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Fibrous based materials in sustainable civil and architectural applications - a review

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Abstract

The aim of this review paper is to present a survey on fibrous materials used in key areas of construction and architectural sectors. Here are highlighted conceptual challenges involved in some of the applications trying to define what we call a "green" building. The main applications reviewed are concrete reinforcement, structural health monitoring, insulation, and architectural membranes. On the other hand, tendencies in the area such as sustainability, weight reduction, enhanced durability and resistance, multi-functionality, bio-mimetization and hybridization are also discussed and analysed.

Key Words: sustainable construction, fibrous materials, concrete reinforcement, geotextiles, insulation, architectural membranes

Introduction

Innovations performed by the defence industry on military equipment's, systems and materials, and by the aerospace industry on new aircraft materials have been expanded, over the last century, to other areas, including the building and architectural sectors.

The search for high performance materials to address the new construction sector challenges, led to the investigation of fibrous materials and the discovering of their high performance potential. The properties include good mechanical resistance, low density, hydrophobicity, light weight, resistance to rot and fungi. Being resistant, light and water repellent, fibrous materials can have superior performance even than steel, since corrosion problems are not presented and they have the main advantage of reducing weight in buildings, as much as 1/30 in comparison to other conventional materials (1) (2) (3).

Besides the need for new materials with improved properties, it was incremented nowadays the conscience for applying more sustainable and ecological solutions. The building sector is greatly affected in this aspect, since most of the energy consumed comes from the houses (40% according to the European Commission). Sustainable policies are being taking serious and worldwide attention is now placed on them, having a governmental regulation by the European Union and the United States (4) (5).

As defined by Derek Clements-Croome, high performance green buildings are: "energy and resource efficient, non-wasteful and non-polluting, highly flexible and adaptable for long term functionality; they are easy to operate and maintain, and are supportive of the productivity and well-being of the occupants" (6). Fibrous materials and structures reviewed in different application areas are assumed as important solutions to contribute for the performance of these green buildings.

Concrete Reinforcement and Structural Health Monitoring

Plain concrete is characterized by a low tensile strength and low fracture resistance. Moreover, concrete reinforced with steel rods presents corrosion problems, which are accelerated when the concrete present cracks or the construction is placed by the sea.

As a solution to these problems, fibres can be added to concrete in order to reinforce the mixture, increasing the fracture toughness and restraining shrinkage cracking performance. Usually short fibres are added randomly distributed into concrete to reinforce the mixture, to offer resistance to crack initiation and, mainly, to crack propagation. The magnitude of strength and other mechanical properties provided to concrete are dependent on the fibre, matrix and fibre-matrix properties, as well as highly influenced by the fibre dispersion within the cement matrix (7) (8).

Other technique, more efficient but more costly, combine unidirectional continuous fibres with polymers and integrate them into composites to conform hybrid fibre reinforced polymer rods (FRPs). These composite rods placed into concrete replace steel and avoid corrosion. Moreover, the FRPs offer huge flexibility in tailoring their properties by selecting different fibre/matrix systems and composite structures (9) (10) (11). Figure 1 shows all the mentioned types of fibrous systems for concrete reinforcement.

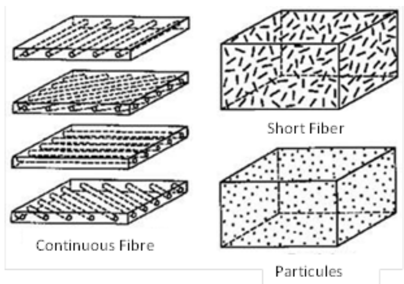


Figure 1 - Types of concrete reinforcing fibrous systems distribution (12)

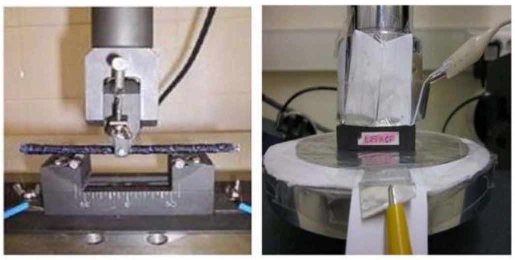
High performance fibres, including glass, aramid and carbon, are used in either of these techniques of concrete reinforcement. Many research projects have been undertaken over the last years to use natural vegetable fibres like sisal, hemp, flax, banana, coconut and eucalyptus. However, the high variation of natural fibres properties has been found as one of the main problems of their use once, this can lead to unpredictable concrete properties.

Short fibres are already popular as concrete reinforcement, and the use of FRPs in civil structures (Figure 2) as replacements of steel is gaining popularity due to their light weight and very good corrosion resistance, despite their cost.

Figure 2 – Composite FRP bars for replacing steel in concrete reinforcement (13)

Nowadays, the need for a health monitoring systems for maintenance and security of the constructed structures is a priority. In the past years, the number of failures in structures by environmental conditions or natural phenomena increased. This is one of the reasons that justify the various research works oriented to develop more economical and efficient monitoring systems, to prevent the catastrophic consequences of these events, giving an opportune alert.

There are systems proposed by researchers based on sensors embedded in the structures, wireless sensor networks ambient vibration-based bridge health evaluation and systems integrated in the cementious structure with piezoelectric-sensing materials adopted to have also reinforcing characteristics. Figure 3 shows a sensing rod developed in the University of Minho.



(a) (b)

Figure 3 – (a) Carbon fibre composite rod tested under 3-poit bending (b) Short fibre composite tested under compression

Sensing materials such as carbon fibres and nanotubes immersed in composite bars reinforce concrete instead of steel and at the same time may perform the structural monitoring. The piezoelectric capacity of such materials is exploited obtaining a sensing behaviour expressed by the change in electrical resistance with flexural strain (11) (14) .

Thermal Insulation

Energy consumption is one of the most important factors when it comes to building sustainability. The efforts to reduce the energy consumed for heating, ventilation and air-conditioning are being redirected to the application of effective thermal insulation systems. Another current, coming from the architectural field, is the design of more bioclimatic environments where the requisites of insulation are diminished. Moreover, the optimization of buildings energy behaviour has been enforced by the scientific and public debates focused on the quality of the urban environment (15).

The Directive 2002/91/EC on the energy performance of buildings introduced the ‘‘energy performance certificate of a building’’ were is referenced that more energy efficient buildings reduce the quantities of fossil fuels consumed and thereby reduce the amount of carbon dioxide and sulphur dioxide emitted into the atmosphere, particularly on a micro- and mesoscale.

In order to minimise the building’s energy consumption by means of thermal protection of its shell, insulating materials with low conductivity values, less than 0.04W/mK, have been developed. The most widely used categories of insulating materials are inorganic fibrous mats (glass-wool and rock-wool) and organic foams (expanded and extruded polystyrene and, to a smaller extent, polyurethane). When selecting an insulation material for a particular application, the first consideration should be the maximum allowable temperature for insulation. Table 1 contains a list of commonly used insulations, an indication of the maximum application temperature, and a reference to a standard specification (16) (17).

Table 1 – Commonly used insulation materials (17)

Type of Insulation Material		Maximum allowed temperature for insulation (K)	ASTM Standard Specification for the material*
1	Mineral fibre pipe (Type 1)	727	C 547
2	Mineral fibre pipe (Type 2)	923	C 547
3	Mineral fibre pipe (Type 3)	923	C 612
4	Mineral fibre board (Type 1A, 1B)	505	C 612
5	Mineral fibre board (Type 2)	727	C 612
6	Mineral fibre board (Type 3)	811	C 612
7	Mineral fibre board (Type 4)	922	C 612
8	Mineral fibre board (Type 5)	1255	C 612
9	Calcium Silicate (Type 1)	922	C 533
10	Calcium Silicate (Type 2)	1200	C 533
11	Perlite block and pipe	922	C 610
12	Cellular glass	700	C 552
13	Polystyrene	348	C 578
14	Polyisocyanurate board	366	C 1289
15	Loose-fill perlite	1033	C 549
16	Loose-fill vermiculite	1033	C 516

Most of the energy wasted due to inadequate insulation is never recovered and the tendency in some of the world's largest economies such as the US, China and India, air conditioning is estimated to triple before 2030, according to the McKinsey/Vattenfall Climate Map. Thus, the implementation of efficient insulation materials is vital for reducing this consumption.

Insulation with high performance fibrous materials achieved a good acceptance because it is possible to reduce the thickness of the insulation laminates, and also their weight, maintaining the same performance as with other mineral insulation materials like asbestos that were found to be toxic.

Architectural Membranes

In the last three decades an impressive progress has been made in the building design to include bioclimatic, biomimetic and thermal protection characteristics. These principles can be distinguished in a particular element of architecture named as "Architectural membrane" more notorious in recent designs for stadiums, airports, train stations and other big spaces (18). Some examples of the applications of these membranes can be appreciated in figure 4.

Figure 4: Various applications of architectural membranes (19) (20)

Architectural membranes (also named as architectural fabrics and textile membranes) are composed by fibrous materials (fabrics) and polymeric coatings. They present adequate properties to build tensioned structures, such as high mechanical resistance, low weight protection against fire and UV rays, having even the capacity to support loads and their own weight. The fabrics generally used are synthetic like polyester, glass, and aramide, and as common coatings polyvinylclhoryde (PVC), polytetrafluoroethylene(PTFE), teflon (PVDF) or silicone (21). The properties of the most used combinations for architectural membranes are presented in table 2.

Table 2 – Properties of the most common architectural membranes (21)

	Polyester fabric with PVC coating	Glass fibre fabric with PTFE coating	Glass fibre fabric with silicone coating	PTFE fabric with PTFE coating
Tensile resistance of weft/warp [kN/m]	115/102	124/100	107/105	84/80
Fabric weight [g/m^2]	1200 (type 3)	1200 (type G5)	1100	830
Trapezoidal strayed weft/warp [N]	800/950	400/400	960/700	925/925
Light transmission variability [%]	10-15	10-20	<80	19-38
Wrinkle recuperation /flexibility	high	low	high	high
Reaction to fire	M2 (8NFP 92 503) B1 (DIN 4102)	M1 (8NFP 92 503) B1/A2 (DIN 4102	A (ASTM E-108) sem toxicidade nem fumos	
Cleanness	Easier with upper layers	self-cleaning	self-cleaning	self-cleaning
Unions by	high frequency	thermic process	vulcanization	sewing
Life cycle [years]	>15-20	>25	>25	
Price	low	high	high	

The resistance of these materials is mainly given by the resistance of the yarns/fibres place normally at 0º and 90º in the fabric. The coating (polymeric resin) aside this, has the function of protecting the fibres against UV rays, abrasion, adverse atmospheric conditions (humidity, rain, snow, etc) and to provide geometrical stability to the fabric. Schematic images of architectural membranes constitution are presented in figure 5.

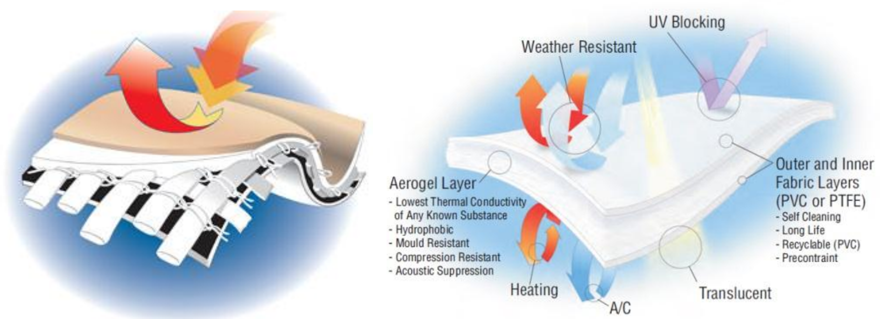


Figure 5 - Architectural membrane constituted by fabric coated with a polymeric resin (22) (23)

The application of these architectural membranes contributed considerably for the reduction of energy consumption (since some membranes let light pass through them), reduction of weight and, on the other hand, gives a flexible material with more freedom of design to the architects. Besides this, the maintenance of these membranes is easier since most of them have self-cleaning surfaces.

Trends

Among the light and resistant materials that are being studied are included polymeric fibre reinforced composites that can be applied in various areas. The principal advantage of these materials is their light weight, significantly less compared to conventional materials.

Regarding thermal insulation, the main trend is the reduction of weight and thickness; researchers are exploring vacuum insulation as a new innovation. In this solutions advanced fibrous materials and structures specially engineered may also play a very important role to fit the last legislation requirements imposed to this sector.

The sustainability of ecological and natural materials is a strong trend, visible mainly in the construction field with the use of natural fibres in various situations, including concrete reinforcement. On the other hand, the strong trend in architecture is the utilization of specially design architectural membranes with enhanced properties, including sensing ability, for covering big spaces, and the implementation of lighter composite sandwich panels for interior divisions.

Conclusion

In conclusion, fibrous materials and structures as lightweight materials that combine very good mechanical properties with ecological characteristics have opened up the possibility of using them in sustainable civil and architectural applications. Fibrous materials can contribute for creating sustainable buildings that save energy, reduce environmental impact and provide a quality indoor environment for their occupants.

There future will bring more technological strategies and alternative visions of how to include fibres for constructing sustainable places with an outline on social constructivist perspective.

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