building would be inexpensive to build, last forever with modest maintenance, but return completely to the earth when abandoned” [12].

One of the most important components of a sustainable building is the material efficiency. Correct selection of BM can be performed by taking into account their complete life time (“from cradle to grave”) and by choosing products with the minimal environmental impacts. For instance, González and Navarro estimated that the selection of BM with low environmental impacts can reduce CO_2 emissions by up to 30% [5]. The use of renewable and recycled sources is widely encouraged as the life-cycle of a building and its elements can be closed [13]. The other factors that greatly affect the selection of BM are their costs and social requirements such as thermal comfort, good mechanical properties (strength and durability), aesthetic characteristics and an ability to construct quickly. Ideally, the combination of all environmental, economic and social factors can give a clear description of a material, and thus helps in a decision making process regarding the selection of the materials suitable for buildings [14].

The primary aim of this review is to analyze recent advances in the area of non-metallic BM and to outline future prospects and challenges.

2. Sustainability Aspects of Building Materials

To address the goals of SD the production of materials must use resources and energy from renewable sources instead of non-renewable ones. Sustainable BM are environmentally responsible because their impacts are considered over the complete life time of the products. Sustainable BM should pose no or very minimal environmental and human health risks [15]. They should also satisfy the following criteria: rational use of natural resources; energy efficiency; elimination or reduction of generated waste; low toxicity; water conservation; affordability. Sustainable BM can offer a set of specific benefits to the owner of a building such as reduced maintenance and replacement costs, energy conservation, improved occupant’s health and productivity, lower costs associated with changing space configurations, and greater flexibility in design [7].

The major environmental burdens include embodied energy of BM and GHG emissions originated from each stage of their life-cycle. Embodied energy is defined as the amount of energy required to produce a material and supply it to the point of use. It is an important measure of the effectiveness of BM in the environmental terms [14]. Embodied energy consists of: energy required for the manufacturing of BM; energy associated with the transportation of raw materials to the factory and of the finished products to the consumer; energy needed for assembling various BM to form a building [16]. The results presented by Thormark indicate that embodied energy in traditional building can be reduced by approximately 10–15% through the proper selection of BM with low environmental impacts [17]. Although the values of embodied energy can vary widely (sometimes by as much as 100%, depending on the number of factors like country, manufacturing processes, recycling technologies, methodology of analysis, fuel costs and destination, *etc.*), they can be considered as reasonable indicators of an overall environmental impact of BM. Table 1 represents data for embodied energy and embodied carbon collected from UK and EU sources and worldwide averages of BM that were used in the UK (except for wood produced in Canada).

In order for decision makers to select materials suitable for sustainable construction, the assessment of their environmental burdens is necessary. For instance, in the US (California) BM can be considered as sustainable after each material has gone through a three-stage process involving preliminary research, evaluation and selection. At first, the research is normally conducted by gathering technical information including material safety data sheets, data tests of indoor air quality, product warranties, source material characteristics, recycled content data, environmental statement, and durability information [7]. After that, further deeper research may be necessary on the issues like building codes, government regulations, building industry articles, *etc.* Secondly, BM must undergo evaluation, which involves confirmation of technical information gathered in the first stage. Life cycle assessment (LCA) is a well-established methodology for evaluating environmental impacts associated with the entire product life time [18]. Although rather simple in principle, LCA can be difficult and expensive [2]. The last step, the selection, often involves the use of tables and matrices to score the specific environmental criteria. The total score of each material will show the product with the best environmental characteristics [7]. However, it is also important for sustainable development to consider social and economic factors as well.

Table 1. Embodied energy and embodied carbon of common and alternative BM (taken from [15]).

Type of Material (1 ton)	**Embodied Energy (MJ/ton)**	**Embodied Carbon (kg of CO_2/ton)**
Limestone	240	12
Stone/gravel chipping	300	16
Rammed earth	450	24
Soil cement	850	140
Concrete, unreinforced (strength 20 MPa)	990	134
Concrete, steel reinforced	1,810	222
Soft-wood lumber (large dimensions, green)*	1,971	101
Soft-wood lumber (small dimensions, green)*	2,226	132
Portland cement, containing 64–73% of slag	2,350	279
Portland cement, containing 25–35% of fly ashes	3,450	585
Local granite	5,900	317
Engineering brick	8,200	850
Tile	9,000	430
Soft-wood lumber* (small dimensions, kiln dried)	9,193	174
Steel, bar and rod	19,700	1,720
Polypropylene, injection molding	115,100	3,900

*Note: System boundary is cradle to average US site.

LCA of BM includes an analysis of the following aspects: resource base; embodied pollution; impact during use; final disposal. Certain sources of raw materials are becoming exhausted; therefore, the use of remaining stocks should be treated with great caution. Most rare materials used in construction can be substituted by others, more abundant or renewable. Environment (natural habitat, flora, fauna and landscape), human health and well-being can be severely damaged by the extraction or harvesting of raw materials and by the production and distribution of BM that make up the whole supply chain of the construction industry. There may also be negative effects for the local communities associated with noise, dust, local transport problems or general disruption. Some extraction processes are inherently rational in terms of resources used, whereas others are extremely inefficient, leading to a significant amount of waste. Attention to this aspect has led to a new trend in manufacturing BM from the waste products of various origins [19]. For instance, utilization of waste products had been successfully implemented in countries like Holland and Japan, where “construction industry practically lack raw materials” [20].

Pollution, caused by the processes taking place during the production of BM, has a huge negative environmental impact as well. Highly processed components must be avoided in the future in favor of the less processed ones, which can serve the same purpose. Reduction of the pollution caused by the combustion of fossil fuels and cutting down the costs of energy required for manufacturing of BM are also the main challenges for the producers of highly energy intensive products, like concrete, bricks, plastics and metals. For example, several British brick manufacturers partially use bio-gas as a fuel for the firing [19]. A wide range of traditional building products (wood treatments, foams, chipboards, vinyl flooring, paints and varnishes) contain compounds, which adversely affect the health of occupants of a building. Although some harmful substances are regulated by health and safety policies such as Control of Substances Hazardous to Health (COSHH), in reality great level of health risks comes from the unknown "cocktail" effect of the many chemicals that are present in the buildings. Further detailed research is required to address these concerns and produce information on health risks associated with possible substances combinations [19]. The use of BM sourced locally can help lessen the environmental burdens. This would considerably cut transportation costs and provide support of the local economies. For instance, a good choice of material suitable for sustainable construction can be timber, available from a local source, used in untreated form and designed for long life. It is preferable to employ the vernacular traditions and skills, often connected with a particular regional material that is acceptable to local planning authorities. Also, it is quite important to take into account an inherent durability and quality of BM and increase them as much as possible. In addition, materials and components should have a good recycling potential [19].

Glass *et al.* mentioned that the construction industry is quite conservative, and currently it is underperforming in addressing such issues as sustainability, low replacement rates, lack of innovation, inadequate level of skills and external factors (oil depletion, water pollution and globalization) [21]. According to recent European building regulations on energy efficiency and to the "Code for Sustainable Homes", new standards are established in order to produce "carbon neutral" buildings [21,22]. In 2003 European Commission released the integrated product policy, aiming to identify within the construction sector products with the best environmental performance [23]. This policy takes into consideration the whole life-cycle of the product. There are three main phases in this approach: environmental impact of products; environmental improvement of products; policy implications. Eco-design and the environmental product declarations (EPD) are employed to implement the integrated product policy. Eco-design is a set of techniques that can design a product with low negative environmental impacts during its complete life-cycle. EPD is a communication tool providing customers and international markets with relevant and verified information on the environmental performance of the products [24]. EPD is based on LCA and contain data associated with the acquisition of raw materials, chemical nature of BM, possible air-land, and water-pollutions and waste generation as well [2].

Researchers use different criteria to classify BM. For instance, Asif *et al.* categorize construction materials into six groups: concrete, metals, wood, stone, plastics and ceramics [9]. Classification conducted by Sun *et al.*, on the other hand, is based on materials environmental impact drivers [18]. By means of this method, 16 groups were identified for the families of materials such as glass and ceramics, ferrous metals, non-ferrous metals, paper, polymers and woods. This classification can be suitable at the early stages of product design and development. Calkins used sustainability criterion and defined the following groups of sustainable BM [15]:

- materials that reduce the use of resources;
- materials that minimize environmental impacts;
- materials that pose no or low human health risks;

- materials that assist with sustainable site design strategies;
- materials from companies with sustainable social, environmental and corporate policies.

The following sections of this review focus on the recent advances in the field of the most common (cement/concrete; wood; brick; stone; ceramics; glass; plastics) and alternative (bamboo; cob; adobe) BM that have non-metallic nature.

3. Concrete and Cement

Concrete as a construction material is widely used for building structural frames, ground-works, floors, roofs, and prefabricated elements [25]. Annually more than 10 billion tons of concrete are produced in the world [26]. Concrete is a durable material with excellent mechanical properties. It is adaptable to different climates, relatively fire resistant, widely available and affordable. Concrete can be molded almost into any shape and can be designed to satisfy almost any performance requirements [26]. It can be reinforced with either steel or fibers. Moreover, recycled materials can be incorporated into the concrete mix, thus reducing consumption of raw materials and disposal of waste products. The use of admixtures—materials added to concrete—becomes very popular as the final composite can have better durability and gains some specific unique properties [15]. Typical composition of concrete is shown in Table 2.

Table 2. Typical constituents of concrete (taken from [15]).

Constituent	Average Content, wt.%
Portland cement	9.3
Fly ash	1.7
Fine aggregate	26
Coarse aggregate	41
Water	16
Air	6

In spite of the advantages mentioned above, concrete unfortunately has an enormous negative impact on the environment. It is estimated that cement and concrete industry generates up to 7% of global anthropogenic CO_2 emissions, and it is set to increase dramatically in the coming decades as the Earth's population grows [15]. Apart from the emissions related to the combustion of fossil fuels, there is a release of CO_2 associated with unavoidable de-carbonation of limestone (raw material) [28]. Concrete manufacturing is responsible for generating not only carbon dioxide but also other air pollutants like carbon monoxide (CO), sulfur oxides (SO_x), nitrogen oxides [$(NO)_x$], hydrogen chloride (HCl), volatile hydrocarbons and particulate matter. Production of concrete causes depletion of non-renewable mineral and water resources required in extremely large quantities. World concrete industry uses 10 billion (in short scale billion) tons of rock and sand, and 1 billion ton of water annually. Although Portland cement composes about 10% of concrete mix (see Table 2), its production accounts for 92% of the total energy demand [15]. Finally, demolition and disposal of concrete structures pose another significant environmental threat [26]. Concrete is estimated to account for up to 70% by weight of construction and demolition waste. At the present moment, concrete industry must take urgent actions in order to reduce the emissions of CO_2 and other air pollutants; to reduce the use of energy; to cut down the use of natural resources (including water); and to minimize the amount of waste generated. The environmental impacts of concrete/cement materials are largely discussed in detail elsewhere [15,25,26,28-30].

The Cement Sustainability Initiative (CSI) is a serious international effort set by ten leading cement companies to reduce the environmental and human health damage caused by cement manufacturing. The group of eighteen cement producers, accounting for 40% of global cement production, is organized under the World Business Council for Sustainable Development. The purpose of this initiative is to implement the main principles of SD and to identify actions needed to achieve SD in cement industry. CSI prepares guidelines and protocols for addressing such issues as energy and CO_2 management, fuel and material use, employee health and safety, reduction of emissions, impacts on land and local communities, and communication [15,28].

Main Strategies Dealing with Challenges of Modern Cement and Concrete Industries

Improvement of durability, mechanical properties and service life of concrete

One of the effective ways to deal with negative environmental impact of concrete is to reduce the total volume of this material needed for a certain construction process by enhancing its performance. It is important to consider the overall quality of BM, which strongly depends on durability and associated mechanical properties and the life time. Habert and Roussel estimated that in France, the reduction of the concrete volume required for a particular building, by increasing the mechanical strength of the concrete, could lead to the reduction of CO_2 emission by approximately 30% [27]. In a report [31] it is claimed that many exposed exterior concrete structures are only in place for half of the designated service time. Premature failure can result in a great amount of resources needed for structures to be fixed, replaced or demolished before the end of their original life time, and therefore causing an extra negative impact. Designing of smaller and thinner concrete sections can also reduce the total amount of materials and energy resources required to produce concrete. However, this implies that the material should have a significant level of strength. There are several solutions for this problem.

The first is the development and application of high performance concrete (HPC). HPC is a type of concrete that has a low water to cement or water to binder ratio, properties of which are improved by the use of super-plasticizers. HPC has a higher level of compressive strength (40–50 MPa) compared to a traditional concrete (15–25 MPa) [30]. It is more economical as the designed structures can be smaller or thinner. It also has a low porosity that makes HPC more resistant to low temperatures and chemical exposure [15].

Secondly, by using self-compacting concrete (SCC), which is defined as “concrete, which without any mechanical action is able to fill a given form without separation” [28]. In 2004 only 1% of European ready-mix construction was SCC. SCC has following economic, social and environmental advantages compared to a traditional concrete:

- less labor involved, thus reducing costs, increasing productivity and allowing to build faster;
- the absence of large voids and inhomogeneities inside SCC results in its improved mechanical characteristics, better performance and longer service life;
- SCC casting requires no additional electrical energy for vibration (as this stage is eliminated);
- low level of noise and the absence of problems normally associated with vibration at the plants and construction sites;
- SCC also has new aesthetic potentials and more complicated geometries can be designed.

SCC technology provides an opportunity to use fine fillers of ground limestone or by-products such as fly-ash, quarry dust *etc.* Ye *et al.* have investigated the behavior of self-compacting cement paste at elevated temperatures [32]. It was found that a dramatic loss of mass was observed in the samples of self-compacting cement paste with addition of limestone filler when temperature is higher than 700 ^{o}C. This implies that SCC made by this type of paste will probably have a bigger damage once exposed to the fire. This can be efficiently avoided when polypropylene fibers (*ca.* 0.5 kg/m^3) are added to the paste.

In general, the use of polymers in manufacturing more sustainable concrete is continuously growing. They can be used for the following applications: concrete crack injections; repair of mortars for concrete and stone; consolidation of masonry; admixtures; and pure polymer concrete building components. Concrete modified with polymers is a composite material consisting of two phases: the aggregate, which is discontinuously dispersed through the material, and the binder, which itself consists of cementitious and polymer phase [33]. The main issues here are physical and chemical incompatibility of polymers and concrete, mechanical malfunctioning and low durability of the finished composite. Depending on the volume fraction of the polymer, the material shifts from polymer cement concrete to polymer concrete. Polymer impregnated concrete is a special composite, in which polymers are combined with concrete. In this case, low-viscosity monomers are injected into the pores of the hardened concrete and polymerized later. The resultant polymers form a second matrix if the pores are interconnected throughout the material [33].

Thirdly, by applying adequate reinforcing techniques that will enhance the durability of concrete structures. There are two ways of concrete reinforcement: steel reinforcing and fiber reinforcing. The idea of reinforcement concludes in the prevention of cracks developing inside the concrete before or after it happened, and as a result will lead to an improved impermeability, strength, weather and impact-resistance of the material [15]. Application of the first method is less preferable as durability of the finished product can be affected by corrosion, and the production of steel has some serious environmental implications (high energy use, emission of hazardous air pollutants, *etc.*). The second method involves inclusion either synthetic (nylon, glass or polypropylene) or natural fibers (vegetable, hemp [34], flax [35], coir, eucalyptus pulp, residual sisal [36]) in to the concrete mix. In spite of the main drawbacks like low durability performance of concrete and incompatibility issues, the consumption of BM made of biological fiber reinforced cement is increasing rapidly, especially in the developing countries having access to significant sources of cellulose fibers [35]. Two articles [36,37] have appeared in the literature that represent overviews of Australian and Brazilian experiences, respectively, in natural fiber reinforced cement composites. The authors state that it is possible to develop a material with properties suitable for building purposes with adequate mix design and taking into account the mechanical properties of fibers [36]. The study conducted by American researchers on self-healing (“bleeding”) concrete has shown that the repair of cracks and filling the voids occurs immediately through the internal release of chemical agents from the fibers or beads embedded into concrete matrix [38].

Fourthly, it is the development of new ultra-high performance cement composites, which have unique structural and aesthetic potential. These are compact reinforced composite (CRC) and Ductal®. CRC is a composite of special fiber reinforced concrete with extremely high compressive strength (150–400 MPa) and reinforcing bars arranged in a particular manner [28,39]. CRC has been used in structural application, mainly for the production of precast elements (balconies and staircases). Ductal® had been developed by three French companies, namely Lafarge, Bouygues and Rhodia [28]. It possesses improved rheological properties and a unique combination of attributes detailed in [40]. In comparison to a traditional concrete, Ductal®’s compressive strength is 6–8 times higher, the flexural strength is 10 times higher, the durability is from 10 to 100 times better. Moreover, Ductal® can deform under excessive loads without rupture and has excellent surface aspects. From an environmental point of view, Ductal® technology requires only 65% of raw materials, 51% of the primary energy and 47% of the overall CO_2 emissions of the traditional concrete [28].

Finally, the use of nanomaterials might be very powerful in order to achieve sustainability objectives. Nanoscience of cements is a relatively new discipline with a huge potential to manipulate the nanostructure of calcium silicate hydrate [41]. Because the full environmental and human impacts of nanoparticles are unknown, they might pose some risks by inhalation or skin absorption during their manufacture, use and disposal [15]. Concrete reinforcement with nanofibers, including carbon nanotubes, has a potential to improve strength of concrete significantly, possibly eliminating the need of the reinforcement with steel. Moreover, nanocoatings containing titanium dioxide (TiO_2) can make self-cleaning buildings in the future, reducing the amount of harmful cleansers used currently. Molecules of TiO_2 have photo-catalytic properties [42]. They release an electric charge when absorbing sunlight that forms reactive radicals, which oxidize the nearby organic (and some inorganic) substances when they exposed to ultraviolet and/or sun rays [15]. The acidic products obtained in this process are washed away by rain or neutralized by alkaline calcium carbonate contained in the concrete. It is reported that nanoparticles of TiO_2 can even reduce air pollution by removing nitrogen oxides [43]. Tests showed that road surfaces with incorporated nano-TiO_2 reduce concentrations of nitrogen oxides by up to 60%. The use of nanoparticles of Portland cement, silica (SiO_2), titanium dioxide (TiO_2), and iron oxide (Fe_2O_3) can significantly improve compressive and flexural strength of concrete [15]. In addition, nanosensors can be integrated into concrete with the aim to collect performance data such as stress, corrosion of steel, pH levels, moisture, temperature, density shrinkage, *etc.* [44].

Reduction of the cement content in the concrete mix by increasing the application of supplementary cementitious materials (SCM)

Reduction of cement use in a concrete mix is most easily achieved through the substitution of Portland cement with other pozzolanic or hydraulic materials [15]. Depending on physical characteristics (grading curve or size), chemical composition and properties of SCM, they can perform either a function of ordinary filler (*i.e.*, they would fill the porosity of the material and thus increase elasticity modulus and improve its mechanical strength) or work as a binding agent (*i.e.*, they would react with water or with clinker hydration products and form stable hydrates). The most common SCM include fly ash (by-product from coal fired power plants), ground granulated blast furnace slag (GGBFS: by-product of steel industry), and silica fume (by-product of semi-conductor industry) [15,26,28,45,46]. Following the increasing popularity of SCM, Meyer in a recent review discusses properties, optimum levels of cement replacement, benefits and disadvantages in the application of each type of substituents [26]. Other SCM that can be used for cement replacement belong to a family of natural pozzolans such as calcined clay, calcined shale and metakaolin [15].

The utilization of industrial waste products as SCM definitely has a positive environmental impact because otherwise they would be land-filled. Moreover, they improve durability and mechanical properties of concrete, reduce thermal stress and cracking. However, in some cases longer set and curing times are required. Damtoft *et al.* stated that in reality the reduction of CO_2 emission is limited when SCM used for the Portland cement production. This is primarily due to the low content of calcium oxide (CaO) in the majority of SCM (except GGBFS). In practice, level of limestone replacement by GGBFS constitutes only 10%. When reductions in fuel consumption are taken into consideration as well, the total reductions of CO_2 emission theoretically do not exceed more than 25%. Also, the availability of GGBFS in the near future is most likely to decrease as existing steel plants are due to be replaced by more efficient electric arc furnaces. Fly ashes (class C) enriched with CaO can also be used to replace limestone in clinker production; however, the availability of this product is limited as well. Therefore, 100% utilization of current world sources of blast furnace slag and class C fly ashes would result in CO_2 emission reductions only by 10% [28]. Habert and Roussel evaluated that in France CO_2 emissions can be cut by 15% by increasing level of clinker substitution on mineral additives, both industrial by-products and natural pozzolans [27]. The authors also stressed that this could be achieved in a medium term perspective, *i.e.*, by 2020. However, in the long time perspective, *i.e.*, by 2050, the authors recommend considering other options, e.g., developing new types of clinker such as sulfoaluminate or belite activated sulfoaluminate clinker that has low CO_2 emission.

Increase in the use of recycled materials in place of natural non-renewable resources

Since aggregate constitutes the largest volume fraction of the concrete mix, the substitution of natural aggregates with recycled products can result in reducing the consumption of raw materials in manufacturing process, in reducing the exploitation of quarries, and can thus result in the minimization of the land areas for disposal. The products that can replace fine and coarse aggregates are: recycled concrete aggregate (RCA); crushed blast furnace slag; sand; brick; glass; granulated plastics; waste fiberglass; mineralized wood shavings; *etc.* This strategy gains a great importance and has been discussed by many authors [26,47-52]. For instance, Sani *et al.* studied leaching and mechanical behavior of concrete containing RCA [47]. It was indicated that the use of recycled aggregate as a 100% replacement of natural aggregate causes an increase in total porosity of concrete, although the leaching rate of sodium, potassium and calcium ions becomes lower as it is directly related to the percentage of macro/meso-pores. Mechanical strength in the presence of RCA drops by approximately 40% compared to a traditional concrete. However, this loss can be contained by adding fly ash. In spite of these negative effects, the authors still suggest that application of RCA would be acceptable as more environmentally sustainable. Compressive strength of RCA can be increased to adequate values of traditional concrete (30–35 MPa) by adding to the mixture SCM (fly ash or silica fume) with the aid of an acrylic-based super-plasticizer and at the same time by decreasing the water/cement ratio [53]. RCA also causes a reduction of elasticity modulus (by 35%), an increase in creep and shrinkage deformations, as well as a higher permeability of concrete, which decreases its durability [26]. A variety of contaminants (soil, plaster, wood, gypsum, asphalt, and rubber) found in recycled concrete can also be an important issue as their presence degrades the durability and strength. Another limitation of using RCA is a larger water consumption compared to an ordinary concrete. Nevertheless, RCA is quite acceptable for many applications. For instance, the successful case is the renewal of Denver’s Stapleton Airport in the US, where 6.5 million tons of concrete had been recycled or reused [54].

Post-consumer glass bottles and post-industrial float glass cullet are offered as suitable aggregates for concrete [26,28,55-58]. Recycled glass has zero water absorption, high hardness, good abrasion resistance, excellent durability and chemical resistance. All these characteristics can improve the overall performance of concrete and impart color and aesthetic properties to it. The only technical problem here is an alkali silica reaction that can occur with coarse glass aggregate (less with fine aggregate). This reaction leads to the formation of a gel, which swells in the presence of water, causing cracks and damage in concrete [15]. Bignozzi *et al.* investigated a new application of matt waste, derived from the purification of cullet by separated collection, as a filler and as a partial Portland cement replacement (up to 50%) for newly blended cement [55]. When it is used as a filler, the resulting composite material showed higher compressive strength (up to 23%) and lower water absorption than self-compacting concrete. These significant improvements of mechanical properties are due to the good pozzolanic activity of the glass. Matt waste of amounts up to 25% was shown also to be very effective in new cement formulations. Kralj proposed a method of recycling of lightweight concrete with aggregate containing expanded glass [56]. Although the values of compressive strength, density and thermal conductivity for a new product are similar to the ones for lightweight concrete containing only aggregate of expanded glass, this technology is necessary for a production of cheaper and more environmentally friendly material. Guerra *et al.* studied an effect of recycled porcelain materials on the mechanical properties of concrete [59]. The substitution of natural aggregate with ceramic debris from sanitary ware waste does not improve significantly the mechanical properties of the new material compared to an ordinary concrete. However, it provides a good opportunity for the recycling of construction industry residues.

There are a number of publications related to the replacement of natural aggregate with the wastes from wood processing activity [60-65]. The research conducted by Becchio *et al.* focuses on the possibility of the mineralized wood concrete production by incorporating wooden waste, which was pre-treated with silica fume [65]. The inclusion of wood aggregate into concrete leads to a decrease of material density and final material becomes lighter. It also improves thermal insulation, although mechanical properties of the composite drop.

There are reports that describe preparation of rubberized concrete composites by replacing fine (up to 10%) and coarse (up to 20%) natural aggregate with waste tire rubber [66,67]. The most common ways of using recycled tires in cement concrete composite are shredding, chipping or grounding the rubber to the particles with sizes ranging from 450 mm to 75 µm [26]. The main drawbacks of this method are a significant decrease of the compressive and tensile strength as well as a reduction of stiffness of the composite product with the increasing amount of rubber in the mix. This can also lead to the earlier developing of cracks and the overall failure of concrete matrix. In order to improve mechanical behavior of concrete, Bignozzi and Sandrolini suggested using a self-compacting technology that helps binding rubber phase with cement matrix [66]. On the other hand, owing to the presence of rubber particles, the concrete can gain extra ductility and energy absorption [26]. Other potential advantages of rubberized concrete are good sound absorption capacity as well as excellent thermal properties. However, the incompatible Young's moduli of rubber and concrete often lead to inadequate mechanical properties of materials.

Recycled waste plastic is not generally available widely [15]. A major obstacle is the poor adhesion of plastic particles with cement matrix, which can also considerably reduce mechanical performance of concrete [26]. This problem can be solved by combining 10–15% of waste plastics with other materials like fly ash, thus leading to the production of lightweight structures and blocks that increase the deformation characteristics of concrete without failure [15].

4. Wood-Based Building Materials

Wood is one of the most common and oldest forms of BM. It is easy to work with, structurally strong construction material suitable for numerous applications, e.g., framing, flooring, roofing and lining. There are different varieties and sources of timber. Sun *et al.* classified 82 types of wood into four groups on the basis of magnitude of their environmental impacts (eco-indicators) [18].

Up until recently such negative factors as deforestation, destruction of natural habitats, acidic rains, high rate of wood consumption, extensive use of toxic preservatives have resulted in wood being viewed as un-sustainable material. A representative consumer survey conducted in Germany has aimed to explore the image of timber as a construction material in general and timber framed houses in particular [68]. The study found that although timber has a positive association with such values as well-being, aesthetics and eco-friendliness, prejudice regarding high combustibility, low durability and extensive maintenance still persists in the minds of consumers. These barriers constitute a real challenge that producers of timber houses would have to face by optimizing processes and products.

An increased use of wood in construction is a rather controversial topic in recent literature. On one hand, forests purify the air and sequester carbon, even after being harvested and processed into lumber products. Furthermore, trees need mainly solar energy to grow and manufacture of wooden materials requires fewer amounts of fossil fuels, and emits less GHG over their life-cycle than other common BM. On the other hand, some wood harvesting practices and techniques have caused the global problems such as clearing large expanses of forests; loss of biological diversity; water and soil pollution due to the liberal use of fertilizers and pesticides; generation of waste that was land-filled [15]. In addition, some wood finishes can release volatile organic compounds, negatively affecting air quality and human health in general. Wood can be considered as a renewable material, and have a huge potential to be sustainable in the future, given the strategy of sustainable forest management and harvesting practices monitored by forest certification programs are in place.

Forests, as a source of wood, play a vital role in the Earth's carbon cycle. Photosynthesis, which occurs in forests, provides an efficient mechanism for the removal of carbon dioxide from the atmosphere and the release of oxygen back to it. This process is the most productive in the new forests where rapid tree grow takes place [15]. Forests, wood and wood products store carbon until its eventual release through burning, bacterial or fungal decay, or consumption by insects [69]. If trees are replanted, carbon sinks would be added to the carbon cycle [70]. In contrast, deforestation leads to an imbalance of carbon flows by the removal of trees that can sequester carbon [15]. It is estimated that that 17.3% of carbon dioxide emissions, caused by humans, are related to deforestation, biomass decay, *etc*. [4]. A sustainable balance can be achieved if the annual harvest level is equal to, or below, the annual forest growth increment [4,71], and when intensive forest management regime is employed [72,73]. Consortium for Research on Renewable Industrial Materials (CORRIM) found that growing wood on the shorter rotations as opposed to longer intervals between harvesting can sequester more total carbon over time [70]. An accumulation of carbon in wood products, by an increase of their consumption or by using long-lived products, can positively benefit the environment, but only in the short or medium term [74]. Some authors believe that, in the long term, a greater use of wood in buildings at the expense of energy-intensive BM and substitution effect of avoiding fossil fuel emissions are more important than carbon stored in wood [69].

It is also important to consider how wood is treated at the end of its life cycle [15]. In the EU, land-filling both combustible and organic waste has been banned [75]. Land-filling is still a common practice in North America and in the developing countries. Residues, resulting from the harvesting of forests and the manufacture of wood products, should ideally be completely utilized to replace fossil fuels [71]. Reclaiming and reusing of wood are also widely encouraged. While untreated wood can be recycled into other products (such as mulch or compost), the treated wood would pose a more significant problem for disposal as it may contain harmful compounds [15]. Some amount of carbon from land-filled wood will return to the soil, but another fraction may decompose into methane, which has a much higher global warming potential than CO_2. Although part of the methane gas can be recovered and used as bio-fuel, the rest of it will be emitted to the atmosphere [74].

The use of timber in construction gains more and more support, especially in the regions with vast forest resources, because it can reduce both the energy demands of the buildings and the concentration of GHG in the atmosphere. Generally, this can be achieved by making use of wood instead of either fossil fuels (fuel or direct substitution) or non-wood materials, such as steel, aluminum and concrete (material or indirect substitution). There is a large potential to increase wood substitution in Europe. Gustavsson *et al.* point at a rather low level of timber use in Western and Central Europe, excluding Scandinavia [76].

In general, there are a large number of recent publications regarding the substitution between timber products and other BM [8,69-74,76-85]. For instance, in the case study by Borjesson and Gustavsson on the multi-storey building in the south of Sweden, the primary energy use and the emissions of CO_2 and methane have been calculated and compared for two design options (either wooden or concrete frame) from life-cycle and forest land-use perspectives [77]. They evaluated that the primary energy input was about 60–80% higher when concrete frames were used. The authors suggested that the net GHG balance is strongly affected by the method, in which wood is being utilized after the demolition of the building. The net GHG emissions estimated to be clearly positive if all of the demolition wood is land-filled and slightly positive if all wood from this building is used instead of fossil fuel. GHG emissions can be improved and even may be negative if demolition wood is re-used. The comparison of timber and concrete design options of the same building was performed by Lenzen and Treloar by employing an Australian environmentally extended input-output framework in a tiered hybrid LCA, and in structural path analysis instead of process analysis [78]. Although the authors of this study reported that values of the energy use are twice as large as in similar study conducted by Borjesson and Gustavsson, the fundamental result, that the concrete-framed building causes higher level of emissions and uses more energy, has been confirmed.

Cole has provided a detailed examination of the energy and GHG emissions associated with on-site construction of a selection of alternative wood, steel and concrete structural assemblies [85]. Significant differences between the amount of energy and GHG emissions were observed for the construction with these materials, indicating that the use of concrete typically involves an order of magnitude higher quantities.

A great majority of scientists are convinced that using wood products in construction can result in lower fossil energy demands and significant cuts of GHG emissions compared to non-renewable alternatives such as steel and concrete [74]. For instance, Buchanan *et al.* found that a 17% increase in wood content of buildings in New Zealand could lead to a 20% decrease in fossil fuel consumption and to a 20% reduction of atmospheric carbon emissions from the manufacture of all BM [69]. This would account for a reduction of about 1.5% of New Zealand’s total emissions. The reduction in emissions is mainly associated with using wood instead of brick and aluminum, and to a lesser extent steel and concrete.

A study conducted by Upton *et al.* focused on the energy requirements and GHG emissions associated with the use of wood-based BM in residential construction in the US [81]. The authors compared houses with similar heating and cooling regimes but using wood-based and non-wood-based construction materials. The differences were estimated over a period of 100 years. The results indicate that houses built with wood-based BM require 10–15% less total energy for non-heating/cooling purposes and their net GHG emissions are 20–50% lower than thermally equivalent houses employing steel-or concrete-based BM.

Salazar and Meil discussed the prospects for carbon-neutral housing by greater wood use on the example of single-family residence [83]. This article compared energy and carbon balance of two residential houses: a typical wood-framed home using more traditional materials (brick cladding, vinyl windows, asphalt shingles, and fiberglass insulation) and a wood-intensive house with maximized timber use throughout (cedar shingles, wood windows, and cellulose insulation). The wood-intensive home’s life-cycle consumed only 45% of the fossil fuels used in the typical house. Including land-fill methane emissions, the wood-intensive house produced 20 tons of CO_2 emission as opposed to 72 tons for typical house. It was estimated that the house with higher wood content can be energy efficient and carbon neutral for 35–68 years in Ottawa region. The authors showed that wood waste can be recovered and used to generate enough energy to completely offset the manufacturing emissions and even partially offsetting the heating or cooling energy demands for this house.

Calkins in a recent book recommended the following strategies for design and specification of sustainable timber [15]:

- use wood resources efficiently, which means: using lowest quality wood for applications; build smaller and durable structures; simplicity in design details; minimal preservative treatments; reduce wood waste; build for disassembly; use engineered wood products;
- use certified wood;
- use reclaimed wood;
- preferential use of natural or low-toxic wood finishes.

The use of residues from agricultural activities can improve conservation of timber stock. Van Dam *et al.* developed an efficient technology to produce boards with high strength and density by processing whole coconut husk without the addition of synthetic binders [86]. The board had excellent mechanical properties, which are similar or even better than commercial wood-based panels. The recycling of wood is encouraged as it effectively addresses the problems of waste management and lack of natural resources, especially in countries like Japan with limited land areas suitable for waste disposal. Obata *et al*. discussed an application of recycled medium density fiberboard to produce a base material for floor heating systems [87].

The industry of wood preservatives and finishes currently focuses on the manufacture of products with improved environmental performance [88]. The comprehensive comparison of various wood preservatives is represented by Calkins [15]. A recent development of micro manufacturing heat treatment with the aid of sodium silicate is at the preliminary stage of testing, but it has a great potential in wood preservation. The use of nanomaterials as wood coatings, preservatives, adhesives, sealants and impregnators has also very promising future [43]. For instance, Calkins mentioned the development of a preservative containing organic insecticide and fungicide embedded in 100 nanometers plastic beads [15]. The suspension of these beads in water had been passed through the wood under pressure. Owing to their nanosize, they were able to disperse completely within the wood fibers. As soon as a finished wood product is well protected from the effect of fungus and insects, it is suitable for application in the exterior structures. Unfortunately, the availability of some new products is limited at the moment.

5. Brick, Stone and Ceramics

Brick is one of the major BM in modern construction industry. It has a very good durability and long service life. Bricks are mainly used for the outer and inner walls construction. Primarily bricks are made of non-toxic natural materials like clay and shale. Furthermore, brick manufacturing has a good potential for utilization of the solid wastes, which can be incorporated into the brick and neutralized by firing at high temperatures. The main environmental concerns all over the world for the brick production process are high energy usage and GHG emissions. For instance, LCA conducted by researchers from Greece quantified environmental performance of brick production in that country [89]. It was shown that most of the emissions are directly associated with the burning of fossil fuels. Among other environmental indicators acidification had a highest value (56%), which is explained by the combustion of low-grade fuel with high sulfur content, producing large amounts of SO_2 and $(NO)_x$.

All these negative factors encourage researchers to develop new type of masonry materials with improved environmental profile [15,89-91]. One of them is unfired clay bricks [91]. The usage of unfired bricks, in place of conventional fired ones, can significantly reduce the energy use and also cut down CO_2 emissions. Unfired clay soil (in the form of sun-baked bricks, mortars or plaster) is classified as a traditional BM that was very popular in the past, especially in rural areas. The main disadvantage of using these products is susceptibility to water damage, which can be avoided by stabilizing the clay soil with the addition of small quantity of lime [92]. Although the durability of lime-stabilized soil remains quite low and further improvement is required [93]. The results of several studies [91,94,95] showed that increase in durability is occurred when GGBFS is added to lime-stabilized systems. Oti *et al.* described a new technology of production of unfired clay bricks containing blended binders: lime and GGBFS [91]. The use of only 1.5% of lime in the formulations makes possible to obtain clay masonry units with engineering standards acceptable for wall construction. The price of the final products was relatively low. Furthermore, unfired clay bricks demonstrated excellent environmental performance; their total energy input was estimated of 657 MJ/ton as opposed to 4,187 MJ/ton for the common fired bricks, while an equivalent output of CO_2 emission was 41 kg CO_2/ton compared to 202 kg CO_2/ton for traditional bricks in mainstream construction. There are also reports in the literature regarding “smart” brick or masonry [96,97]. This approach consists in incorporating sensors that monitor environmental parameters such as force, stress, temperature, tilt and moisture.

Stone can be considered as a low impact BM, if quarried locally, minimally processed and used appropriately. There is a tendency of rehabilitating the use of dry stone for modern sustainable construction [98]. The environmental burdens and potential applications of natural stone and aggregate are extensively discussed by Calkins [15].

According to a LCA of BM conducted by Asif *et al.*, ceramic tiles are quite energy-intensive (32,240 MJ) that accounts for 15% of the total embodied energy in the house [9]. Nicoletti *et al.* presented a comparative LCA carried out for marble and ceramics used as flooring materials [99]. The analysis indicated that marble tiles have better environmental performance compared to ceramic ones. In case of ceramics, due to the composition of raw materials used for the glaze production, the emission of arsenic and lead containing compounds took place.

6. Glass and Plastics

Windows are very important in sustainable construction of residential and commercial buildings. They are responsible for heat transfer, provision of daylight, ventilation, weather protection and acoustic insulation. Due to the high heat conductivity of the glass, an unwanted heat gain or loss takes place between building and surroundings. There are several ways to improve energy conservation and windows sustainability: use of low-emissivity (low-e) coatings; replacement of air with inert gases; adjustment of the gap between glass panes in double or triple glazing. Low-e coatings improve thermal characteristics of the windows by blocking the transmission of rays with wavelengths responsible for solar heat gain [100]. Lampert reported that low-e glass accounts for almost 40% of the insulated glass market in the US [101]. The optimization of the thickness of air layer in glazing cavity [102] or substitution of the air with gases having low thermal conductivity (argon or krypton) [103] can significantly reduce energy losses. A design, incorporating thermal breaks between inner and outer surfaces of frames, can also considerably improve thermal insulation. In addition to this, the material of a window frame, which normally has a higher U-value than the glazing component, must be considered. Generally, wooden frames provide better thermal insulation compared to aluminum or plastic ones. Moreover, the lower values of embodied energy make the timber frames more sustainable than aluminum, uPVC, steel and aluminum-clad timber types of frames [103].

The emergence of chromogenic technology gave a start to a range of new products, often called "smart" or switchable BM [101,104-108]. Electrically switchable chromogenic devices could either change their color or transmittance due to the action of an electric field [105]. These devices can be incorporated into glass or plastic materials. The main advantage of electrochromics (EC) is that the low electric field is required only during the switching operations. Common types of electrically powered technologies are EC, suspended particle devices (SPD), also known as an electrophoretic media, and phase dispersed liquid crystals (PDLC) [101,104,105]. Currently, the most popular products are EC-windows, which change their color upon exposure to ultraviolet and thus can control light, glare and heat entering a building [101,106]. Witter *et al.* reported about gasochromic windows that could change their transmittance characteristics [108]. In this case, when glass containing a layer of tungsten oxide (WO_3) covered with a very thin layer of platinum, is exposed to diluted hydrogen gas, it changes its color due to the reduction of WO_3. This process can be reversed by introducing diluted oxygen. The main advantages of these windows are high solar transmittance in the bleached state and simple layer configuration that does not require transparent conducting electrodes. The prototype of SPD windows in "on" and "off" positions is represented by Lampert [101,104]. An active layer of the glazing consists of needle-shaped dipole particles (less than 1 mm long) suspended in a polymer. In "off" position the particles are randomly arranged, absorbing the light. When an electric field is applied, particles align and transmission is increased. The principle of the optical switching in all systems based on liquid crystals (LC) is the reorientation or twist of their molecules, which causes the change in materials transmittance. PDLC can be obtained either by embedding LC droplets into polymer matrix or when LC fills the voids of polymer network. In "off" position PDLCs are translucent due to the light scattering effect. When an electric field is applied ("on" position), the reorientation of LC directors changes refractive index of LC domains and devices become transparent. Composites that combine electro-optical and chromogenic response change their transmittance within milliseconds [105].

Numerous products used in construction are made of plastic, e.g., pipes and drainage systems, composite lumber, panels and fences, *etc.* Plastics impart such properties to the BM as water-and decay-resistance, durability, flexibility, relatively light weight, integrated color and low maintenance. They can incorporate a substantial amount of recycled products or can be recyclable themselves. Nevertheless, plastics can have negative effects on the environment including high consumption of fossil fuels required for their productions; release of toxic by-products like heavy metals and furans during their manufacture, use and disposal; generation of large amounts of waste. The most common plastics used in building construction are: high-density polyethylene; cross-linked polyethylene; polypropylene (PP); polyvinyl chloride; polystyrene; polyacrylonitrile; *etc.* Characteristics, associated risks and benefits of these materials are discussed by Calkins [15]. In recent literature there are accounts of two main tools that improve environmental impacts of plastic BM: reuse/recycle and development of new materials with better sustainable properties [15,109,110]. The interest in the field of reinforced plastic composites is rapidly growing [110-113]. The finished composites, which could contain a certain amount of different additives (aluminum, steel, glass, ceramics, nanoclays, natural or synthetic fibers), have better mechanical properties and higher potential for further recycling. Xu *et al.* presented a LCA study carried out in New Zealand for wood-fiber-reinforced PP composite and compared it to a traditional PP [110]. Composite pre-forms, containing natural fibers in the amount of 10%, 30% or 50% by weight, were produced by compression molding. The authors mentioned the following advantages of bio-fibers over the synthetic glass ones: low costs, low density, renewability, excellent chemical resistance, good strength and significant processing benefits. They also concluded that environmental performance of the composite improves due to its lower density than original PP.

Some researchers express concerns about the structural integrity of composite materials [38,111,114]. This indicates that the cracks can develop inside the material upon loading. Further repair of these micro-cracks is difficult or sometimes even impossible. Therefore, the development of self-repairing composites is very important. Unlike a conventional repair, self-repair would occur with the aid of materials contained within damaged structure. The process begins as soon as damage has happened without affecting an overall performance of the structure [11,111]. In this case, the principles of biomimetics and biological self-healing are applied [11]. An ability to use this technique in fiber reinforced polymer composites has been demonstrated by several authors [111,114-117]. For instance, Pang and Bond have developed novel hollow fiber reinforced polymer composite [111]. The release and infiltration of UV fluorescent dye occur from fractured hollow fibers into the damaged parts of the composite. This method can also visually highlight the damage on its surface [111]. The researchers from the University of Illinois (USA) have developed a material with an encapsulated healing agent and a solid catalyst dispersed in the matrix of polymer. Once a crack is formed, these microcapsules rupture and release healing agent into the damaged area. Its subsequent exposure to the catalyst initiates polymerization resulting in the filling the crack. A good level of mechanical strength recovery is observed. The negative effects of moisture swelling and destruction of the composite are also significantly mitigated [116,117].

7. Alternative Building Materials

Due to the exhaustion of non-renewable resources in the near future, there will be a shift in construction towards BM with low embodied energy and that are preferentially available locally [118]. Although it must be acknowledged that in some cases transportation costs can be compensated if non-local materials with better overall performance can be found. Compared to the common BM (concrete, steel, wood and plastics), these materials have a range of beneficial properties such as low toxicity, durability, low level of GHG and other pollutants emissions, high recycling potential and minimal processing requirements. Many of them are biodegradable and do not produce hazardous by-products. Examples of these products include bio-based [15,19,119-124] and earthen [15,19,125-128] BM.

Bio-based BM are generally originated from renewable organic constituents of plants and animals. The resources for these products could be agricultural crops and residues, animal wastes, forest materials and post-consumer biological waste [15]. The examples represented in recent literature include bamboo, straw bales, fiber crops, agricultural residues and plant seed oils. Bamboo, as a sustainable alternative to traditional BM, has attracted attention of many researchers [119-124]. Bamboo, which is a member of giant grasses, is an abundant material in tropical regions of Latin America, Asia and Africa. Thanks to its excellent mechanical properties, light weight, flexibility, high growing rate and relatively low costs, bamboo has many opportunities as sustainable BM, especially in the areas where it occurs naturally [120,129]. The use of bamboo is growing rapidly, particularly in the sector of house interior, for production of laminate flooring, panels, chipboards and fireboards [15]. van der Lugt *et al.* discussed the possibilities of using bamboo as a building material in Western Europe [119]. In this study the suitably of bamboo culms for construction of supporting structures was assessed from the environmental and economical points of view. It was shown that bamboo has a very low environmental impact (20 times better) compared to other more conventional BM. The authors also mentioned the problems associated with the application of bamboo, such as difficulties in joining techniques due to its hollow round form. This issue can be solved by laminating the material. The financial assessment of a bridge in the Amsterdam Woods showed that among other BM bamboo is the least expensive, even with included costs for its transportation from Costa Rica.

De Flander and Rovers have presented quantitative analysis of a laminated bamboo-framed house [121]. It was shown that bamboo has a great advantage in annual yield per forest area compared to a traditional wood. It was demonstrated that one laminated bamboo-framed house can be build from one hectare of bamboo forest. Calkins mentioned the other barriers reducing bamboo overall performance, leading to its short service life: developing cracks for minimally processed culms; slippery outer surface when its wet; susceptibility to the attack of insects, fungi and microbes; deterioration of durability upon the exposure to adverse weather [15]. Obviously, some time and efforts will be required to overcome these issues and make bamboo strong and competitive building material that meets the standards of modern construction.

Materials for earthen construction such as hydrated lime, clay, cob, adobe (mud bricks), compressed earth blocks and rammed earth have been known and used for many years all over the world. Currently, there is a growing interest in these BM as sustainable alternatives to traditional concrete, brick and wood. Many recent publications raise questions related to the soil characterization, manufacturing process and materials testing [130-135]. Earthen BM normally contain soil with some percentage of clay (less than 20%) and water.

Collet *et al.* demonstrated that pre-fabricated cob blocks can be used in modern construction [127]. It was shown that the thermal behavior of south facing 50 cm thick cob wall is about the same as the one for concrete block wall with 7–9 cm of insulation. An additional 5 cm of insulation for the cob wall makes it equal to the dense concrete block with the insulation layer of 15 cm. In another study, Kouakou and Morel examined an effect of clay as a natural binder on the mechanical properties of adobes [126]. Traditional adobe and pressed adobe blocks were studied. Once the adobes dried, they were subjected to a compression testing. The results showed that the mechanical strength depends on the manufacturing process and the content of water in the adobes. Pressed adobe blocks were more homogeneous than traditional adobes and had a higher compressive strength with the gain of approximately 50%.

Loss of strength when saturated with water, erosion due to the wind or driving rain, low dimensional stability are the main problems that have to be eliminated in order to provide successful future application of earthen BM. Nevertheless, it should be noted that the use of bamboo, straw bales, cob, adobe, rammed earth is growing in popularity. Case studies and modern examples of buildings are widely represented in publications [19,128].

8. Conclusions

Nowadays, principles of sustainability have become mandatory in order to tackle global warming and the associated climate change. Governments of several countries have adequate policies in place with a view to controlling and improving the current state of construction industry. The major actions include minimization of energy consumption in the buildings, rational use of natural resources and stricter control of the emissions. All these measures should be systematically applied during the selection of materials suitable for sustainable buildings and construction activities. General issues on the selection BM are sourcing, performance, maintenance and cost.

The present review has analyzed the recent innovations, techniques, tools and strategies in the sector of non-metallic BM spanning over a decade. The main approaches could be summarized into the following:

- Use of renewable energy resources for extraction of raw materials, for manufacturing, processing, finishing and transportation of BM
- Use of materials originated from renewable sources
- Reduce the consumption of disproportional amount of natural resources
- Emphasis on BM available locally and affordable even for poor communities. Although, in some cases, when non-local materials produced on a larger scale than non-local, the transportation of them for long distances can be more beneficial.
- Rehabilitation and application of some vernacular building skills and techniques
- Elimination of energy, water or materials wastage by using manufacturing processes with closed cycle
- Increase the use of waste or recycled products as raw materials or additives to design composite BM with improved environmental performance
- Increase the potential for reuse or recycle of BM or structures
- Increase durability, strength and total service life of traditional and alternative BM
- Design and use composite BM, combining materials with different properties, to achieve improved standards of performance
- Design non-polluting BM required very low maintenance and repair.

With the aim to achieve sustainable BM in the near future, one of the main strategies would be to improve the functionality and environmental performance of traditional materials through the use of more sustainable technologies, for example, utilizing nanotechnology. Producers of sustainable BM will also have to make them more affordable and harmless for human health and the environment.

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