Architectural Membranes for improving the functional performance of buildings

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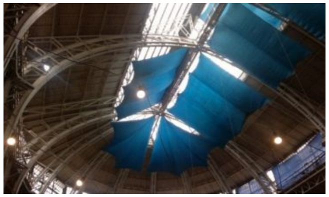

keywords
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thermal regulators
functions

A well designed envelope separates the interior from the exterior so that the internal conditions are maintained with the minimum energy consumption. Due to its reduced weight, architectural membrane solutions may present some functional problems, namely acoustic and hygrothermal, when compared to conventional, heavier solutions. However, they also have potential and ecological advantages that can be exploited to enable the functional optimization of existing buildings in a sustainable way, due to the minimal use of material and the fact that they are dry assembling, easily reusable and recyclable solutions. This paper presents some emergent technologies for applying architectural membranes in building envelope, revealing ways to overcome the limitations for that they are recognized. Current trends include: hybrid membranes and coatings resulting from nanotechnology solutions; membranes with embedded smart technologies (batteries, LEDs, sensors), membranes incorporating Phase Change Materials and membranes for the purification and regulation of indoor air quality. Technological innovation in this field has advanced at an

extraordinary pace in the last decades and has generated solutions that in some cases present functional performance equivalent to conventional solutions, but with less environmental impact.

Conventional buildings

Buildings with strong thermal inertia allow stable thermal conditions to be achieved throughout the day and year [Mendonça, 2005]. The stability of these conditions results from the combination of well dimensioned fenestrations, thermal mass and insulation, which should be complemented, only to the extent of what is strictly necessary, with mechanical equipment (e.g. radiators, furnaces, stoves, air conditioning, etc.). The thermal mass helps to balance the variations between the internal and external conditions: it absorbs the heat when the temperature increases above the comfort range and releases it inwards when the outside temperature decreases under the comfort range.

Membrane buildings

Buildings made exclusively with architectural membranes, inserted in the group of lightweight constructions, do not generally ensure thermal mass or even insulation. Exterior temperature variations are reflected inside the building almost instantly, and heating and cooling gains are quickly lost through the building envelope. However, architectural membranes can perform significantly in thermal insulation through the addition of multiple layers filled with insulating materials, with relatively

	Visible Light Transmission	Weight	Embodied Energy	U value
	(%)	(kg/m^2)	(kWh/m^2)	$(W/(m^2.^oC))$
Clear glass 6mm	85	15.00	73.6	3.03
Double glass 6(10)6mm	70	28.80	147.2	1.92
Polycarbonate clear panel (10mm)	83	2.00	48.4*	1.83
PVC coated polyester	26	0.84	18.3*	2.90
idem, two layers with air gap of 100mm	13	1.68	36.6*	1.85
PTFE coated fiberglass	21	0.81	14.4*	0.83
idem, two layers with air gap of 100mm	4-6	1.62	28.8*	0.72
ETFE foil (0,2mm) $1710Kg/m^3$	95	0.34	4.83	3.03
idem, two layers with air gap of 100mm	n.a.	0.64	9.66	1.92

*Deduced values by [Mendonça, 2005](considering just the embodied energy to make the two components of the material and excluding manufacture)

tab.01 - *Synthesis of functional properties of membrane materials compared to glass. Adapted from Mendonça (2005)*

low costs [Mendonça, 2005].
Normally, the architectural membranes are about one millimeter thick and have a proper weight of 1 kg/m² or less. Even when compared with a simple 6mm thick glazing, which weighs approximately 15 kg/m², the difference is very significant, even more if compared to a simple wall of hollow brick, which presents a proper weight of more than 150 kg/m².
The U value (heat transfer coefficient) of a single membrane is approximately 5 W/(m².C). Comparatively, the average U value required for an opaque façade in Portugal is approximately 0.4 W/(m² °C) and for a glass façade approximately 2.4 W/(m² °C), what means that, as in a glass facade, a double layer is required, as well as controlled fenestrations area.
This means that the properties such as thickness, mass and thermal conductivity on which the conventional thermal mass is supported assume unimportant values in the case of architectural membranes, the thermal mass and thermal resistance of the architectural membranes are practically null. As a result, buildings constructed with architectural membranes are particularly sensitive to changes in weather conditions, being affected much faster and significantly than buildings constructed with conventional heavyweight materials. Even in a relatively favourable climate on a sunny day, the indoor air temperature of a building with architectural membrane can become 20°C hotter than the outside air temperature, and the surface temperatures recorded on membranes with high solar absorption capacity can reach 45 to 50°C [Mendonça, 2005]. Additionally, there is no significant thermal delay between the temperature

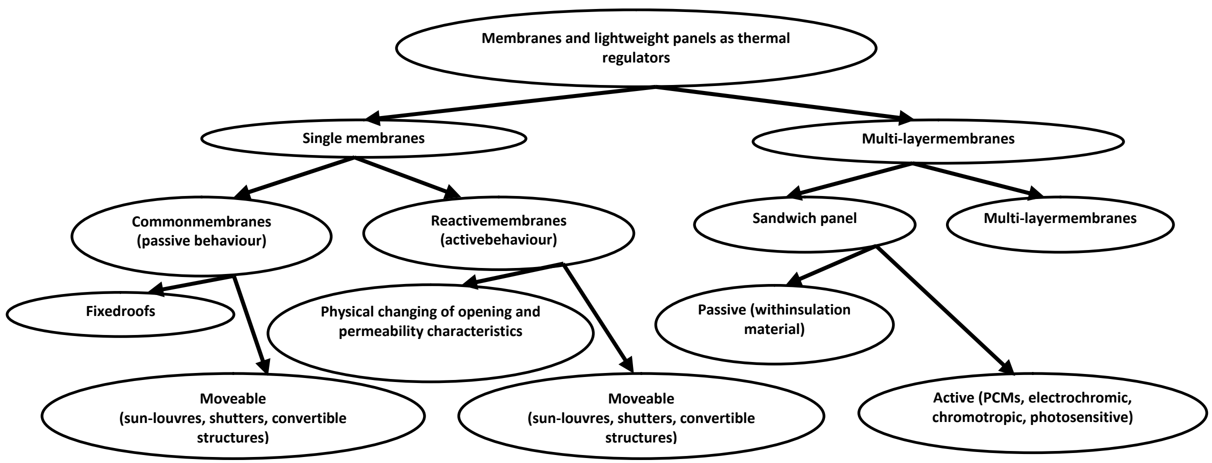


fig.01 - Classification of membranes and lightweight panels as thermal regulating elements [Mendonça, 1997]

variation on the outer surface and the resulting change on its interior surface.

Functional aspects - advantages and disadvantages of membrane constructions

The functional aspects associated with membrane constructions in the buildings' envelope are summarized in tab.02. Although there are many advantages associated with the application of membranes in architecture, there are also some obstacles / limitations. Many strategies can be developed to increase the thermal efficiency of membrane systems in the envelope of buildings with application in architecture (see fig.01).

Thermal performance

Harvie [Knippers et al., 2011] and Devulder [Architen Landrell, 2009] studied the thermal aspects related to membrane materials and buildings. The main role of the materials in the exterior envelope of the buildings is to mediate the relationship between the exterior and the interior in order to maintain the internal conditions with the minimum use of material and energy resources. This is not simple, as external conditions change during the day and throughout the year. For example, in certain situations, there is a need for the building envelope to contain or reject the heat. Given this example, one must consider that the building envelope has to do this while performing

Thermal apects	Lighting aspects	Moisture aspects	Acoustic aspects	Loading and durability aspects	Applicability for active solar technology:	Other aspects:
• Solar transmission/ absorption/ reflection; Integration options for phase change materials (PCM); • Surface emissivity/ absorption in the long-wave infrared range; • Reflection in long-wave infrared range; • Selectivity of transmission; Soiling behaviour of surfaces;	• Transmission/ absorption and reflection of visible light; • Colour fidelity of reflection/ transmission; • Refractive behaviour; • Scattering the light;	• Tightness with respect to precipitation an gases (mainly water vapour); • Integration options for getter materials; • Resistance to water and chemicals;	• Sound absorption/ reflection/ transmission/ attenuation capacity; • Flanking transmission capacity;	• Mechanical load-carrying capacity to production/ erection, vandalism, weather (e.g. hail); • Resistance to UV radiation; • Chemical resistance with respect to substances dissolved in precipitation, to salt-laden air (e.g. coastal sites) and others;	• Applicability for solar thermal systems: water or air based; • Applicability for photovoltaic systems.	• Electro-magnetic shielding; • Electrical conductivity; • Electro-minescence; • Thermo-chromism; • Memory effect; • Micro or Nano structure options.

tab.02 - Main functional aspects associated with membrane constructions in the buildings' envelope (adapted from [Knippers et al., 2011]) multiple roles, such as: obtain solar gains, allow access and views, ventilate, protect from noise, protect from intrusion, etc. Additionally, designing a thermally comfortable building is complex, since thermal comfort depends on several factors that can be conflicting, such as: air velocity, radiant temperature, relative humidity; clothing, metabolism, health status of occupants, etc.

Thermo-optical properties of membranes

Without mass and thermal insulation, the architectural membranes affect the interior of the spaces delimited by the amount of heat transferred and its internal surface temperature. The calculation of the amount of heat transmitted directly by the membranes through solar radiation in a single layer configuration is relatively simple, and is based on their translucency. However, according to Harvie [Devulder, 2005], the calculation of the amount of heat introduced into the space resulting from an internal membrane in a double layer configuration is more complex and is based on: (1) solar absorption (optical property that can be measured); (2) heat exchanges with adjacent air (in and out) by convection (the smooth surface of the membranes allows efficient convection) and (3) infrared radiation exchange between the interior and exterior. These thermo-optical properties depend on the angle of incidence of solar radiation. As the incident radiation angle increases, the reflectance and absorption (in percentage terms) of the remaining incident radiation increases and this causes the transmittance to decrease. Therefore, to accurately model the performance of architectural membranes, it is necessary to know the angles of solar absorption, transmittance and emissivity.

The same transparency of a glass pane is impossible to achieve on polymer membranes. However, in terms of changes, adaptability and production methods, polymer membranes may offer much more possibilities. The membranes can also be used to promote shading and prevent overheating of an interior space. The penetration of natural light through a membrane roof, for example, can potentially result in the reduction of artificial light consumptions. In many cases, it is only possible to control and redirect inconvenient natural light with additional shading systems using membranes (example on fig.02). It is possible to take advantage of the reflective characteristics of the membranes to reflect the solar radiation to the sky, or to reflect it in a way that is beneficial for the occupants of a building. Polymer membranes are the only materials that allow building large free spans and, at the same time, light-permeable structures. With the PTFE membrane it is possible to achieve a light permeability of 40%, and with thermopolymers it can reach 85%. These features enhance energy efficiency by reducing the consumption of artificial light in buildings.

fig.02 - Architectural Membrane for light control and diffusion in Food Market, Kiev, Ukraine (photo from the author)

Improving thermal performance

New developments enhance the use of architectural membranes by increasing their thermal performance through the creation of effective thermal mass and adjustment of optical properties without a significant increase in their own weight, namely:

- multilayer membranes can provide insulation levels with U values ranging from 2 to 2.5 $W/(m^2.C)$ for double membranes [Architen Landrell, 2009];
- ETFE pneumatic membrane structures composed of five layers can provide thermal insulation equivalent to a double or triple glass solution but with one tenth of the weight [Architen Landrell, 2009];
- membranes with reduced emissivity have been developed to reduce the absorption and emission of long wavelength radiation [Enob, 2015] - in order to overcome the thermal performance limitations of membranes, new developments, such as low emissivity coatings for membranes, allow membrane building solutions to assume more functions in the outer skin of buildings, for example to benefit thermal transfer properties of translucent surfaces.
- sandwich solutions are being developed with the incorporation of thermal insulation and reaching U values as low as 0.2 $W/(m^2.C)$ [Architen Landrell, 2009];
- development of membranes that include components made from other materials, such as insulation panels, glass or photovoltaic cells;
- the ability to print images or patterns on the surface of a membrane has a significant impact on the optical properties.

Non-conventional thermal mass (lightweight) embedded in membrane

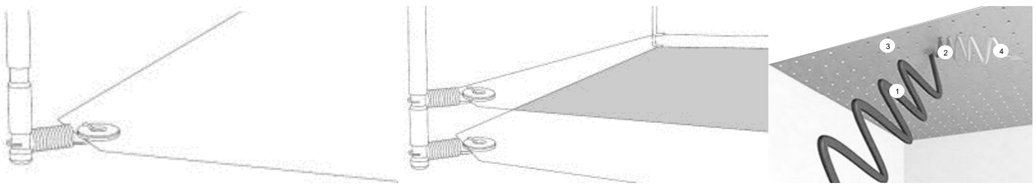
Phase change material (PCM) began in the 1970s with a NASA research program [Hale, Hoover & O'Neill, 1971]. Phase-change textiles include microcapsules, which store and release energy through the phase change of materials. Pause explored and presented results of the application of PCM to membranes in their studies [Pause, 2008]; phase change means the change from liquid state to solid state or vice versa. PCMs are generally encapsulated in sandwich or honeycomb panels, help to stabilize the temperature gap between day and night and are already used in textile membrane applications for buildings. According to the results of the monitoring in test cells, Mendonça concluded that there are benefits in the integration of these materials into passive solar strategies [Mendonça, 2005].

Translucent thermal insulation in membrane
The company Solarnext AG and the group Hightex worked with the Institute of Technology of Georgia to produce a roof with high thermal insulation and that allowed the passage of light. The result consisted of a pneumatic membrane structure filled with aerogel. The incorporation of aerogels in the solutions with PTFE or ETFE membranes allows to reach coefficients of thermal transmission of 0.76 $W/(m^2.C)$ to a thickness of 2.5 cm [Birdair, 2011]. The Tensotherm™ Nanogel® product is an example of a thermosetting membrane developed and produced by the American company Birdair. This product consists of two layers of PTFE coated fiberglass membrane filled with a layer of nanogel. The thermal-regulating property of this material is based on the phase-shifting properties of nanogel [Birdair, 2010].

Acoustic performance
According to [Knippers et al., 2011], the thinner the absorbent material, the better the absorption of low frequencies. Various measures can be taken to achieve this effect. These measures are based on the optimization / activation of surfaces enclosing a compartment (ceiling, walls, glazed surfaces, etc.) by installing additional elements such as: (1) perforated surfaces with suitable backing layers; (2) layer of insulation material on ceilings (with open and closed cells); (3) reflecting components, sound absorbers (e.g. with micro perforations), screens, etc.
There are membranes that include micro-perforations with diameters between 0.2mm and 0.8mm, specially developed to improve the acoustic conditions of a room. With a single membrane it is possible to reduce the reverberation time (fig.03 (a)) and, by doubling membranes, the sound absorption effect can be increased (fig.03 (b)). Because of their lightness and translucent variants, micro-perforated membranes are suitable for rehabilitating existing buildings (fig.03 (c)). These membranes can be applied together with thermally active surfaces, as they do not compromise their performance. For example, using a printed membrane with a reflective colour pattern under a glass cover can achieve thermal and acoustic benefits thanks to the reflection of long waves of heat radiation and the reduction of associated heat losses.
When evaluating and optimizing the acoustics of the compartments with membrane solutions, it is recalled that due to their reduced mass and flexible surface nature, airborne sounds are transmitted directly and poorly reflected, especially in the low frequency range. This makes the membrane structures bad acoustic insulation solutions. However, according to Mendonça heavier membranes

coated with absorbent materials or micro-perforation may have some acoustic absorption effect [Mendonça, 2005].
The materials used in pneumatic structures are airtight inside and so it is not possible to add absorbent materials. The use of membranes with 3D meshes is suitable for outdoor use and represents another option for improving sound insulation. Generally, these spacer meshes (3D) are between a membrane and a second support layer with a distance of approximately 500 mm. The resulting cavity can be filled with sand, for example, and with a minimum thickness and weight it is possible to achieve a sound insulation of approximately 35 dB in 20 mm [Knippers et al., 2011].

Functionalization of architectural membranes
A vast field of highly relevant research and development covers the functionalization of membranes through the modification of their surfaces (in fibrous or film structures), or through the smart combination of materials (fibres, fabrics, etc.).
The concept of smart membranes became known in the textile industry in the 1990s. Innovations in the area of functional and smart membranes are continuously developed and commercial applications are actively created. The smart membranes are composed of fibres and materials that have functional properties and that interact with their surroundings; are divided into three subgroups: passive, active, and reactive [Mendonça, 1997]. The difference between the passive and active membranes is that the passive ones detect stimuli in the envelope, while the active ones react to the sensed stimuli. Reactive membranes have the ability to detect, react and adapt their behaviour according to their environment [Tao, 2001] [Addington & Schodek, 2005].
The stimuli that smart materials detect include: chemical reactions, moisture, electricity, force, magnetism, movement, light, pressure, sound and temperature. Reaction to these stimuli may result in changes in material conductivity, electrical



a) b) c)

fig.03 - Translucent and micro perforated membrane solution to improve the acoustic conditions of a compartment: (a) single membrane and (b) double membrane [Knippers et al., 2011]. (c) Scheme of reduction of the reverberation time of a perforated membrane: (1) Initial sound; (2) Transformation of sound into thermal energy; (3) Perforated membrane; (4) reduced sound [Barrisol, 2015]

properties, shape, optical characteristics, colour and properties related to light and structure. For example, cotton fabric with a blend of polyalcohol (used for tents) becomes impermeable when it comes in contact with moisture. There are also membranes with ceramic fibres - able to block radiation; textiles sprayed by gas ionisation and coated with metal - which prevent the penetration of electromagnetic radiation and radio signals; membranes that change colour in response to fluctuations in UV radiation or temperature; phosphorescent membranes that can absorb sunlight and slowly release it when the sun disappears; and membranes that can absorb or eliminate odours, but combined with air renewal. In addition to impregnation or lamination, these properties can also be incorporated into the membranes through printing or sewing [Clevertex, 2005]. One limitation of these "smart" additions to the membranes is that only a small amount can be added without adversely affecting the mechanical properties thereof.
Euratex [Euratex, 2006] recognizes that research areas of high priority for the textile industry include: (a) custom performance with advantage to users - through the ability of materials to adapt or change their properties according to the environmental conditions of their surroundings; (b) reduction of the environmental and energy impact of the processes used for the functionalization of membrane materials; (c) increased flexibility and efficiency in the development of products and materials through design.

A portuguese example of membrane functionalization was obtained through a partnership between the CITEVE and CENTI research centers and the Têxteis Penedo company under the "CORTFEE" project. This project resulted in the development of a product - functionalized and energy efficient curtains to reach a reduction of energy consumption between 2 to 3% [Têxteis Penedo, 2015]. This functionalized membrane has the following characteristics: thermal inertia control (reduction of thermal load in summer and increase of heat retention in winter); reduction of heat exchanges; significant reflection of incident radiation; contribution to energy efficiency and thermal comfort; malleability and lightness.

Conclusions

The possibilities of using the membrane materials in the construction are almost unlimited. However, according to Ollenhauer [Ollenhauer, 2011] in their study on the market "Textiles in Architecture", membrane producers find difficulties on implementing these solutions. This is related to the strong cyclical nature of the construction industry, long certification procedures, and, above all, the task of communicating the developments in this industry to a diverse and highly fragmented group of professionals.
The membranes have potentialities, but also limits of application in buildings. In some cases, poor durability (for example uncoated textile membranes) and the fact that it is impossible to erect a

membrane construction without the support of a rigid structure constitute some of its limitations. However, a membrane can result from the combination of different materials, such as glass, wood or metals, resulting in more interesting constructive solutions than considering these separately, for example allowing to achieve almost "unlimited" durability. Thanks to the improved characteristics of membrane materials - in terms of the strength-to-weight ratio, durability, flexibility, absorption properties, fire resistance - these can replace conventional building materials such as steel and other metals, wood and plastics [Grabe, 2010]. Architectural membranes offer efficient and aesthetic solutions, not only due to their lightness, mechanical and chemical properties, but also when functionalized for applications in the construction sector. An example of application where membranes have not been frequently employed so far is the use of multilayer composites. In these cases, it is possible to optimize each layer relative to its material functional properties. Larger applications, such as storage / thermal insulation and / or sound insulation, may be obtained by the integration of other suitable materials within the multilayer composite. Airborne and possibly phase change materials are in principle suitable for improving multilayer membrane structures - making them multi-purpose components, assuming advanced functions with respect to thermal insulation. Other functions, such as electrical conductivity, electroluminescence or integrated nanostructures, will also be relevant, positively altering the functional properties of the envelope. Membrane properties can be specifically adapted to change the functional conditions of buildings. In ecological terms they present lowe use of energy and resources associated with its production, as well as easier reuse and recycling possibilities.

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