PICTURE THIS: A NEW PERSPECTIVE ON TENSILE MEMBRANE DEGRADATION

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Summary. This paper advances understanding of the degradation mechanisms in PET-PVC coated membranes by identifying the critical role of lichen colonization. These insights establish a framework for more rigorous condition reporting methodologies, thereby supporting improved resilience and adaptive strategies in the context of climate change.

1 INTRODUCTION

Popularity of architectural membrane solutions to provide shelter, shade and enclosure spread rapidly during the 1990s and 2000s. Many projects adopted a PVC coated Polyester fabric (PET-PVC) which had an anticipated life expectancy of 15 to 25 years at that time. As these structures now reach or exceed that service life, material degradation insight becomes increasingly relevant, helping owners to manage risks associated with their built assets.

A growing body of recent research is revisiting this topic. Much of the available literature[1,2] is understandably focused on the reduction of tensile strength resulting from exposure to a variety of weathering factors. They build on the long-established expectation that loss of plasticisers embrittles the PVC leading to cracking and subsequent UV degradation of the PET. Whilst this remains a widely accepted model[1,2], findings from an Accelerated Knowledge Transfer project[3] suggest it is time to reframe how we understand and address degradation processes in practice.

This paper considers how end-of-life is defined for membrane structures and presents an alternative degradation process based on visual and microscopic inspection of a selection of new and naturally weathered fabrics from real structures. It is particularly relevant to a key reason structures reach their useful end of life, namely that their appearance fails to meet the expectations of the owners. The paper offers insights into the biological process of degradation and considers how this can prompt stakeholder action as a positive response to climate change. How should we specify and maintain membranes structures to extend their life and what needs to change to help owners manage risk?

2 MEMBRANE PERFORMANCE IN CONTEXT

Whilst the intent of this paper is not to provide a detailed review of coated membranes, some

background information is required to contextualise the findings and assist in understanding the degradation processes presented.

2.1 A brief overview of PET-PVC membrane formulation development

There are many combinations of base materials available for the use on tensioned membrane structures. The focus of this research was on a polyethylene terephthalate (PET) base fabric with a polyvinyl chloride (PVC) coating used widely across all global regions and especially in Europe where there are a number of producers supplying a range of strength grades and formulations.

Essentially the PET substrate carries the tensile load and the PVC provides protection to the load carrying fibres. Additives to the PVC coating include plasticizers for flexibility, TiO2 for whiteness and UV resistance, and a range of fillers, flame retardants, and anti-fungal agents. Over the years the formulations have adjusted to take advantage of newer compounds (e.g. TiO2) as well as phasing out less desirable chemicals (e.g. Arsenic). To encapsulate these base components, a finish is applied to the top and bottom surfaces (**Figure 1**).
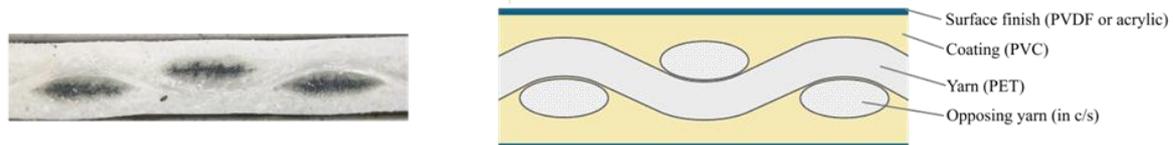
Figure 1: Typical membrane construction; cross sectional image and diagrammatic interpretation (as used in degradation stages below)

Prior to the 1990s this finish was primarily an acrylic on both surfaces. As producers strived to achieve parity with the allegedly 'self cleaning' nature of Glass-PTFE membranes, PVDF finishes were introduced in gradually more complex chemical formulations. The improvements brought greater confidence in longevity of the membranes supported by extended warranty periods, typically around 5 years in the 1980s up to 25 years on some high-end products today.

Whilst this confidence is underpinned by artificial ageing tests, of which several specifications and methods exist (refer Asadi[1] and Joao[2] for details), the consensus is that it is unlikely that they represent real world conditions for most structures, omitting elements such as cyclic loading and nature-based activity/biological action (bird guano, lichen growth etc.). What they do provide is an indication of longevity at point of sale.

Equally, warranty terms are often linked to having maintained the structure correctly, but details of how to do this are sparse. A review of maintenance guidelines from five producers suggested regular inspections, typically at least every 6 months. However, an indication of cleaning periods is often not provided and suggested to be dependent on the site specifics and level of dirt accumulation. Without guidance on what this might be, owners are left to rely on the experience of the maintenance companies, who may typically suggest an annual clean.

All producers state that their PVDF-finished products were (relatively) low maintenance and would typically 'self clean', yet there was rarely any mention of the impacts of guano or biological action as described in this paper.

2.2 Business need

There is a portfolio of existing structures approaching their 'end of life'. The owners of these structures need to understand the risks associated with their built assets to plan maintenance

and replacement strategy. Given the age of these structures, warranty periods will have expired. It is very difficult to answer the question "How long will my structure continue to last?" with a high degree of confidence. The answer is complex and depends on both the history of the structure to date, as well as a prediction of what may happen in the future. These aspects rely on many structure, site specific and interrelated factors. Understanding degradation is therefore important as it provides a framework for assessing the current state of the membrane, whilst clarity on how structures reach their end of life sets limiting criteria to be met in the future.

2.3 Current state of condition reporting

Owners will normally have in place some form of facilities management regime, especially for larger assets, which will include provision for condition surveys, maintenance and cleaning. The resulting condition report will often be based on a visual inspection of both the membrane, the connecting hardware and support structure, and report on physical damage (as a result of mechanical intervention) and potentially subsequent repairs.

Only in special cases will the report include commentary on life expectancy. This level of detail will normally only be possible by an in-depth structural assessment and removal of membrane samples to determine the residual structural resistance (by tensile and tear strength tests). However, removal of samples is problematic as it compromises the structural integrity and continuity of an existing structure, and whilst feasible welding of patches becomes increasingly difficult as the membrane ages.
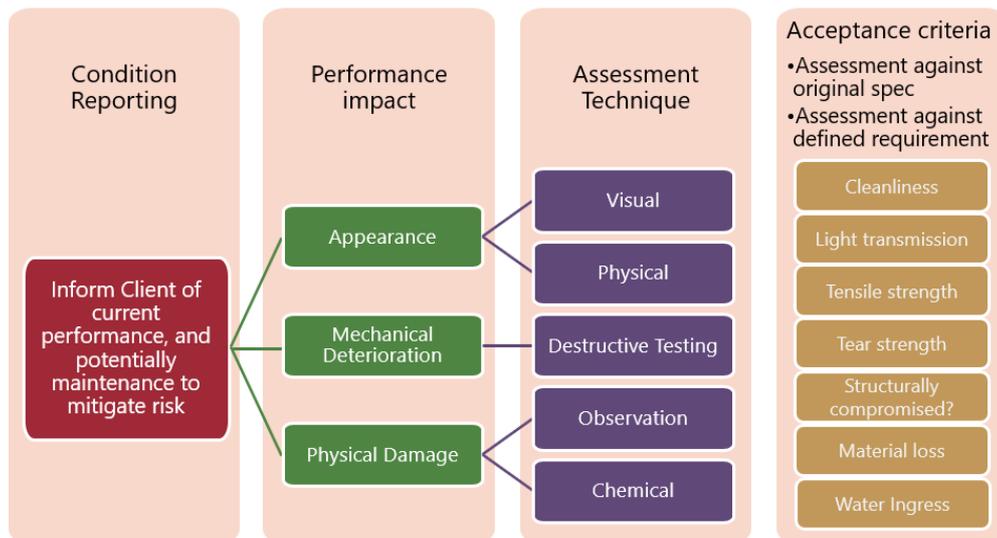
Figure 2: Condition reporting, indicating purpose, performance impact considerations, assessment techniques, and examples of acceptance criteria for gathered data

In general terms, the ideal condition report would consider the impacts and techniques shown in **Figure 2**. Pre-determined key performance indicators (KPI) defined at the start of a project could, over the life of the structure, be monitored against the acceptance criteria, similar to those shown. In practice however, this level of detail may not be possible for a variety of reasons including cost, risk (eg. the removing physical samples described above) and perceived benefit. Hence, current condition reports tend only look at the appearance and any physical damage, based on visual techniques, general observations, and experience of the surveyor.

2.4 Understanding degradation and end-of-life

An understanding of the factors influencing end-of-life provides a rational basis for determining inspection criteria during condition surveys and reporting. A common understanding of what is meant by 'end-of-life' is when the membrane fails to perform its designated purpose, and this is often linked to mechanical failure of the membrane structure. In practice, however, replacement decisions are often driven primarily by the membrane's appearance, rather than by assessments of its mechanical or structural integrity.

In the author's experience, membranes rarely, if ever, fail directly as a result of the membrane capacity being exceeded by loading below the original design criteria, even if degraded after weathering. Whilst structural membranes do occasionally fail mechanically, this is usually the result of poor detailing, impact of airborne debris, material defects, extreme loading events (outside of original design parameters) or interventions such as fire, vandalism, human or animal activity. These events should not be seen as through life degradation.

Degradation is the reduction of performance over time and for the membrane material, considering end-of-life scenarios, this can be categorised as aesthetic failure or mechanical failure, which echo two of the impacts listed in **Figure 2**. Degradation under both these categories will be accelerated by inappropriate maintenance (mechanically or chemically excessive, or lack of maintenance), and nature-based activity (microbial, lichen, and plant growth and aggressive deposits). Aggressive environments (salty, sandy, highly polluted) will also contribute, but these are addressed to some degree by allowances in the structural design.

As stated in section 2.1, focus has been on degradation of mechanical properties, and aesthetic failure has been largely ignored.

2.5 Samples in this study

The AKT project gathered PET-PVC samples of new fabrics produced by Serge Ferrari, Mehler, Sioen, and SaintClair, and unused old stock produced by Serge Ferrari (1995), Mehler (2016), and Verseidag (1987). Grade and finish varied across the samples, but images to capture visual appearance and continuity of the surfaces did not show significant features relating to degradation, even for the old stock samples which had been stored in office environments. They form a useful reference point but are generally not presented here.

Specifically, the focus is on identifying features of degradation pertaining to membranes which have been exposed to external conditions for a number of years. Images of real world naturally weathered membranes were taken of extracted and in-situ samples using mobile microscopy techniques as described in section 3. These included dismantled structures dating from 1998, 2007, (and a Glass-PTFE membrane from 1994), and existing structures dating from 1991, 1998, 2014, 2020. Further detail, including producer name, membrane grade and structure location is not provided here for confidentiality reasons, but does not detract from the findings.

3   VISUAL TECHNIQUES

3.1 Overview of methods

To investigate the adequacy of different methods and equipment used for capturing images of the sample condition, a selection of techniques with increasing levels of detail and resolution were compared (**Figure 3**). In general terms, this increase in detail comes at the expense of increasing cost and reduced portability. The importance of cost and portability are worth

mentioning. To build a robust database, many images are required so a lower cost option is preferable if it provides the necessary level of detail. Equally, portability enables images to be gathered in-situ, without the need to remove samples. The removal of samples is not only problematic with the potential to compromise the existing functionality of the membrane (structural, aesthetic, protective) but also has an associated cost. Static methods, which must be carried out remotely in the laboratory, could still be used on targeted samples if beneficial.
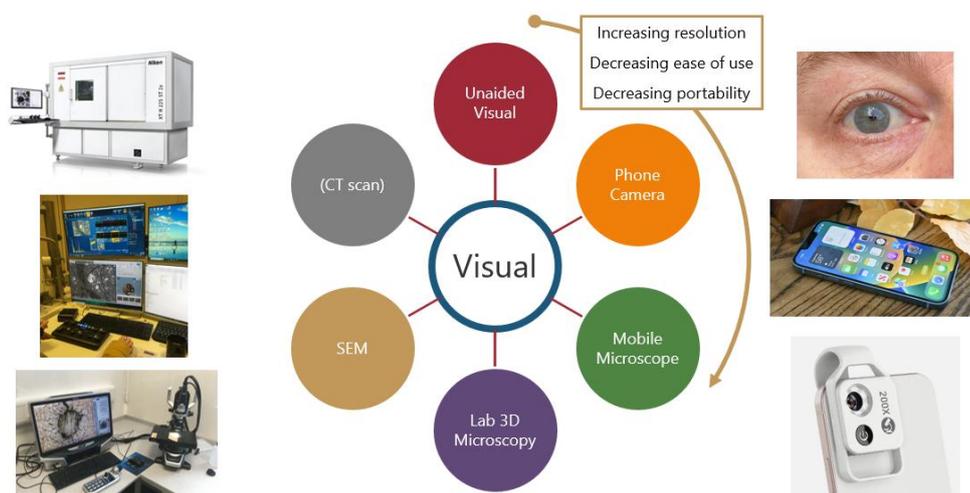
Figure 3: Visual techniques: (clockwise from top right) Naked eye, camera phone, mobile microscopy, 3D microscopy, scanning electron microscopy (SEM), computed tomography (CT)

3.2 Assessment of output

Typical output examples (**Figure 4**) provide a comparative view of the level of detail each method can achieve. All images relate to the same sample of PET-PVC taken from a coastal structure and aged at approximately 25 years. All the PVDF finish had been lost from natural weathering, as confirmed by energy-dispersive X-ray spectroscopy (EDX) analysis and scanning electron microscopy (SEM) imaging. Samples were noticeably stiff (inflexible) when handled compared to new material, and possessed crazed/cracked surfaces, evidencing significant loss of plasticiser. The loss of finish had increased the ability of biological growth to adhere to the surface which was removed before capturing the images in (b) to (f) enabling inspection of the membrane condition.

These and other pictures (images) gathered during the project confirmed that a basic visual inspection with the naked eye, or with photography at a distance, provides very little information on surface condition, despite it being the basis for many inspections. It also showed that 'dirty' surfaces conceal the true condition of the membrane finish and coating.

Standard mobile camera pictures demonstrate only minor improvements but may highlight suspect areas or features. Specifications vary and are improving, but typically an area of around 90mmx60mm can be captured in focus, dependent on the lens specification. However, with a mobile microscope attachment (similar results would likely be achieved with portable digital microscopes and a laptop) a high resolution image is possible for an area of approximately 9mmx6mm. Display zooming functionality can then be used to identify significant detail at yarn and fibre filament level without loss of focus.

The mobile microscopes can provide a similar level of detail to lab microscopy but with less functionality. A three-dimensional microscope (3DM) manufactured by Keyence (model

VHX5000), was trialed in the AKT project. This equipment has interchangeable lenses providing a range of magnification levels. Fully focused composite 3D images are created by stitching together multiple images over a range of depth of fields. This enables the additional functionality to generate cross-sectional profiles and estimations of surface roughness.

Lab-based techniques such as SEM offer additional functionality and be combined with chemical techniques for greater insight, such as EDX (mentioned above) to visualise chemical distribution within the surface. Fourier Transform Infrared (FTIR) scans can be used to identify bond vibrations within the molecular structure. Whilst not a visual technique per se, FTIR can be used with microscopy to determine the chemical nature of precise areas on a sample, enabling identification of organic matter within the coating. Finally, computed tomography (CT) scanning produces a three-dimensional visual model which can be sectioned.
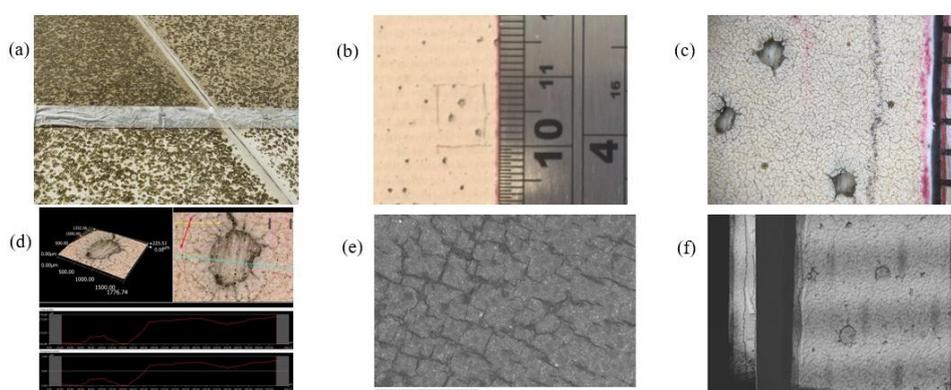
Figure 4: Results from different visual techniques on 25 year old PET-PVC (a) naked eye, biological growth (b) mobile camera phone, dark spots/pinholes (c) mobile microscope, visible yarns (d) 3D microscopy, visible yarns (e) scanning electron microscope (SEM), cracked PVC coating (f) CT model, through-construction imagery

3.3 An alternative degradation pathway revealed

During the assessment of these techniques a new route to degradation became apparent, not based on mechanical failure associated with weathering and embrittlement, but as a result of nature-based activity and lichen growth. In several of the aged samples, the pictures revealed organic growth and fine tendrils penetrating the weave, prompting further analysis using the higher end techniques to confirm initial observations. The findings led to a new interpretation of how a membrane may degrade aesthetically because of biological action, and a hypothetical mechanism is presented in section 4.3 below.

4 MEMBRANE DEGRADATION

Degradation and end-of-life scenarios have been defined, with degradation of the membrane attributed to the two underlying pathways presented here.

4.1 Weathering pathway (embrittlement)

The commonly accepted[1,2,3] degradation pathway results from the exposure to environmental conditions such as ultraviolet light, moisture, temperature, and loading (especially wind and snow) which leads to natural weathering degradation. The stages associated with this pathway are summarised in **Figure 5**. It begins with crazing and cracking in the finish layer associated

with membrane response to physical and thermal loading. These cracks accelerate plasticiser migration by diffusion, increasing brittleness and promoting further cracking and crazing of the PVC layer. As plasticiser loss progresses, the underlying PET yarns become exposed to UV radiation, resulting in photo-degradation, fibre fracture, and ultimately perforation of the membrane. This sequence builds on the well-established understanding that plasticiser loss drives PVC embrittlement, surface cracking, subsequent exposure and degradation of the load-bearing fibres and results in a loss of tensile strength capacity.
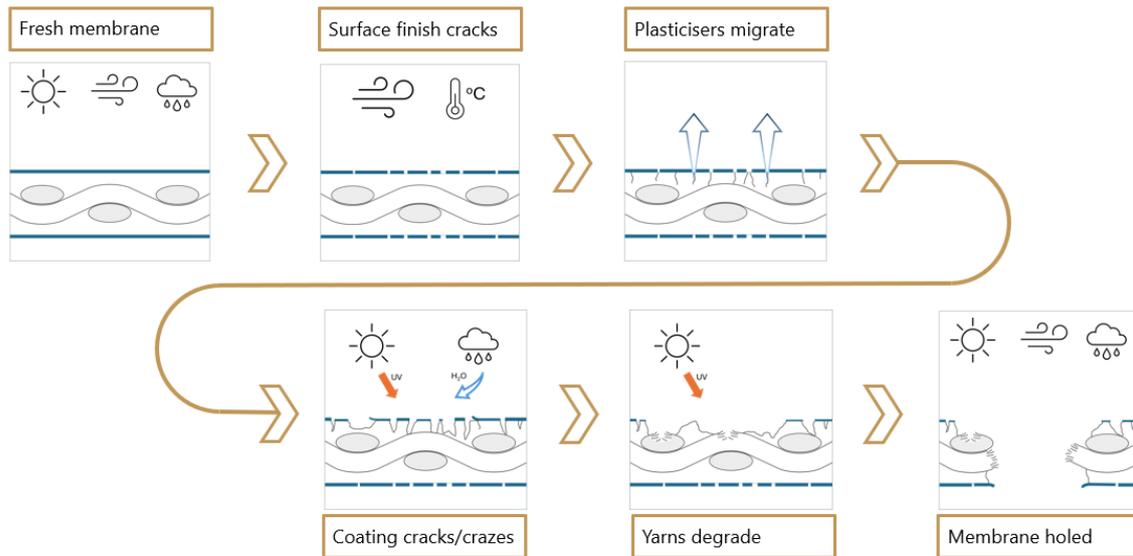
Figure 5: Weathering pathway: stages of degradation resulting from environmental conditions

The images in **Figure 6** give an indication of how these stages appear under the microscope. Cracks and crazing can align to yarn directions but may also present as a random pattern. The 3DM image highlights the surface unevenness with the yarn layout plainly visible. The extreme degradation examples have been affected by pressure washing and an aggressive microclimate.

Figure 6: Visual examples of weathering degradation; top row: new PVDF coatings, crazing in the finish (21yrs but concealed under a clamp plate), spots and cracks in the coating (25yrs); bottom row: 3DM image showing fabric structure, extreme case (33yrs)

Nature-based activity is often acknowledged in research papers[1,2,4] investigating natural and artificial weathering but there is no further explanation of how this may degrade materials. The following sections seek to address this.

4.2 Introduction to lichens

Whilst biological activity may occur in several forms, those presented here relate to lichens.

Lichens are a complex symbiotic organism formed by fungi and photosynthetic partners (algae and cyanobacteria). Over the past 15 years their complexity has been identified further[5] to show the presence of other bacteria, yeast and microorganisms. They occur in three principal growth forms: fruticose, crustose, and foliose. All three types were observed during the course of the research with a selection of images presented in **Figure 7**.

They thrive on a wide range of substrates, including coated membrane structures, and typically anchor themselves in surface irregularities such as holes, cracks, seam edges, or areas enriched by deposits like guano. Their growth is sustained by rainwater for moisture, sunlight for energy, and nutrient inputs from environmental deposits. Once established, rhizines (root-like tendrils) can penetrate beneath protective coatings, making removal difficult and accelerating localised deterioration. Colonisation also alters the membrane's performance, reducing light transmission and darkening the surface, thereby affecting both its functional and aesthetic properties.


Fruticose · Foliose · Crustose
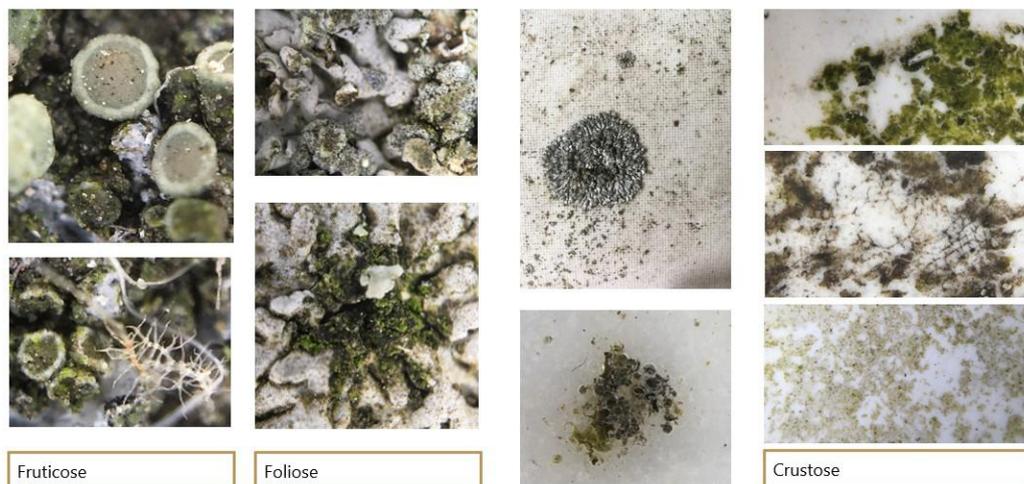
Figure 7: Examples of lichen growth on membranes; PET-PVC (left and right) Glass-PTFE (centre)

4.3 Biological action pathway (the new perspective)

A new degradation pathway is identified from the analysis of the collated pictures. The hypothesised stages associated with this pathway are summarised in **Figure 8**. The initial stage echoes that of the weathering pathway, where the surface finish cracks and crazes, but even small pre-existing discontinuities could enable organic deposits such as guano to adhere and accumulate. These nutrient-rich sites promote biological colonization in the sunny, moist environment. Lichen rhizines penetrate beneath the coating, and although cleaning removes surface soiling, residual rhizines facilitate rapid recolonization from existing cracks and defects, undermining the bond between finish and coating. Progressive degradation of the coating and underlying layers exposes the PET yarns, which subsequently deteriorate under UV and

moisture, ultimately resulting in membrane perforation and hole formation.
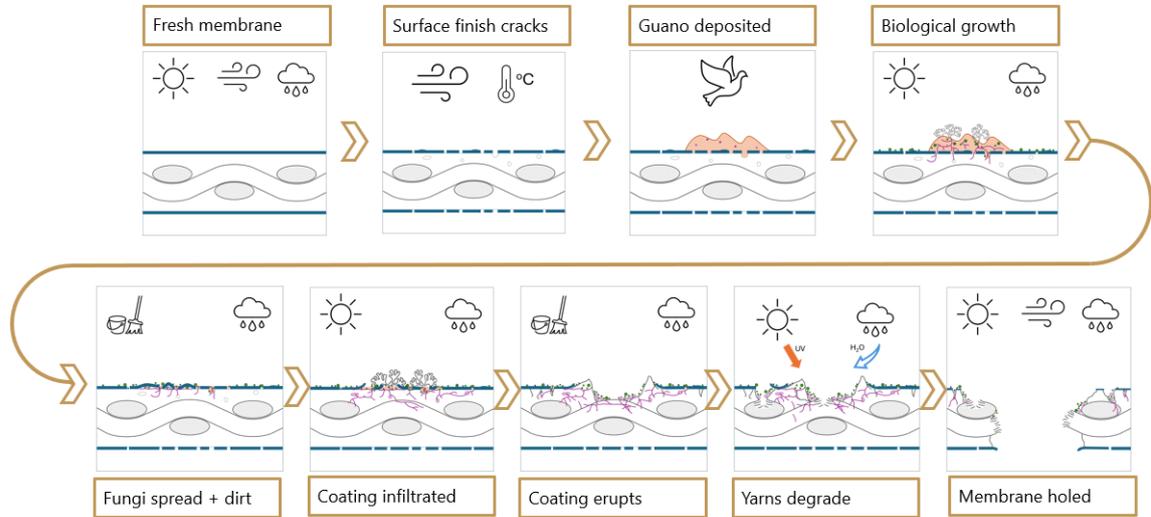
Figure 8: Biological action pathway: stages of degradation by lichen growth and proliferation

The top sequence of images in **Figure 9** highlight different stages of the formation of a hole in the coating due to lichen growth, often occurring at the high point of the weave where the coating is thinnest. The bottom row of images evidence residual organic matter present after cleaning. Samples were from various structures and locations demonstrating that this is not an unusual occurrence.
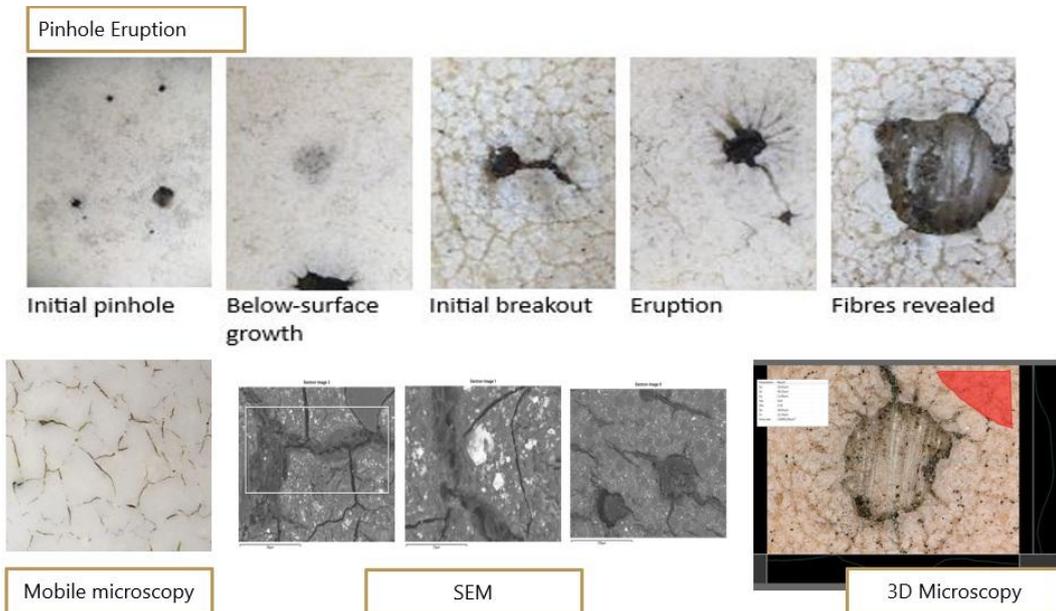
Figure 9: Visual examples of biological degradation; top row: lichen growth sequence creating a pinhole eruption and exposed yarns; bottom row: residual biological growth in surface crazing, SEM images of fungal remains, 3DM image confirming rhizines tendrils

5   WHAT ARE THE IMPLICATIONS?

Two alternative pathways to degradation have been presented and evidenced visually.

However, it is expected that these will not occur in isolation but more concurrently. The degree to which each contributes to the eventual demise of the structure will be dependent on the specifics of the location, environmental exposure, and the maintenance regime adopted. But just as the fungus and algae work symbiotically to enhance their individual impact, so too will the two degradation processes with the potential for each one to accelerate the rate of the other.

With respect to the biological action pathway, lichen growth and spread is inevitable. Despite efforts by the producers to develop and improve high-end finishes to the membrane, these have been shown to only slow the spread of lichens and not prevent them. This is not only true for PET-PVC membranes, but also for Glass-PTFE membranes. Growth begins immediately on exposure and is relatively rapid (less than a year) and once established, it can be considered as 'impossible' to remove. Whilst highly basic (pH>11) or acidic (pH<3) solutions may be able to kill the fungi upon which the lichen is based, these are also detrimental to the chemical make-up of the membrane and are prohibited by the producer warranties. Similarly, high-pressure water washing removes elements of the membrane coating and finish as well as the organics.

Once engrained within the coating and fabric, the density of the particles, even after cleaning, will increase over time to severely impact the aesthetic appearance of the surface and reduce light transmission. This organic matter harbours moisture for other biological growth, which can degrade fibres directly through direct attack or production of extreme pH environments.

6   FUTURE ACTIONS AND OPPORTUNITIES

6.1 Responding to climate change.

The increasing impacts of climate change has brought renewed focus on the construction sector, where globally it accounts for 37% of emissions according to UN reports. Three aspects to mitigate climate impact are considered.

Firstly, the reuse and recycling hierarchy is presented in various forms, but the latest version of PAS2080:2023[6] simplifies the hierarchy to "avoid, switch, improve" in order of priority. Avoidance may translate to avoiding or delaying the replacement of an ageing structure and assessing the needs of the project more rigorously at the outset. Switching to different membrane products if, after assessing the alternatives, they are deemed to fulfil the performance requirements (even if not equal in relative terms) could offer whole life carbon reductions. Improving resource use by sympathetic assessment of the condition of membranes and lowering of the acceptance threshold as it nears its end-of-life. This may draw from the appropriate choice of materials at the inception of a project or the mapping of a bespoke maintenance regime from the outset.

Secondly, in Europe, but echoed globally in several regions, proposals to restrict production and use of fluorinated compounds (collectively termed PFAS) gathers speed, coordinated through the European Chemicals Agency (ECHA[7]). Irrespective of when or to what extent these restrictions are introduced, avoiding the use of fluorine-based compounds in coatings and finishes where they are not required or serve no real benefit over the lifetime of a structure should be considered.

Thirdly, the aim should be to optimise the use of resources and materials to maximise lifetime of the asset. Any action to extend this, such as managing expectations on maintenance and planning accordingly, should be encouraged.

6.2 Adapting current practice

In real terms, the responses noted mean that 'business as usual' needs to adapt considering the new perspective on membrane degradation which impacts the appearance of the structure. The following are suggested.

Membrane materials should be specified appropriately. If there are options to use materials which are more recyclable and have adequate performance these should be considered. Coatings should not be over specified; there is little benefit in selecting a high-end PVDF coating for a short-lived temporary structure. The choice of colour may yield benefits; whilst white would appear to be the colour of choice, the whiter the fabric the more it will show the dirt. Choosing a cream, beige, grey or silver finish for example, makes dirt accumulation less obvious and examples exist including, a bridge walkway canopy at Paddington railway station (UK) adopting a silver fabric appropriate to the transport environment above which it sits).

Expectations around visual appearance and end-of-life should be managed from the outset of a project. This requires the owner to be fully appraised of how the appearance will change over time and enable specific thresholds for cleaning and end-of-life replacement to be monitored and acted upon.

From the manufacturer and installer perspective, a tailored a maintenance regime should be developed in conjunction with the owner. Whilst this is currently often part of an operations and maintenance manual, it is proposed that these become more site, location and structure specific. Regular inspections, which the owner could also be trained to do, and frequent collection of data would help adjust the plan over the lifetime of the structure.

7 FUTURE RESEARCH

This new perspective on membrane degradation opens a variety of opportunities for future research through the value chain. The database of referenceable samples and structures remains low despite a growing research interest in degradation over recent years, evidenced by the increased number of research papers,. A change in practice by those who inspect, maintain and dismantle the structures at their end-of-life, and indeed the owners themselves, could provide valuable samples for further testing if they are retained as opposed to being discarded. This would grow the database, evidencing membrane performance and longevity, especially if these could be linked to location, environmental conditions and meteorological records. It is felt that this would also be invaluable to producers, who could even consider incentivising this practice.

It has been demonstrated that the impact of nature and biological growth on tensile membranes is significant, but as a relatively uninvestigated topic, more research is required. Can the mechanisms for lichen development and spread across and within the membrane structure be better characterised? How effective are the anti-fungal additives used by the producers? And can this propagation process be interrupted?

As the world introduces increasing restrictions on certain chemicals to protect the environment, real world performance data comparing PVDF finishes to acrylic finishes needs to be assimilated so that benefits can be matched with risks. Understanding the alternative and concurrent degradation processes is fundamental to this.

Finally, developing a digital twin of the membrane condition to model the impact of environmental factors, alongside generative AI techniques, could assist in the prediction of site-specific performance. This in turn would assist in defining ageing factors used in the original design (k_{age}, CEN/TS 19102:2023[8]) and benefit clients in quantifying risk.

8 CONCLUDING REMARKS

This paper presents an alternative view on the degradation of structural membranes based on visual and microscopic inspection of a selection of new fabrics, unused old stock and samples taken from real world naturally weathered structures. The observations point toward nature-based activity, such as biological growth and surface contamination, as a potential accelerant in the degradation process challenging current assumptions and offering a new perspective on membrane condition assessments.

In light of these findings, the paper reflects on how 'end-of-life' is defined and measured in the new paradigm of climate change. The discussion considers whether; visual deterioration and acceptance criteria should be more precisely defined to customize cleaning regimes and manage client expectations; the appropriate use of high-performance coatings so as not to over specify; and how the industry may better advise clients and practitioners with respect to maintenance and inspection to extend the life expectancy of structures.

9 ACKNOWLEDGEMENTS

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