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A study on the durability properties of textile membranes for architectural purposes

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Abstract

The durability of textile membranes in outdoor architectural applications is a key factor to be considered in a specific project design. The degradation of the polymers within the coating and its propagation to the fibres contributes to the loss of functional performance, mainly in terms of mechanical properties. The aim of this work was to study the durability of two architectural membranes: one produced with polyester fibre coated with polyvinylchloride (PVC) and other produced with glass fibre coated with polytetrafluorothylene (PTFE) at the initial stages of environmental exposure. These materials were subjected to an *in-situ* degradation in a real environment and a rapid degradation by the action of moisture and ultraviolet radiation in an accelerated aging chamber over a period of 2160 hours (3 months). The effect of these agents on the degradation and thus the durability of the membranes was evaluated by the loss of mechanical performance (tensile strength test) and thermal performance levels (Alambeta test). In addition to mechanical and thermal analyses, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analysis were performed, in order to understand the effect of the degradation agents on the surface of the membranes. The mechanical performance of the polyester/PVC membranes has shown unchangeable properties, while the glass fibre /PTFE membrane has presented a reduction on tensile strength properties. These reduction was more significant when the membrane were subjected to the accelerated degradation test, showing a decrease of resistance of about 34 % and 43 % on longitudinal and transversal direction, respectively for the period of 2160 hours. SEM images of polyester/PVC membranes did not show any significant difference over time, however EDS analysis showed a loss of 52 % of the chlorine element. For glass fibre /PTFE membrane, SEM and EDS analysis didn't show any significant difference over degradation time.

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1. Introduction

The planet is going through a major crisis in terms of obtaining natural resources and fossil fuels and sustainable solutions are constantly being sought. One of the worrisome topics besides this is the fact that energy consumption is growing worldwide and water is becoming increasingly expensive, resources that are extensively being used in the conventional construction industry [1]. Current strategies to reduce these parameters include the use of eco-efficient building materials with low embodied energy that at the same time are useful for the urban space [2]. Examples of eco-efficient structures are the architectural membranes that have been successfully used in many projects of modern architecture [3, 4, 5]. The development of innovative polymeric coatings and their combination with fibrous structures (fabrics) based on high-performance synthetic fibres results in a composite material with interesting properties for buildings, such as high mechanical strength, hydrophobicity (water repellency) protection against fire and sun, capacity to support loads and their own weight and resistance to tearing and fungi [5].

Synthetic polymers such as polyester, glass, and aramid are commonly used as fabric materials, in which the yarns/fibres are interlaced in two mutually perpendicular directions (0° and 90º) in order to achieve the desired degree of strength, translucency and impermeability [4]. As coatings, polymers such as polyvinylchloride (PVC), polytetrafluoroethylene (PTFE), polyvinylidene difluoride (PVDF) and silicone have been applied. These have been reported to impart shielding properties to the fabrics' fibres by protecting them against UV radiation, abrasion, adverse atmospheric conditions (humidity, rain, snow, etc.) and to provide geometrical stability to the fabric [5]. Therefore, this type of structures has been commonly applied as a sustainable solution to replace steel and concrete [6].

Membrane structures can be seen as flexible and adaptive systems that adjust to different environments according to the necessities, e.g. responding to climate variations. They are meant to protect the building against environmental actions, at the same time allowing the natural light to enter into the space [7, 8]. The use of membrane structures in public facilities such as outdoor coverage passages, stations and stadiums have increased in recent years, since it allows for creating larger built spaces [9]. Being thin membrane materials they are very light and transparent, possessing highly solar-reflective properties, which allows for absorbing little solar heat, keeping their surface temperatures low when irradiated by solar radiation [10]. As a result, a space with both daylighting and natural ventilation can be provided. Apart from that, the architectural membranes are able withstand environmental factors and structural loads, presenting a greater lightness when compared to conventional materials with similar mechanical characteristics [4]. Moreover, it allows saving energy through natural light control and internal temperature.

Apart from the interesting functional properties these structures provide, the study of the durability of the fabrics and coatings within the architectural membrane is a growing concern. The progressive degradation of the membrane over time modifies its components and properties, causing tearing phenomena [4]. This is problematic if we consider the demanding technological development we are facing nowadays that requires durable and sustainable materials for the market. It is therefore important to understand the behavior of architectural membranes over time, to what extent their durability is affected and which implications it brings for its efficiency.

Herein, we have studied the durability of two commonly used composite materials in architectural membranes: one produced with polyester fibre coated with polyvinylchloride (PVC) and other produced with glass fibre coated with polytetrafluorothylene (PTFE) at the initial stages of environmental exposure, by subjecting them to an in-situ degradation in a real environment and a rapid degradation by the action of moisture and ultraviolet radiation in an accelerated aging chamber over a period of 2160 hours. This work intends to contribute to the understanding of the phenomena that leads to the initial deterioration of architectural membranes and that often prevents its use on a wider scale.

Nomenclature

PVC	Polyvinylchloride

PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene difluoride
QUV	Accelerated weathering tester
SEM	Scanning electron microscopy
EDS	Energy dispersive spectrometer
EBSD	Electron Backscatter Diffraction
λ	Thermal conductivity
A	Thermal absorptivity
R	Thermal resistance

2. Materials and methods

2.1. Materials

The architectural membranes comprised of polyester fibre membrane coated with PVC and glass fibre membrane coated with PTFE was purchased from commercially available membranes in the market.

2.2. Durability tests

The membranes were subjected to degrading conditions in two different environments: one that mimics real conditions of use and the other under laboratory-controlled conditions using an accelerated aging apparatus. In both methods the membranes have been exposed to ultraviolet radiation, heat and humidity at exposure times of 360 h, 720 h, 1080 h, 1440 h and 2160 h.

To perform the durability tests under the real environment conditions, the membranes were placed in lab-made support composed of several wires with appropriate spacing so that the membranes are flat and grip each other to promote a greater orientation to sunlight and weather. The accelerated degradation of architectural membranes was assessed according to the standard AATCC Test Method 186-2001. Briefly, the membranes were exposed to UV light and humidity using a QUV accelerated weathering tester. The membranes were placed under a fluorescent lamp with a wavelength of 340 nm, corresponding to UVA light. The UVA exposure cycle was 16 hours with a temperature of 50 °C, followed by a water pulverization at 50ºC and an exposure time of 24 hours.

2.3. Membrane characterization

After exposure to real environment and accelerated degrading conditions the architectural membranes were characterized in terms of physical performance by calculating the thermal properties using Alambeta equipment. The mechanical performance was assessed using the universal machine Hounsfield H 100 KS. Scanning electron microscopy (SEM) was used to assess the membrane differences at nanoscale between the aged and the non-aged membrane. The equipment used to make the images (NanoSEM - FEI Nova 200 (FEG/SEM); EDAX - Pegasus X4M (EDS/EBSD)) is an ultra-high resolution field-emission Scanning Electron Microscope, with integrated microanalysis X-ray system (EDS - energy dispersive spectrometer) and Electron Backscatter Diffraction (EBSD) that allows for obtaining elemental analysis, providing small and micro-spot X-ray analysis and mapping.

3. Results and discussion

Degradation is the ability of a certain material to lose their physical and chemical properties over time due to climatic factors. It is a complex process in which UV radiation, applied tension and weather conditions (temperature variations, rain and humidity) plays a key role in the deterioration of the polymer properties within the coating, imparting significative damage to the membrane [11]. Moreover, with time, architectural membranes absorb chemicals from the environment of the region where they are placed, which may also induce chemical reactions that promote the damage of the coating. Taking into consideration the requirements of this demanding market, the architectural membranes should be able to withstand the degradation caused by the climate factors over its lifetime [12]. Two commercially available architectural membranes comprised of polyester fibre/PVC and glass fibre/PTFE were subjected to normal weather conditions for 2160 h (90 days) and to accelerated degradation conditions in order to evaluate their durability in terms of initial degradation when exposed to the environmental conditions.

The thermal properties were further evaluated on both membranes in terms of thermal conductivity (λ) and thermal resistance (R). The only factor affected by the ageing process was the thermal conductivity in both real and accelerated ageing, which was decreased with time in both membranes. This means that material lost somehow his ability to conduct heat, which is a good characteristic since it improves the insulation properties of the membranes. Despite this variation was not so significant, this behavior was already envisioned for other applications [13]. The thermal resistance was slightly increased for the time studied, which is in good agreement with the λ values presented.

Table 1. Thermal properties of polyester/PVC membranes and glass fibre /PTFE membranes before ageing (0h) and after ageing (1080h and 1800h).

			0 h	1080 h	1800 h
Polyester/PVC membranes	λ (W.m*K)	Real	0.106 (CV ± 4 %)	0.099 (CV ± 2 %)	0.097 (CV ± 3 %)
		QUV	0.106 (CV ± 4 %)	0.095 (CV ± 1 %)	0.094 (CV ± 4 %)
	R (m^2*K/W)	Real	4.84 (CV ± 5 %)	5.06 (CV ± 1 %)	5.28 (CV ± 2 %)
		QUV	4.84 (CV ± 5 %)	5.42 (CV ± 2 %)	5.22 (CV ± 3 %)
Glass /PTFE membranes	λ (W.m*K)	Real	0.070 (CV ± 5 %)	0.055 (CV ± 3 %)	0.057 (CV ± 4 %)
		QUV	0.070 (CV ± 5 %)	0.073 (CV ± 2 %)	0.068 (CV ± 4 %)
	R (m^2*K/W)	Real	4.84 (CV ± 6 %)	5.06 (CV ± 5 %)	5.28 (CV ± 6 %)
		QUV	4.84 (CV ± 6 %)	5.42 (CV ± 2 %)	5.22 (CV ± 2 %)

The mechanical performance of the membranes was also assessed by determining their tensile strength at each time point when exposed to both real and accelerated ageing conditions. This test was developed in order to understand the behavior of architectural membranes when exposed to moisture, heat and ultraviolet radiation, either in terms of rapid degradation in the laboratory and in real degradation conditions. The mechanical properties of the polyester/PVC membranes were maintained with time while the glass fibre/PTFE membrane presented a reduction on tensile strength properties. This reduction was more significant when the membrane was subjected to the accelerated degradation test, showing a decrease on resistance of about 34 % and 43 % on longitudinal and transversal direction, respectively for the period of 2160 h (Fig. 1). For the real conditions, however, the tensile strength reduction was only 15 % in the longitudinal direction and 12 % on the transversal direction for the same period (Fig. 1). The reason for this loss might be due to the fact that the interaction between the fibres within the fabrics begins to fade and further between the fabrics and the coatings, which eventually leads to membrane ripping.

These results are surprising since glass/PTFE based membranes have been considered the most durable membranes, with a project life in some cases exceeding 30 years. PTFE coating is extremely durable and weather resistant [14] while the glass fibre provides the strength and permanence for the material [15]. PVC-based membranes on the other hand are considered less durable with a lifespan of 10-15 years if exposed to high levels of UV [16]. Nevertheless, previous studies have proven the improved mechanical strength of PVC-based membranes, in which the yarns that are aligned straight inside the composite, are capable of being oriented in different directions and to respond in a successful way to the applied efforts [5]. This study indicates that the failure of some structures might be indeed related to the loss of mechanical strength due to environmental factors. The study of these phenomena in the degradation of the membranes is of particular importance in the design of more efficient and durable materials.

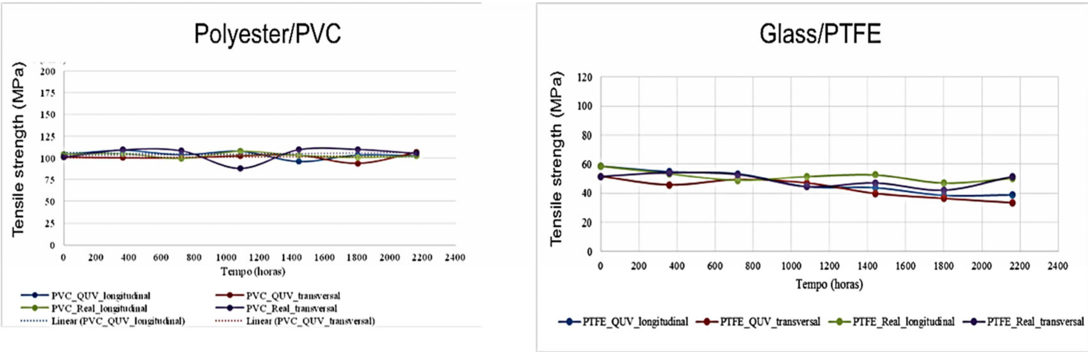

Fig. 1. Effect of the ageing process on the tensile strength of the polyester/PVC and glass/PTFE membranes.

In order to understand these results, a morphological study of the membrane was performed using SEM. A clear difference was observed before and after ageing on the surface of the Polyester/PVC membrane. Despite the non-aged membrane possess holes due to manufacturer defects, the aged membranes seem to possess cracks and zones on the material where the coating does not exist (Fig. 2).

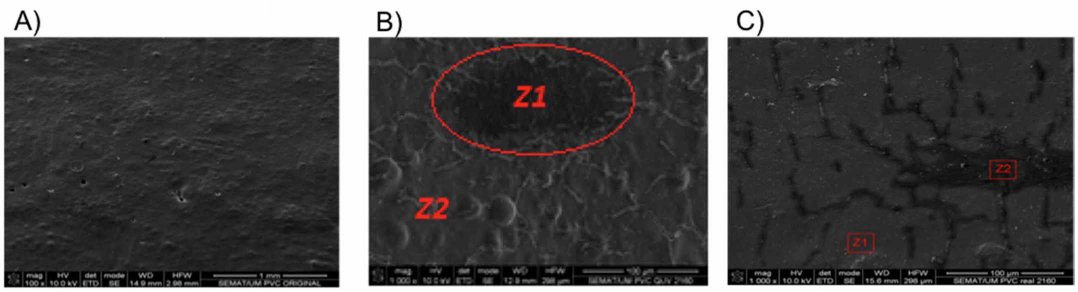

Fig. 2. SEM micrographs of the Polyester/PVC membrane: A) without ageing effect (100x magnification); B) aged 2160 h, at real conditions (1000x magnification) and C) aged 2160 h with QUV (accelerated) (1000x magnification).

Using the SEM equipment, the chemical composition analysis of the surface of the membrane was assessed for the marked zones and a reduction of the chemical element chlorine in about 52 % on both zones tested and in both aged samples (Fig. 3). PVC contains chlorine in its chemical structure and since this element is reduced it can be concluded that the PVC coating is being highly degraded with time. Despite the fact that no reduction on the mechanical performance was observed for this membrane it can be clearly seen that the coating is highly affected by the environmental factors and may induce failure in the structure after some time. This is in agreement with the reported reduced lifespan of this kind of PVC based structure. Even though polyester provides the mechanical strength, the membrane will soon fail in its protection properties against UV and adverse atmospheric conditions. In fact, increased surface soiling has been observed on Polyester/PVC membranes. The material gets darker, the absorption of heat increases, higher temperatures accelerate the chemical aging, the softeners vanish, the material gets more brittle, small cracks appear on the coating, and finally the fibres are affected and tensile strengths are reduced.

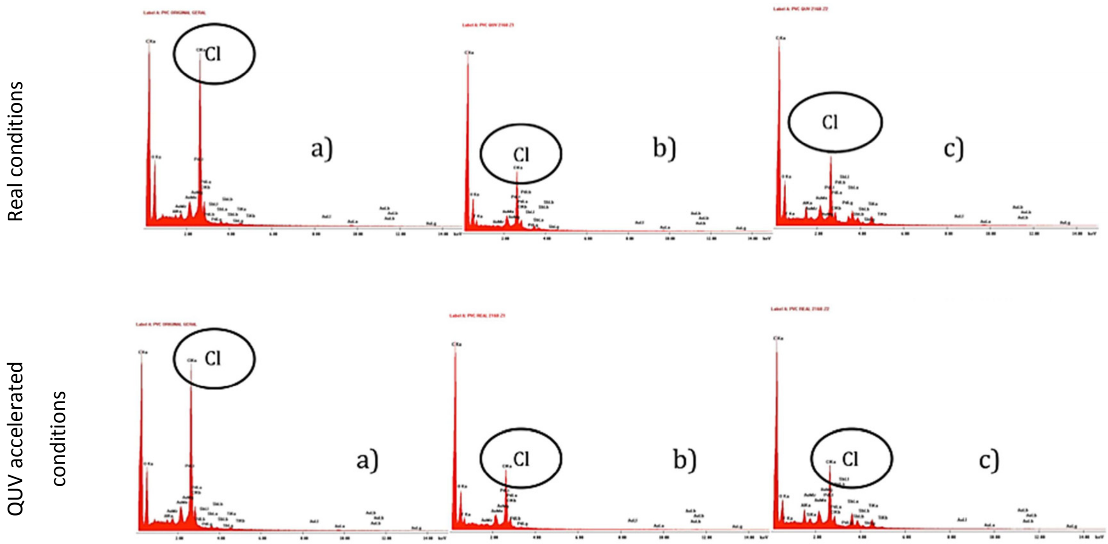

Fig. 3. Chemical composition analysis of Polyester/PVC membrane from the zones marked in Fig. 2: a) without ageing; b) 2160 h ageing zone 1 (Z1) and c) 2160 h zone 2 (Z2)

The same evaluation was performed to the membranes composed of glass fibre /PTFE and as can be seen in Fig. 4, no significant changes were observed on the surface of the membranes after the ageing process. The images present the same morphology and as expected, by analysing the chemical composition of the membranes no differences on the spectra were found, indicating that the membranes' coating maintain their integrity after ageing process (Fig. 5). The previously observed reduced mechanical strength for this membrane could thus be attributed to the glass fibre fabric since no significant morphological and chemical changes could be observed on the membrane surface. Moreover, it is well known that PTFE possess "self-cleaning" properties, which allow the material to keep its high initial solar reflectance [17].

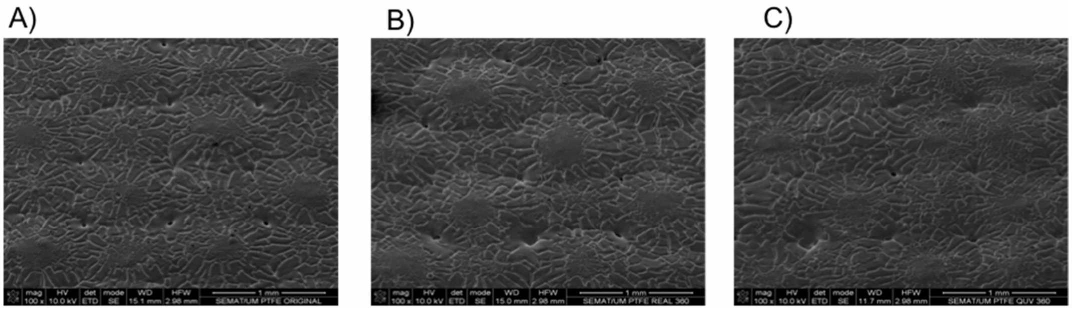

Fig. 4. SEM micrographs of the glass fibre /PTFE membrane: A) without ageing effect (100x magnification); B) aged 2160 h, at real conditions (100x magnification) and C) aged 2160 h with QUV (accelerated) (100x magnification).

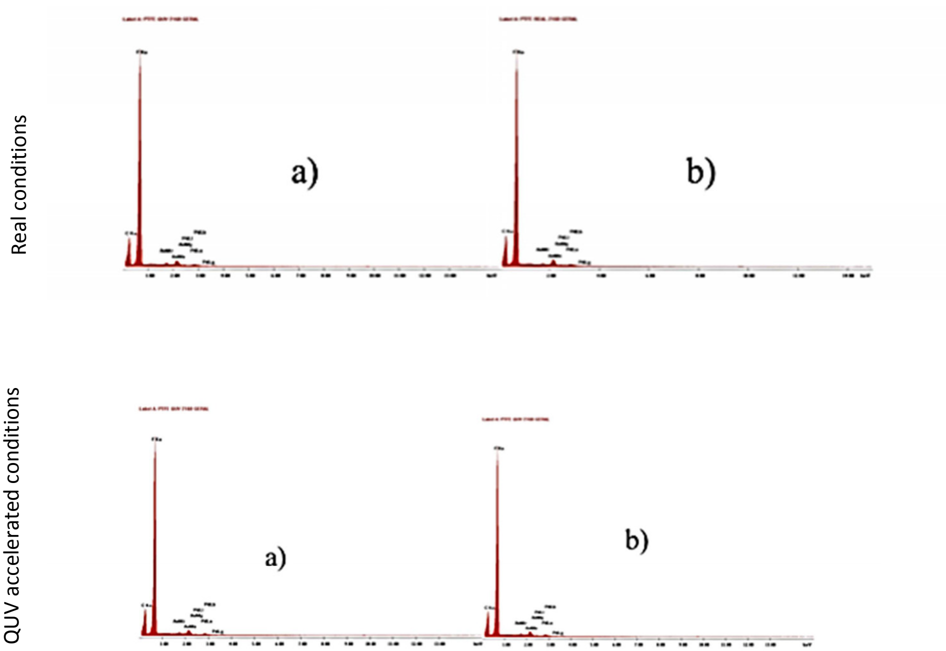

Fig. 5. Chemical composition analysis of glass fibre/PTFE membrane from the surface of the micrographs from Fig.4: a) without ageing; b) 2160 h ageing zone 1 (Z1) and c) 2160 h zone 2 (Z2).

4. Conclusions

In an actual context where the reduction of the use of natural resources is mandatory and the renewal in the field of architecture and engineering is necessary, the architectural membranes are increasingly claimed as innovative concept of a "light" and sustainable material for construction. Sustainability seeks for the reduction of the ecological footprint, which has been increasing for many years, and architectural membranes has been playing a central role in replacing materials such as concrete and steel. With the increasing use of these structures worldwide, their behavior when exposed to different weather conditions on the physical and mechanical performance remains unknown. Therefore, it is necessary to understand how these two performances change over time, both in terms of real aging and accelerated aging. In this study, the influence of a real and accelerated climate conditions on commercially available architectural membranes were performed and analyzed in terms of physical and mechanical performance.

The thermal performance of the membranes was found to be mostly stable over time. The values did not change significantly, reaching a balance on the course of study. In terms of mechanical performance, polyester/PVC membrane was found to be as resistant before and after ageing. On the other hand, for the glass fibre/PTFE membrane a reduction on the mechanical resistance was observed, being this more pronounced when the accelerated ageing conditions were applied. By analyzing the surface of these membranes under SEM we could conclude that the resistance of the polyester/PVC membrane is mainly due to the polyester fibrous structure since PVC is clearly degraded after the ageing process. On the other hand, the loss of resistance observed for the glass fibre/PTFE membrane is mainly due to the glass fibre since no morphological changes are observed in the PTFE coating. Even though these results suggest that the membranes are degraded when exposed to normal and accelerated climate conditions further studies using more exposition time should be performed to assure that such properties are really lost, maintained over time or get worse leading to the degradation of the architectural membranes. Future studies will also include a broader variety of materials and different suppliers. This work has contributed for understanding the phenomena that leads to the initial deterioration of architectural membranes, which may help on finding solutions to obtain a more durable and thus sustainable material.

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